Towards better detection of sport-related concussion in Australian football

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List of Terms

AD	Alzheimer's Disease
AE	Athletic Exposure
AFL	Australian Football League
ANAM	Automated Neuropsychological Assessment Metrics
BOLD	Blood Oxygen Level-Dependent
CARE	Concussion Assessment, Research and Education
CIR	Concussion Interchange Rule
CISG	Concussion in Sport Group
CNT	Computerised Neurocognitive Tests
CT	Computerised Topography
CTE	Chronic Traumatic Encephalopathy
DSM-5	Diagnostic and Statistical Manual of Mental Disorders 5th Edition
DTI	Diffusion Tensor Imaging
fMRI	Functional Magnetic Resonance Imaging
GCS	Glasgow Coma Scale
HAE	Head Acceleration Event
HIA	Head Injury Assessment
HIAf	Head Injury Assessment form
HIAf+ve	Players who demonstrated observable concussive signs
HIAf-ve	Players who did not demonstrate observable concussive signs
HITS	Head Impact Telemetry System
ICD-10	International Classification of Diseases-10th Edition
ImPACT	Immediate Post-Concussion Assessment Tool
IMS	Impact Monitoring System
JLT	Jardine Lloyd Thompson Group
KDT	King-Devick Test
LOC	Loss of Consciousness
mBESS	modified Balance Error Scoring System
MRI	Magnetic Resonance Imaging

MRS	Magnetic Resonance Spectroscopy
mTBI	Mild Traumatic Brain Injury
NAA	N-acetyl-asparate
NAB	National Australia Bank
NFL	National Football League
NHL	National Hockey League
NRL	National Rugby League
PCS	Post-Concussion Syndrome
PCSS	Post Concussive Symptom Scale
PLA	Peak Linear Acceleration
PPV	Positive Predictive Value
PRA	Peak Rotational Acceleration
PTA	Post Traumatic Amnesia
RTS	Return to Sport
SAC	Standardized Assessment of Concussion
SCAT	Sport Concussion Assessment Tool
SCAT3	Sport Concussion Assessment Tool – 3rd Edition
SCAT5	Sport Concussion Assessment Tool – 5th Edition
SDMT	Symbol Digit Modalities Test
SWI	Susceptible Weighted Imaging
TBI	Traumatic Brain Injury
TMT	Trail Making Test
VOMS	Vestibular/Ocular-Motor Screening

Abstract

Detection of concussion in sport remains complex. To date, multiple efforts are made to continually revise and standardise operational criteria for a diagnosis of concussion. Discrepancies, however, remain within the literature making uniformity across clinical practice difficult. Concussion is characterised by a range of non-specific, multimodal clinical features which require comprehensive assessment. Assessment, however, initially requires the detection of players suspected of concussion and this is largely reliant upon symptom self-report, which is subject to individual bias. Measuring acceleration of the head following an impact using wearable accelerometer devices represents a potential objective method of detecting players who may require concussion screening. Research analysing accelerometer outputs have revealed multiple match-related factors that influence exposure to head impacts. Many studies now employ concomitant video footage review to help identify situational factors (skill execution, cause of impact) that underpin exposure. Additionally, acceleration values have been identified in association to a risk of concussion in sports. Most research however, has been conducted in helmeted sports, with no studies exploring the sport-specific dynamics of head impacts in professional Australian football.

Video footage review to detect players with observable concussive signs and suspected concussion is becoming a widely established practice in professional sports due to the relative objectivity in detecting concussive signs (e.g., was motor imbalance observed?) compared with symptom reporting (e.g., did the player report dizziness?). Expert personnel and advanced video technology are, however, not

present at community sports. The Australian Football League (AFL) has provided resources to facilitate the identification of players who require further concussion assessment, including a list of observable concussive signs which constitute part of the Head Injury Assessment form (HIAf). To date, no study has explored the utility of these variables in the HIAf to identify community players with poorer performance on concussion assessment measures who may be suspected of having sustained a concussion.

The primary aims of this thesis were: 1) to quantify the exposure of video verified head acceleration events (HAEs) in male and female professional Australian football players, as well as to characterise situational factors associated with these HAEs, and explore the effect of sex, player position and player experience in relation to the frequency and magnitude of HAEs; 2) to investigate the potential utility of the accelerometer output to augment current best practice in concussion screening in professional Australian football and, 3) to explore the utility of items in the HIAf as a method of identifying male and female community Australian football players with poorer performance on concussion assessment measures.

The first study explored the difference in exposure to HAEs across sex, player position and player experience using output from a non-helmeted accelerometer (X-Patch). Additionally, concomitant video footage review was used to verify HAEs, and to characterise the playing situations in which HAEs occur. The findings indicated exposure to HAEs was greater in male compared to female players, while no difference in exposure was evident across player position or level of player experience. It was found that playing situations in which players have limited control of the football were commonly associated with impacts. An incidence rate analysis revealed that in comparison to males, females had a two-fold risk of incurring a head impact in the skill execution of catching (marking) the ball, which is a situation commonly associated with concussion. This study was the first to quantify HAE exposure and identify situations with potential for injury in professional Australian football players. These findings provide important methodological considerations for future studies, and practical implications with regards to skill development and protective tactics to mitigate risk of injury in certain playing situations. This manuscript “An investigation of factors associated with head impact exposure in professional male and female Australian football players” has been accepted for publication (February 2020) in *The American Journal of Sports Medicine*.

The second study explored the utility of the X-Patch output to augment current best practice in concussion screening within professional Australian football using acceleration thresholds previously associated with concussion. The results revealed that not all players who were identified to have a HAE above acceleration thresholds were identified by club personnel for further concussion screening. Utilising these thresholds, however, did not identify all players with suspected concussion who required further assessment. Thus overall, use of specific acceleration values as provided by the X-Patch are not sufficiently reliable to help identify players who require further concussion screening in professional sports. In future, further technological improvement of non-helmeted wearable accelerometers might provide real-time measurement of HAEs and help detect players who require further screening in light of increasing evidence to suggest there are individual-specific thresholds for concussion. This however, must be weighed against player and/or staff cost, especially at community sports, where resources are limited. This manuscript “The potential of head acceleration measurement to augment concussion screening in professional Australian football players” is currently under review in the journal of *Physical Therapy in Sport*.

The third study examined the utility of observable concussive signs included in the HIAf as a method to identify male and female community Australian football players with poorer outcomes on concussion assessment measures. All observations were conducted live from the sideline by personnel with basic training and without video footage review in order to mimic the real-world application of the HIAf. Using the Sport Concussion Assessment Tool-3rd (SCAT3) and Cogstate, it was found that players who were observed to have concussive signs (HIAf+ve) were characterised by greater symptom severity and worse cognitive outcomes acutely post-match in comparison to control players who did not demonstrate concussive signs (HIAf-ve). This was evident after matching groups on sex, age, education level, concussion history, baseline mood, time from baseline to post-match assessment, and controlling for ratings of acute pain post-injury. A significantly greater proportion of HIAf+ve players also demonstrated individual clinically-relevant decline on cognitive outcome measures and balance performance post-match in comparison to HIAf-ve players. These results suggest use of concussive signs as per the HIAf represents a rapid method to identify players likely to demonstrate poorer clinical outcomes on concussion assessment measures in community sports. These findings highlight areas of further research to develop and standardise protocols for utilising such resources to detect players suspected of concussion in community sports. This manuscript “Concussion screening in community-level football: The association between observable signs of concussion, SCAT3 and Cogstate performance” is under review in

the *Journal of Science and Medicine in Sport*. Overall, this thesis represents an evaluation of the literature and synthesis of key findings from three novel studies that offer both theoretical and practical implications to improve the detection of concussion in sport.

Thesis Including Published Works Declaration

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis. This thesis includes one research article accepted for publication and two research articles submitted for publication and currently under review. The core theme of this thesis is to explore methods of improving the detection of players with suspected concussion in professional and community Australian football players. The ideas, development and writing up of all the papers in the thesis were the principal responsibility of myself, the candidate, working within the Turner Institute for Brain and Mental Health (School of Psychological Sciences) under the supervision of Dr. Catherine Willmott, Professor Biswadev Mitra and Dr. Andrew McIntosh. The inclusion of co-authors reflects the fact that the work came from active collaboration between researchers and acknowledges input into team-based research. In the case of three chapters, my contribution to the work involved the following:

Thesis Chapter	Publication Title	Publication Status	Nature and % of student contribution	Nature and % of Co-author's contribution
Two	An investigation of factors associated with head impact exposure in professional male and female Australian football players	Accepted for publication	Formulation of concept, data collection and analysis, and writing of manuscript; 65%.	1) Biswadev Mitra: statistical consult, manuscript critical review & result interpretation; 10% 2-4) Andrew McIntosh, Patrick Clifton, Michael Makdissi: statistical consult & manuscript critical review; 3% 5). Jack Nguyen*: Data management assistance & manuscript critical review; 4% 6-9) Peter Harcourt, Teresa Howard, Peter Cameron, Jeffrey Rosenfeld: Manuscript critical review; 3% 10) Catherine Willmott: formulation of experimental design, management of research team and project oversight, manuscript critical review, result interpretation; 15%
Three	The potential of head acceleration measurement to augment current best practice in concussion screening in professional Australian football players	Under Review (& accepted for publication during thesis examination)	Formulation of concept, data collection and analysis, and writing of manuscript; 65%.	1) Catherine Willmott: formulation of experimental design, management of research team and project oversight, result interpretation & manuscript critical review; 10% 2-9) Andrew McIntosh, Teresa Howard, Patrick Clifton, Michael Makdissi, Peter Harcourt, Peter Cameron, Jeffrey Rosenfeld, Jack Nguyen*: statistical consult and manuscript critical review; 10% 10) Biswadev Mitra: formulation of experimental design, result interpretation & manuscript critical review; 15%
Four	Concussion screening in community-level football: The association between observable signs of concussion, SCAT3 and Cogstate performance	Under Review	Formulation of concept, data collection and analysis, and writing of manuscript; 70%.	1-2) Biswadev Mitra, Michael Makdissi: Statistical consult & manuscript critical review; 10% 3-9) Patrick Clifton, Jack Nguyen*, Peter Harcourt, Teresa Howard, Peter Cameron, Jeffrey Rosenfeld, Brendan Major: Manuscript critical review; 5% 10) Catherine Willmott: Formulation of experimental design, management of research team and project oversight, manuscript critical review & result interpretation; 15%

Note. *Co-Author(s) is a Monash student.

I have renumbered sections of the manuscripts submitted for publication and/or under review in order to generate a consistent presentation within the thesis.

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I, the principle supervisor, hereby certify that the above declaration correctly reflects the nature and extent of the student's and co-authors' contributions to this work. In instances where I am not the responsible author I have consulted with the responsible author to agree on the respective contributions of the authors.

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Publications and Presentations During Candidature

Publications

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Chapter One:

General Introduction

1.1 Conceptual Framework

The term ‘concussion’ stems from the Latin verb *concutere* meaning ‘to shake’ or ‘vibrate violently’ and it is used to indicate limited and transient neurological and behavioural impairment following a force applied directly or indirectly to the brain (Mayer, Quinn, & Master, 2019; Pervez, Kitagawa, & Chang, 2018). Concussion, however, is a clinical entity with no universal consensus in definition. To date, several medical organisations and sports governing bodies have provided operational criteria for concussion, each with distinct and overlapping clinical features making the application of uniform criteria difficult across the literature (Carroll, Cassidy, Holm, Kraus, & Coronado, 2004; Mayer et al., 2019; McCrory, Feddermann-Demont, et al., 2017). Terminology with reference to concussion is also discrepant. Concussion is often used synonymously with mild traumatic brain injury (mTBI), mild head injury or cerebral contusion within the medical field, thereby complicating the development of clinical practice guidelines (Anderson, Heitger, & Macleod, 2006; Pervez et al., 2018). Additionally, much conjecture remains with regards to the classification of concussion as an equivalent or possibly less severe separable entity to mTBI (Mayer et al., 2019; Pervez et al., 2018; Sharp & Jenkins, 2015). The development of a consistent and standardised definition of concussion is therefore of tremendous value for clinical research, and importantly, the translation thereof toward clinical practice.

Over the past two decades, efforts have been made to standardise discrepant criteria for a diagnosis of concussion to improve detection and management within clinical practice. To date, the Berlin Consensus Statement on Concussion in Sport is one of the most comprehensive frameworks for establishing the operational criteria of concussion (McCrory, Meeuwisse, et al., 2017). This statement represents a collaboration between multiple experts (collectively known as the Concussion in Sport Group; CISG) who systematically summarise the current state of knowledge every four years and seek expert consensus to operationalise concussion (Meeuwisse et al., 2017). At present, eleven sport-governing bodies including the Australian Football League (AFL), the National Football League (NFL), the National Hockey League (NFL) and National Rugby League (NRL), have endorsed this statement in order to harmonise practice and facilitate uniform concussion management (Patricios et al., 2018).

According to the CISG, a sports-related concussion is a traumatic brain injury (TBI) caused by an impact to the head or to the body with a force transmissible to the head, resulting in the rapid-onset of transient neurological impairment (McCrory, Meeuwisse, et al., 2017). Throughout the consensus statement, however, both 'sport-related concussion' and 'concussion' (i.e., caused by non-sporting injury) are used interchangeably with no distinguishable characteristics provided for each. The clinical boundary for what constitutes concussion in sport and non-sporting concussions is somewhat arbitrary and largely driven by sporting bodies which seek to develop, improve and standardise practical guidelines for concussion management under consistent terminology (McCrory, Feddermann-Demont, et al., 2017). It is therefore the term 'concussion' which will be used hence forth in this thesis, whilst acknowledging the focus is sports-related concussion. To date, many other consensus-based concussion position statements have been released (Broglio et al., 2014; Giza et al., 2013; Guskiewicz et al., 2004; Harmon et al., 2019; Harmon et al., 2013; Herring et al., 2011). These however, lack specificity with regards to key clinical features that operationalise concussion – including the onset, duration and resolution – relative to the CISG statement (McCrory, Feddermann-Demont, et al., 2017).

In spite of this, the CISG statement does not provide further insight with regards to the classification of concussion in relation to the TBI spectrum, and specifically mTBI (Kazl & Torres, 2019; Mayer et al., 2019; McCrory, Feddermann-Demont, et al., 2017). The Glasgow Coma Scale (GCS) is a widely accepted form of stratifying TBI severity into mild (GCS score of 13 to 15), moderate (GSC score of 9 to 12) or severe injury (GCS score of 8 or less; Teasdale & Jennett, 1974). According to the American Congress of Rehabilitation Medicine, other diagnostic features of mTBI in addition to a GCS of 13 to 15 also include a loss of consciousness (LOC) of 30 minutes or less and/or short-term post-traumatic amnesia (PTA) no greater than 24 hours (Kay et al., 1993).

The diagnostic boundaries of mTBI, however, are not always consistent. In a review by the World Health organisation (WHO) Collaborative Center Task Force for mTBI, discrepancies were found in the duration of LOC (e.g., ranging from 5 to 30 minutes), PTA (e.g., ranging from less than 30 minutes to 24 hours) and GCS scores (14 or 15 only) used to differentiate mild from more severe forms of TBI (Carroll et al., 2004). In addition, the authors found the term 'concussion' was used interchangeably with mTBI, or as a standalone term without any reference to mTBI despite the application of diagnostic clinical features related to mTBI.

Concussion is sometimes conceptualised a separable and less-severe clinical entity to mTBI despite the lack of distinct symptom profiles, diagnostic criteria or objective biomarkers to support this (Mayer et al., 2019; Pervez et al., 2018; Sharp & Jenkins, 2015). In their review of diagnostic nosology for mTBI, Mayer et al. (2019)

review distinct categorisations of injury that are proposed to exist within the spectrum of mTBI. In this spectrum, concussion is observed to be the least severe form of recognised injury, encompassing all other probabilities of greater injury severity. It has been posited that a subset of concussions, therefore may progress to mTBIs despite lacking clear nosology boundaries, while a further subset of mTBIs with positive neuroimaging findings progress to be complicated mTBIs (Kashluba, Hanks, Casey, & Millis, 2008; Williams, Levin, & Eisenberg, 1990).

Overall, the Berlin Consensus Statement on Concussion in Sport provides an exemplar framework for the operational criteria of concussion. There is yet, however, substantial variability in diagnostic boundaries to identify concussion and/or mTBI. The interchangeable application of this terminology without the use of injury-specific standardized criteria make distinct clinical features difficult to establish. Use of probabilistic models of injury, where concussion lies on a continuous spectrum with increasing likelihood of structural damage from very mild to severe TBI more accurately depicts the current state of knowledge of concussion (Mayer et al., 2019; Sharp & Jenkins, 2015).

1.1.1 Difficulties Operationalising Concussion

Developing consistent criteria for concussion, as a clinical entity, is limited by several inherent factors. Concussion is associated with non-specific symptoms thereby lacking diagnostic specificity (Craton & Leslie, 2014). In the context of concussion, sensitivity refers to the accuracy in detecting those with concussion, while specificity refers to the accuracy in detecting those without a concussion. As it stands, the presence of any non-specific clinical symptom (e.g., headache) post-impact can indicate concussion, increasing the likelihood of a false positive (i.e., Type I error). In addition, the persistence of any of these symptoms preventing a return to sport (RTS), may plausibly reflect a typical response to exercise (e.g., headache due to dehydration), daily stress in response to other psychosocial factors (e.g., being a doctoral student), or perturbed sleep rather than symptoms resulting from concussion itself (Balasundaram, Athens, Schneiders, McCrory, & Sullivan, 2016; Edmed & Sullivan, 2012).

The clinical presentation of concussion is also largely heterogeneous. Concussion may occur without frank or 'hallmark' neurological signs (e.g., LOC) and with considerable variability in reported symptoms that are not confined to one domain (McCrea, Iverson, Echemendia, Makdissi, & Raftery, 2013; McCrory, Meeuwisse, et al., 2017). This has led to an extensive list of well-documented somatic (e.g., headache, vomiting, nausea), cognitive (e.g., attention, concentration, memory) and emotional symptoms (e.g., anxiety, irritability, aggression, depression) that may present post-injury (Alla, Sullivan, Hale, & McCrory, 2009). In many cases, however, concussion remains difficult to detect due to a lack of awareness and knowledge about concussion, the under reporting of symptoms, or the occurrence of delayed symptomatology thereby complicating the detection of concussion (Asken et al., 2016; McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004; White et al., 2014).

Despite an increasing focus on concussion research, variability in the conceptualisation of concussion is common and this partly reflects the non-specific nature of symptoms experienced, as well as the heterogeneity in clinical presentation observed post-injury which make clear distinctions difficult (Makdissi et al., 2017; McCrory, Feddermann-Demont, et al., 2017).

1.2 Epidemiology

Globally, TBI is a significant cause of health loss and economic burden to health-care systems. In 2016, the global prevalence of individuals living with disability following TBI was estimated to be 759 per 100,000 population (James et al., 2019). The most recent census data available from Australia reveals that 22,710 TBI-related hospitalisations occurred between 2004 to 2005, equating to 70.1 per 100,000 population and an estimated direct cost of $184 million for hospital care during this period (Helps, Henley, & Harrison, 2008). Between 2002 and 2011, a state-wide epidemiological study of Victoria revealed there were 4,745 hospitalisations due to concussions in sport for people aged 15 years or older, with an estimated total hospital cost of $2 million per year (Finch, Clapperton, & McCrory, 2013). Interestingly, the most common sporting activities leading to hospitalisations were team-based football codes accounting for 36% (*n* = 1709) of all hospitalisations. This overall represented a 61% increase of hospitalisations due to concussion in sport over a nine-year period after accounting for increased rates of sport participation.

Rates of concussion, however, are likely underestimated. Not all individuals with concussion seek medical attention or report their symptoms reliably (McCrea et al., 2004; Williamson & Goodman, 2006). Lack of uniform criteria for concussion similarly impact epidemiological endeavours, thereby limiting estimations of the true incidence of concussion (Clay, Glover, & Lowe, 2013; Prien, Grafe, Rossler, Junge, & Verhagen, 2018).

1.2.1 Concussion in Contact Sport

Players participating in contact sports have an elevated risk of concussion (Kerr et al., 2017; O'Connor, Baker, et al., 2017). O'Connor, Baker, et al. (2017) conducted a comparative analysis of concussion rates among 27 high school sports during the seasons of 2011-12 through to 2013-2014 using athletic exposure (AE, one athlete [or player] participating in one practice or match) as a common denominator. The authors found the highest concussion rate per 10,000 AEs occurred in contact sports such as football (9.21), lacrosse (6.65) and soccer (6.11) and then limited contact-sports such as baseball (0.86), volleyball (2.50) and softball (3.57); or non-contact sports such as swimming (0.92), tennis (1.59) or gymnastics (2.65).

In Australia, contact sports such as Australian football and rugby are among the top five sporting activities with the highest rate of hospitalisation for concussions, with a rate of 80.3 and 49.9 per 100,000 participants respectively (Finch et al., 2013). According to the AFL Injury Survey, six to eight concussions occur per 1,000 player hours at the professional level, which equates to one concussion every three matches per team (AFL, 2017). These statistics, however, possibly underestimate concussion rates by including injuries that only resulted in a missed match or *time loss*. In a study analysing concussion rates of one AFL team between 2000 and 2013 irrespective of missed matches, 140 concussions were recorded among 45 participating players equating to a rate of 17.6 concussions per 1,000 player hours (Gibbs & Watsford, 2017).

Concussion rates at the community level of the sport appear to be lower, though increasing with time. Surveillance studies of head/neck/face (HNF) injuries across the season among community Australian football players revealed an incidence concussion rate of 0.5 to 1.2 per 1,000 player hours (Braham, Finch, & McCrory, 2004; Fortington, Twomey, & Finch, 2015). Community Australian football, unlike the professional level of the sport, is rarely staffed by experienced medical personnel trained to recognise concussion, thereby likely leading to underestimation of concussion rates. In the abovementioned studies, personnel with limited training were tasked to record injury rates, including concussion.

In comparison, studies wherein concussion detection was conducted by highly experienced medical staff across the season demonstrate an elevated concussion incidence rate of 3.2 to 6.1 per 1,000 player hours (Costello, Ernest, Kaye, O'Brien, & Shultz, 2018; Makdissi et al., 2010). The increasing concussion rates observed at community sports, however, may also reflect increasing participation rates as well as improvements in the protocols for concussion detection. Presently, the AFL offer such protocols for use by community coaches, parents and players where medical staff are not always available with the aim of reducing concussion in sport (Davis, Makdissi, Harcourt, Clifton, & McCrory, 2017).

1.3 Pathophysiology

A direct impact to the head or impact to the body with a transmissible force to the head (e.g., whiplash injury) can result in pressure gradients and strain propagation of brain tissue with the potential for brain injury (Gurdjian, Lissner, & Evans, 1961; Holbourn, 1943; Ommaya & Hirsch, 1971; Ommaya, Hirsch, Flamm, & Mahone, 1966). Focal and diffuse injury occurs when the pressure gradient and strain of the brain tissue exceed tolerable limits for said tissue (King, Ruan, Zhou, Hardy, & Khalil, 1995; King, Yang, Zhang, Hardy, & Viano, 2003). At the tissue-level, primary and secondary cascading pathological events are posited to occur (see Figure 1) which compromise cerebral metabolism (Barkhoudarian, Hovda, & Giza, 2016; Giza & Hovda, 2014; Romeu-Mejia, Giza, & Goldman, 2019).

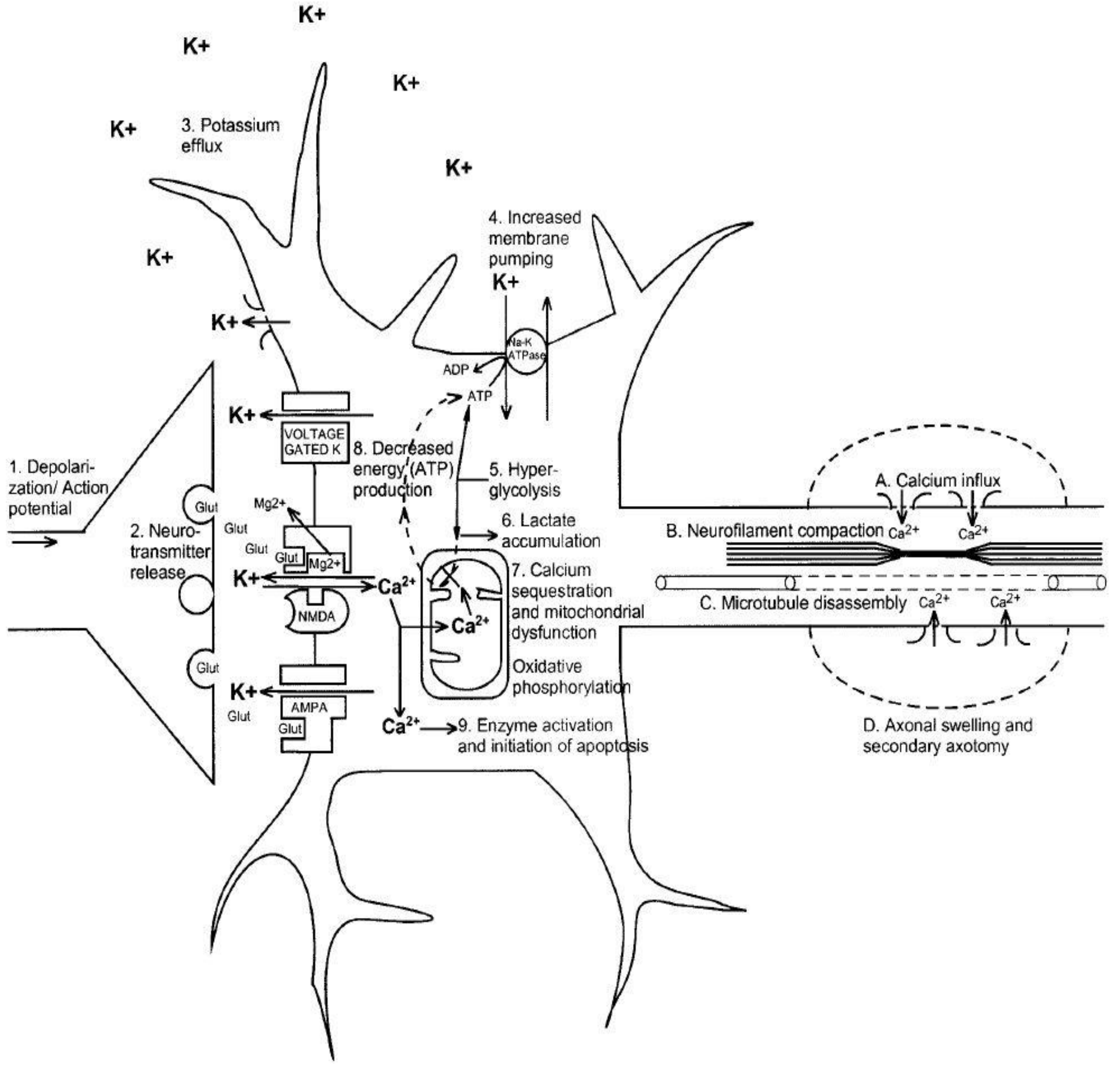

Figure 1. The neurometabolic cascade of concussion. Adapted with permission from “The molecular pathophysiology of concussive brain injury – an update” by G. Barkhoudarian, D. A. Hovda, & C. C. Giza, 2016, Physical Medicine and Rehabilitation Clinics of North America, 27, pp. 375. AMPA = d-amino-3-hydroxy-5-methyl-4-isoxazole-popionic acid; ATP = Adenosine Triphosphate; Ca^2+ = Calcium; K+ = Potassium; Glut = Glutamate; Mg2+ = Magnesium; Na+ = Sodium; NMDA = N-methyl-D-aspartate.

According to this model (see Figure 1), an impact to the head prompts an indiscriminate release of excitatory neurotransmitters (glutamate; Steps 1 and 2), which leads to post-synaptic neuronal depolarization and the considerable efflux of potassium (K^+; Step 3) and influx of calcium (Ca^{2+}). An immediate attempt to restore the membrane potential taxes the sodium-potassium pumps, which demand an increasing production of adenosine triphosphate and subsequently, glucose metabolism (Steps 4 and 5). The accelerated glycolysis can lead to increased lactate production and accumulation, resulting from impaired oxidative metabolism. This form of mitochondrial dysfunction is occurring concurrently due to mitochondrial sequestration of the intracellular surplus of Ca^{2+} (Steps 6 and 7). This state of hypermetabolism occurs in the context of reduced cerebral blood flow, thereby leading to a disparity in energy supply and demand (i.e., energy crisis) and the unchecked accumulation of Ca^{2+} which can directly activate pathways leading to cell death (Steps 8 and 9; Barkhoudarian et al., 2016; Johnson, Stewart, & Smith, 2013). In addition, the stretching of axons post-impact lead to increased axolemmal permeability and flux of Ca^{2+} which disrupt the axonal neurofilaments and microtubules, thereby impacting post-traumatic neural connectivity (Steps A to D). This form of neural unrest represents a “window of vulnerability”, wherein any secondary impact occurring before the complete resolution of the first impact-related neuropathology may further compound neuropathological damage and prolong the brain’s recovery (Giza & Hovda, 2001; Hovda et al., 1983; Hovda et al., 1999). Typically, this “window of vulnerability” lasts between one to two weeks, thereby mimicking the clinical trajectory of concussion recovery although considerable heterogeneity in recovery trajectories remain (Giza & Hovda, 2001; Makdissi et al., 2017; McCrory, Meeuwisse, et al., 2017; Vagnozzi et al., 2008). A possible explanation for this is individual variability in biological factors underpinning this process, including differences in cerebral blood flow, cascading-related changes in cerebrospinal fluid viscosity and cellular energy efficiency as a function of hydration status, physical fatigue and lactic acid accumulation (Eckner, Sabin, Kutcher, &

Broglio, 2011).Studies employing rodent models suggest worse metabolic and neuro-inflammatory outcomes are associated with a second concussion sustained within a short-period of time of the first concussion thereby supporting this theory (Gao et al., 2017; Prins, Alexander, Giza, & Hovda, 2013; Tavazzi et al., 2007; Vagnozzi et al., 2007). Animal tissue-sampling procedures (e.g., awake craniotomy), however, cannot be employed in human trials which mostly rely on advanced neuroimaging.

1.3.1 Neuroimaging

Traditional structural imaging (e.g., computerised topography, CT, or magnetic resonance imaging, MRI), however, very seldom detect the subtle neurometabolic cascades or axonal abnormalities associated with concussion (Giza & Hovda, 2001; Klein et al., 2019; Shenton et al., 2012). Modern developments in MRI sequencing, such as Susceptibility Weighted Imaging (SWI), provide greater sensitivity to the intracranial blood products (e.g., microhaemorrhages; Haacke, Xu, Cheng, & Reichenbach, 2004). While some studies have demonstrated a relationship between SWI-detected microhaemorrhages and neurological outcomes following concussion, results are largely mixed (Kirov, Whitlow, & Zamora, 2018).

Functional imaging methods have also been explored as potential diagnostic measures of concussion. McAllister et al. (1999) was one of the first to employ functional MRI (fMRI) to demonstrate that greater blood-oxygen level-dependent (BOLD) activation of working memory circuitry (right parietal and middle frontal gyrus) was evident in concussed players when compared to non-sporting healthy controls. These finding were identified despite comparable working memory (N-Back) task performances between groups, thereby suggesting greater neuronal resources (i.e., neural compensation) were required to achieve neurotypical performance following concussion. While multiple studies since have shown generally consistent findings (Cook et al., 2019), the nature of these findings vary. A formative review of the literature including brain activation (i.e., fMRI) and functional connectivity (i.e., resting-state fMRI) task-based studies revealed concussion is associated with increased resource use (i.e., hyperactivation and hyperconnectivity), reductions in focal and integrated network responses (i.e., hypoactivation and hypoconnectivity), or most commonly, both (Caeyenberghs, Verhelst, Clemente, & Wilson, 2017; Cook et al., 2019). Concussive-related alterations in brain activation, however, follow a similar time course to clinical recovery of concussion (Meier et al., 2019).

Additionally, diffusion tensor imaging (DTI) has been used to examine the size and shape of water diffusion to determine white matter tract integrity (Basser, Mattiello, & LeBIhan, 1994). In general, however, widespread inconsistencies in white matter diffusion metrics, such as fractional anisotropy (Asken, DeKosky, Clugston, Jaffee, & Bauer, 2018; Dodd, Epstein, Ling, & Mayer, 2014) and mean diffusivity lack the necessary specificity for meaningful clinical application (Asken et al., 2018). Asken et al. (2018) attributed such discrepancies to variability in control groups, analytic techniques, and reporting methods to identify brain regional differences.

Other non-invasive methods to examine subtle cerebral metabolic changes include Magnetic Resonance Spectroscopy (MRS; Moats et al., 1995; Ross & Michaelis, 1994). The most significant and consistent finding in the literature with use of MRS is that concussion is associated with lower concentrations of N-acetyl-asparate (NAA) – a metabolite underpinning healthy neuronal metabolism (Gardner, Iverson, & Stanwell, 2014; Kirov et al., 2018) and high levels of choline suggesting abnormalities in glial cells responsible for maintaining homeostasis (Kirov et al., 2018). Using MRS, it is also found that following a single concussion, players recover depressed NAA levels 30 days post-injury, while players with a secondary concussion within 15 days of their initial injury require 45 days (Vagnozzi et al., 2008). While spectroscopy markers and clinical correlates of concussion demonstrate that injury is reversible following concussion, heterogeneity in study designs and the level of expertise required to administer and interpret results attenuate the widespread application of this method (Giza & Hovda, 2014; Kirov et al., 2018). Moreover, concussion reflects subtle and non-specific functional disturbances of the brain. This, in comparison to the grossly detectable features associated with more severe forms of TBI (e.g., skull fracture, subarachnoid haemorrhage) makes neuroimaging, in general, less applicable within clinical practice for concussion (Douglas et al., 2019; Smith et al., 2019).

1.4 Acute Clinical Presentation

The clinical presentation of concussion may be characterised by somatic (e.g., headache), cognitive (e.g., difficulty remembering) or emotional symptoms (e.g., feeling anxious), observable concussive signs (e.g., motor incoordination) as well as vestibular/oculo-motor (e.g., postural instability) and/or neurocognitive deficits on formal assessment (e.g., attentional deficit) and neuropsychiatric (e.g., irritability) or sleep disturbances (e.g., drowsiness, somnolence; McCrory, Meeuwisse, et al., 2017). There is preliminary evidence to suggest that concussion sequelae may be stratified by clinical profiles including *anxiety/mood* or *cognitive/fatigue* subtypes (Kontos, Sufrinko, Sandel, Emami, & Collins, 2019). Clinical profiles however, are predominantly informed by symptom report, which remain largely heterogonous on presentation (Howell, Kriz, et al., 2019; McCrea et al., 2013). The following section is a limited summary of the multifaceted sequelae following concussion, while screening, assessment and diagnosis will be discussed later in this chapter.

1.4.1 Symptoms

Concussion is associated with a range of non-specific symptoms, broadly encompassing the somatic/vestibular, cognitive/sensory, emotional and sleep/arousal domains (Kontos, Elbin, et al., 2012; McCrory, Meeuwisse, et al., 2017). Somatic and vestibular symptoms can include headaches, nausea, vomiting, balance problems and dizziness. Cognitive and sensory symptoms include "feeling slowed down" or "mentally foggy", difficulty concentrating or remembering, experiencing vision problems and sensitivity to light or noise. Sadness, feeling nervous or anxious, irritability, or "feeling more emotional" are common emotional symptoms associated with injury. By contrast, sleep and arousal symptoms can include drowsiness, fatigue or low energy, or having trouble falling asleep. Documentation of concussion symptoms is wholly reliant on self-report, and therefore reliant upon the awareness and willingness of the individual to respond reliably (Alla et al., 2009; McCrea et al., 2004). Symptom documentation is conducted by the use of widely established symptom scales, which were designed to measure the presence and intensity of key symptoms that were produced using plain language (e.g., "feeling more emotional"). There are, however, approximately 20 different symptom scales for concussion assessment, all published with slight variations in the naming and number of symptoms included thereby making comparisons challenging (Alla et al., 2009; Valovich McLeod & Leach, 2012).

While the symptom profile for concussion is largely heterogeneous, there are symptoms that emerge more commonly than others following concussion. An analysis of symptom profiles from 2004 concussions among 1945 players from 27 North American high school sports revealed headache (94.7%), dizziness (74.8%), difficulty concentrating (61.0%), sensitivity to light (46.6%) and sensitivity to noise (39.3%) were most frequently endorsed (O'Connor, Baker, et al., 2017). Most concussions (54.9%) were associated with five or more symptoms and most players reported symptom resolution within seven (40.7%) to fourteen days (21.7%) post-injury. In Australian football, headache is also the most commonly reported symptom post-concussion (80% to 90%; Collie, Makdissi, Maruff, Bennell, & McCrory, 2006; Makdissi et al., 2010). Players, on average, may endorse three to four symptoms per concussion, with a mean time to symptom resolution of two days from injury (Makdissi et al., 2010). Interestingly, symptoms less frequently reported, such as fatigue/lethargy (37.5%) and sleep disturbance (26.1%) are associated with longer recovery (Makdissi et al., 2010).

1.4.2 Observable Signs

A LOC was traditionally accepted to be the hallmark feature of concussion (Gasquoine, 1998). There are now six observable signs that are considered to be most useful in the identification of possible concussion following expert consensus among seven professional sporting bodies (Davis et al., 2019) including: *no protective action in fall to ground*, *impact seizures* (clonic movements), *tonic posturing*, *motor incoordination*, *a blank or vacant look*, and *loss of responsiveness* (can include LOC). While the latest derived consensus makes use of the term *video signs*, other studies employ heterogeneous terms including *observable signs of concussion*, *clinical signs of concussion*, *visible signs*, or *objective concussive signs* (Davis et al., 2019; Echemendia, Bruce, et al., 2017; Gardner, Wojtowicz, et al., 2017; Makdissi & Davis, 2016a). For consistency, the term ‘observable concussive signs’ will be used hence forth in this thesis. The inclusion of additional observable concussive signs or combination thereof is also evident in the literature and this has been identified, where possible, in the following discussion.

Observable concussive signs have the advantage of providing greater objectivity (e.g., was motor incoordination observed?) in the process of screening concussion relative to subjective symptom report (e.g., was dizziness reported by player?). There are specific observable concussive signs (no protective action in fall to ground, impact seizures [including tonic posturing], motor incoordination, blank or vacant stare) that are regarded to be confirmatory of a concussion diagnosis, while others are suggestive of probable (loss of responsiveness) or possible (facial injury, clutching at head, slow to get up) concussion diagnosis following further assessment (Davis & Makdissi, 2016; Makdissi & Davis, 2016a). At present, research exploring identification of players with observable concussive signs occurs predominantly by experienced medical personnel and use of retrospective video footage analysis at the professional level of sports.

A video review of 201 matches from the 2014 NRL season including 60 players with concussion diagnoses and 96 non-concussed players screened for suspected concussion under the Concussion Interchange Rule (CIR) revealed concussion was most frequently associated with *slow to get up* (100%), a *blank or vacant stare* (75%), *clutching at head* (63.3%), *gait ataxia* (including *motor incoordination*; 58.3%), *loss of responsiveness* (including *LOC*; 40%) and rarely, *impact seizures* (5%; Gardner, Howell, Levi, & Iverson, 2017). In this sample, players with concussion diagnoses were 2.35 (Relative Risk 90% CI = 1.40 – 4.30) and 1.52 (Relative Risk 90% CI = 1.06 – 2.10) times more likely to exhibit a *blank and vacant stare* or *loss of responsiveness* respectively. Interestingly, only 10% (223/2240 observations) and 58.7% (212/361 observations) of all observed to be *slow to get up* and *clutching at head* respectively were considered for further screening by the CIR suggesting low specificity of these signs (i.e., this sign otherwise caused by fatigue or orthopaedic injury).

When treated independently, no single combination of observable concussive signs demonstrates high levels of discriminative ability to detect concussion (Bruce et al., 2017; Gardner, Howell, & Iverson, 2018). In addition, not all observable concussive signs are associated with a concussion diagnosis. In their video review of 2460 NHL matches, Echemendia, Bruce, et al. (2017) found 47% (*n* = 94) of 202 concussions were associated with an observable concussive sign. Consistent with earlier data, a *blank or vacant stare* (7.59, 95% CI = 1.4 - 41.2), *loss of responsiveness* (4.11, 95% CI = 1.9 - 8.9) and, additionally, *motor incoordination* (1.73, 95% CI = 1.2 - 2.5) had a greater positive likelihood of concussion diagnosis with positive predictive values (PPVs) of 67%, 52% and 31% respectively. By contrast, only 1 in 10 (PPV = 10%) players exhibiting *slow to get up* were diagnosed with concussion.

At the professional level of Australian football, PPVs are reported to be higher possibly reflecting inconsistent operational criteria and expert input. In a video review of 102 randomly-selected episodes of possible concussion from 414 AFL matches, including 45 medically-confirmed concussions, high PPVs were found for a *blank or vacant stare* (100%) and *motor incoordination* (81%; Makdissi & Davis, 2016a). This review however, was conducted by expert AFL personnel with extensive background in detecting concussion unlike the non-medical personnel with limited training who were recruited in other studies (Echemendia, Bruce, et al., 2017; Gardner, Levi, &

Iverson, 2017). In studies with NRL and NHL players, a *loss of responsiveness* (including *LOC*) has previously included observations of a player who “does not protect” or “fails to reflexively brace” in fall to ground, which is a distinct and individual observable concussive sign in AFL studies (Davis & Makdissi, 2016; Echemendia, Bruce, et al., 2017; Gardner, Howell, et al., 2017; Makdissi & Davis, 2016a). *No protective action in fall to ground* is one of the top ranked signs that is specific (95%) to concussion diagnosis while a *loss of responsiveness* is reported to be less specific (75%) and less common in concussion diagnoses (Davis & Makdissi, 2016; Makdissi & Davis, 2016a).

Only one study to date has explored the clinical outcomes of observable concussive signs as detected in 38 players throughout the 2014 NRL season (Gardner, Wojtowicz, et al., 2017). Players exhibiting a *loss of responsiveness* (including *no protective action in fall to ground*; 28.9%, *n* = 11) demonstrated significantly worse balance performance on formal testing compared to players without this observation. More than half of the overall sample (53%, *n* = 20), however, was comprised of players with medically confirmed concussions who exhibited significantly worse clinical outcomes compared to the non-concussed group. All players were nonetheless pooled together and grouped on the basis of specific observable concussive signs irrelevant of injury outcome thereby making comparisons biased.

The multifaceted sequelae of concussion are not limited to subjective symptom reporting and the observation of concussive signs. Instead, concussion sequelae can also encompass functional deficits which require formal assessment of vestibular and ocular motor performance, neurocognitive performance and neuropsychiatric and/or sleep disturbance.

1.4.3 Vestibular and Ocular-Motor Deficits

A central role of the vestibular system is to process information about motion, equilibrium and spatial awareness in conjunction with visual and somatosensory input (Hellebrandt & Braun, 1939; Shumway-Cook & Horak, 1986). Concussion can be associated with disruption of vestibular function (e.g., transient stress or damage of vestibular organs post-impact) thereby leading to poor balance and postural instability (Guskiewicz, 2011; Kontos et al., 2019; Murray, Reed-Jones, Szekely, & Powell, 2019; Valovich McLeod & Hale, 2015). Approximately 19% of concussions are characterised primarily by vestibular dysfunction (Kontos et al., 2019). Commonly reported symptoms such as dizziness (61% to 78%) or balance problems (30%) (Guskiewicz, Weaver, Padua, & Garrett, 2000; Lovell et al., 2006; O'Connor, Baker, et al., 2017) have been previously associated with formal metrics of balance impairment in concussed players, thereby suggesting a much greater prevalence of this profile (Broglio, Sosnoff, & Ferrara, 2009). The formal assessment of balance and postural stability requires players to perform coordinated motor movements or maintain a static position through a series of structured activities (Guskiewicz, 2011; Valovich McLeod & Hale, 2015). In their seminal work, Guskiewicz, Perrin, and Gansneder (1996) evaluated the postural stability of 10 concussed and 10 non-concussed high school and collegiate North American football players, and found concussed players exhibited significantly greater postural impairment at one to three days post-injury. Since then, numerous studies have provided similar findings of players with concussion having significant difficulties resisting swaying, falling, or maintaining balance on assessment, with deficits lasting three to five days post-injury

(Feigenbaum et al., 2019; Guskiewicz, Ross, & Marshall, 2001; McCrea et al., 2003; Parrington et al., 2019; Riemann & Guskiewicz, 2000).

Oculo-motor dysfunction following concussion can be associated with impairment of versional (i.e., saccades and smooth pursuit) and vergence (i.e., convergence & divergence) eye movements (Galetta et al., 2011; Galetta et al., 2013; Leigh & Zee, 2006; Leong et al., 2015; Mucha et al., 2014; K. L. Pearce et al., 2015). This is most typically observed in the form of reduced speed in visual scanning and difficulty converging the eyes while focusing on a near target, which have been linked to brain dysfunction (Heitger et al., 2009). Approximately 16% of individuals with concussion experience oculo-motor dysfunction as a primary deficit, including subjective complaints of “blurry vision”, “eye strain” or “difficulty focusing” (Kontos et al., 2019). Symptom report, however, is not always consistent with the outcome of formal assessment. In a study of 100 adolescents (mean age of 14.5 years) with concussion, 69% were found to meet criteria for a vision disorder including convergence insufficiency and saccadic dysfunction (Master et al., 2016). Only 29% of the entire sample, however, had reported having “vision problems”.

1.4.4 Neurocognitive Deficits

Concussion can have substantial adverse effects on neurocognitive (or *cognitive* or *neuropsychological*) performance within the first 24 hours post-injury (Belanger & Vanderploeg, 2005; Broglio et al., 2019) and is typically detected with use of sideline evaluation tools, computerised testing or paper-and-pencil tests (e.g., Trail Making Test, TMT, Symbol Digit Modalities Test, SDMT; Feddermann-Demont et al., 2017).

According to a systematic review including 33 prospective studies representing 2416 sport players, cases of concussion were predominantly associated with deficits in memory and learning (58.3%), executive functioning (54.5%) and attention (50%; Feddermann-Demont et al., 2017). Differences in operational criteria of cognitive domains, however, can be a source of significant variability in large systematic reviews thereby requiring caution. A review of 11 published meta-analyses of concussive-related sequelae revealed that effect sizes for cognitive domains were largely heterogeneous, especially for executive functions (Cohen's *d* = -0.11 to 0.72) due to inconsistent criteria (e.g., phonemic fluency defined as an independent construct; Karr, Areshenkoff, & Garcia-Barrera, 2014).

Some evidence also suggests reports of symptoms are reflective of the underpinning neurocognitive deficit. In a study of 32 concussed players (*n* = 23 North American football players), greater severity ratings of the symptoms "feeling mentally foggy", "difficulty concentrating" and "difficulty remembering" were significantly associated with detriments in reaction time and verbal memory (Broglio, Sosnoff, & Ferrara, 2009). Neurocognitive performance, however, is more sensitive to the deleterious effects of concussion in comparison to symptom report. McCrea et al. (2005) demonstrated that 31% (*n* = 21) of 68 players with concussion reporting to be symptom-free at two days post-injury continued to demonstrate impairments in immediate and delayed memory recall, processing speed or verbal fluency. In another study of 75 concussed players, 62.5% were correctly identified to have concussion based on neurocognitive impairments in verbal memory, visual memory, or processing speed at one day post-injury, while only 16.7% were additionally identified based on their symptom report (Broglio, Macciocchi, & Ferrara, 2007).

Barth et al. (1989) were among the first to identify neurocognitive deficits within 24 to 48 hours post-injury in a sample of 2350 college North American football players using baseline performance as a comparative reference. Maddocks and Saling (1996) later provided similar findings in a sample of 130 professional AFL players, of which 10 sustained concussion and were characterised by significantly slower visuomotor performance (i.e., response time to initiate movement toward stimuli) in comparison to non-concussed players at five days post-injury**.** A study comparing eight concussed and 15 non-concussed community Australian football players revealed various visuomotor deficits may be evident as early as 48 hours post-injury including slowed finger dexterity, response and movement time to stimuli, when compared to non-concussed players (A. J. Pearce et al., 2015)**.**

It appears concussed players not only exhibit visuomotor deficits, they also lack the benefit from practice effects observed in non-concussed players upon repeat exposure of testing. In sample of 56 North American football players (28 with concussion), Eckner, Kutcher, Broglio, and Richardson (2014) found that players without concussion demonstrated a trend towards improvement in visuomotor performance, while performance was comparatively stable in the concussed group. Similarly, Putukian et al. (2015) examined a multi-sport cohort of 263 male and female players and found concussed players (*n* = 32) demonstrated an attenuation of expected improvement with practice as observed in non-concussed players (*n* = 231) at re-test.

Concussion can also impact basic cognition including orientation (e.g., “what year is it”?), concentration (e.g., digit recall) and recent memory recall (e.g., five word-list recall; McCrea, 2001; McCrea, Kelly, Kluge, Ackley, & Randolph, 1997). In a large prospective study of 1631 college North American football players, significant deficits in orientation, concentration and recent memory recall were evident acutely post-injury among 80% of 94 concussed players, which did not resolve until five to seven days post-injury (McCrea et al., 2005; McCrea et al., 2003). Context-dependent orientation (e.g., “at which ground are we?”) appear to be more severely impacted by concussion in comparison to general orientation (Maddocks, Dicker, & Saling, 1995). While players with concussion are more likely to perform uniformly in general orientation, tasks of concentration and recent memory recall remain useful in detecting individual variability with concussive-related sequelae at 24 hours post-injury (Chin, Nelson, Barr, McCrory, & McCrea, 2016; Putukian et al., 2015; Sufrinko, McAllister-Deitrick, Womble, & Kontos, 2017; Wang et al., 2016).

Deficits in processing speed and attention are also commonly associated with concussion (Broglio, Macciocchi, et al., 2007; Maddocks & Saling, 1996; McCrea et al., 2003). In a follow-up study of 75 concussed players undergoing testing within 24 hours post-injury, it was demonstrated that 52.2% had clinically-significant neurocognitive impairment (i.e., more than one standard deviation on two or more tests) in both processing speed and complex attention (Broglio, Macciocchi, et al., 2007). These neurocognitive deficits generally remain evident within 48 hours post-injury and do not resolve until seven days following concussion (McCrea et al., 2003). Subtle processing speed and attentional sequelae associated with concussion are also evidenced by impairment of simple and complex reaction time with use of computerised testing (Collie, Maruff, Makdissi, et al., 2003; Howell, Osternig, Van Donkelaar, Mayr, & Chou, 2013; Howell, Osternig, & Chou, 2018; Lunter et al., 2019; Nelson, LaRoche, et al., 2016). A serial assessment of 78 professional and nonprofessional Australian football players with concussion revealed that recovery of processing speed and complex attentional deficits occurred concurrently with resolution of symptoms while impaired simple and complex reaction time remained evident for an additional two to three days post-injury, suggesting greater sensitivity with these outcomes (Makdissi et al., 2010). Significant slowing of simple and complex reaction time is evident within 24 (Wang et al., 2016), 32 (Louey et al., 2014) and 72 hours post-injury (Gardner, Shores, Batchelor, & Honan, 2012; Howell et al., 2018) with normal performances evident by eight days post-injury (Nelson, LaRoche, et al., 2016).

Aspects of higher cognition including verbal memory and executive functions are also susceptible to concussion. Approximately 35% to 39% of concussed players demonstrate impaired immediate verbal recall and verbal fluency within one day post-injury (Broglio, Macciocchi, et al., 2007). At two days post-injury, 23% of concussed players continue to exhibit deficits in delayed verbal recall and recognition, as well as verbal fluency and – to a lesser extent – mental flexibility, which largely returns to baseline by seven days from injury (McCrea et al., 2005; McCrea et al., 2003)**.** Use of computerised testing at 24 hours post-injury reveals that concussed individuals (including non-sporting causes) commit significantly more errors and exercise inefficient search strategies during working memory and executive function tasks compared to individual with orthopaedic injury (Lunter et al., 2019). When examining reaction time during task-switching and working memory tasks, individuals with sports concussion also demonstrate deficits within 24 hours (Wang et al., 2016) and up to two months post-injury (Howell et al., 2013).

Overall, a large body of research has been devoted to the characterisation of neurocognitive sequelae following concussion. The abovementioned studies were included in this limited review on the basis that they included concussed and non-concussed controls with rigorous and clearly stated baseline and post-injury follow-up time points. Generalising these findings, however, require the following caveats: the majority of study samples are comprised entirely (e.g., Eckner, Kutcher, et al., 2014; McCrea et al., 2005; A. J. Pearce et al., 2015; Wang et al., 2016) or mostly (i.e., 80% and above; Broglio, Macciocchi, et al., 2007; Chin et al., 2016; Howell et al., 2013; Nelson, LaRoche, et al., 2016) of male players at the collegiate level with few studies (e.g., Chin et al., 2016; McCrea et al., 2003; Putukian et al., 2015) exploring potential confounders that may influence clinical outcomes in concussed players (as discussed in Section 1.9.2).

1.4.5 Neuropsychiatric and Sleep Disturbances

Much of the literature remains focused on the neurocognitive outcomes and symptomatology of concussion, while fewer studies have explored behavioural and emotional outcomes. A recent systematic review of 103 studies investigating mental health in professional players revealed only 27 were peer-reviewed and provided quantitative data on mental health (Rice et al., 2018)**.** Depression (19 studies) and anxiety (7 studies) were most commonly examined, while no conclusions could be drawn for other mental health domains. In professional players, depressive symptoms were associated with concussion while evidence for anxiety was mixed. Seven of the included studies utilised samples comprised of retired professional players and retrospective recall of concussion history, which also limits conclusions. For example, one study found a significant correlation between depressive symptoms and lifetime history of concussion after controlling for cardiovascular risk factors, headaches, and arthritis (Didehbani, Munro Cullum, Mansinghani, Conover, & Hart, 2013). It remains difficult to establish, however, whether depressive symptoms preceded concussion or were the result thereof as there was no consideration of proximal factors (e.g., life events, quality of life) that could explain depression above and beyond self-reported incidents of concussion up to 30 years ago.

There is nonetheless evidence from prospective studies to suggest there is an elevated rate of neuropsychiatric disturbance following concussion. In a study of 75 concussed high school and collegiate players, higher levels of symptoms associated with depression (on the Beck Depression Inventory) from baseline were evident at two, seven and fourteen days post-concussion (Kontos, Covassin, Elbin, & Parker, 2012). Meier, Bellgowan, et al. (2015) demonstrated elevated anxiety symptoms among a sample of 17 concussed players at one day and one week post-injury in comparison to 27 non-concussed players**.** Symptom levels, however, were comparable between groups at one month post-injury.

Interestingly, many symptoms of depression and anxiety overlap with key concussion symptomatology. In their critical review of neuropsychiatric outcomes post-concussion, McAllister and Wall (2018) identified a significant overlap of symptoms (e.g., irritability, more emotional, nervous or anxious, sadness) between concussion checklists (e.g., Rivermead Post Concussion Symptoms Questionnaire) and validated instruments to screen depression (e.g., Beck Depression Inventory) and anxiety (e.g., Hamilton Anxiety Scale)**.** Therefore, players who endorse emotional symptoms following concussion are necessarily endorsing depressive and/or anxiety symptoms commonly purported in screening tools of these domains. A secondary, and yet important distinction these authors make is the difference between having *psychiatric symptoms* and a *psychiatric disorder*. While concussion may be associated with elevated symptoms of depression and anxiety post-injury, this does not reflect clinical criteria for an anxiety or major depressive disorder (as per Diagnostic and Statistical Manual of Mental Disorders 5th Edition, DSM-5; APA, 2013).

Sleep and/or wake disturbances have also been noted following concussion. In a sample 261 youth players (*M* age = 14.8 years) assessed within 10 days of experiencing concussion in sport, almost half (45%) reported trouble falling asleep and 64% of this subgroup missed two or more days of school as a result (Howell, Oldham, Brilliant, & Meehan, 2019)**.** Report of difficulties initiating sleep and poor sleep quality following concussion are also associated with delayed recovery (Chung et al., 2019; Wiseman-Hakes, Gosselin, Sharma, Langer, & Gagnon, 2019). Objective sleep disturbances are also documented following concussion, including greater nocturnal wakefulness and poor sleep architecture (i.e., less Stage N2 [light sleep] and REM sleep; Mollayeva et al., 2017) as well as increased nocturnal hyperarousal (i.e., increased beta power during NREM sleep; Arbour et al., 2015). Sleep disturbances are sometimes confused for aberrant wakefulness and arousal. In their quantitative electroencephalogram study of REM and NREM cycles comparing concussed (*n* = 10) and healthy (*n* = 11) players, Gosselin et al. (2009) found concussion was associated with increased delta and decreased alpha power during wakefulness suggesting decreased physiological arousal.

1.5 Delayed Clinical Presentation

Concussion can be associated with a delay in symptom onset of three to six hours post-injury (Guskiewicz et al., 2003; Makdissi et al., 2001) or possibly longer. In a sample of 44 players (North American football and ice hockey) with concussion, 23% reported symptom onset later in the match, after the match, later at night or in subsequent days (Duhaime et al., 2012). Evidence from cross-sectional analyses of injury data from 97 concussed players in a multi-sport cohort (e.g., football, lacrosse, track) found 52% of players did not immediately experience concussion symptoms (Asken et al., 2016). These players experienced significantly longer recovery times in comparison to players with immediate symptom onset.

Not all players with concussion and delayed symptom onset, however, seek medical care and this prevalence may therefore be underestimated. Furthermore, it remains to be seen if delayed symptom onset is just epiphenomenal to a delay in symptom reporting (e.g., delayed reporting by player motivated to remain in the match; McCrea et al., 2004; White et al., 2014). In other words, delayed symptom onset, delayed recognition of symptom onset by the player and delayed reporting of symptom onset by the player may reflect different aetiologies and may require distinct interventions and detection methods to further elucidate the delayed clinical presentation of concussion.

1.6 Subclinical Presentation

A common misconception within the concussion literature is the indiscriminate use of *subconcussion* and *repetitive head impacts* as interchangeable terminology. These terms, however, have important implications and should be addressed individually.

1.6.1 Subconcussion

Subconcussion (or *subconcussive blow*, *subconcussive injury*, *minimal brain injury*) has been defined as a cranial impact involving a mechanical transfer of energy to the brain causing damage to axonal and neuronal integrity without the expression of clinical or neurobehavioural correlates (i.e., without a concussion diagnosis; Bailes, Petraglia, Omalu, Nauman, & Talavage, 2013; Dashnaw, Petraglia, & Bailes, 2012). It has been proposed that a history of subconcussion can have long-term deleterious consequences (e.g., chronic neurodegenerative syndromes) on the basis that: 1) primary and secondarily-cascading neuropathological changes are associated with every head impact, and 2) these neuropathological changes have a cumulative burden with potential for long-term neurological dysfunction (Dashnaw et al., 2012).

The term ‘subconcussion’, however, lacks operational precision and necessarily implies there are precise diagnostic thresholds for concussion and all concussion are detected accurately (Belanger, Vanderploeg, & McAllister, 2016; McAllister & McCrea, 2017). For example, a systematic review of 56 included studies using search criteria for subconcussion in sport found a considerable lack of consistency and clarity with regards to operational criteria and measurement of variables related to subconcussion (e.g., how to detect subconcussion; Mainwaring, Pennock, Mylabathula, & Alavie, 2018). In addition, no organisational or medical body recognises subconcussion as a clinical entity (Mayer et al., 2019). Instead, more precise terminology of this is regarded to be a *head impact* or *head impacts without concussion* (Belanger et al., 2016; Mainwaring et al., 2018).

1.6.2 Repetitive Head Impacts

Concern remains that long-term exposure to repetitive head impacts among player populations is associated with lifetime neuropathology and neurocognitive deficits (McKee et al., 2009a; Stern et al., 2011). While there is very limited evidence to support the purported lifetime consequences of exposure to repetitive head impacts (as discussed in section 1.7.2), studies assessing short-term within-or between season neuropathological and neurocognitive outcomes remains mixed and not without limitation.

With regards to neuropathological outcomes, Bazarian, Zhu, Blyth, Borrino, and Zhong (2012) found significant post-season changes in fractional anisotropy and mean diffusivity were associated with the self-reported number of repetitive head impacts during the season. In addition to the potential bias in self-report, however, these neuroimaging changes occurred in both directions thereby lacking structural or functional meaning. Moore, Lepine, and Ellemberg (2017) controlled for bias in player self-report of repetitive head impacts by video recording matches for randomised verification and found no relationship between recorded head impacts and neuropathological alterations of attentional event-related brain potentials among soccer players without concussion (*n* = 16). This group, however, exhibited similar neuropathological activation patterns to concussed players (*n* = 14) which were different to non-contact sport controls (*n* = 19). It is worth noting that all soccer players in this study were actively participating in sport and it was unknown how many ‘subconcussive’ players had sustained concussion throughout this term. Studies exploring neurobiological markers of injury (e.g., S100B; neurochemical marker of TBI) have similarly identified post-match decrements when compared to pre-season levels (Chamard et al., 2012; Oliver et al., 2016; Rogatzki et al., 2016). These studies, however, inferred the occurrence of head impacts from player participation in contact sport thereby limiting conclusions.

A similar trend is evident with studies exploring neurocognitive outcomes. A recent systematic review of 17 studies exploring neurocognitive outcomes in relation to *indirect* head impact exposure (i.e., inferred by player participation or self-report) found only 11% (*n* = 16) of 140 total primary neurocognitive assessment scores were significantly associated with impact exposure (Mainwaring et al., 2018). It was found, however, the majority of these studies were characterised by ‘weak’ or ‘moderate’ methodologies. Not included in their review were the Concussion Assessment, Research and Education (CARE) consortium results by Katz et al. (2018) who analysed the baseline of 15,681 (41% female) racially and socio-economically diverse community players in North America over two years**.** These authors found no clinically-meaningful deficits in neurocognitive or vestibular function nor differences in neuropsychiatric outcomes between players in contact (53%), limited contact (31%) or non-contact (17%) sports between pre-season baselines.

Overall, studies exploring the association between long-term participation in contact sport (e.g., estimated age of first exposure, routine sport participation) and neurocognitive outcomes demonstrate no cumulative detriments to performance (Caccese et al., 2019; Eckner et al., 2019). This body of literature, however, inferred the occurrence of repetitive head impacts through participation in contact sport which do not provide specific estimates of head impact exposure thereby limiting conclusions. While repetitive head impacts may be formally quantified with use of wearable accelerometer devices, measuring this across multiple contact and non-contact sports would be logistically challenging. Instead, limited studies have examined direct measurements of head impact exposure and clinical outcomes within the same contact sports (as discussed in section 1.11.9).

1.7 Long-Term Clinical Outcomes

The clinical presentation of concussion is reported to be short-lived and reflect transient neurological impairment with recovery occurring in a graded manner within 10 to 14 days post-injury (McCrory, Meeuwisse, et al., 2017). Not all players with concussion, however, recover in the expected timeframe and this may be associated with individual factors such as pre-existing neuropsychiatric comorbidities thereby complicating treatment (Makdissi et al., 2017). Parallel to this, are the purported consequences (e.g., progressive neurodegenerative syndromes) of long-term exposure to repetitive head impacts (including concussion) which, despite lacking firm empirical evidence, remain a sensationalist topic in the media and wider community (Ahmed & Hall, 2017).

1.7.1 Prolonged Recovery

Recovery following concussion is defined as the resolution of post-injury clinical symptoms and the return of neurotypical functioning (McCrory, Meeuwisse, et al., 2017). Prolonged recovery, however, is observed in 10% to 30% of concussive cases depending on the cohort (e.g., 10% to 15% in North American and Australian football) and the time frame that defines ‘prolonged recovery’ (Makdissi, Cantu, Johnston, McCrory, & Meeuwisse, 2013; Makdissi et al., 2017; McCrory et al., 2013). A systematic review of 25 articles including 1,035 (56% male) concussed players with ‘persistent postconcussive symptoms’ (i.e., greater than 10 days) demonstrated there was marked heterogeneity with regards to the definition of ‘persistent’ and various time frames were proposed ranging from ‘greater than ten days’ to ‘greater than two months’ post-injury (Makdissi et al., 2017). Traditionally, these individuals were characterised to have post-concussion syndrome (PCS) necessarily implying that a prototypical constellation of symptoms develop in concert within this subgroup. While there is evidence there are commonly reported symptoms associated with prolonged recovery (e.g., headache, poor concentration, memory problems, fatigue, sleep difficulties) thereby suggesting an underlying unitary syndrome, these symptoms remain non-specific to concussion (Makdissi et al., 2017). For instance, using the definition for PCS (i.e., reporting at least three features following concussion including headache, dizziness, fatigue, irritability, impaired memory, impaired concentration, insomnia) provided by the International Classification of Diseaseses-10 (ICD-10; WHO, 2016), Voormolen et al. (2019) found almost half (45.1%) of 11,759 healthy respondents from the general population in Italy, The Netherlands and the United Kingdom met criteria for PCS.

This complicates intervention and management of concussed players, where acute and subacute clinical symptoms are the most consistent predictor of prolonged recovery (Iverson et al., 2017). Furthermore, there is evidence to suggest prolonged recovery post-concussion is associated with pre-existing psychosocial factors. In their systematic review of 101 articles exploring factors associated with prolonged recovery, Iverson et al. (2017) found factors such as pre-injury history of mental health problems (yet not attention deficit hyperactive disorder or learning disorder) were associated with an increased risk for longer recovery. Similarly, a retrospective case-control study comparing 40 patients with prolonged recovery (i.e., symptoms beyond three months post-injury) to 80 matched-control patients (i.e., symptom resolution within three weeks post-injury) found psychological factors, such as premorbid mood disorders, a family history of mood disorders and co-existing psychosocial stressors were significant predictors of prolonged recovery (Morgan et al., 2015).

The effect of pre-existing psychosocial factors, however, is likely more extensive. Ponsford et al. (2019) examined a cohort of 343 patients with concussion (inclusive of non-sporting injuries) and found that the presence of premorbid psychological/psychiatric problems was associated with a 2.75 increased likelihood of reporting symptoms at seven months post-injury (Ponsford et al., 2019). Using the ICD-10 criteria for PCS, Losoi et al. (2016) found 62.5% of concussed patients (*n* = 16) who met criteria at 12 months post-injury were characterised by modifiable psychosocial risk factors at one month post-injury (e.g., depression, post-traumatic stress-disorder, low psychological resilience) as well as demonstrated significantly greater insomnia, fatigue, and worse quality of life at six month post-injury. Interestingly, 100% of controls (*n* = 5) who reported prolonged symptoms at 12 months also shared a similar mental health profile.

Whilst the association between pre-existing psychosocial factors and protracted recovery is commonly identified in non-sports related concussion (e.g., due to car accidents, falls, etc), there is emerging evidence to suggest these premorbid factors can also be detrimental to recovery following concussion in sport and therefore remain of clinical importance (Trinh, Brown, & Mulcahey, 2020). Moreover, these studies are largely consistent with the view that prolonged recovery following concussion is not a single pathophysiological entity, and is largely associated with coexisting and confounding pathologies that do not reflect concussive injury alone (Makdissi et al., 2017).

1.7.2 Chronic Traumatic Encephalopathy

In 1928, Martland coined the term *punch drunk* to conceptualise a neurological syndrome with predominant motor features resulting from significant exposure to head trauma among boxers (Martland, 1928). This syndrome was later termed *traumatic encephalopathy* (Parker, 1934) and *dementia pugilistica* (Millspaugh, 1937), until Critchely (1949) first introduced the concept of *chronic traumatic encephalopathy* (CTE). Roberts (1969) later examined 224 retired boxers randomly selected from a cohort of 16,781 United Kingdom boxers and found 17% were characterised by mild (11%) or severe (6%) neurological features of CTE (e.g., motor ataxia, pyramidal problems).

In the mid 2000s, a case series began investigating CTE features in non-boxing football players (predominantly NFL) leading to the proposal of a broad spectrum of clinical symptoms and neuropathological findings, distinct disease stages and phenotypes (McKee et al., 2009b; Omalu et al., 2005; Omalu, Fitzsimmons, Hammers, & Bailes, 2010; Stern et al., 2013). With limited empirical basis, CTE was defined as a neurodegenerative disease that is characterised by the accumulation of hyperphosphorylated tau protein (p-tau) in neurons and astrocytes in a pattern that is unique from other tauopathies, including Alzheimer’s disease (AD) and frontotemporal degeneration, with possible early-or late-onset functional progressive decline following long-term exposure to repetitive head impacts, concussions or both (Gavett, Stern, & McKee, 2011; Montenigro et al., 2014; Stern et al., 2013). While distinct neuropathological features of CTE are proposed (termed modern CTE; Gardner, Iverson, & McCrory, 2013) it remains unknown if the neuropathological profile of CTE is necessarily neurodegenerative and associated with progressive dementia (Iverson, Keene, Perry, & Castellani, 2018; McAllister & McCrea, 2017). Further to this, the link between long-term participation in contact sport and CTE is largely contentious.

Much of the evidence to support CTE is derived from select case studies undergoing post-mortem brain examinations or retrospective survey (McKee et al., 2009b; Omalu et al., 2005; Omalu et al., 2010; Stern et al., 2013). In contrast, systematic and formative critical reviews of the literature demonstrate limited empirical evidence to support the clinical correlates of CTE. A systematic review of 158 published autopsy cases between 1850 and 2013 revealed that 20% to 50% of cases with clinical features of CTE did not have concomitant neuropathology, and 5% of those with CTE neuropathology did not demonstrate the associated clinical features (Gardner et al., 2013). Of the 85 autopsies conducted in players, 20% demonstrated an independent neuropathological profile of CTE, 51% had neuropathological features of CTE and other known syndromes (e.g., AD, Lewy-Body), 24% demonstrated no neuropathology and 5% demonstrated neuropathology of another syndrome and not CTE. There have, nonetheless, been proposals for distinct operational criteria of CTE, which are focused on specificity over sensitivity, without prediction of pathologic change or concrete bounds to distinguishing a disease category (McKee et al., 2016; Montenigro et al., 2014; Reams et al., 2016). For example, a comprehensive case series including six individuals with no known history of repetitive head impacts (or concussion) revealed five met the neuropathological criteria by McKee et al. (2016) for CTE (Iverson, Luoto, Karhunen, & Castellani, 2019).

There yet remains a lack of rigorous epidemiological, cross-sectional or prospective studies to substantiate the progressive course of CTE (Iverson et al., 2018; McAllister & McCrea, 2017). Perhaps a more concise summary of the current state of knowledge and relevant implications is provided by the following conclusion from Iverson et al. (2018):

> "*The confident assertions of causation [for CTE] by some researchers stand in juxtaposition with the fact that the etiologies of much better characterised sporadic neurodegenerative disease, each of which is inexorably progressive, are mostly unknown*" (p. 18).

1.8 Screening and Detection of Concussion

Concussion detection is a complex process. Sporting events are fast-paced, spontaneous, and evolve in a highly dynamic manner, thereby making injury identification difficult. Concussion is considered to be an evolving injury that often occurs without frank neurological features, making concussion screening challenging (McCrory, Meeuwisse, et al., 2017). There is now a greater emphasis to develop objective methods for rapid screening of concussion in sport, rather than definitive methods of diagnosing head injury (Patricios et al., 2017). Rapid screening of concussion is critically important to reduce the risk of further head or musculoskeletal injury and prolonged recovery. Individuals with concussion following an impact with a transmissible force to the head are proposed to have a "window of vulnerability" that is characterised by short-lived neuronal dysregulation (as discussed in section 1.2; Giza & Hovda, 2001; Hovda et al., 1983; Hovda et al., 1999).

Research indeed suggests players with concussion who RTS prematurely have an elevated risk of repeat injury in the short-term. In a follow-up study exploring concussion incidence and recovery, it was found that 91.7% (11 of 12) of repeat concussions occurred within 10 days of the first concussion (Guskiewicz et al., 2003).

Similarly, Cross, Kemp, Smith, Trewartha, and Stokes (2016) found that players with concussion (*n* = 150) were 60% more likely to sustain a subsequent injury of any type, and had significantly shorter time until a subsequent injury, when compared to players without concussion in the same season. In their study, 38% of players with concussion reported ongoing symptoms and failed to achieve a valid neuropsychological test (i.e., a score within 1.65 age-normative SDs from their baseline test) before commencing a gradual RTS suggesting not all players had experienced a full recovery.

Incurring a secondary injury also has post-acute implications for recovery. For instance, Heyer et al. (2016) found that among 1922 youth with concussion, 42.6% continued to participate in sport immediately after the injury, and this was associated with a 1.13 increased risk of prolonged recovery of concussion symptoms. Similarly, youth players who are reported to have sustained a secondary impact within 24 hours of the primary concussive event demonstrated significantly greater symptom burden and prolonged recovery in comparison to players with a single concussive event (Terwilliger, Pratson, Vaughan, & Gioia, 2016). In adults, a delayed removal from the match following concussion is associated with a 2.2 increased likelihood of prolonged recovery (Asken et al., 2016). It was unknown, however, if in this study adult players had sustained a second concussion.

The use of multimodal testing guided by expert consensus is now recommended best practice in concussion screening (Patricios et al., 2017). Many systematic protocols to assist triaging players suspected of concussion have been developed for use at the professional sporting level (Fuller, Fuller, Kemp, & Raftery, 2017; Patricios et al., 2018). At the core of these systems is the use of advanced video technology by qualified personnel (e.g., team clinician or independent spotter) to identify players suspected of concussion. The availability of such expertise and technology is limited in community sports where concussion detection is largely reliant on the concussion knowledge of players and team personnel.

1.8.1 Video Footage Review

At the professional sporting level, video footage review is used to facilitate rapid screening of concussion by conducting observation of suspicious events with potential for injury (e.g., head impact during tackle) and subsequently, observations of the player's behaviour for concussive signs (e.g., impact seizure) in order to inform decision-making regarding player removal for further evaluation (Patricios et al., 2018). The added advantages of having slow-motion replay and multiple viewing angles with zoom capabilities also allows improved characterisation of injury mechanisms, which can be used to identify modifiable risk factors of concussion (e.g., skill execution with greater risk of injury) and inform stricter rule development (e.g., reducing contact).

According to Bahr and Krosshaug (2005), injury mechanism is an important determinant of injury outcome. In their comprehensive framework of injury causation, the authors consider injury mechanism to be a multifaceted construct that requires consideration of the playing situation (e.g., offensive versus defensive play), player behaviour (e.g., skill execution) and gross (e.g., whole body description) or detailed (e.g., joint/tissue biomechanics) biomechanical descriptors of the inciting event that precipitate injury. For example, in the NFL there are plays with considerable risk for injury. A *passing play* is a playing situation with potential for considerable gain, wherein a quarterback will throw the ball to a receiver who is running toward the end of the field to achieve a *touch down* (i.e., goal of six points; Goodell, 2019). In this play, receivers are highly susceptible to interception from the opposition with the potential for injury. Recently, a video review of 322 concussion cases with a determinable concussive event among 401 NFL players across two seasons demonstrated that 50% of concussions occurred in passing plays (Lessley et al., 2018). In their study, the authors found cornerbacks, who cover receivers, sustained the most concussions (22.7%), and most concussions were caused by tackling another player (41%), and head-to-body impacts (46%). These findings suggest players are more likely to incur concussion in playing situations with potential for a high reward while executing unsafe or high-risk offensive tactics.

In Rugby Union, the Head Injury Assessment (HIA) protocol has been implemented in the Laws of the Game since August 2015 and this involves a three stage systematic process of evaluating players suspected of concussion, primarily resting on video footage review in the initial stage (C. W. Fuller et al., 2017). An evaluation the implemented video review across 64 Super Rugby matches during 2015 season found club personnel without access to sideline video missed one event of suspected concussion every 2.3 matches relative to one every 4.3 matches with sideline video (Gardner, Kohler, et al., 2018). Events detected by sideline video which led to temporary (*n* = 28) or permanent (*n* = 18) removal of a player were in large agreement (67% to 78%) with the decision of independent clinicians post-season. The use of retrospective video analysis also detected four additional players who required immediate player removal and were missed entirely. Other evidence suggests that the propensity to initiate a HIA protocol is greatest with offensive tactics. In their video review of 611 HIA events during 1,516 Rugby Union matches between 2013 and

2015, Tucker et al. (2017) found tackles accounted for 76% of all HIAs and tacklers were 2.59 times more likely to undergo a HIA relative to ball carriers.

Purposeful player-to-player contacts are frequently associated with concussion in NHL, though most often in situations when the contacted player has limited situational awareness or control of the puck. Hutchison, Comper, Meeuwisse, and Echemendia (2015) conducted a video review of 4,299 NHL matches from the season of 2006-2009 and identified 158 concussions with direct contact of the head. Among these, 47% were caused by impact to the side of the head and 76% of concussions were incurred when the player had 'just released' or was not in possession of the puck. Only 10% of concussions were deemed to be accidental collisions. Such information can help inform rule modification to mitigate injury. For example, banning body checking at the youth level of ice hockey has led to significant reductions in the rate of concussion (Emery et al., 2010; Krolikowski et al., 2017).

Similar patterns of injury mechanism for concussion are found in the AFL. A review of 82 concussions incurred during the 2011 season revealed that situations frequently associated with concussion, such as a marking contest (25-32%) and tackling and/or being tackled (21-31%) were not frequently penalised (i.e., 21-50%) despite the likelihood of illegal contact above the shoulder (Makdissi & Davis, 2016b). In a follow-up analysis of 212 incidents of possible concussion, 47% were subsequently confirmed as concussion and only 15% were missed during the video review further supporting the efficacy of such protocol (Makdissi & Davis, 2016a).

As discussed earlier (section 1.4.2), use of video review to detect observable concussive signs are becoming widely-used criterion for the rapid screening of players with potential concussion (Davis et al., 2019). These signs are also reported to be highly indicative of concussion diagnosis or probable concussion (Davis & Makdissi, 2016; Makdissi & Davis, 2016a). The utility of these signs to identify players with suspected concussion have informed the development of triage systems to aid concussion screening at community sports, such as Head Injury Assessment form (HIAf; Clifton, Harcourt, Gastin, & Makdissi, 2016). This form provides instructions to remove the player for further assessment of concussion on the basis of symptoms reported by the player or any concussive signs that are witnessed by an observer. The detection of concussive signs, however, is often conducted by expert personnel and translation may prove difficult. When compared with expert personnel, 'naïve' or otherwise non-expert personnel with limited training do not achieve the same discriminant ability to detect suspicious match events (Hutchison, Comper, Meeuwisse, & Echemendia, 2014) or concussive signs (Echemendia, Bruce, et al., 2017; Gardner, Levi, et al., 2017) associated with concussion.

This preliminary evidence, however, demonstrates non-expert personnel with limited training could reliably detect observable concussive signs (Echemendia, Bruce, et al., 2017; Gardner, Levi, et al., 2017). Presently, there is no research demonstrating the utility of such criterion in community sports, which in addition to lacking advanced video technology, would be reliant on live observation. Instead, concussion detection remains largely reliant on concussion knowledge and awareness in these settings.

1.8.2 Limitations in Community Sports

Concussion guidelines for community sports are generally more conservative than professional level protocols. According to the Concussion in Sport Australian Position Statement, players with suspected concussion who have a headache or ‘pressure in the head’ should be immediately and permanently removed from sport until cleared by a medical practitioner (Elkington, Manzanero, & Hughes, 2019). Headaches, however, like many other symptoms are non-specific and caused by other extraneous factors (e.g., flu, dehydration; Balasundaram, Athens, Schneiders, McCrory, & Sullivan, 2017). There is, nonetheless, sufficient evidence to warrant a stricter approach to concussion management in community sports.

In addition to under-reporting of symptoms, 66% to 71% of players who do not report concussive symptoms think the injury is not sufficiently serious to warrant medical attention (LaRoche, Nelson, Connelly, Walter, & McCrea, 2016; McCrea et al., 2004). Players also have very limited awareness of concussion symptoms, with fewer than 40% recognising symptoms such as feeling more emotional, irritable, nervous or anxious as potentially related to concussion (Cournoyer & Tripp, 2014). In a focus group with community Australian Football players regarding compliance with concussion guidelines, players also believed compliance would lead to their unnecessary removal by coaches/trainers who cannot distinguish between concussive symptoms or other (e.g., due to fatigue; White, Donaldson, Sullivan, Newton, & Finch, 2016).

There is evidence to suggest coaches and/or trainers do in fact have limited knowledge regarding concussion. A survey of 882 Australian football and rugby coaches/trainers revealed 40% incorrectly identified factors such as “whether player wants to come off” or “how tough the player is” as important determinants to consider when removing the player following a head impact (White et al., 2014). Interestingly, perceived difficulty to exercise concussion safety guidelines also impacts compliance among club personnel. Some of the greatest challenges to implementation of concussion guidelines include resistance by other coaches/trainers, parents and players disputing decisions about RTS as well as a perceived lack of time (Kemp, Newton, White, & Finch, 2016). It is nonetheless important to remember formal evaluation and diagnosis of concussion is made by medical practitioners who incorporate multimodal assessment as part of their comprehensive neurological examination (Elkington et al., 2019; McCrory, Meeuwisse, et al., 2017). This level of expertise, however, is not present at community grounds and requires referral to suitably qualified personnel for assessment (Baugh et al., 2015; Kroshus, Rivara, Whitlock, Herring, & Chrisman, 2017; Putukian, Aubry, & McCrory, 2009; Wicker & Breuer, 2015).

1.9 Assessment of Concussion

In sport, the best practice guidelines recommend that players suspected of concussion undergo a multimodal assessment to effectively evaluate the broad spectrum of potential sequelae typically observed within the acute and delayed clinical presentation of concussion (McCrory, Meeuwisse, et al., 2017). A secondary consideration for this approach is that presently there is no definitive evidence to substantiate the diagnostic accuracy of any single instrument to detect concussion reliably and no instrument should replace a comprehensive neurological examination (Patricios et al., 2017). In practice, clinicians seek to employ a *hybrid approach* - which is a combination of both computerised neurocognitive testing and paper-and-pencil testing - in order to capitalise on the benefits from both assessment modalities and optimise the sensitivity to detect the multifaceted sequelae of concussion (Echemendia, Thelen, et al., 2019; Kontos, Sufrinko, Womble, & Kegel, 2016). Paper-and-pencil testing, however, encompass a range of rigorously standardized test measures which require advanced expertise and background knowledge in psychometric theory and neuropsychological assessment thereby posing logistical challenges with regards to the appropriate access to trained neuropsychologist on site (Echemendia, Herring, & Bailes, 2009; McCrory, Meeuwisse, et al., 2017).

Clinicians, instead, may employ sideline evaluation tools (see section 1.9.3) or in-room computerised neurocognitive testing (see section 1.9.4) to better inform rapid decision-making regarding a diagnosis of concussion following appropriate training and supervision (Broglio et al., 2019; Echemendia et al., 2009). Post-injury outcomes can be informed by referencing baseline or normative values, in order to identify clinically relevant decline for the concussed individual. There are, however, important demographic (e.g., sex, age) and match-related (e.g., under-reporting) considerations which can impact the clinical outcomes of concussion assessment.

1.9.1 Baseline and Normative Values

The assessment of post-concussive deficits requires the use of reference values to identify the extent of post-injury decline from neurotypical expectation. Reference values for which to compare against post-injury outcomes can be provided with use of the *baseline method* (i.e., established before the sporting season) or *normative method* (i.e., established using population-base normative values). Previous studies have found the use of *normative method* is sensitive (69% to 87%) to post-concussion deficits without use of baseline values (Echemendia et al., 2013; Gardner et al., 2012; Louey et al., 2014). The use of *normative methods* overcome the need to evaluate all players before the season, and overcomes the psychometric limitations associated with repeat testing (e.g., test-retest reliability; Iverson & Schatz, 2015). The *baseline method,* however, can help detect subtle effects of concussion, such as the attenuation of practice effects from repeat exposure (Echemendia, Putukian, Mackin, Julian, & Shoss, 2001). The *baseline method* can also help control for individual variability in performance using reliable change methodology, which helps determine the extent of improvement or deterioration in performance that is above and beyond the inherent psychometric limitations of test measures (Barr & McCrea, 2001; Jacobson & Truax, 1991).

1.9.2 Important Considerations

1.9.2.1 Age

There is evidence to suggest that increasing age is associated with better performance on baseline and post-injury assessment. A systematic literature review of 21 articles exploring important elements to improve sideline evaluation of concussion found that baseline neurocognitive and balance performance of college players were comparatively better than younger high school or youth players (Feddermann-Demont et al., 2017). Following concussion, high school players also demonstrate worse neurocognitive and balance performance at two to five days post-injury (Covassin, Elbin, Harris, Parker, & Kontos, 2012; Nelson, Guskiewicz, et al., 2016) and take longer (e.g., one to two days) to recover in comparison to college-aged players (Cancelliere et al., 2014; Iverson et al., 2017; Nelson, Guskiewicz, et al., 2016). These findings therefore suggest that age, in daily practice, can help clinicians determine expected baseline values and trajectories of recovery post-injury among community sport divisions which may include both adolescent (i.e., 16 years to 18 years) and college-aged (i.e., above 18 years) players.

1.9.2.2 Sex

There is emerging evidence to suggest concussion impacts male and female players differentially. Concussion rates collected from 10,604 cadets (2,421 females) participating in sports over a three year period since 2014 revealed that female sex is associated with a 2.02 (95% CI = 1.70 - 2.40) increased risk of sustaining concussion regardless of the injury setting (e.g., academy training-related versus sport-related; Van Pelt et al., 2019). Among sports in which both sexes participate (i.e., baseball, basketball, crew, cross-country, lacrosse, soccer, swimming, tennis, indoor/outdoor track), it is found that concussion is 1.56 more likely in female compared to male players even after including a sport (lacrosse) in which contact is limited for female players only (O'Connor, Baker, et al., 2017).

Female sex is also found to be a significant predictor of greater symptom severity from the day of injury to three days post-injury (Houck, Asken, Bauer, & Clugston, 2019) and is associated with a greater risk of prolonged recovery spanning longer than one month post-injury (Iverson et al., 2017). Additionally, the proportion of females (29.0%) who are characterised by prolonged recovery after one concussion tends to be higher than males (16.7%; Varriano et al., 2018).

A compelling argument suggests that higher concussion rates among females is largely due to trait-based differences including greater conscientiousness and honesty in responding, which mitigate underreporting of symptoms (Dick, 2009). Research shows that male and female players have comparable concussion knowledge of symptoms though females are still more likely to report symptoms to an authority figure (Wallace, Covassin, & Beidler, 2017). Evidence for the utility of baseline symptom report to distinguish sex differences at post-injury assessment, however, is largely mixed. A meta-analysis of 21 studies examining sex differences found females were 43% more likely to endorse any symptom of concussion at baseline in comparison to males, however this effect was not evident in post-injury assessment (Brown, Elsass, Miller, Reed, & Reneker, 2015). Other studies have demonstrated there may be other factors interacting with female sex that could account for inconsistent findings. Gallagher et al. (2018) found symptom severity was comparable between the sexes, however, females with no current use of a hormonal contraceptive reported higher symptom severity compared to female contraceptive users.

Sex differences also extend beyond subjective symptom reporting. A meta-analysis of 91 independent samples of concussion revealed that females (Cohen's *d* = -0.87) consistently experienced worse neurocognitive outcomes within one to ten days following concussion in comparison to males (Dougan, Horswill, & Geffen, 2014). This is in stark contrast with findings from other studies which typically show females outperform males at baseline assessment of neurocognitive performance thereby suggesting post-injury effect of concussion is greater than expected (Chin et al., 2016; Combs, Ford, Campbell, Carneiro, & Mihalik, 2019; Cottle, Hall, Patel, Barnes, & Ketcham, 2017; Covassin, Elbin, Harris, et al., 2012). Overall, there is a general trend in the literature to suggest that females have an elevated risk of concussion and related sequelae in comparison to males. Further studies, however, are required to establish the likelihood of this effect.

1.9.2.3 Cognitive Reserve

The theory of *brain reserve capacity* by Satz (1993) proposes that individuals have differing cognitive abilities or ‘reserves’ that act as buffers when the brain is injured and therefore, individuals may respond differently to the same TBI. This *cognitive reserve* is typically indexed by IQ or socioeconomic variables such as educational and occupational attainment (Levi, Rassovsky, Agranov, Sela-Kaufman, & Vakil, 2013). Research in this field suggests that individuals with concussion who are characterised by lower cognitive reserve demonstrate worse neurocognitive and balance performance at baseline (Chin et al., 2016). Post-injury, lower cognitive reserve is also associated with an elevated risk of experiencing greater concussion symptoms (Oldenburg, Lundin, Edman, Nygren-de Boussard, & Bartfai, 2016) and lower neurocognitive functioning within one to two months (Donders & Stout, 2019) and three months post-injury (Stenberg et al., 2020) as well as protracted recovery and delayed return to work at six months post-injury (Stulemeijer, van der Werf, Borm, & Vos, 2008).

1.9.2.4 Mood

Pre-existing mood disturbances can impact baseline and post-injury assessment. Putukian et al. (2015) found increased self-rating of depressive (Patient Health Questionnaire-9) and anxiety (Generalised Anxiety Disorder-7) symptoms were associated with greater symptom endorsement and symptom severity at baseline. Emotional items of these measures, however, overlap with concussion symptom scales thereby possibly reflecting the same underlying construct (McAllister & McCrea, 2017). A study by Weber et al. (2018) of 8,652 players with concussion drawn from the CARE consortium (Broglio, McCrea, et al., 2017) revealed that players with a history of physician diagnosed depression and/or anxiety also had a higher number of concussion symptom endorsement and symptom severity at baseline. Consideration of pre-existing mood disturbances is important as it not only informs expected rates of symptom report at baseline, it can also impact neurocognitive performance (Kontos, Covassin, et al., 2012; Putukian et al., 2015). Kontos, Covassin, et al. (2012) found higher reported levels of somatic depression (e.g., loss of energy, tiredness/fatigue, agitation) at seven days post-injury were proportionally associated with slower reaction time in a sample of 75 concussed high school and college players. Similarly, at 14 days post injury reported levels of somatic depression were also associated with lower visual memory scores. It is therefore, important to consider mood disturbances at baseline, as these might impact both symptom report and post-injury neurocognitive performance.

1.9.2.5 History of Concussion

There is strong evidence to suggest having a history of concussion is associated with an increased risk of repeat concussion within the same or future sporting seasons (Marshall, Guskiewicz, Shankar, McCrea, & Cantu, 2015; Putukian, Riegler, Amalfe, Bruce, & Echemendia, 2018; Tsushima, Siu, Ahn, Chang, & Murata, 2019; Van Pelt et al., 2019). It is yet to be explored, however, if this is the result of a more latent-construct such as high risk-taking behaviour or high sensation-seeking, thereby increasing the player’s likelihood of involvement in playing situations with potential for concussion.

Conversely, a large body of research is not in support a relationship between a history of concussion and having generally worse neurocognitive performance. According to a systematic review exploring predictors of concussion recovery, a greater number of studies did not show a relationship between prior concussions and worse neurocognitive outcomes. These studies, however, varied tremendously with regards to methodology, statistical power, and sample size (Iverson et al., 2017). Research has demonstrated that differing types of assessment (e.g., paper and pencil versus computerised testing) do not account for this effect (Bruce & Echemendia, 2009). Both systematic reviews (Alsalaheen, Stockdale, Pechumer, Giessing, et al., 2017; Iverson, Brooks, Lovell, & Collins, 2006) and select studies exploring a history of one or more concussions stratified by groups (e.g., one, two, three, four or more) similarly demonstrate no association to long-term neurocognitive detriments (Brooks et al., 2016; Brooks et al., 2018; Dretsch, Silverberg, & Iverson, 2015; Gardner, Howell, & Iverson, 2019; Mannix et al., 2014).

Perhaps, what is more relevant to the immediate assessment is the time since the last concussion, as it is more likely that two concussion in short succession (e.g., apart by one week) have a compound effect on neurocognitive performance relative to having a concussion history in the previous season.

1.9.2.6 Non-Specific Symptom Prevalence

Concussion symptoms are prevalent in non-injured populations in association to other psychosocial and lifestyle factors. Approximately 45% of the healthy population endorse three or more clinical symptoms of concussion at any one time, and these are predominantly associated with reports of having low income, having a serious illness, caring for someone with a serious illness or being a student (Voormolen et al., 2019). There also appears to be specific psychosocial factors that are associated with increased symptoms within student cohorts. In a survey of 605 university students (449 females) of which 65% participated in recreational sports, alcohol consumption in the past 24 hours and trouble sleeping were the strongest predictors of symptom endorsement and symptom severity, followed by mental fatigue, stress, anxiety and depression (Balasundaram et al., 2016). Not surprisingly, these factors reflect the lifestyle (e.g., social festivities) and psychosocial stressors (e.g., writing a thesis) that are characteristic of being a student. A large majority of this population, however, participate in sport thereby suggesting these factors are an important consideration in the assessment of concussion when utilising symptom assessment.

1.9.2.7 Under-Reporting Symptoms and Motivation

Within sport, multiple factors influence the reliability of symptom reporting, including subjective bias and interview format. In high school sports, the most common reason for players to under-report their symptoms post-injury include lacking awareness that the injury was serious enough to warrant medical attention (66.4%) or motivation not be withheld from the match (41%; McCrea et al., 2004). More recent studies, however, suggest these rates may be higher. Kerr, Register-Mihalik, Kroshus, Baugh, and Marshall (2016) examined responses from 707 (65.9% male) former college players of multiple sports (19.2% football) and found 214 players recall not disclosing concussion. Of these, 78.9 % (*n* = 56) were motivated by a desire to remain in the match and 70.4% (*n* = 51) did not know it was concussion.

Player perceptions that “most players” engage in safe-reporting behaviours are also significantly associated with a lesser likelihood to under-report symptoms throughout the season (Kroshus, Kubzansky, Goldman, & Austin, 2014). Lastly, players who lack concussion awareness are more likely to require the use of structured symptom scales in order to elicit reliable responding. For example, Iverson, Brooks, Ashton, and Lange (2010) found that individuals with a concussion (*n* = 61) were six times more likely to endorse symptoms during the completion of self-report questionnaire in comparison to an open-ended interview where players were encouraged to provide a list of symptoms spontaneously.

The validity of baseline neurocognitive performances is also subject to player motivations. Indeed, players may intentionally underperform during baseline neurocognitive testing to obscure any potential concussive-related impairments detected upon post-injury assessments in order to hasten a return to the playing field or to avoid missing future match participation (Bailey & Arnett, 2006). This is largely evidenced by baseline performance that is unusually impoverished for an otherwise non-injured or neurologically-intact player, as well as evidenced by a relative improvement in neurocognitive performance during post-injury assessments that is otherwise not clinically-indicated (Abeare et al., 2019; Bailey, Echemendia, & Arnett, 2006). It is suggested that these specific patterns of performance can serve as useful markers of suspect motivation and therefore, aid in the process of assessing validity upon testing (Bailey & Arnett, 2006; Rabinowitz, 2019).

1.9.2.8 Fatigue and Pain

Other potential factors likely to confound the assessment of sport concussion are the effects of exercise-related fatigue and pain on clinical outcomes. It is reported that symptom scores increase comparably in both concussed and non-concussed individuals acutely post-exercise though this effect is short-lived (Balasundaram, Sullivan, Schneiders, & Athens, 2013). More recently, it was found that at-rest players without concussion endorsed significantly fewer symptoms, and performed more efficiently (i.e., faster and commit less errors) in testing of balance and postural stability when compared to testing immediately following exercise (Lee, Howell, Meehan, Iverson, & Gardner, 2017). Exercise-related fatigue can therefore have an effect on performance independent of concussion and this is mostly relevant within the acute period of assessment.

In sport, exertion, strain, or existing injuries may impact clinical outcomes through the adverse effect of pain (Docherty, McLeod, & Schultz, 2006). Pain instinctively draws our attention to signal potential injury or bodily harm (Eccleston & Crombez, 1999). Pain is therefore distracting and associated with additional cognitive processing thereby limiting available mental resources for other neurocognitive performances (Moore, Keogh, & Eccleston, 2013; Sanchez, 2011). There are psychological factors, such as pain tolerance and pain intrusiveness, which can regulate the adverse effect pain depending on the individual’s characteristics and past experience. Thornton, Sheffield, and Baird (2019) demonstrated that players in contact sport, who exhibited greater pain tolerance and direct coping strategies (e.g., view pain positively), were able to execute a visuomotor task assessing speed and accuracy better than players in non-contact sports. Interestingly, players in contact sport with greater years of player experience (i.e., above 3 years) had a higher pain tolerance than their less experienced counterparts suggesting the adverse effects of pain within contact sport cohorts remain prevalent.

1.9.3 Sideline Assessment Tools

The on-field or sideline assessment of sports concussion is designed to rapidly assess post-concussion sequelae by documenting the presence of clinical symptoms and/or detecting decline in multiple domains commonly affected by concussion (e.g., neurocognitive performance, vestibulo-ocular function; Feddermann-Demont et al., 2017). Concussion assessment by the sideline is brief and distinctly different to traditional models of neuropsychological evaluation which require extensive test batteries and quiet controlled environments (Moser et al., 2007). While there is concern that sporting grounds have too many distractions thereby questioning the validity of test performance, research has shown neurocognitive performance obtained by the sideline is comparable to that obtained under controlled clinical environments (Onate, Guskiewicz, Riemann, & Prentice, 2000). It should be noted, however, that a sideline evaluation is not a replacement for formal neuropsychological assessment nor indicative of a concussion diagnosis which ultimately requires a comprehensive neurological examination (Echemendia et al., 2013; McCrory, Meeuwisse, et al., 2017). To date, some of the most widely used sideline tools for concussion assessment include the Sports Concussion Assessment Tool (SCAT; Moody, Feiss, & Pangelinan, 2019).

1.9.3.1 Sport Concussion Assessment Tool

The most recent iteration of the SCAT, the SCAT-5th edition (SCAT5), is a consensus derived multimodal assessment tool encompassing a range of previously utilised subcomponents in the clinical evaluation of concussion (Echemendia, Broglio, et al., 2017; McCrory, Meeuwisse, et al., 2017). The SCAT5 maintains a large consistency with its predecessor, the SCAT-3rd edition (SCAT3) which was derived from the 4th International Consensus Conference on Concussion in Sport in 2013 (Echemendia, Broglio, et al., 2017; McCrory, Meeuwisse, et al., 2017). The SCAT3 was the most recent iteration when this research program began and was therefore utilised in this project. The limitations of using the SCAT3 in comparison to the SCAT5 are later discussed (see Chapter Five).

To date, the SCAT3 is the most widely used non-computer based measure to evaluate the acute effects of concussion (Moody et al., 2019) and targets several key areas including: observable signs of concussion; level of consciousness by index of the GCS (Teasdale & Jennett, 1974); context-dependent orientation with use of the Maddocks Questions (Maddocks et al., 1995); demographic and medical history; rating of clinical symptoms with use of a graded symptom scale; brief neurocognitive testing with the Standardized Assessment of Concussion (SAC; McCrea et al., 1997); vestibular function by index of postural stability and balance performance using the modified Balance Error Scoring System (mBESS; Guskiewicz, 2001) and the tandem gait test; finger-to-nose coordination; and a brief neck examination regarding range of motion, tenderness and limb sensation and strength (Guskiewicz et al., 2013; McCrory et al., 2013).

To date, there is very little evidence to support the use of a SCAT composite score (Guskiewicz et al., 2013). Post-concussive sequelae are after all multifaceted, thereby requiring individualised assessment. Extensive literature to date has been devoted to exploring the validity and reliability of independent components within the SCAT3, with a greater focus on use of the symptom scale, the SAC, and mBESS to help inform concussion assessment.

The SCAT3 graded symptom scale contains 22 items that are rated on interview by the player or clinician, using a 7-point Likert scale from 'none' (0) to 'severe' (6) to indicate the severity of each symptom at the time of the assessment (McCrory et al., 2013). Two metrics are provided including the total symptom number (maximum score of 22) and symptom severity (maximum score of 22). Studies with use of the SCAT3 graded symptom scale have indicated strong reliability (88% to 94%) and specificity (91% to 100%), with comparatively lower sensitivity (64% to 89%) to detect concussion most likely due to the wide prevalence of these symptoms among non-injured populations (Guskiewicz et al., 2013; Voormolen et al., 2019). Reliability scores at one and two year intervals reflecting real-world time intervals for baseline assessment between seasons are less forgiving (40% to 41%; Broglio, Katz, Zhao, McCrea, & McAllister, 2018). At 24 hours post-injury, SCAT3 symptom assessment remains considerably powerful (Cohen's *d* = 1.52) in detecting concussive effects despite the inherent limitation of subjective bias in self-report, with comparable specificity (79% to 92%) and sensitivity (47% to 72%) at three to five days post-injury (Chin et al., 2016; Downey, Hutchison, & Comper, 2018).

The SAC (McCrea, 2001; McCrea et al., 1997) is a brief neurocognitive test that assesses general orientation, concentration, and immediate and delayed memory recall with a maximum score of 30 for all correct responses. The SAC is reported to have modest reliability (39% to 71%) and relatively high specificity (76% to 91%) and sensitivity (80% to 94%), with the greatest capacity to detect concussive deficits within the first 48 hours post-injury (Broglio et al., 2018; Guskiewicz et al., 2013). The SAC may be subject to ceiling effects with simple items (e.g., months backwards) yet not complex items (e.g., delayed recall, six digit recall) which often detect the greatest between-subject variability in performance (Shehata et al., 2009). Normative data suggests only 15% or less of the player population have an overall score of 24 or less at baseline (Downey et al., 2018; Hänninen et al., 2016; Putukian et al., 2015) and very few players (i.e., 5% to 7%) show worsening of more than two or three points on repeat testing (Broglio et al., 2018; Chin et al., 2016; Hanninen et al., 2017; Putukian et al., 2015). By contrast, concussed players may exhibit an average decrease of four points from baseline values post-injury (Barr & McCrea, 2001). While the SAC is subject to practice effects, this effect is short-lived and does not typically extend beyond seven days (Chin et al., 2016; Putukian et al., 2015).

The mBESS (Guskiewicz, 2001, 2003) measures an individual's capacity to maintain three stances (e.g., stance with both feet together, with the non-dominant foot only, and non-dominant foot behind dominant foot). Each stance is held for 20 seconds with eyes closed whilst standing on a firm surface (e.g., concrete, field). The test administrator counts the number of errors committed, such as swaying greater than 30° (degree) of abduction, stumbling, falling out of position greater than five seconds or eye opening with a maximum possible score of 30 errors. Balance performance on the mBESS correlates well with laboratory-based measures of balance and sway, providing criterion-related and construct validity (Bell, Guskiewicz, Clark, & Padua, 2011; Guskiewicz, 2011; Riemann, Guskiewicz, & Shields, 1999). Modest to high reliability (41% to 98%) has been found for the mBESS, in addition to high specificity (91% to 96%) within one to seven days post-injury (Broglio et al., 2018; Guskiewicz, 2003; McCrea et al., 2005). Less than 10% to 15% of the player population commit six to ten errors on the mBESS at baseline (Downey et al., 2018;

Hänninen et al., 2016; Putukian et al., 2015). At repeat testing, it is rare (i.e., 5% to 9%) to make more than two or three additional errors from baseline values (Chin et al., 2016; Hanninen et al., 2017), although some research suggests wider distribution of errors in a normal curve with up to nine errors in the 5th percentile (Broglio et al., 2018; Putukian et al., 2015). The mBESS is noted to have limited sensitivity (34% to 64%) likely due to the range of orthopaedic factors (e.g., ankle injury, body pain) which could similarly impact balance performance (Docherty et al., 2006; Guskiewicz et al., 2013; McCrea et al., 2005; Wilkins, McLeod, Perrin, & Gansneder, 2004). In addition, the scoring system of the mBESS relies on the administrator's ability to recognize and document errors (e.g., was swaying 30° degrees or greater?), in which agreement is variable across intra-rater (74% to 98%) and inter-rater (54% to 96%) reliability scores (Finnoff, Peterson, Hollman, & Smith, 2009; Riemann et al., 1999; Valovich McLeod et al., 2004). It is therefore preferable to administer the mBESS in conjunction with the graded symptom scale and SAC, which have improved capacity to detect concussive sequelae when administered together (McCrea et al., 2005).

1.9.3.2 King-Devick Test

The King-Devick Test (KDT; King & Devick, 1976) requires participants to read aloud a series of numbers with variable spacing from left to right on three test cards. During this task, speed (in seconds) and accuracy (i.e., omission or commission errors) are recorded to detect impairment in rapid number naming, saccadic eye movement and concentration. It was originally designed to assess the reading efficiency among paediatric populations with possible dyslexia (Oride, Marutani, Rouse, & Deland, 1986). Over recent years, however, the KDT has been implemented as a rapid sideline assessment of possible oculo-motor dysfunction (e.g., reduce visual scanning speed) associated with concussion (Galetta et al., 2011; Galetta et al., 2013). The discriminant ability of the KDT to detect concussion is varied with sensitivity values ranging from 53% to 86%, and specificity ranging from 69% to 90% (Galetta et al., 2015; Molloy, Murphy, & Gissane, 2017). While the KDT is demonstrated to have strong test-retest reliability (91%), it has a high false-positive rate (36%) in comparison to the Vestibular/Ocular Motor Screening (VOMS) testing (2%) within the post-injury phase (Worts, Schatz, & Burkhart, 2018). More recent estimates of sensitivity (62%) and specificity (84%) among 84 concussed professional Canadian football players and 63 non-concussed players post-exercise suggests the KDT has limited discriminant ability as a standalone tool in assessing concussion (Naidu, Borza, Kobitowich, & Mrazik, 2018). In addition, the iPad KDT testing modality results is significantly slower completion time in comparison to the spiral-bound paper form among non-injured players (Clugston et al., 2019). Manufacturing instructions which accept “any worsening” from baseline upon repeat testing as an abnormal test result also exaggerate the test sensitivity thereby promoting synthetic results among the literature (Legarreta, Mummareddy, Yengo-Kahn, & Zuckerman, 2019). Indeed, Breedlove et al. (2019) found that 27% of players with repeat baseline testing across two years among 883 multi-sport players “failed” their second year baseline.

1.9.4 Computerised Neurocognitive Testing

Over the last decade, use of computerised neurocognitive testing (CNT) to help assess concussion has become a widely established practice among organised sports. The application of CNT offers certain efficiencies to the evaluation process of concussion. These include more accurate measurement of reaction time (to the hundredth of a second) thereby detecting greater between-subject variability in performance and subtle decline following concussion, while attenuating administrative error and inter-rater reliability issues (Johnson, Kegel, & Collins, 2011; Schatz & Zillmer, 2003). Use of CNT, however, also has limitations including limited sampling of neurocognitive functioning, and the attempted automatisation of evaluation which largely requires clinical judgment (Echemendia et al., 2013). It is therefore advised that CNT is use concomitantly to other assessment modalities in the overall evaluation of concussion. At present, two of the most widely used CNTs for post-concussion assessment are Cogstate and the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT; Feddermann-Demont et al., 2017; Moody et al., 2019).

1.9.4.1 Cogstate

Cogstate (or *Cogsport* or *Axon Sport*; Cogstate, 1999; Collie, Maruff, Makdissi, et al., 2003) is a 15 minute CNT that measures accuracy (percentage of correct responses) and simple and complex reaction time (in milliseconds) across four tasks. These task require processing speed (i.e., Detection Task), attention (i.e., Identification Task), visual learning (i.e., One-Card Learning Task) and working memory (i.e., One-Back Task). The transformation of reaction time (i.e., using a logarithm to the base of 10) and accuracy (i.e., using the arcsine square root) are recommended and widely established practice among the literature in order achieve normality and reduce the probability of Type I errors (Bland & Altman, 1996; Maruff et al., 2006). Only accuracy of the One-Card Learning Task is advised within general practice as it most closely reflects the underlying construct being measured while reaction time is recommended for use of the other three tasks (Maruff et al., 2009).

Cogstate stimuli consist of playing cards presented individually or concurrently depending on the task. Respondents press keyboard letters ‘D’ (yes) or ‘K’ (no) to signal their response according to task demands (e.g., “have you seen this card before?”). More comprehensive batteries of Cogstate include additional tasks (e.g., Groton Maze Learning Task for executive functioning) for use with other clinical populations (e.g., AD), however, only sport concussion research pertaining to the four-task Cogstate will be reviewed here.

Cogstate was first validated using a sample of 300 healthy young adults including 240 AFL players and also 232 professional Norwegian soccer players (Collie, Maruff, Makdissi, et al., 2003; Collie, Maruff, McStephen, & Darby, 2003; Straume-Naesheim, Andersen, & Bahr, 2005). Test-rest intervals of one hour, two days and one week show modest to strong test-retest reliabilities for reaction time (45% to 90%), though lower reliabilities for accuracy (14% to 82%). Using *p* values of less than 0.01 to establish statistical significance in a sample of 215 healthy adults, Maruff et al. (2009) found performance on the four Cogstate tasks correlated most strongly with performance on traditional measures of the corresponding neurocognitive function suggesting good construct validity. For example, performance in the One-Back task was strongly correlated with Digit Span (*r* = .81), while One-Card Learning correlated strongly (*r* = .79 to .83) with visual learning performance in the Brief Visual Memory Test and recall of the Rey Complex Figure Task. Similarly, performance on the Detection task correlated strongly (*r* = .70 to .81) with TMT A and Grooved Pegboard, while performance on the Identification task correlated strongly (*r* = .74 to .78) with TMT A & B, as well as SDMT.

Studies exploring discriminant ability of Cogstate reveal modest to high sensitivity (69% to 97%) and specificity (87% to 92%) with use of baseline or normative values (Louey et al., 2014). Makdissi et al. (2010) identified 70.8% of 78 concussed AFL players who were observed to have deficiencies in at least one of four Cogstate tasks post-injury in comparison to baseline values. Similarly, Nelson, LaRoche, et al. (2016) compared three CNTs among a sample of 165 concussed and 166 non-concussed high school and college players with assessments at 24 hours, 8, 15 and 45 days post-injury. They found the false positive rate of Cogstate (22% to 28%) was comparably lower at all time points in comparison to the ImPACT (30% to 43%) and the Automated Neuropsychological Assessment Metrics (ANAM; 25% to 30%). Furthermore, the true positive rate on the basis of decline on two or more tasks, was comparable between Cogstate and the ImPACT at 24 hours post-injury (34.2% vs. 34.5%) and greater for Cogstate at 8 days post-injury (12.5% vs. 8.3%). A meta-analysis including 18 studies representing 2,674 participants exploring reliability of the above mentioned CNTs revealed Cogstate had the highest proportion of outcomes with acceptable reliability (i.e., above 75%) for three of four tasks with One-Card Learning task being the exception (Farnsworth, Dargo, Ragan, & Kang, 2017).

1.9.4.2 Immediate Post-Concussion Assessment and Cognitive Testing

The ImPACT (ImPACT® Applications, Inc., 2002; Maroon et al., 2000) is 25 minute CNT comprised of six tasks (i.e., Word Memory, Design Memory, X’s and O’s, Symbol Match, Color Match, Three-letter Memory). ImPACT tasks translate to five composite scores (i.e., Verbal Memory, Visual Memory, Visual Motor Speed, Reaction

Time, Impulse Control) of neurocognitive function. The psychometric properties of ImPACT are varied, with the lowest reliability for Verbal Memory (29%) and highest for Visual Motor Speed (71%) across three days with test-rest intervals of 24 hours (Register-Mihalik et al., 2012). Longer test-retest intervals of 1, 7, 14, 45 and 50 days to reflect the likely follow-up of concussed players also revealed similar reliability scores (23% to 88%; Broglio, Ferrara, Macciocchi, Baumgartner, & Elliot, 2007; Resch et al., 2013). Improved test-rest reliability (46% to 85%) were observed with longer test-retest intervals (i.e., one and two years), however these are unrealistic of routine assessment following concussion (Elbin, Schatz, & Covassin, 2011; Schatz, 2009).

Discriminant analysis of the ImPACT battery reveal it is highly sensitive (79% to 93%) and specific (81% to 96%) to concussion (Broglio, Ferrara, et al., 2007; Broglio, Macciocchi, et al., 2007; Schatz & Putz, 2006; VanKampen, Lovell, Pardini, Collins, & Fu, 2006). All of these studies, however, included a composite score of the symptom scale, as per obtained by administering the adjunct Post Concussive Symptom Scale (PCSS) provided with the ImPACT battery. Alsalaheen, Stockdale, Pechumer, Broglio, and Marchetti (2017) conducted a recent systematic review comparing the difference between composite scores of symptoms and neurocognitive performance of ImPACT using data from 17 included studies representing 29 independent samples. After adjusting for time since injury, the authors found the largest effect post-injury was detected by the PCSS (Hedges g = -0.81), while ImPACT neurocognitive measures were associated with small to moderate effects (Hedges g = -0.43 to -0.67).

This was largely consistent with findings from Nelson, LaRoche, et al. (2016) which revealed the sensitivity of ImPACT to detect neurocognitive decline within 24 hours post-injury (24.4% to 39.5%) diminished to 5.2% when the analysis was exclusive to asymptomatic players. While the ImPACT provide an extensive bank of normative values, these detect invalid performance approximately 20% of the time (Gaudet & Weyandt, 2017) and overestimate performance among injured players (Katz et al., 2018).

1.9.4.3 Automated Neuropsychological Assessment Metrics

The ANAM Sports Medicine Battery (ANAM4, 2010) is a subset of twelve tasks from the ANAM test library that take approximately 25 to 30 minutes to complete. The ANAM Sports Medicine Battery (or variably termed ‘ANAM’ only) is used to assess concussion by testing attention, mental flexibility, cognitive-processing efficiency, arousal/fatigue level, learning recall and working memory with *throughput scores* (i.e., composite scores) of speed and accuracy (Cernich, Reeves, Sun, & Bleiberg, 2007; Reeves, Winter, Bleiberg, & Kane, 2007). Unfortunately, the ANAM has no uniform application across the literature, with various studies making use of five (Kaminski, Groff, & Glutting, 2009; Register-Mihalik et al., 2013), six (Reeves et al., 2007; Segalowitz et al., 2007), seven (Bleiberg et al., 2004) or eight (Nelson, Guskiewicz, et al., 2016) of the recommended tasks in their analyses. Modest to strong reliability coefficients (44% to 96%) are reported at test-retest intervals of one or two week among healthy high school and college students (Kaminski et al., 2009; Segalowitz et al., 2007). These values, however, are reduced considerably (14% to 38%) at intervals of two weeks or more (up to four months with an average of 47 days; Register-Mihalik et al., 2013). Register-Mihalik et al. (2013) also found the sensitivity to concussion of any single-subtest score was low (1% to 15%) while specificity was considerably high (87% to 100%). In addition, the ANAM has been shown to have the lowest detection rate of players with concussion at 24 hours (48%) and eight days (31%) post-injury when compared to Cogstate and the ImPACT (Nelson, Guskiewicz, et al., 2016).

1.10 Diagnosis and Management of Concussion

According to the 2017 CISG, concussion may be suspected in the presence of one or more clinical features (e.g., player report of dizziness, player observed to have motor incoordination; McCrory, Meeuwisse, et al., 2017). Diagnostic decisions, however, are often difficult in light of the heterogonous presentation of concussion. The diagnostic process is ideally multidisciplinary, where possible, and based on a comprehensive history taking and neurological assessment (McCrory, Meeuwisse, et al., 2017). Individuals with diagnosed concussion may be subject to repeat follow-up in order to track recovery and/or worsening of the presenting clinical features. These time intervals are arbitrary and largely reflect the natural time course of concussion recovery (e.g., 1, 3, 5, 7, or 14 days; McGrath & Eloi, 2019). A potential limitation in the treatment of concussion is the lack of any single definition or standardised management protocol among the medical disciplines involved in the care of concussed individuals, such as neurology, neurosurgery, psychiatry, physical medicine and rehabilitation as well as neuropsychology (Mayer et al., 2019). This is particularly troublesome, with new data suggesting that long-term treatment of individuals with prolonged recovery can benefit from multidisciplinary input (Makdissi et al., 2017).

There is preliminary evidence to suggest that individuals with prolonged recovery may benefit from individualised pharmacologic treatment (e.g. neurostimulants or antiemetics for fatigue or nausea respectively; Petraglia, Maroon, & Bailes, 2012). According to a systematic review of 28 studies exploring rehabilitation strategies following concussion, only three studies had explored pharmacological interventions to reduce recovery time (Schneider et al., 2017). These studies indicated that while pharmaceutical intervention may be useful in symptom management (reducing headache pain of post-injury) there was no evidence to suggest this form of intervention led to faster recovery.

Many guidelines for concussion management in sport recommend complete rest (i.e., restricting all usual activity) following concussion until total resolution of symptoms is observed (Broglio et al., 2014; McCrory et al., 2013). In some cases, however, prolonged periods of complete rest post-injury can actually hinder recovery (Leddy, Baker, & Willer, 2016; Silverberg & Iverson, 2013). At present, there is little evidence to support the efficacy of complete rest beyond a period of 24 to 48 hours post-injury (Schneider et al., 2017). Instead, Schneider et al. (2017) advises that players should commence a graded return to activities by this point.

1.10.1 Return to Sport

The RTS guidelines outlined by the CISG in 2017 can be described as a five stage-process, which systemically increases exposure to graded levels of physical and cognitive activity every 24 hours (McCrory, Meeuwisse, et al., 2017). In stage one, players resume daily activities that do not provoke symptoms and players later progress to stage two (e.g., light aerobic exercise) through to five (e.g., full contact practice) if they remain asymptomatic at rest, before resuming normal sporting activity. The greatest concern with prognosis of concussed players undergoing a RTS protocol is adherence. In the United States, there is evidence that this criterion is becoming more stringent. Since 2009, the state of Washington passed the first sport concussion law called the *Zackery Lystedt law,* followed by a further 47 states by 2013 which all now enforce RTS laws (Washington State Legislature; 2009). In general, the legislation mandates the following: psycho-education regarding of concussion in sport to all participating bodies (e.g., players, parents, coaches), removal of players suspected of concussion, and prevention of RTS for players until they have been seen by appropriate health professionals.

Despite these guidelines, many clinicians continue to experience difficulties making RTS decisions. These difficulties include determining the state dependent nature of symptoms (concussive or not), which measurement variable to use (symptom frequency or symptom severity), and whether any symptom or subset thereof requires more attention in comparison to other symptoms (Alla, Sullivan, & McCrory, 2012). In addition, it is difficult to mandate the uniform application of prescriptive RTS protocols due to differences in recovery rates between older and younger players, female compared to male players and other individual factors like mood and exercise (Ellemberg, Henry, Macciocchi, Guskiewicz, & Broglio, 2009; Iverson et al., 2017; West & Marion, 2014).

Lack of stringent RTS guidelines also invites discrepant practices driven by competing interests in the professional sporting world, such that professional players at-risk of post concussive sequelae are permitted back on the field without a proper follow-up (McNamee, Partridge, & Anderson, 2015). In Australia, the AFL-endorsed RTS guidelines state that players suspected of a concussion are medically assessed and do not RTS on the same day (Davis et al., 2017). In a study of injury data from 2007 to 2008 for 1,564 community football players, it was found 47% players (*n* = 34) who had sustained a concussion continued to play on the same day suggesting poor management of concussed players in relatively recent times (Fortington et al., 2015).

Further, in a sample of 187 rugby union players who sustained at least one or more concussions during the season, Hollis, Stevenson, McIntosh, Shores, and Finch (2012) found that a large majority (78%) did not receive RTS advice following their head injury and all who did receive advice failed to comply with the recommended three-week off play period endorsed by the International Rugby Board.

1.11 Measurement of Head Acceleration Events

An impact to the head, or body with a transmissible force to the head, may lead to primary and secondarily cascading neuropathological events (as discussed in section 1.2). At present, however, there is no viable method for the in-vivo measurement of tissue-level response following a head impact. Whilst in-vivo experimentation in the form of device implantation has been previously posited (Benzel, Miele, Bartsch, & Gilbertson, 2015), it is justly precluded by regulatory bodies representing research protection principles of human subjects. Instead, the detection of skull or head acceleration events (HAEs) is utilised as a surrogate measure of tissue-level damage. Acceleration is provided by the rate of change in velocity across two time points, and can be estimated for both linear and rotational accelerations of the head. Linear acceleration-deceleration of the head is measured in gravitational units (*g*) equal to acceleration due to the earth's gravity (i.e., approximately 9.81 m/s^2); whilst rotational (or angular) acceleration-deceleration is measured in units of radians per second square (rad/s^2). The capacity to detect and monitor HAEs in-vivo during sport has the potential utility of providing objective measures of concussive injury by establishing acceleration thresholds associated with these events.

One method of estimating acceleration and brain-tissue deformation post-impact is via laboratory-based reconstruction of real-life impacts using finite element computational modelling and gold-standard anthropometric test devices (e.g., Hybrid III headform; Mertz, 1985; Mertz, Prasad, & Nusholtz, 1996). For example, Patton, McIntosh, and Kleiven (2013) used a finite element model of the human head to estimate linear and acceleration forces from 27 concussion cases previously analysed by McIntosh et al. (2000). The authors found that in all cases, an impact to the temporal region of the head caused coronal rotations resulting in strain injury of the thalamus, corpus callosum and white matter regions leading to concussion.

Laboratory-based simulation employing a human facet model called the Mathematical Dynamic Models has been used to estimate HAEs from analysis of video footage of 65 concussion cases in Australian football (McIntosh et al., 2014). These authors found that the head was most vulnerable to lateral impacts with an estimated 75% likelihood of concussion occurring following a rotational acceleration of 2,296 rad/s^2 or following a linear acceleration of 88.5 *g*. The efficacy of protective gear in sport has also been assessed with use of Hybrid III head and neck systems (i.e., a dummy matching the mass and geometrical properties of the head). McIntosh and Patton (2015) found the resultant linear acceleration incurred by the headform with use of a mouthguard (85 *g*) were considerably lessened in comparison to the bare headform post-impact (130 *g*) supporting its routine use for boxers.

Overall, laboratory-based analysis provides considerable insight regarding the kinematic insult to the brain following concussion. These analyses, however, are time-consuming and heavily reliant on costly methodologies as well as requiring technical expertise and use of human surrogate models that are not subject to real-life dynamics of sport (Hanlon & Bir, 2010; Newman, Beusenberg, Shewchenko, Withnall, & Fournier, 2005).

1.11.1 Accelerometer Device

Alternatively, the in-vivo detection of HAEs during sport can be achieved with use of wearable accelerometer (or *sensor* or *biosensor*) devices including the widely-implemented Head Impact Telemetry System (HITS; Simbex, Lebanon, NH). The HITS is a 6-single (or 12-single) axis accelerometer system placed inside sporting helmets (Crisco, Chu, & Greenwald, 2004; Greenwald, Chu, Crisco, & Finkelstein, 2003) used in North American football (Broglio et al., 2010; Duma et al., 2005), ice hockey (Mihalik et al., 2012) and boxing (Beckwith, Chu, & Greenwald, 2007; Stojsih, Boitano, Wilhelm, & Bir, 2010). The HITS is reported to have comparable measurements of HAEs to that achieved with the Hybrid III headform and employs wireless Bluetooth technology to provide real-time estimates of HAEs (Beckwith, Greenwald, & Chu, 2012; Duma et al., 2005; Funk, Rowson, Daniel, & Duma, 2011). The magnitude of HAEs is most commonly indexed by the peak linear acceleration (PLA) and peak rotational acceleration (PRA) of each HAEs as well as the frequency or number of HAEs. While the HITS also implements the Head Injury Criterion (Henn, 1998) to compute the HITS severity profile (Greenwald, Gwin, Chu, & Crisco, 2008) this metric is not widely employed (O'Connor, Rowson, Duma, & Broglio, 2017). A large body of research implementing the HITS have revealed several match-related factors that can influence exposure to HAEs, including the competition level, session type (i.e., match or practice) and differences in player positions depending on the sporting code.

1.11.2 Competition Level and Session Type

Competition level, as a surrogate of age, is proportionally related to HAEs. Hence the risk of sustaining a HAE is 1.8 times higher in college players compared to high school players, whose risk in turn is three times higher compared to youth players (O'Connor, Rowson, et al., 2017). When comparing high school (n = 16) and college (n = 40) football players, college players more frequently sustain HAEs with PLAs above 60 g and 98 g (Schnebel, Gwin, Anderson, & Gatlin, 2007). College football players (n = 46) are also demonstrated to have an average of 12 HAEs above 90 g per season (Crisco et al., 2010; Gysland et al., 2012). In general, the literature suggests that head impact exposure – as detected by the HITS among North American football and ice hockey players – increases with the level of competition (see Table 1).

Table 1
Normative Distribution of Head Acceleration Events in North American Football and Ice Hockey Players Across Different Levels of Competition

	Median Frequency Per Player		PLA (g)	PRA (rad/s^2)
	Per Season	Per Session	Median (95th)	Median (95th)
Youth				
6 to 8 years[1]	107[a] - 161	9 - 11	15 - 16 (38 - 40)	641 - 686 (2052 - 2347)
9 to 14 years[2]	211 – 252	8 - 16	19 – 22 (44 – 63)	839 – 1557 (2034 – 4782)
High School[3]	520 - 774	24 – 25[a]	21 – 27[a]	1670 – 1834[a]
College[4]	1177 – 1400[a]	79 - 173	21 – 23 (63)	1400 (4378)

Note. [1]Daniel, Rowson, and Duma (2012); Young, Daniel, Rowson, and Duma (2014); [2] Bellamkonda et al. (2018); Cobb et al. (2013); Daniel, Rowson, and Duma (2014); Mihalik et al. (2012); Munce, Dorman, Thompson, Valentine, and Bergeron (2015); Reed et al. (2010); Urban et al. (2019); Young, Rowson, and Duma (2014); [3] Broglio et al. (2011); Broglio, Martini, Kasper, Eckner, and Kutcher (2013); Broglio, Sosnoff, Shin, et al. (2009); Broglio, Surma, and Ashton-Miller (2012); Schmidt, Guskiewicz, et al. (2016); Schnebel et al. (2007); [4] Crisco et al. (2010); Crisco et al. (2011); Gysland et al. (2012); Mihalik, Bell, Marshall, and Guskiewicz (2007). [a] Value reported as mean. PLA = Peak Linear Acceleration; PRA = Peak Rotational Acceleration.

In contact sport, practice sessions involve multiple drills of match-related contact activity (e.g., tackling, defending) with the potential for HAEs. Studies quantifying exposure to HAEs therefore often include both match and practice sessions within their observations. Research suggests, however, that sporting activity during matches is associated with a greater exposure to HAEs in comparison to activity during practice, irrespective of the competition level (Broglio et al., 2013; Crisco et al., 2010).

Among high school football players, the average number of HAEs sustained per match (24) is significantly higher compared to practices (21; Broglio et al., 2013). Contact also appears to be more intense during matches. Munce et al. (2015) found the 95th percentile PLA (55 *g*) and PRA (3,707 rad/s^2) of HAEs incurred during practice among youth football players were comparatively lower than the counterpart PLA (63) and PRA (4782 rad/s^2) during matches suggesting players incur HAEs of greater magnitudes more commonly in competitive play. In their study of 181 college football players across three teams, Crisco et al. (2011) found HAEs per match were two to three times higher than HAEs per practice. Interestingly, teams in this study with the most practice sessions had the lowest median HAEs per player.

This suggests practice sessions are varied, and differentially expose players to HAEs based on the intended drill and coach instructions (e.g., practicing tackles versus practicing running) thereby making it difficult to quantify exposure. Matches, by contrast, offer the most naturally occurring context and dynamics of contact in sport.

1.11.3 Player Position

The frequency and magnitude of HAEs is also influenced by player position. In North American football, defensive linemen (i.e., centers, tackles, guards) are 1.69 and 1.98 times more likely to incur a HAE in comparison to offensive (i.e., quarter back, running back, tight end) and defensive (e.g., defensive tackle, ends) skill players respectively (Broglio, Sosnoff, Shin, et al., 2009). Broglio et al. (2013) found that the mean frequency of HAEs per player was greater for offensive and defensive linemen (1,076 HAEs) during the season when compared to tight ends and running backs (779 HAEs). Interestingly, higher mean PRAs were incurred by tight ends or running backs (1,754 rad/s^2) compared to linemen (1,677 rad/s^2) suggesting some player positions in high school football are prone to fewer HAEs of a greater magnitude.

Similarly, in a sample of 254 college football players, it was found that running backs consistently experienced HAEs with the greatest magnitude when compared to other positions, including linemen (Crisco et al., 2012). In the NFL, running backs will attempt to catch a forward pass (i.e., a passing play) from the quarter-back and run with the ball, while defensive and offensive linemen line up across each other to block or push the opposition. In this sense, linemen incur more HAEs by their frequented involvement in pushing and/or blocking. This, however, involves running short distances likely resulting in low speed collisions and low HAE magnitudes. By contrast, running backs run greater distances and are subject to interception by other defensive positions such as linebackers who are also involved in similar play dynamic. In fact, there is evidence to suggest exposure among linebackers (63.84 g - 157.50 g) and running backs (60.51 g - 77.68 g) is comparable (Guskiewicz & Mihalik, 2011).

Knowledge that certain playing positions are associated with an elevated risk of exposure to HAEs can help inform working models of injury risk (Bahr & Krosshaug, 2005). Individuals in playing positions (e.g., running backs) who become involved in playing situations known to be associated with an elevated risk of concussion (e.g., passing play) present situations that require careful consideration by team physicians for screening concussion (Bahr & Krosshaug, 2005; Lessley et al., 2018).

To date, the large majority of research has been conducted with collegiate and high school male players in North American football and ice hockey which are characterised by sport-specific codes (O'Connor, Rowson, et al., 2017). Very few studies have explored the HAEs exposure in Australian football. North American players wear multiple protective gear, including hard-shell helmets as well as shoulder and chest pads and are engaged in linear styles of play, wherein players are required to carry the football to the opponent's *end zone* mostly through structured tackles (i.e., gridiron football positions) and highly directional plays (e.g., forward pass, rushing pass; Goodell, 2019). In ice hockey, players equally wear protective gear, yet have fewer field restrictions and achieve unique speeds along the ice with potential for collision reflecting sport-specific dynamics of the match (Flik, Lyman, & Marx, 2005).

In Australian football, players must score by kicking the ball between two goal posts, and advance the ball by means of kicking the ball, hand balling (i.e., holding the ball with one hand and hitting it under with the other hand), running and bouncing the ball, or 'marking' (i.e., catching) the ball after it has been kicked by another player (Laws of the Game; AFL, 2019). In this match, players wear no protective equipment, have no field restrictions, and are subject to bumps and tackles from multiple directions.

Players in midfield positions (e.g., centre, wing, rover, ruck rover) often run greater distances at faster speeds and have the highest frequency of involvement in match activities (e.g., bumps, tackles, smothers) as well as contact to the ground compared to forward and defender positions (Dawson, Hopkinson, Appleby, Stewart, & Robers, 2004; Wisbey, Montgomery, Pyne, & Rattray, 2010). Midfield positions also incur the greatest proportion (42% to 45%) of all injuries recorded per season as a result of contact with other players (Braham, Finch, McIntosh, & McCrory, 2004; Gabbe, Finch, Wajswelner, & Bennell, 2002). At present, however, the in-vivo detection of HAEs in Australian football remains limited and this requires the use of wearable non-helmeted accelerometers, such as the X-Patch.

1.11.4 Non-Helmeted Accelerometer Device

The X-Patch is small device (3 cm x 2 cm) that contains a triaxial accelerometer and gyroscope that sample at a rate of 1,000 Hz and is triggered to record data samples of 100 milliseconds (10 milliseconds preimpact and 90 milliseconds post impact) for any acceleration that exceeds 10 *g* following direct or indirect contact to the head. The Impact Monitoring System (IMS) proprietary software will reduce each sample (i.e., 100 milliseconds) to single values providing an individual PLA and PRA value for each HAEs. At time this project began, we made use of the first generation X-Patch which was commercially available from X2 Biosystems, who have now been incorporated by Prevent Biometrics®. The X-Patch is placed over the mastoid process behind the ear using double sided adhesives and has the added advantage of coupling with the skin and motion of the skull relative to the use of helmets, which can move independently of the head (Post & Hoshizaki, 2012).

Several validation studies utilizing the Hybrid III headform to provide ground values of acceleration for comparison with the X-Patch output have subsequently highlighted important caveats. McCuen et al. (2015) tested five X-Patch independently and found an overall mean error rate of 50% for X-Patch PLA and PRA values. One of their five X-Patch, however, was a potential outlier producing an error rate of 18% to 47% across 100 trials thereby making conclusions difficult. Nevins, Smith, and Kensrud (2015) evaluated ball impacts (e.g., soccer, softball) and found “generally good agreement” between the headform and X-Patch values for PLA. Siegmund, Guskiewicz, Marshall, DeMarco, and Bonin (2016) found the X-Patch detected 95% of impacts made to the headform, with a median error rate of 7%, which was later concurred by Cummiskey et al. (2017) who found a mean absolute value of device error for PLA of 7.74%. McIntosh et al. (2019) however, recently reported that measures of PLA by the X-Patch may be 17% greater than reference values of the headform. By contrast, the error rate for PRAs are varied and range from 9.48% to 245.7%, therefore indicating this metric is not recommended for use (Cummiskey et al., 2017; McIntosh et al., 2019; Siegmund et al., 2016; Tiernan, Byrne, & O'Sullivan, 2019).

The X-Patch also includes an algorithm to filter false positives events (originally designed to detect clacks or mouth clenching with use of the X2 mouthguard; King, Hume, Gissane, Brughelli, & Clark, 2016). Press and Rowson (2017) analysed the video footage of 26 female college soccer players instrumented with the X-Patch across 26 practices and 20 matches in order to quantify HAE exposure. The authors found the discriminant ability of the algorithm was limited, misclassifying up to 35% of HAEs as spurious. In their field study of 97 Australian football players instrumented with X-Patch and video recorded across one match, McIntosh et al. (2019) found the discriminant ability of the algorithm was virtually at chance level (51.7%). Both studies optimized their analyses by electing a PLA threshold of 30 *g* and above in order to control for false positive detection of common non-contact sporting activity (e.g., jumping, landing, running) which is typically associated with PLA within the range of 10 *g* to 30 *g* (Arndt, Cargill, & Hammoud, 2004; Bussone et al., 2009). With these important caveats in mind, it is important to critically appraise the literature. It should be noted that most studies identifying caveats with use of the X-Patch were published after this research program commenced.

To date, only one study has examined the in-vivo utility of the X-Patch in a sample of 68 (34 male) community Australian football players for one match (Willmott et al., 2018). In this study, males sustained a significantly greater number of HAEs (M = 31.15, SD = 25.17) compared to females (M = 17.63, SD = 13.20). Not all HAEs included in the analysis were verified by video. A limited video review of 45 HAEs above 30 *g* among 24 players, however, revealed Australian football players incurred a median PLA of 43 *g* across a single match.

1.11.5 Sex Differences

A large body of research suggests there are differences in the acute clinical presentation of concussion between the sexes (as discussed in section 1.9.2.2). Further evidence from the field of biomechanics in sport, however, suggest males have an elevated risk of exposure to HAEs, in comparison to female players. Yet, very few studies have explored this potentially different exposure among sports in which both sexes compete.

Research with ice hockey players instrumented with HITS suggests median HAEs per season are significantly higher in male (287 to 374) compared to female (170 to 179) players (Brainard et al., 2012; Wilcox et al., 2014). Among youth ice hockey players, females similarly incur 21 fewer HAEs then their male counterparts per match per season, however, this might be explained by differences in match regulations which prohibit body checking in female ice hockey only (Mihalik, Wasserman, Teel, & Marshall, 2019). Male ice hockey players are also 1.3 times more likely to sustain a HAE with PLAs above 100 *g* while female are 1.1 times more likely to sustain a HAE with a PLA below 50 *g* (Brainard et al., 2012). Interestingly, mean-level analysis may obscure clinically relevant differences between sexes. In a study 21 male and 19 female ice hockey players instrumented with the X-Patch, the mean PLA for females (18.8 *g*) and males (17.1 *g*) was statistically different (Eckner, O'Connor, Broglio, & Ashton-Miller, 2018). Females, however, sustained greater PLAs even when evaluating the top 10%, 5% and 1% of all HAEs.

In lacrosse, a study with 14 female and 15 male players wearing the X-Patch revealed no significant difference in frequency of HAEs, despite having limited contact regulations in female’s lacrosse (Reynolds et al., 2016). Reynolds et al. (2017b) also compared male and female soccer players in practice session and found no difference in frequency and magnitude of HAE, however sex-comparable exposure in matches was not assessed. Lastly, King, Hume, Gissane, Kieser, and Clark (2018) recorded HAEs using the X-Patch among 21 female rugby players across nine matches, and found players sustained a median of 14 HAEs per player per match with a median (and 95Th) of 15 (and 41) *g*. This exposure appeared comparatively lower to male rugby players instrumented with the X2 Mouthguard in a separate study, who sustained a mean of 95 HAEs per player per match, with a mean PLA of 22.2 *g* (King, Hume, Brughelli, & Gissane, 2015). Differences in device technology and user location (e.g., ear, mouth) however, necessarily bias comparisons.

Furthermore, all the abovementioned studies with use of the X-Patch did not employ video verification and included all HAEs above 10 *g* once these were processed by the propriety algorithm to filter false impacts, thereby limiting conclusions. Further studies are required with more rigorous methodologies to elucidate potential differences in HAE exposure between the sexes.

1.11.6 Player Experience

There is preliminary evidence to suggest that greater player experience is associated with a reduced burden of HAEs. Player experience, however, is a heterogonous construct and difficult to operationalise. One could argue that players with greater experience in their chosen sport are more likely to execute skills accurately and safely (e.g., tackling while protecting their head), which in turn, is associated with a reduced likelihood of incurring HAEs. Swartz et al. (2019) recently explored the efficacy of helmetless-tackling drills to reduce HAEs among 115 (56 control) youth football players (14 to 17 years) instrumented with an alternative non-helmeted accelerometer, the Smart Impact Monitor (SIM-G^{TM}, Triax Technologies, Inc. Norwalk, CT). This study found a reduction in the number of HAEs during matches at four and seven weeks post-training in the exposed group only. Kerr et al. (2015) also explored the utility of educational programs targeting development of proper tackling techniques among youth football players (8 to 15 years). Similarly, they found a significant reduction in the mean number of X-Patch recorded HAEs within practice sessions relative to youth controls without this intervention. These HAEs, however, were not video verified.

Experienced players may also exhibit greater situational awareness of their environment thereby having better preparedness in response to anticipated collisions (e.g., bracing for impact, evading manoeuvres). By contrast, players who exhibit unsafe behaviours are more likely to increase their exposure to HAEs. For example, ice hockey players instrumented with HITS who reported high levels of aggression also experience HAEs of higher magnitudes in comparison to players with low levels of aggression, despite having a comparable frequency of HAEs (Schmidt, Pierce, et al., 2016). These findings suggest players with high aggression may exercise unsafe contact behaviour that is more likely to result in HAE of a greater magnitude.

Research with female soccer players revealed that unintentional deflections and headers with improper techniques (i.e., performed with top of the head) are associated with greater magnitudes of HAEs in comparison to purposeful and proper headers (Harriss, Johnson, Walton, & Dickey, 2019; Lamond, Caccese, Buckley, Glutting, & Kaminski, 2018). In ice hockey, there is trend for players to incur HAEs of a greater magnitude following unanticipated collisions in comparison to anticipated collisions (Mihalik et al., 2010). Anticipation, however, is subject to individual bias on assessment (e.g., "did the player appear to be looking in the direction of the impending body collision?") thereby limiting analyses.

1.11.7 Characterisation of Playing Situations With Head Acceleration Events

An important development in the field of injury detection in sport, including concussion, is the application of accelerometer use with concomitant analysis of video footage. Inclusion of video footage provides an opportunity for characterisation of playing situations in which HAEs occur and help identify important determinants of injury (Bahr & Krosshaug, 2005). Knowledge of these factors can inform areas of need for further skill development and rule modification to mitigate injury. Video analysis also allows verification of HAEs and reduces the likelihood of Type I errors by excluding false positives among HAEs recorded by the non-helmeted X-Patch.

For example, in their study with the use of video footage review, Press and Rowson (2017) found that the frequency (2.16) and PLA (32 *g*) of HAEs per player were higher in matches compared to the frequency (1.69) and PLA (20 *g*) of HAEs related to practices. Furthermore, these authors found 87% to 96% of verified HAEs were sustained by performing headers, with midfielders incurring the greatest mean number of HAEs (94) compared to defenders (60) and forwards (53). These findings highlighted positional differences with increased risk to HAE burden largely resulting from one type of skill execution at matches after excluding falsely recorded HAEs. One of the study's limitations, however, was the omission of coding for body impacts, which can lead to an indirect HAE through inertial loading (McIntosh et al., 2019).

Nevins, Hildenbrand, Vasavada, Kensrud, and Smith (2019) analysed the video footage of male (*n* = 8) and female (*n* = 15) soccer players instrumented with the X-Patch over the course of eight and nine matches respectively and coded both head and body impacts, as well as mechanisms of play. The authors found female players experienced more HAEs per player per match in comparison to males (1.57 vs 1.30) however, the proportion of HAEs due to direct head impacts was higher in males (68%) compared to females (38%). Furthermore, a ball-to-head impact (i.e., header) was associated with the highest median PLA for males (33.2 *g*) and females (23.2 *g*), while a ball-to-body impact amidst other body impact-types (e.g., ground, other player body) remained high for males only. These findings suggest that diverse player situations impact the sexes differentially, and the frequency of HAEs alone is not a sole indicator of HAE exposure.

Analysis of specific playing situations further highlight differences in sporting codes. Among 11 male players wearing the X-Patch who sustained 165 verified HAEs, the incidence rate per 1,000 player participations (match or practice) was demonstrated to be lowest for ball-to-head impacts (3.69) and highest for head-to-body impacts (118.08; Vollavanh et al., 2018). The authors, however, made use of the proprietary algorithm to filter false HAEs and only coded for head impacts thereby limiting the accuracy of their observations. In a study by Cortes et al. (2017), video footage of 35 female lacrosse players instrumented with X-Patch playing over two seasons (2014-15) were analysed for head and body impacts resulting in 58 verified HAEs. Of these, 48% resulted from direct impact to the head suggesting almost half of HAEs may be lost when coding for head impacts alone.

In a detailed video analysis of this sample by Caswell et al. (2017), it was revealed that midfielders sustained the most HAEs (48.3%) followed by defenders (20.7%) and attackers (19%), however the greatest median PLA (37.8 *g*) was incurred by attackers. Interestingly, most verified HAEs (43.1%) were caused by the contact with the lacrosse stick and these were associated with a median PLA of 31.4 *g*. In contrast, less frequented HAEs due to contact with ball (12.1%) were associated with the highest median PLA (38.8 *g*). Furthermore, the majority of HAEs (72.5%) occurred when players did not have possession of the ball thereby highlighting playing situations associated with a greater burden of incurring HAEs. Another strength of this study was the application of incidence rate analysis, which revealed approximately six HAEs caused by contact with the stick occurred per 100 player exposures (i.e., participations) thereby highlighting the expected rate of playing situations with potential for injury. The authors, however, did not provide body-or head-specific rates and only verified HAEs identified by the propriety algorithm of the X-Patch.

In semi-professional rugby league matches, incidence rate analysis per player minute reveals that players sustain one verified HAEs above 20 *g* every ten minutes following a direct head impact, with a greater exposure for forwards (1 per 7.2 minutes) compared to backs (1 every 13.3 minutes; Carey et al., 2019). In this study, a video footage review of eight rugby league players wearing the X-Patch across the Newcastle Rugby League 2016 competition was conducted. The results further revealed that of all 536 verified HAEs following a direct head impact, 52% occurred during a *hit-up* play situation where the ball carrier (i.e., backs) charges directly into an organised defensive line. In this scenario, the backs accounted for 56% (169) of verified HAEs indicating variations of HAE exposure between different positions under specific circumstances such as the hit-up plays, which is a play commonly leading to use of the concussion interchange use at the professional rugby level (Gardner et al., 2016).

At the level of the AFL, concussions predominantly occur when players are engaged in a marking contest (25% to 32%), being bumped (17% to 20%), tackling (11% to 13%), or being tackled (10% to 18%; Makdissi & Davis, 2016b). No published studies to date, however, have quantified the HAE exposure within professional Australian football. Additionally, few studies have explored potential sex differences in exposure to HAEs while accounting for important methodological considerations with use of non-helmeted accelerometer such as the X-Patch.

1.11.8 Acceleration Thresholds Associated With Concussion

A working model to quantify HAEs in real-time with the application of accelerometer devices begs the question of whether these devices can help identify an injury tolerance level or threshold at which concussion is most likely to occur. Accelerometer devices alone are not sufficient for the diagnosis of concussion which requires medical assessment (Patricios et al., 2017). In theory, detecting the tolerable limits of acceleration (i.e., PLA and PRA) for HAEs that lead to concussion would help provide more objective markers of concussion risk and supplement the overall process of concussion screening. To date, the large body of research exploring normative distribution of exposure to HAEs across multiple sports are generally skewed toward the low end of the severity, however, specific playing situations with potential for concussion have been identified to cause HAEs of a greater magnitude. Only select studies to date have explored the magnitude of HAEs associated with concussion.

According to a review of the literature and meta-analysis of 13 studies quantifying match-and practice-related HAEs across multiple sports, the average PLA and PRA associated with a concussive event was found to be 98.68 (95% CI = 82.36 - 115.00) *g* and 5,776.60 (95% CI = 4,583.53 - 6,969.67) rad/s^2 respectively (Brennan et al., 2016). It is important to consider that significant variability remains among acceleration thresholds associated with concussion, with PLAs ranging from 69.7 to 145 *g* (O'Connor, Rowson, et al., 2017).

Laboratory-based simulations suggest the likelihood of concussion increases with higher magnitudes of HAEs possibly explaining variability in these acceleration thresholds. For example, using an injury risk-curve pooled from laboratory-based biomechanical data of injured and non-injured AFL and NFL players, it was found that PLA values of 56 *g*, 76 *g*, 95 *g* are associated with a 25%, 50% and 75% likelihood of concussion (Kleiven, 2007; McIntosh, 2012; Mclntosh et al., 2010). To date, however, there is very limited in-vivo measurement of HAEs associated with concussion to inform acceleration thresholds associated with concussion in non-helmeted sport.

Even fewer studies have explored these thresholds in female players. There is evidence suggesting females may have a reduced biomechanical tolerance to concussion compared to their male counterparts. In a three-year study examining the head impact kinematics of 58 female ice hockey players instrumented with HITS, nine were diagnosed with a concussion, of which four were associated with a single HAE at the time of concussion with an average PLA of 43 *g* (Wilcox et al., 2015). This was comparatively lower to the acceleration threshold previously established for concussion in male football players of 100 *g* (Beckwith, Greenwald, Chu, Crisco, Rowson, Duma, Broglio, McAllister, Guskiewicz, Mihalik, et al., 2013; Broglio et al., 2010; Guskiewicz et al., 2007). The average PRA of 4,029.5 rad/s^2 however, was comparable to previously reported PRAs of 4,253 rad/s^2 (Beckwith, Greenwald, Chu, Crisco, Rowson, Duma, Broglio, McAllister, Guskiewicz, Mihalik, et al., 2013).

A potential factor underpinning such differences is posited to be a reduced biomechanical tolerance to mitigate HAEs among females, who in turn, are more susceptible to concussion at lower acceleration thresholds as result of anthropometric differences between the sexes. For example, under controlled conditions (e.g., heading a ball launched with precise speed, force and angle) females exhibit a greater PLA compared to males (Caccese et al., 2018; Tierney et al., 2008). In comparison to males, females generally exhibit less isometric neck (flexor an extensor) strength, smaller neck girth, and lower head mass which are associated with lower levels of head-neck stiffness to mitigate an impact (Hildenbrand & Vasavada, 2013; Tierney et al., 2008; Tierney et al., 2005; Vasavada, Danaraj, & Siegmund, 2008). It is worth noting, however, that lower anthropometric measures are not inherent qualities of sex. Eckner, Oh, Joshi, Richardson, and Ashton-Miller (2014) found greater isometric neck strength and anticipatory activity were independently associated with decreased kinematics of the head after an impulsive loading among male and female players across the age spectrum. While sex differences in anthropometric features generally exist, it is the anthropometric features that appear proportionally related to an individual's ability to mitigate HAEs following impact (Bretzin, Mansell, Tierney, & McDevitt, 2017).

1.11.9 Clinical Outcomes Associated With Head Acceleration Events

At present, there is no evidence to support a link between long-term exposure to repetitive head impacts and lasting neurodegenerative disease. Very few studies, however, have examined the link between direct measures of repetitive head impacts by quantifying HAEs and short-term clinical outcomes.

Studies exploring the neuropathological correlates of exposure to non-concussive HAEs examine pre-and post-season changes in white matter integrity (i.e., using DTI) in relation to exposure metrics provided by HITS. Research in this field suggests that post-seasonal changes in fractional anisotropy and mean diffusivity of brain regions – including the amygdala, hippocampus, corpus callosum and cerebellum – are associated with an elevated exposure metrics of frequency and magnitude of HAEs (Bazarian et al., 2014; Davenport et al., 2014; McAllister et al., 2014; Merchant-Borna et al., 2016). Changes in diffusion metrics, however, are not direct markers of white matter abnormality and yet lack functional significance (Asken et al., 2018; McAllister et al., 2014).

In another study exploring the neuropathological correlates in non-helmeted soccer, Chrisman et al. (2016) employed single-match observations with the X-Patch in a sample of youth soccer players and found no evidence of brain insult on post-match MRIs which might lack the sensitivity to detect possible functional deficits following exposure. By contrast, studies of North American football players employing sampling methods that are more sensitive to neural deficits (e.g., MRS, biomarkers blood sampling) and concomitant HITS observations throughout the season suggests that 'high-magnitude' HAEs (e.g., above 60 *g* or 90 *g*) are associated with structural (i.e., increased tau) and functional (i.e., NAA) markers of neuronal and axonal injury post-impact (Joseph et al., 2018; Poole et al., 2015).

Evidence of neurocognitive correlates following repetitive HAEs without concussion are similarly mixed. McAllister et al. (2012) compared the difference in pre-season to post-season assessment (i.e., almost 4 weeks post-match) among 214 varsity football and ice hockey players instrumented with HITS and found reduced performance in processing speed ImPACT scores were associated with greater PLA throughout the season. Gysland et al. (2012) similarly examined post-season changes in neurocognitive and balance performance (within 3 weeks of last match) from baseline in 46 non-concussed collegiate football players. These authors, however, found no association to HAEs incurred throughout the season. Longer time intervals between player's last contact exposure (i.e., last seasonal match) and assessment might further reduce the discriminant ability of measures employed in these studies (e.g., ImPACT, ANAM) thereby contributing to mixed findings.

A similar trend, however, is evident in studies employing post-match assessments. For example, Talavage et al. (2014) found that high school football players (*n* = 4) who had no clinically-evident concussion and incurred higher frequencies of HAEs throughout the season also demonstrated a significant reduction in verbal and visual ImPACT scores during an in-season assessment 48 hours post-match. Interestingly, these players also exhibited decreased fMRI activation of brain regions underpinning working memory functions (i.e., middle frontal gyrus). Caution, however, is warranted with such a small sample size. Using the SCAT3 in a sample of

53 healthy community Australian football players, Willmott et al. (2018) compared the change score performance from baseline to post-match assessment (within 60 minutes) and found no association between performance and the frequency or magnitude of HAE. In this study, however, not all HAEs recorded by the X-Patch underwent video verification.

Overall, there is a paucity of research exploring the link between repetitive head impacts as indexed by measurement of HAEs and short-term clinical outcomes. Studies quantifying HAEs provide better estimates of head impact exposure. These findings, however, remain mixed and are subject to certain limitations.

1.12 Summary and Research Directions

The CISG Consensus Statement provides a comprehensive framework for the various considerations necessary in the appropriate detection and management of concussion in sport (McCrory, Meeuwisse, et al., 2017). Despite these efforts, discrepant operational criteria remain, with no uniform application of concussion guidelines among the literature or clinical practice. Difficulty harmonising practice for concussion detection and management stems from the complex and non-specific features of this clinical entity. The acute presentation of concussion is multifaceted and largely heterogonous. Multiple efforts over the past decades have elucidated the various domains a clinician must consider when evaluating the injured player. Comprehensive neurological evaluation encompasses assessment of neurocognitive and vestibulo-ocular motor performance as well as neurobehavioral and/or sleep and wake disturbances. This, however is often prompted by symptom report from the individual, which is subject to potential bias and limited awareness/knowledge of concussion. Concussion is an evolving injury, and in some cases, associated with delayed symptom onset. The timely detection of players suspected of concussion is of utmost importance in order to mitigate the risk of repeat injury and prolonged recovery.

A standardised method for the rapid screening of concussion across various professional sporting bodies involves the identification of players with observable concussive signs. This method provides greater objectivity in the screening process, relative to reliance of symptom report. These protocols, however, are utilised by medically qualified personnel with expert background in concussion detection alongside use of advanced video technology. At present, the AFL endorse and provide multiple resources to aid community personnel identify players suspected of concussion, including a list of observable concussive signs and triage protocols depicted in the HIAf. No study to date, however, has evaluated the efficacy of this tool to aid non-expert personnel in concussion screening live from the sideline in community sports where expert personnel and advanced video technology are rarely present.

Both sideline assessment tools and CNTs have been developed and field tested to aid in the process of screening concussive-related sequelae. Multimodal assessment is currently recommended to cover the wide breadth of impairment possible following concussion. Among these tools are the KDT which is a single modal assessment tool with limited psychometric properties in comparison to multimodal assessment provided by the SCAT. Similarly, both ImPACT and ANAM are CNTs reported to have limited discriminant capacity for concussive-related impairment in comparison to Cogstate. The SCAT3 and Cogstate may be used in tandem to detect poor clinical outcomes in players suspected of concussion with use of baseline or normative reference values. Multiple factors known to influence clinical outcomes of concussion must be considered (e.g., age, sex, mood, pain).

The in-vivo detection of HAEs can help quantify head impact exposure in sport. A large body of research in this field has helped identify a host of factors (e.g., level of competition, playing position, player experience) that are associated with an elevated risk of exposure to impacts. Select studies exploring the relationship between HAEs and short-term neurocognitive outcomes have mixed findings. Further, some methodological limitations are evident making conclusions difficult. The normative distribution of HAEs are – generally – lower in comparison to acceleration values associated with concussive events. Most of these studies, however, have been conducted with use of wearable accelerometers, fitted in helmets within North American sporting codes.

Quantifying exposure in non-helmeted sports requires the use of non-helmeted accelerometers such as the X-Patch. There is increasing evidence to suggest females have an increased susceptibility to concussion at lower acceleration thresholds, as well as having an increased susceptibility to concussive related sequelae. Limited studies with use of the X-Patch have been conducted among sports in which both sexes compete (lacrosse, rugby, soccer, community Australian football) and are generally in support of sex-based differences in frequency and magnitude of head impacts. With time, use of the X-Patch has highlighted important methodological considerations that can be addressed to improve the reliability of the X-Patch output. A novel method to verify HAEs includes video footage review, which concurrently allows the characterisation of important determinants of injury mechanism associated with HAEs. Paradigms coupling measurement of HAEs and video characterisation along with incidence rate analysis may provide a finer-grained appraisal of injury risk.

To date, no study has explored the exposure of HAEs in professional male and female AFL players, with considerations of exposure factors (e.g., playing positions, player experience). In addition, evidence that certain acceleration thresholds may be associated with concussion present an opportunity to explore if accelerometer output can provide an objective method of identifying players who require further concussion assessment at the professional level.

In order to identify important determinants of injury and quantify exposure of HAEs in the non-helmeted sport of professional Australia football, the first aim of this thesis was to measure HAEs and investigate the association of HAEs to sex, player position and player experience, as well as to characterise the situations in which verified HAEs occur while incorporating important methodological considerations with use of the X-Patch. The second aim of this thesis was to explore the potential utility of the X-Patch to augment current best practice in concussion screening at the professional level, by implementing previously established acceleration thresholds associated with concussion.

Lastly, in light of evidence suggesting there is utility in observing concussive signs to identify players who require further concussion assessment, and given resources are limited in community sports, it was the third aim of this thesis to assess the efficacy of the publicly available HIAf to identify male and female community players with observable concussive signs and poorer performance on clinical outcomes, as per the SCAT3 and Cogstate, while controlling important factors known to influence outcomes on these measures.

The completion of this thesis was conducted by publication and each study represents a self-contained manuscript submitted for publication. In accordance with this structure, some repetition of methodology will be evident between Chapter Two and Chapter Three which are separately submitted manuscripts. Manuscript one (Chapter Two), “An investigation of factors associated with head impact exposure in professional male and female Australian football players” has been accepted for publication in *The American Journal of Sports Medicine*. Manuscript two (Chapter Three), “The potential of head acceleration measurement to augment concussion screening in professional Australian football players” is currently under review with journal of *Physical Therapy in Sport*. Manuscript 3 (Chapter Four), “Concussion screening in community-level football: The association between observable signs of concussion, SCAT3 and Cogstate performance” is currently under review with the *Journal of Science and Medicine in Sport.*

Chapter Two:

An Investigation of Factors Asscoiated With Head Impact Exposure in Professional Male and Female Australian Football Players

Original Article

An Investigation of Factors Associated With Head Impact Exposure in Professional Male and Female Australian Football Players

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This chapter constitutes a manuscript accepted for publication to *The American Journal of Sports Medicine* and was therefore formatted in accordance with the journal requirements. Sections of the chapter below, however, were formatted in a manner consistent with the remainder of this thesis.

2.1 Abstract

Background: Exposure to head acceleration events (HAEs) has been associated with sex, player position and player experience in American football, ice hockey and lacrosse. Little is known of these factors in professional Australian football. Video analysis allows HAE verification and characterization of important determinants of injury. **Purpose:** To characterize verified HAEs in the non-helmeted contact sport of professional Australian football and investigate the association of sex, player position and player experience with HAE frequency and magnitude.

Study Design: A prospective observational study.

Methods: Professional Australian football players wore a non-helmeted accelerometer for one match, with data collected across 14 matches. HAEs with peak linear accelerations (PLAs) ≥ 30 *g* were verified with match video. Verified HAEs were summarized by frequency and median PLA and compared between the sexes, player position and player experience. Characterization of match related situations of verified HAEs was conducted and the head impact rate per skill execution was calculated.

Results: 92 male and 118 female players were recruited during the 2017 season. Males sustained more HAEs (median: 1; IQR: 0 - 2) than females (median: 0; IQR: 0 - 1; p = 0.007) during a match. The maximum PLAs incurred during a match were significantly higher in males (median: 61.8 *g*; IQR: 40.5 - 87.1) compared to females (median: 44.5 *g*; IQR: 33.6 - 74.8; p = 0.032). Neither player position or experience were associated with HAE frequency. Of all verified HAEs, 52% (n = 110) occurred when neither team had possession of the football and 46% (n = 98) were caused by contact from another player attempting to gain possession of the football. A subset of HAEs (n = 12, 5.7%) resulted in players seeking medical aid and/or being removed from the match (median

PLA = 58.8 *g*; IQR: 34.0 - 89.0), with two (male) players diagnosed with concussion following direct head impacts and associated PLAs of 62 *g* and 75 *g* respectively. In the setting of catching (marking) the football, females exhibited twice the head impact rate (16 per 100 marking contests) than males (8 per 100 marking contests).

Conclusions: Playing situations in which players have limited control of the football are a common cause of impacts. Males sustained a greater exposure to HAEs compared to females. Females, however, sustained higher exposure to HAEs than males during certain skill executions, possibly reflecting differences in skill development. These findings can therefore inform match and skill development in the emerging professional women's competition of Australian football.

Keywords: Non-Helmeted Accelerometer, Professional Athletes, Head Impact Biomechanics, Wearable Accelerometers**,** Sports-Related Concussion, Sports Injury.

2.2 Introduction

Australian football is a non-helmeted sporting code of extreme physical endurance demanding high-speed running, jumping, landing and disposing of the football among team players by ‘handballing’ (i.e., holding the ball with one hand and hitting it with a clenched fist of the other) or kicking the football [3]. After the football is kicked, players become involved in a ‘marking contest’ wherein players huddle in close proximity while attempting to ‘mark’ (i.e., catch) or spoil the football without the opposition or ground contacting the football first. A player who successfully marks the football is awarded a kick without any interference from the opposition. If the mark fails, the football can be further contested on the ground (i.e., ground ball) and any player with obvious or clear possession of the football can be tackled by the opposition. Other players, however, can legally protect or ‘shepherd’ the ball carrier by using their own body to ‘bump’ or ‘block’ the opposition from tackling the ball carrier. Hence, this sporting code has many sources of permissible body contact. Australian football players are frequently prone to head and body impacts from multiple angles, typically resulting in orthopedic injuries (most commonly involving the lower limbs) as well as concussion [2]. At the professional level in the Australian Football League (AFL), it is estimated that six to eight concussions occur per 1000 player hours, which equates to one every three matches for a standard team of 22 players [2].

With the advent of wearable sensor systems it has become possible to conduct in-vivo measurement of head acceleration events (HAEs) by quantifying peak linear acceleration (PLA, in g) and peak rotational acceleration (PRA, in rad/s^2) [23, 44]. Evidence from helmeted sporting codes, predominantly American football and ice hockey, suggests factors such as sex, player position and, to an extent, player experience may influence exposure to HAEs [13, 25, 51, 53, 55]. Previous studies have explored injury mechanisms of concussion and the associated PLA and PRA values through laboratory-based reconstructive analysis [27, 42]. To date, little is known about the frequency or magnitude of exposure to HAEs detected in-vivo not necessarily resulting in a clinical diagnosis of concussion, or potential determinants of this exposure in the non-helmeted Australian football code. The professional level of competition additionally provides a prime setting to explore these factors, as the literature exploring head kinematics in American football players suggests impact exposure is positively correlated with the match level [46].

A limitation of previous studies quantifying HAEs in non-helmeted contact sports has been the use of one of the only available instruments, the Prevent Biometrics (previously X2 Biosystems) X-Patch®, with acquisition rates of PLA reported above 10 *g* [49] and without video verification [35]. Video review of time-stamped match-related HAEs reveals the X-Patch® is subject to the over estimation of head impact exposure due to registration of non-injurious activity (e.g., jumping, running, landing) associated with very low thresholds and subsequently poor false-positive detection (i.e., poor reliability of in-built software algorithm) [14, 43, 48]. Studies now increasingly employ video review for verification of HAEs which additionally enables descriptive analysis of associated player situations in which HAEs occur [14, 15 ,32].

According to Bahr and Krosshaug's (2005) comprehensive model of injury causation, the playing situation (e.g., phase of play), player behavior (e.g., skill execution) and gross biomechanical descriptors (e.g., cause of impact, head and body impact location) are important determinants of injury causation [5]. Whilst player and situational factors associated with clinically diagnosed concussions have been documented in Australian football players [26, 38, 41], the characterization of exposure to all HAEs are yet to be explored, particularly at the professional level.

The aim of this investigation was to quantify and characterize HAEs verified on video review in the non-helmeted contact sport of professional Australian football. Further to this, the study aimed to investigate the association of sex, player position, and player experience on frequency and magnitude of verified HAEs on video review in a cohort of professional male Australian Football League (AFL) and female Australian Football League Women's (AFLW) players.

2.3 Method

2.3.1 Design and Population

This prospective observational pilot study was approved by the Monash University Research Ethics Committee (Project Number: 0785). Study participants were recruited from nine of the available ten professional Victorian based male AFL teams who played across four weeks during the 2017 Jardine Lloyd Thompson Group (JLT) Community Series; and from all eight professional AFLW teams who played across four weeks in the 2017 NAB (National Australia Bank) AFL Women's competition. Once team management had agreed for the team to participate individual players provided informed consent. Inclusion criteria were consent to participate in the study and consent to wear an X-Patch® for one entire match. Demographic information was gathered post-match including age, player position and player experience (number of years playing community football and number of years playing professional football). For statistical analysis, player positions were grouped into forward (i.e., key forward, general forward), midfield (i.e., midfielder, midfielder-forward, ruck, wing) and defender (i.e., key defender, general defender) positions. Player experience was stratified into four categories: 0 to 5 years; 6 to 10 years; 11 to 15 years and more than 15 years. Each player participated in data collection for a single match only, across a total of 14 matches. Additional demographic data were gathered retrospectively from official league online records, including weight, height, and player statistics with regards to the total incidence of skill execution for the matches observed (kicks, tackles, marks, handballs, contested possessions). Limited records were available for weight for female players as this was the inaugural year of female player participation in this sporting code at the professional level.

2.3.2 Accelerometer Device

At the time of this study, the X-Patch® was the only commercially available device that could be applied to the head, without the need for a helmet, headband and/or mouthguard. All X-Patch® devices were tested for basic functionality (e.g. battery life) prior to use. The X-Patch® was affixed using the prescribed instructions: placed on the skin behind the ear over the mastoid using double-sided adhesives and counterbalancing the application of the patch between the left and right side across participants. To further secure the X-Patch®, a strip of BodyPlus® sports strapping tape was placed across the device.

The X-Patch® (purchased in 2015 from X2 Biosystems Inc., Seattle, WA) contains a triaxial linear accelerometer and triaxial gyroscope sensor. Laboratory-based and in-vivo analysis of the X-Patch® revealed PLA demonstrated a greater reliability and lower variance when compared to PRA [43, 58]. On this basis, only PLA was utilized for this study. The X-Patch® cannot differentiate between a direct head impact or an impact to another body location leading to an inertial loading of the head [19, 43, 48]. The X-Patch® continuously samples at a frequency of 1 kHz and is triggered to record 100 ms of time-stamped data for any acceleration event with a PLA exceeding 10 *g*.

The Impact Monitoring System (IMS; X2 Biosystems) proprietary software was used to obtain a time-stamped data set of multiple PLA values per accelerometer device per player. The IMS in-built algorithm to identify spurious PLAs (i.e. false positives due to non-contact events such as jumping, running) was disabled due to the lack of reliability of this software and all PLAs were included for analysis [48, 56]. Each accelerometer was cleared of data before it was utilized again. Data from accelerometer devices that became detached or faulty were excluded. Extreme values were also excluded, and were defined as a frequency of HAEs measured by the X-Patch® with PLAs above 10 *g* per player that exceeded $n = 150$ [56].

2.3.3 Outcome

The primary outcome measure was time-stamped HAEs with PLAs ≥ 30 *g* per player that could be verified on video. The threshold of PLA ≥ 30 *g* was selected on the basis of supporting evidence that: HAEs with PLA < 30 *g* may not be easily identified on video and may be confounded by non-injurious events that typically occur in the AFL and everyday activity, such as jumping, running fast and stopping or landing [4, 28, 45, 48, 54]. HAEs with a low PLA are also associated with a very low likelihood of concussion such that PLAs of 20 *g*, 30 *g*, 40 *g* and 50 *g*, respectively, have a 4%, 7%, 12% and 19% likelihood of concussion based on 98 AFL and National Football League (NFL) laboratory-based reconstructed impacts with and without concussion [40]. Data from large cohort studies with North American football players are consistent with this demonstrating that only high magnitude PLAs (e.g., ≥ 96 *g*) yield the highest predictive value of concussion, with at least a minimum of 70 *g* to 75 *g* required to cause injury [12, 24, 29].

The AFL provided video footage of the live broadcast feed for each observed match, incorporating tight, wide, low and/or elevated views of match events. The video review was completed independently by two neuropsychology trainees (JR and JN). Review of match footage for male (generally 80 minutes) and female players (generally 60 minutes) was unlimited with any playback speed permissible to ensure reliable verification of HAEs.

All video footage and X-Patch output were dated and timestamped allowing the verification of X-Patch detected HAEs by precisely matching the HAEs to the corresponding event in video footage. A window of +/- 1 minute was used to account for potential discrepancies in exact time frames (e.g., quarter time was extended as a result of a stoppage) [15, 19, 48]. HAEs were considered *verified* if: a) there was a clear and unobstructed view of the player in the video footage during the inspected time frame and b) if there was clear visible contact to the head or body of the X-Patch® wearing player (i.e., impacted player) by another player and/or object (e.g., ground, goal post, fence) during the inspected time frame [15, 19]. HAEs that occurred in close succession (e.g., within 30 seconds) were reviewed and treated independently, thereby resetting the inspection window for each HAE on review. No single contact event was associated with more than one HAE. Individual video verified HAEs with PLAs ≥ 30 *g* were further characterized by player situation (quarter, phase of play, number of players involved in the impact) and player behavior (skill execution by the impacted player at the time of impact) as well as gross biomechanical descriptors (cause of impact and body impact location) and outcome of the verified impact.

2.3.4 Analysis

Inter-and intra-rater reliability analysis were conducted to provide measures of rating consistency for factors used to characterize all verified HAEs with PLAs ≥ 30 *g* using Cohen's Kappa, intraclass correlations (ICCs) and percentage agreement. In addition, the verified head impact rate per execution of common Australian football skills were calculated with corresponding 95% confidence intervals (CI). These rates were calculated as the sum of verified and direct head impacts during a skill execution (e.g., head impacts sustained while executing a tackle) divided by the total number of executions for said skill (e.g., total number of tackles) as shown below.

$$\text{Head Impact Rate}= \frac{\sum \text{verified head impacts} \geq 30\text{ g while executing a skill}}{\sum \text{total number of executions of skill}}$$

2.3.4.1 Comparative Analysis

Continuous normal or near normally distributed variables (age and height) were summarized using mean (standard deviation) and statistical differences assessed using Student's t-test. Nominal and ordinal variables were categorized and presented using proportions and statistical differences assessed using the chi-square test (highest level of education, player position, and player experience stratified by sex). All verified HAEs with PLAs ≥ 30 *g* were reduced per player for comparative analysis. Skewed continuous variables and discrete variables (frequency of HAEs and PLAs) were summarized using median (inter-quartile ranges) and differences assessed using Mann-Whitney U Test. Differences between three or more medians were compared using a Kruskal-Wallis test by ranks. Statistical significance was defined as $p < 0.05$ with Bonferroni corrections, where appropriate, to control for family-wise error in cases of multiple comparisons. All data were analyzed using SPSS (IBM Version 25, Armonk, NY).

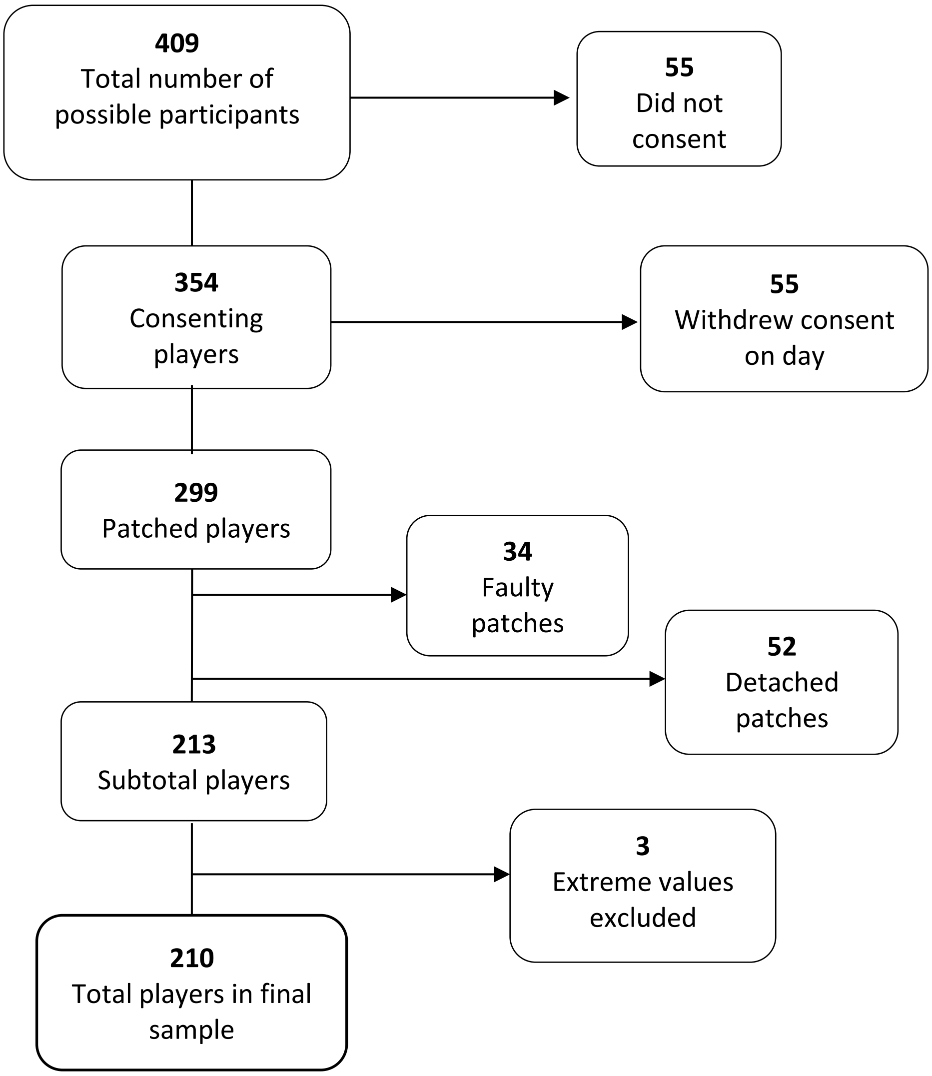

Figure 1. Participant inclusion.

2.4 Results

A total of 17 teams were observed for one entire match across 14 matches out of the total 56 matches comprising the assessed competitions (JLT Community Series = 27 matches; AFLW Premiership = 29 matches). Within these teams, 354 players consented to participate in the study however 55 players withdrew their consent on match-day (84% response rate). In addition, 86 players had patches that detached (60%) or became faulty (40%) and HAEs from these patches were excluded from further analysis [25]. Data from three male players determined to have an extreme number of HAEs (HAE n = 342, 301, 226 respectively) were excluded, resulting in n = 210 players included for analysis (Figure 1). Demographics and match-related information are outlined in Table 1. Males (n = 92) and females (n = 118) were well matched for age and height. Weight was not compared statistically given the limited number of measurements available for female players. Significant differences were evident across level of education (with more females having undertaken tertiary education) and player experience (males had significantly more years of player experience).

Table 1
Participant Demographics

Item	Male n = 92	Female n = 118	p-value
Age at assessment* (years)	24.0 (3.8)	24.7 (4.2)	0.25
Height* (centimeters)	188.2 (6.9)	177.2 (7.0)	0.17
Weight* (kilograms)	87.8 (7.5)	66.3 (5.9)^	--
Highest Level of Education, n (%)			< 0.001
Secondary Studies	77 (84%)	72 (61%)	
Tertiary Studies	15 (16%)	46 (39%)	
Player position			0.26
Forwards	25 (27%)	26 (22%)	
Midfielders	34 (37%)	57 (48%)	
Defenders	33 (36%)	35 (30%)	
Years of player experience			< 0.001
0 – 5 years	12 (13%)	48 (41%)	
6 – 10 years	18 (20%)	42 (36%)	
11 – 15 years	23 (25%)	23 (19%)	
More than 15 years	39 (42%)	5 (4%)	

*Summarized using mean (standard deviation).
^ Limited records for female players, resulting in n = 16.

There were a total of 4957 unverified HAEs ≥ 10 *g*, of which 336 unverified HAEs were ≥ 30 *g,* and 211 HAEs (see Appendix A for distribution) were verified impacts identified in video analysis (herein after referred to as HAEs). Measures of rating consistency across the factors used to further characterize HAEs revealed good to excellent inter-rater (ICC: 0.769 - 0.984) and intra-rater reliability (ICC: 0.663 – 1.00; see Appendix B for comprehensive results).

Of the 210 players included for analysis, 102 players sustained HAEs ≥ 30 *g*, with the remaining n = 108 players not sustaining HAEs ≥ 30 *g*. The distribution of HAEs frequency, sub-grouped by sex, is displayed in Figure 2 below. In the overall sample (n = 210), males (median of 1; IQR: 0 - 2) sustained more HAEs during the observed match compared to females (median of 0; IQR: 0 - 1), *p* = 0.007.

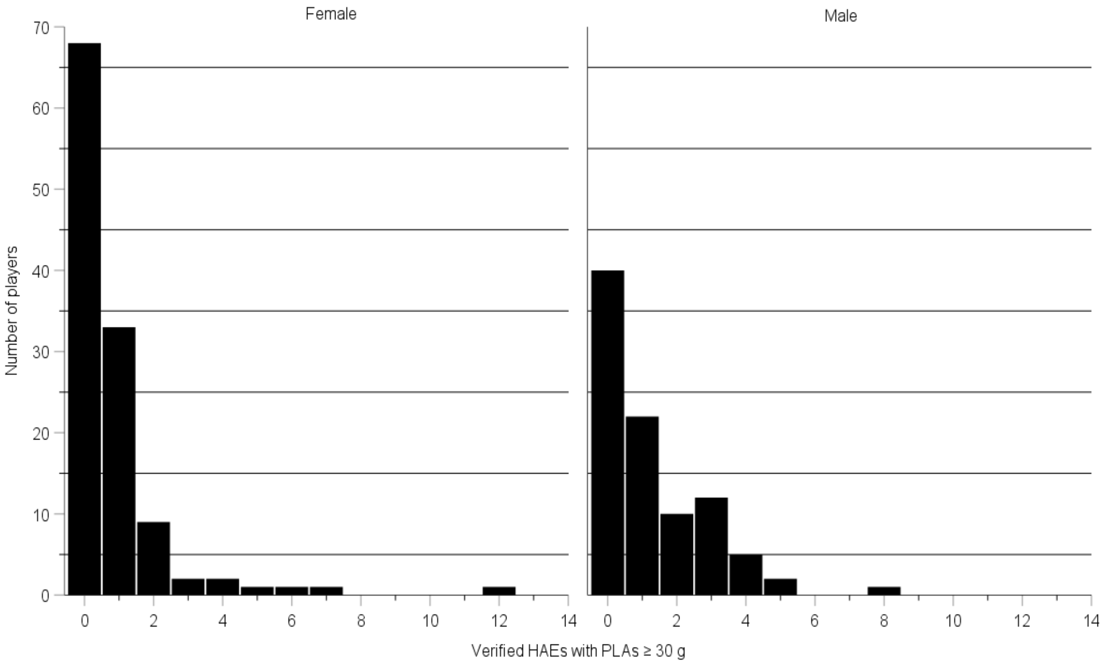

Figure 2. Distribution of video verified head acceleration events (HAEs) with peak linear accelerations (PLAs) ≥ 30 *g* (x-axis) grouped by the number of players (y-axis) stratified by sex during a match. Note the value of 0 on the x-axis does not align with the y-axis in order to illustrate the number of players with frequency of n = 0 HAEs with PLAs ≥ 30 *g*.

The association between player experience, player position and HAEs are summarized in Table 2. In the overall sample (n = 210) there was no association between player position, *p* = 0.74, or with player experience, *p* = 0.056, and the frequency of HAEs ≥ 30 *g*.

Table 2
Distribution of Verified Head Acceleration Events ≥ 30 *g* per Player by Player Position and Player Experience

	Frequency N = 210	PLA *g* N = 102	
	Median (IQR)	Median (IQR)	Max median (IQR)
Player Position			
Forward	0.00 (0 – 2)	48.8 (40.5 – 64.8)	61.3 (44.0 – 100.9)
Midfield	1.00 (0 – 1)	40.6 (32.9 – 55.0)	45.2 (33.1 – 81.2)
Defender	0.00 (0 – 1)	41.4 (34.9 – 54.6)	52.6 (36.1 – 75.2)
Player Experience			
0 – 5 years	0.50 (0 – 1)	45.9 (35.8 – 56.9)	50.0 (35.8 – 83.2)
6 – 10 years	0.00 (0 – 1)	40.7 (35.7 – 60.0)	48.7 (38.6 – 76.9)
11 – 15 years	0.00 (0 – 1)	41.0 (32.7 – 45.7)	43.5 (32.8 – 88.6)
Above 15 years	1.00 (0 – 2)	47.9 (37.4 – 62.3)	61.8 (40.5 – 77.0)

PLA = Peak linear acceleration

Analysis of players who sustained HAEs ≥ 30 *g* (n = 102), revealed n = 52 male players sustained a comparable median PLA of 45.7 *g* (IQR: 37.5 - 62.8 *g*) to n = 50 female players who sustained a median PLA of 41.2 *g* (IQR: 33.6 - 53.1 *g*); *p* = 0.12. Among this group, however, male players typically sustained a significantly higher maximum PLA of 61.8 *g* (IQR: 40.5 - 87.1 *g*) when compared to females who had a maximum PLA of 44.5 *g* (IQR: 33.6 - 74.8 *g*); *p* = 0.032 (see Appendix A Table 7 for distribution).

Analysis of players who sustained HAEs ≥ 30 *g* (n = 102) revealed no association between player experience, *p* = 0.47, or with player position, *p* = 0.15, and the median PLA sustained. While the results in Table 2 reveal forwards sustained a higher maximum PLA compared to midfielders and defenders, this was not statistically significant, *p* = 0.20. Similarly, there was no association between player experience and maximum PLA, *p* = 0.69.

2.4.1 Characterization of Head Acceleration Events

2.4.1.1 Playing Situation

Of all HAEs, 55.4% occurred during the first half of the match, and 44.6% occurred during the second half of match. The median PLA of HAEs during the first half of the match was 41.4 *g* (IQR: 35.0 - 53.7) while the median PLA in the second half was 45.45 *g* (IQR: 34.3 - 70.1). More than half of the HAEs occurred during contested play when neither team had clear possession of the football (n = 110, 52.1%), while the remainder were almost evenly distributed between an offensive or defensive phase of play as seen in Table 3. HAEs occurring during a contested phase of play resulted a median PLA of 45.3 *g* (IQR: 34.8 - 63.4). When stratifying phase of play by sex, the proportion of HAEs occurring during contested play was 56.4% (n = 62) in female players and 43.6% (n = 48) in male players, while the proportion of HAEs occurring during offensive and defensive play were 67.3% (n = 68) in male players and 32.7% (n = 33) in female players.

Table 3
Verified Head Acceleration Events ≥ 30 *g* by Playing Situation and Cause of Impact

Fields	n (%)	Median PLA	IQR
Quarter			
1	64 (30.3%)	41.2	35.0 – 62.0
2	53 (25.1%)	41.4	35.5 – 50.3
3	40 (19.0%)	47.6	34.9 – 75.0
4	54 (25.6%)	45.4	32.8 – 69.0
Number of Players			
1	10 (4.7)	41.1	34.1 – 52.6
2	144 (68.2)	42.0	35.4 – 60.5
3	31 (14.7)	45.6	33.7 – 68.6
4+	26 (12.3)	44.6	33.0 – 69.6
Phase of Play			
Contested Play	110 (52.1)	45.3	34.8 - 63.4
Offence	48 (22.7)	38.7	33.2 – 58.9
Defense	53 (25.1)	42.4	36.7 – 62.4
Cause of Impact			
Marking Contest	52 (24.6)	41.3	34.0 – 66.8
Contested Ball	46 (21.8)	47.6	35.5 – 78.1
Tackling	33 (15.6)	44.9	36.1 – 53.3
Being Tackled	31 (14.7)	41.2	34.4 – 59.2
Ground Ball	22 (10.4)	39.9	34.2 – 49.6
Shepherding	17 (8.1)	46.0	35.8 – 64.8
Other	10 (4.7)	37.4	31.8 – 43.8
Goal Post/Fence	0 (0)	0	--

PLA = Peak linear acceleration
IQR = Interquartile Range

2.4.1.2 Player Behavior

An evaluation of the players’ behavior with regard to skill execution at the time of the HAE demonstrated that 26.1% (n = 55) of HAEs occurred while the player was contesting a ground ball (see Figure 3), while 25.1% (n = 53) occurred when the player was attempting to mark or spoil the ball (i.e., marking contest; see Figure 4). Players executed a tackle during 16.1% (n = 34) of HAEs and a handball during 9.5% (n = 20) while bumping/shepherding was being executed in 8.1% (n = 17) of HAEs.

Figure 3. Contested ball on the ground (Ground Ball).

Figure 4. Marking contest.

2.4.1.3 Gross Biomechanical Descriptors

The most common cause of a HAE was due to incidental contact from another player who was also attempting to mark or spoil the football, or contesting a ground ball (n = 98, 46.5%), while contact when being tackled or tackling the opposition was the second most common cause (n = 64, 30.3%) as seen in Table 3. An impact due to incidental contact from another player while contesting a ground ball resulted in a median PLA of 47.6 *g*. Interestingly, shepherding or bumping/blocking was only a cause of impact in 8.1% (n = 17) of HAEs, though resulting in a median PLA of 46.0 *g* (IQR: 35.8 - 64.8). For male players, HAEs caused during a ground ball situation resulted in the highest median PLA of 59.7 *g* (IQR: 39.0 - 108.2 *g*), while for female players, a HAE caused during shepherding resulted in the highest median PLA of 52.6 *g* (IQR: 35.1 - 85.2) as seen in Table 4.

With regard to body impact location, the majority of HAEs resulted from a direct impact to the head (n = 74, 35.1%), followed by chest/shoulder (n = 57, 27%), back (n = 29, 13.7%), abdomen/hips (n = 21, 10%) and upper or lower limbs (n = 19, 9%) while the impact location for a subset of HAEs could not be determined (n = 11, 5.2%). The median PLA of HAEs resulting from direct head impacts was 48.41 *g* and the median PLA for HAEs resulting from impact to other body locations was 40.51 *g*. Of all HAEs resulting from a direct head impact, 51.4% (n = 38) occurred to the side of the head and this resulted in a median PLA of 52.63 *g*, while the median PLA of all other head impact locations was 46.26 *g*.

Table 4
Verified Head Acceleration Events ≥ 30 *g* by Cause of Impact and Sex

	Male			Female		
	n (%)	Median PLA	IQR	n (%)	Median PLA	IQR
Marking Contest	32 (27.6)	50.0	37.8 – 73.4	20 (21.1)	37.3	32.7 – 54.1
Contested Ball	24 (20.7)	59.7	39.0 – 108.1	22 (23.2)	43.5	34.0 – 71.2
Tackling	21 (18.1)	42.7	34.5 – 53.3	12 (12.6)	46.9	37.6 – 58.2
Being Tackled	22 (19)	39.1	33.0 – 65.3	9 (9.5)	47.0	38.7 – 54.6
Ground Ball	4 (3.4)	34.6	31.9 – 67.5	18 (18.9)	42.5	34.7 – 49.6
Shepherding	10 (8.6)	43.0	35.9 – 48.0	7 (7.4)	52.6	35.2 – 85.2
Other	3 (2.6)	32.8	31.9 – 37.2	7 (7.4)	41.1	33.1 – 46.9
Goal Post/Fence	0 (0)	0	0 - 0	0 (0)	0	0 - 0

PLA = Peak linear acceleration

The majority of HAEs (n = 194, 91.9%) did not result in an observed injury while very few HAEs (n = 5, 2.4%) resulted in player discomfort (i.e., exhibiting facial expression of pain post-impact). HAEs resulting in no observed injury and player discomfort had a median PLA of 41.6 *g* (IQR: 34.7 - 60.8 *g*) and 52.0 *g* (IQR: 42.1 - 64.8 *g*) respectively. A small subset of HAEs (n = 12, 5.7%) resulted in players seeking medical aid and/or being removed from the match with a median PLA of 58.8 *g* (IQR: 34.0 - 89.0). In this category, PLAs for HAEs following a body impact (n = 2) were 30 *g* and 32 *g*; while PLAs for HAEs following a direct head impact (n = 10) ranged between 53 *g* to 139 *g* with one PLA being 31 *g*. There were two (male) players who were diagnosed with concussion following direct head impacts with associated PLAs of 62 *g* and 75 *g* respectively.

2.4.1.4 Head Impact Rate

The incidence of verified direct head impacts occurring per mark was highest (9 per 100 marking contests) among all impact rates per skill execution as seen in Table 5. Females exhibited almost twice the head impact rate per mark (16 per 100 marking contests) and per contested possession (8 per 100 contests) relative to male players. Conversely, males exhibited twice the head impact rate per tackle (4 per 100 tackles) compared to female players (2 per 100 tackles).

Table 5
Head Impact Rate of Verified Head Acceleration Events ≥ 30 *g* by Skill Execution

	Male			Female			Total		
	HI	AE	HI/AE (95% CI)	HI	AE	HI/AE (95% CI)	HI	AE	HI/AE (95% CI)
Contested Possessions	12	298	4 (2 - 7)	15	200	8 (5 - 12)	27	498	5 (4 - 8)
Marks	13	166	8 (5 - 13)	7	45	16 (8 - 31)	20	211	9 (6 - 14)
Handballs	6	371	2 (1 - 4)	2	117	2 (0 - 7)	8	488	2 (1 - 3)
Tackles	5	136	4 (2 - 9)	3	130	2 (1 - 7)	8	266	3 (2 - 6)
Kicks	2	373	1 (0 - 2)	0	246	0	2	619	0 (0 - 1)

HI = The number of head impacts
AE = Athletic-exposure defined by the number of total skill executions
All head impacts rates per skill execution, or HI/AE are presented per units of 100

2.5 Discussion

This study is the first to identify and characterize match-related factors in which video verified HAEs occur in the non-helmeted contact sport of professional Australian football, and the first to explore the association of sex, player position and player experience to the frequency and magnitude of HAEs. Primary findings revealed the frequency of HAEs ≥ 30 *g* and the maximum PLAs incurred during the match were statistically higher in male, compared to female players, while the median PLA was comparable between sexes. Despite notable magnitudes of HAEs for median and maximum PLAs in forwards relative to midfielders and defenders, the association between player position and exposure to verified HAEs ≥ 30 *g* was not statistically significant. Nor was there an identified association between player experience and frequency of HAEs. The highest rate of direct head impacts per skill execution occurred while marking or spoiling the ball (9 per 100 marking contests), with females exhibiting twice the head impact rate (16 per 100 marking contests) compared to male players (8 per 100 marking contests).

2.5.1 Sex Differences

Sex differences in frequency of HAEs in sport have not been consistently demonstrated. Studies comparing sex in ice hockey found male players sustain almost twice the number of HAEs (mean of 6.3 to 7.7 per match) when compared to female players (mean of 3.7 to 5.3 per match) [25, 55]. In collegiate lacrosse, male and female players sustain comparable frequencies of HAEs, however male players incur a greater PLA per HAE in comparison to female players, possibly reflecting differences in sporting rules across the codes, wherein body contact is allowed in male and not female competitions [49]. In our study, male players sustained a statistically higher number of verified HAEs ≥ 30 *g* when compared to female players. This may result from differences in match duration between professional male and female matches, which last approximately 80 and 60 minutes respectively [3]. Other match related factors such as head impact rate per skill execution outlined below also likely contribute to the observed sex difference.

Differences in the magnitude of HAEs between the sexes are also variable [9, 49, 55]. It has been reported that male hockey players are more likely to sustain impacts greater than 100 *g* in comparison to their female counterparts [9]. Only one study to date has explored sex effects across impact magnitude and frequency of HAEs in a sample of community Australian football players. Willmott et al. (2018) found comparative PLAs for HAEs ≥ 10 *g* obtained in a single match, however males sustained significantly more HAEs (mean = 31.2, SD = 25.2) than female players (mean = 17.6, SD = 13.2) [56]. In the present study, male players sustained a comparable median PLA to female players. The maximum PLA value, however, was significantly higher in male players, suggesting sex differences in head impact magnitude may be under estimated with analysis of average or mid-point values [50]. A potential factor underpinning sex differences in PLA is body mass. In this sample, male and female players were comparable in height although males appeared to be heavier in weight. Data for weight of female players, however, was limited to n = 16 thereby invalidating statistical comparisons of this metric. Body mass is one of many independent risk factors that predominantly interact with other internal (e.g., skill level) and external factors (e.g., sporting regulations) underpinning injury causation [5]. For example, Brainard et al. found male ice hockey players sustained significantly greater PLAs in comparison to female players who had significantly lower weight and height in comparison to males [9]. In ice hockey, 'body checking' or purposeful contact is not permitted for female players, thereby reducing the likelihood of HAEs with a greater magnitude in comparison to male players. In this context, the sporting regulations serve as a protective factor for players characterized by other predisposing factors of injury (e.g., sex and body composition).

For concussion, acceleration thresholds are more widely established in male players [46]. Findings increasingly identify that concussion is associated with PLA values of approximately 100 *g* but can range from 70 *g* to 145 *g* [6, 10, 40, 46]. In the current study, male players sustained maximum PLAs with a median (62 *g*) that border on this injury-threshold. An important consideration is the potential variability in injury-thresholds between individuals. Recently, Rowson and colleagues found concussion was associated with a linear acceleration of 68 *g* but this ranged from 54 *g* to 94 *g* in collegiate football [50]. Therefore, establishing individual-specific tolerance values may be more useful, rather than use of specific or mean acceleration values which have poor prognostic utility [47]. This would require an ongoing assessment of players and contributing factors surrounding each individual case of concussion (e.g., playing situation, level of fatigue, pre-existing injury, playing surface) in addition to routine monitoring of head impact kinematics over a season, subject to further technological improvement.

2.5.2 Player Position and Player Experience

Player position was not significantly associated with frequency or magnitude of video verified HAEs, suggesting equal positional exposure at the professional level. Previous studies have found exposure to HAEs can be determined by player position [11, 20, 21]. In American football, there is considerable variability in head impact exposure across different positions, with mean PLAs varying between running backs (offensive position with restriction: 60.5 - 77.7 *g*) compared to linebackers (defensive position with no restriction: 63.8 - 157.5 *g*) [33]. In community Australian football, midfield positions appear to have an increased vulnerability to injury. Players in midfield positions (e.g., center, wing, follower) run greater distances at faster speeds and have the highest frequency of involvement during the match and contact to the ground, compared to forwards and defenders [22, 57]. Midfielders often incur the greatest proportion (42% to 45%) of all injuries recorded per season when compared to forwards or defenders as a result of contact with other players [8, 30]. In one community Australian football sample, midfielders sustained a higher frequency of HAEs although these were not verified by video analysis [35]. By contrast, our findings revealed forwards appeared to have the highest median (48 *g*) and maximum (61 *g*) PLA sustained during the match, although this was not statistically significant. It is possible a single-match observation may not sufficiently capture positional differences at the professional level of the match thereby requiring seasonal observations. Alternatively, given the movement patterns of modern professional footballers and close proximity of the majority of players to the football at all times, it is also possible that position designations are less relevant.

Further, it appears that years of player experience is not necessarily a protective factor with regard to head impact exposure in Australian football. There is some evidence to suggest more experienced American football players develop greater situational awareness and execute more skilled defensive and protective tactics that may lessen the exposure to HAEs [53]. In our study, the total number of years playing football, as an index of player experience, may not sufficiently account for other factors that could also be associated with experience, such as level of risk-taking behavior, the quality of skill being executed (e.g., number of successful marks), exercise of protective mechanisms (e.g., number of times protecting head), or number of match infractions due to illegal play (e.g., tackling a player who is not in possession of the football).

2.5.3 Characterization of Verified HAEs

The characterization of verified HAEs ≥ 30 *g* using video analysis revealed 52.1% (n = 110) HAEs occurred in playing situations when neither team has possession of the ball, and most often between two players including the impacted player. The median PLA of the second half of the match (quarter 3 and 4) ranged from 45 *g* to 47 *g* while the median PLA of the first half (quarter 1 and 2) was 41 *g*. The most common skills executed by the impacted player at the time of a verified HAE were either contesting a ground ball or engaging in a marking contest, both resulting in a notable median PLA of 47.6 *g*. When stratifying this by sex, male players sustained a median PLA of 59.7 *g* during contested play. By contrast, shepherding or bumping/blocking, a less common cause of impact, resulted in a median PLA of 52.6 *g* in female players. At the professional level of Australian football, male and female players are frequently subject to impacts of a considerable magnitude as the match progresses and during situations in which players have limited control of the ball and their surrounding environment relative to defensive or offensive tactics. These results demonstrate the value of adding a secondary source of information (video analysis) to quantify head kinematics and identify playing situations with risk of injury to players [14, 15, 19].

Only a small subset of HAEs (n = 12, 5.7%) resulted in the players seeking medical aid and/or being removed from play, and this was associated with a median PLA of 58.8 *g*. Most of these impacts were caused by incidental contact during a marking contest or contested ground ball.

Incidence rate analysis revealed the head impact rate occurring per marking contest was the highest among all head impact rates per skill execution, with female players exhibiting twice the head impact rate per marking contest compared to male players. Male players, by contrast, exhibited twice the head impact rate per tackle relative to female players. At the professional level of the AFL, a marking contest and tackling are player situations in which concussion predominantly occurs and are therefore of considerable risk for injury consistent with the current findings [38]. The incidence rate per marking contest in female players suggests females may have a two-fold risk of incurring an impact to the head in these situations compared to male players and this may reflect differences in skill development between the sexes.

Development of common AFL skills encompasses practice of safety behaviors to mitigate injury, such instructions on how to land, fall or brace for impact [1]. The long-standing involvement of male players at the professional level of Australian football, however, has possibly resulted in greater skill development relative to the newly introduced cohort of professional female players. In 2017, the inaugural women's competition at the professional level of Australian football was characterized by more congested play with an average stoppage every 60 seconds compared to a stoppage every 78 seconds during the men's competition [7]. In comparison to female matches, male matches were characterized by more successful disposals and possessions of the ball possibly reflecting more highly developed skill execution. In addition, predictors of match outcome in female matches are found to be playing situations that are regarded to have a greater likelihood of success such as the ratio between the number of entries within a 50-metre boundary from the goal post (i.e., 'inside 50') and actual goals, as well as uncontested possessions (i.e. possession of the ball under no physical pressure from the opposition) [7]. In fact, it is found that winning and losing female teams have similar skill profiles suggesting other factors such as activity profiles or individual physical fitness may account for match outcome.

2.5.4 Limitations

The current study did not examine rotational head kinematics. Factors potentially associated with head impact exposure (e.g., sex, player position, player experience) have previously been associated with differences in rotational acceleration [46, 51]. The free-roam nature of Australian football may increase the likelihood of oblique head impacts[42] in comparison to other sports where the match tactics lend themselves to more to directional impacts such as American football. The X-Patch® detection of PRA however, is not sufficiently reliable for use when compared to PLA (see section 5.3 for an outline of the X-Patch limitations) [43, 52, 58].

The single match exposure rate per player prevented comparison of head impact rates across sex to other sporting codes. Recording of HAEs across an entire season would enable more informative measures of risk exposure (i.e., incidence rate per player per match, or player exposure per 1000 hours) to explore determinants of risk and also facilitate comparison across various sporting codes.

Of note, the NAB AFL Women's Competition serves as the female premiership season, while the JLT Community series for male players is the prelude to their premiership season later in the year. Further, the JLT Community Series is a chance for the AFL to trial rule modifications that often aim to further protect the player and reduce injuries. Therefore, the current results may not be generalizable across the entire competitive male premiership season.

2.5.5 Conclusions

This study identified playing situations that resulted in HAEs at the professional level of non-helmeted Australian football. Sex differences in the frequency and maximum PLAs sustained by professional Australian football players were identified, with more impacts and greater maximum PLA sustained by male players. No statistically significant association was evident for player position or player experience and head impact exposure. Female players exhibited twice the head impact exposure compared to male players when contesting or spoiling a mark, possibly reflecting sex differences in skill development.

Future research making categorical comparisons (e.g., male vs. female) of exposure to head impacts in match-settings should consider exploring the upper range of PLA distribution (e.g., upper percentiles) to better identify head impact exposure that is of clinical relevance. Use of gross descriptors – such as number of years playing football – may not be sufficiently sensitive to represent the multifaceted nature of risk to injury. Instead, individualized variables (body mass, injury tolerance, risk-taking and safety or protective behavior) and more detailed match-related factors (e.g., contact exposure due to field restrictions/match rules & tactics) can potentially predict exposure to head impacts in sports. Knowledge that certain playing situations have a potential to cause HAEs of greater magnitudes (e.g., marking contest) among specific players (e.g. female players) can inform match and player development with regards to coaching drills, individual skills training, and rule revision as required. In contact sport, increasing rates of injuries which become apparent as the match progresses [16, 31, 36] might be reduced by instituting the more frequent interchange rotation of novice players thereby mitigating exposure to head impacts and possible injury.

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2.7 References

1. AFL. *The official AFL level 1 coaching manual: The coach*. Victoria, Australia: Australian Football League; 2016.

2. AFL. *26th Annual AFL Injury Survey*. Melbourne, Victoria, Australia: Australian Football League (AFL); 2017.

3. AFL. *Laws of Australian Football*. Melbourne, Victoria, Australia: Australian Football League (AFL); 2019.

4. Allen ME, Weir-Jones I, Eng P, et al. Acceleration perturbations of daily living. *Spine.* 1994;19(11):1285-1290.

5. Bahr R, Krosshaug T. Understanding injury mechanisms: A key component of preventing injuries in sport. *Br J Sports Med.* 2005;39(6):324-329.

6. Beckwith JG, Greenwald RM, Chu JJ, et al. Timing of concussion diagnosis is related to head impact exposure prior to injury. *Med Sci Sports Exerc.* 2013;45(4):747-754.

7. Black GM, Gabbett TJ, Johnston RD, Cole MH, Naughton G, Dawson B. A skill profile of the national women's Australian football league (AFLW). *Science and Medicine in Football.* 2018;3(2):138-142.

8. Braham R, Finch CF, McIntosh A, McCrory P. Community level australian football: A profile of injuries. *J Sci Med Sport.* 2004;7(1):96-105.

9. Brainard LL, Beckwith JG, Chu JJ, et al. Gender differences in head impacts sustained by collegiate ice hockey players. *Med Sci Sports Exerc.* 2012;44(2):297-304.

10. Brennan JH, Mitra B, Synnot A, et al. Accelerometers for the assessment of concussion in male athletes: A systematic review and meta-analysis. *Sports Med.* 2016;47(3):469–478.

11. Broglio SP, Martini D, Kasper L, Eckner JT, Kutcher JS. Estimation of head impact exposure in high school football: Implications for regulating contact practices. *Am J Sports Med.* 2013;41(12):2877-2884.

12. Broglio SP, Schnebel B, Sosnoff JJ, et al. The biomechanical properties of concussions in high school football. *Med Sci Sports Exerc.* 2010;42(11):2064-2071.

13. Caccese JB, Buckley TA, Tierney RT, Rose WC, Glutting JJ, Kaminski TW. Sex and age differences in head acceleration during purposeful soccer heading. *Research in Sports Medicine.* 2018;26(1):64-74.

14. Carey L, Stanwell P, Terry DP, et al. Verifying head impacts recorded by a wearable sensor using video footage in rugby league: A preliminary study. *Sports Med Open.* 2019;5(1):9.

15. Caswell SV, Lincoln AE, Stone H, et al. Characterizing verified head impacts in high school girls' lacrosse. *Am J Sports Med.* 2017;45(14):3374-3381.

16. Chahla J, Sherman B, Cinque M, et al. Epidemiological findings of soccer injuries during the 2017 gold cup. *Orthop J Sports Med.* 2018;6(8):2325967118791754.

17. Cicchetti DV. Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. *Psychological Assessment.* 1994;6(4):284-290.

18. Cohen J. A coefficient of agreement for nominal scales. *Educ Psychol Meas.* 1960;20(1):37-46.

19. Cortes N, Lincoln AE, Myer GD, et al. Video analysis verification of head impact events measured by wearable sensors. *Am J Sports Med.* 2017;45(10):2379-2387.

20. Crisco JJ, Fiore R, Beckwith JG, et al. Frequency and location of head impact exposures in individual collegiate football players. *J Athl Train.* 2010;45(6):549-559.

21. Crisco JJ, Wilcox BJ, Beckwith JG, et al. Head impact exposure in collegiate football players. *J Biomech.* 2011;44(15):2673-2678.

22. Dawson B, Hopkinson R, Appleby B, Stewart G, Robers C. Player movement patterns and game activities in the Australian Football League. *J Sci Med Sport.* 2004;7(3):278-291.

23. Duma SM, Manoogian SJ, Bussone WR, et al. Analysis of real-time head accelerations in collegiate football players. *Clin J Sport Med.* 2005;15(1):3-8.

24. Duma SM, Rowson S. Every newton hertz: A macro to micro approach to investigating brain injury. Paper presented at: Engineering in Medicine and Biology Society, 2009. EMBC 2009. Annual International Conference of the IEEE, 2009.

25. Eckner JT, O'Connor KL, Broglio SP, Ashton-Miller JA. Comparison of head impact exposure between male and female high school ice hockey athletes. *Am J Sports Med.* 2018;46(9):2253-2262.

26. Ekegren CL, Gabbe BJ, Finch CF. Medical-Attention Injuries in Community Australian Football: A Review of 30 Years of Surveillance Data From Treatment Sources. *Clin Sports Med.* 2015;25:162-172.

27. Fréchède B, McIntosh AS. Numerical reconstruction of real-life concussive football impacts. *Med Sci Sports Exerc.* 2009;41(2):390-398.

28. Funk JR, Cormier JM, Bain CE, Guzman H, Bonugli EB, Manoogian S. Head and neck loading in everyday and vigorous activities. *Annals of Biomechanical Engineering.* 2010;39(2):766-776.

29. Funk JR, Duma S, Manoogian S, Rowson S. Biomechanical risk estimates for mild traumatic brain injury. 2007;51:343-361.

30. Gabbe B, Finch C, Wajswelner H, Bennell K. Australian football: Injury profile at the community level. *J Sci Med Sport.* 2002;5(2):149-160.

31. Gardner AJ, Iverson GL, Quinn TN, et al. A preliminary video analysis of concussion in the National Rugby League. *Brain Inj.* 2015;29(10):1182-1185.

32. Gellner RA, Campolettano ET, Smith EP, Rowson S. Are specific players more likely to be involved in high-magnitude head impacts in youth football? *J Neurosurg Pediatr.* 2019;24(1):47-53.

33. Guskiewicz KM, Mihalik JP. Biomechanics of sport concussion: Quest for the elusive injury threshold. *Exercise and Sport Sciences Reviews.* 2011;39(1):4-11.

34. Hallgreen KA. Computing inter-rater reliability for observational data: An overview and tutorial. *Tutor Quant Methods Psychol.* 2012;8(1):23-34.

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

36. King D, Hume PA, Clark T. Nature of tackles that result in injury in professional rugby league. *Research in Sports Medicine.* 2012;20(2):86-104.

37. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics.* 1970;33(1):159-174.

38. Makdissi M, Davis G. Using video analysis for concussion surveillance in Australian football. *J Sci Med Sport.* 2016;19(12):958-963.

39. McHugh ML. Interrater reliability: the kappa statistic. *Biochem Med (Zagreb).* 2012;22(3):276-282.

40. McIntosh AS. Biomechanical considerations in the design of equipment to prevent sports injury. *Proc Inst Mech Eng P J Sport Eng Technol.* 2012;226(3-4):193-199.

41. McIntosh AS, McCrory P, Comeford J. The dynamics of concussive head impacts in rugby and Australian rules football. *med Sci Sports Exerc.* 2000;32(12):1980-1984.

42. McIntosh AS, Patton DA, Frechede B, Pierre PA, Ferry E, Barthels T. The biomechanics of concussion in unhelmeted football players in Australia: A case-control study. *BMJ open.* 2014;4(5):e005078.

43. McIntosh AS, Willmott C, Patton D, et al. An assessment of the utility and functionality of wearable head impact sensors in Australian Football. *J Sci Med Sport.* 2019;22:784-789.

44. Naunheim RS, Standeven J, Richter C, Lewis LM. Comparison of impact data in hockey, football, and soccer. *J Trauma Acute Care Surg.* 2000;48(5):938-941.

45. Ng TP, Bussone WR, Duma SM. The effect of gender and body size on linear accelerations of the head observed during daily activities. *Biomed Sci Instrum.* 2006;42:25-30.

46. O'Connor KL, Rowson S, Duma SM, Broglio SP. Head-impact–measurement devices: A systematic review. *J Athl Train.* 2017;52(3):206-227.

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

48. Press JN, Rowson S. Quantifying head impact exposure in collegiate women's soccer. *Clin J Sport Med.* 2017;27(2):104-110.

49. Reynolds BB, Patrie J, Henry EJ, et al. Quantifying head impacts in collegiate lacrosse. *Am J Sports Med.* 2016;44(11):2947-2956.

50. Rowson S, Duma SM, Stemper BD, et al. Correlation of concussion symptom profile with head impact biomechanics: a case for individual-specific injury tolerance. *J Neurotrauma.* 2018;35:681-690.

51. Schmidt JD, Pierce AF, Guskiewicz KM, Register-Mihalik JK, Pamukoff DN, Mihalik JP. Safe-play knowledge, aggression, and head-impact biomechanics in adolescent ice hockey players. *J Athl Train.* 2016;51(5):366-372.

52. Siegmund GP, Guskiewicz KM, Marshall SW, DeMarco AL, Bonin SJ. Laboratory validation of two wearable sensor systems for measuring head impact severity in football players. *Ann Biomed Eng.* 2016;44(4):1257-1274.

53. Swartz EE, Broglio SP, Cook SB, et al. Early Results of a Helmetless-Tackling Intervention to Decrease Head Impacts in Football Players. *J Athl Train.* 2016;50(12):1219-1222.

54. Vijayakumar V, Scher I, Gloeckner DC, et al. Head kinematics and upper neck loading during simulated low-speed rear-end collisions:A comparison with vigorous activities of daily living. *Mechanical Systems Journal.* 2006;115(6):155-166.

55. Wilcox BJ, Machan JT, Beckwith JG, Greenwald RM, Burmeister E, Crisco JJ. Head-impact mechanisms in men's and women's collegiate ice hockey. *J Athl Train.* 2014;49(4):514-520.

56. Willmott CM, McIntosh AS, Howard T, et al. SCAT3 changes from baseline and associations with X2 patch measured head acceleration in amateur Australian football players. *J Sci Med Sport.* 2018;21(5):442-446.

57. Wisbey B, Montgomery PG, Pyne DB, Rattray B. Quantifying movement demands of AFL football using GPS tracking. *J Sci Med Sport.* 2010;13(5):531-536.

58. Wu LC, Nangia V, Bui K, et al. In vivo evaluation of wearable head impact sensors. *Ann Biomed Eng.* 2015;44(4):1234-1245.

2.8 Appendix

2.8.1 Appendix A Distribution of Verified Head Acceleration Events

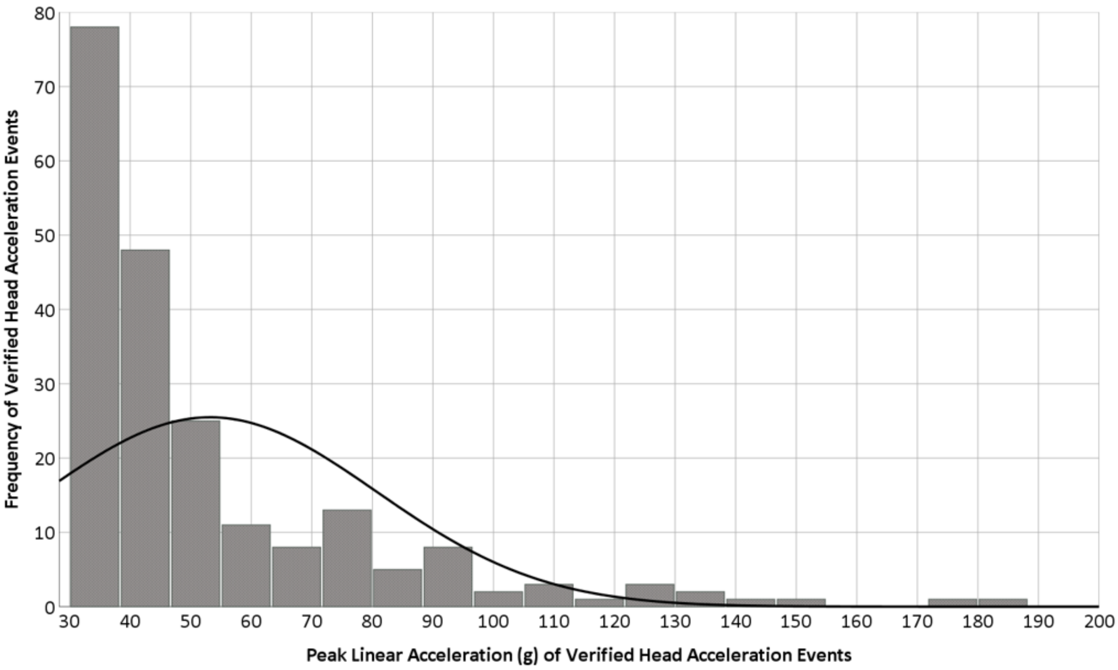

Figure 5. A plot demonstrating the frequency of verified head acceleration events (y-axis) with the corresponding peak linear acceleration (x-axis) and fitted with a normal curve line.

Table 6
Descriptive Statistics for all Verified Head Acceleration Events With Peak Linear Accelerations Above or Equal to 30 *g*

n	211
Mean (SD)	53.2 (27.5)
Standard Error	1.9
Median (IQR)	42.7 (34.8 - 62.2)
5th and 10th Percentile	31.3 and 31.9
90th and 95th Percentile	92.9 and 113.2
Mode	30.0
Min to Max	30.0 to 181.2
Kurtosis (SE)	4.59 (0.33)
Skewness (SE)	2.04 (0.17)
Log10 Kurtosis (SE)	0.37 (0.33)
Log10 Skewness (SE)	1.07 (0.17)

Table 7
Distribution of Verified Head Acceleration Events for Median and Maximum Peak Linear Accelerations for Male and Female Players

	5th	10th	25th	50th	75th	90th	95th
Median PLA							
Female, n = 50	31.3	31.9	33.6	41.2	53.1	68.4	120.9
Male, n = 52	32.0	32.8	37.5	45.7	62.8	83.7	106.4
Max PLA							
Female, n = 50	31.3	31.9	33.6	44.5	74.8	117.4	137.8
Male, n = 52	32.2	33.5	40.5	61.8	87.1	126.7	157.2

PLA = Peak Linear Acceleration

2.8.1 Appendix B Video Coding Reliability Assessment

Inter-rater reliability was conducted for ten randomly selected verified impacts. Intra-rater reliability was conducted for an additional ten randomly selected verified impacts previously coded by JR and JN each, thereby making a sample total of 30 randomly selected verified impacts for reliability assessment. Both raters coded these cases independently. Cohen’s Kappa was calculated for nominal factors and intraclass correlations (ICCs) were calculated for ordinal factors [34, 39]. Percentage agreement was also calculated, and produced as the number of agreement scores divided by the total number of scores. Average measures intraclass correlations (ICCs) were based on absolute agreement using a two-way mixed effects model with coders as the fixed effect and provided with 95% confidence intervals. Cohen’s Kappa revealed *good* to *very good* inter-and intra-rater reliability [18]. These were consistent with the ICCs, which revealed *good* to *excellent* reliability and percentage agreement, with *moderate* to *almost perfect* agreement [17, 37].

Table 8
Interrater Reliability Provided by Intra-Class Correlations with 95% Confidence Intervals, Cohen's Kappa and Percentage Agreement

Field	IRR1			IRR2			IRR3		
	ICC (95% CI)	K	%	ICC (95% CI)	K	%	ICC (95% CI)	K	%
Number of Players	.862 (.437 - .966)		70	.953 (.807 - .988)		80	.816 (.180 - .911)		80
Outcome	.880 (.521 - .970)		70	1.00		100	1.00		100
Phase of Play	.769 (.170 - .941)	.600	80	1.00	1.00	100	1.00	1.00	100
Skill Execution	.789 (.083 - .948)	.730	80	.992 (.968 - .998)	.872	90	.966 (.870 - .991)	.861	90
Cause of Impact	.984 (.936 - .996)	.740	80	.663 (-.359 - .916)	.747	80	.979 (.918 - .995)	.747	80
Body Impact Location	.816 (.303 - .954)	.661	80	1.00	1.00	100	.780 (.168 - .945)	.706	90
Head Impact location	.964 (.864 - .991)	.848	90	1.00	1.00	100	1.00	1.00	100

IRR1 = Interrater Reliability
IRR2 = Intra-rater reliability for JR
IRR3 = Intra-rater reliability for JN
ICC = Intraclass correlations
K = Cohen's Kappa

Chapter Three:

The Potential of Head Acceleration Measurement To Augment Concussion Screening in Professional Australian Football Players

Original Article

The Potential of Head Acceleration Measurement to Augment Current Best Practice in Concussion Screening in Professional Australian Football Players

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This chapter constitutes a manuscript submitted (and under review) to the journal of *Physical Therapy in Sport* and was therefore formatted in accordance with the journal requirements. Sections of the chapter below, however, were formatted in a manner consistent with the remainder of this thesis. This chapter was accepted for publication during the examination of this thesis (Reyes et al., *Physical Therapy in Sport, 43*, 210-216).

3.1 Abstract

Objective: To explore the potential utility of head acceleration event (HAE) measurements to augment identification of players for further concussion screening in non-helmeted contact sport.

Design: Prospective observational pilot study.

Participants: 210 (118 female) professional Australian football players in 2017 season.

Methods: Players wore the X-Patch® for one match. Players with HAEs above thresholds associated with concussion, 95 *g* (males) or 85.5 *g* (females), were compared to players identified to have suspected concussion by club personnel during the game. Video review of matches was undertaken by a physician blinded to HAEs to identify players with concussive signs.

Results: Among 26 players (50% female) with HAEs above threshold, two players were screened for concussion. Of the remaining 24 players, nine were not visible on video at the HAE time, six sustained verifiable head impacts, and nine sustained verifiable body impacts with no head impacts. Among 184 players with HAEs below threshold, five players were screened.

Conclusion: Players were identified to have head impacts and suspected concussion in the absence of HAEs above threshold. Use of X-Patch® was not sufficiently reliable for identifying players for further concussion screening in professional Australian football.

Keywords: Head Impact Biomechanics, Wearable Accelerometers**,** Sports-Related Concussion, Concussion Screening.

3.2 Introduction

Australian football is a highly dynamic non-helmeted contact sport involving high-speed running, jumping, landing, and disposing of the ball by a short-distance ‘handball’ (i.e., holding the ball with one hand and hitting it underneath with a clenched fist of the other) or kicking the ball to achieve a long-distance disposal (AFL, 2019). Players who ‘mark’ or catch the ball cleanly – that is – without the opposition contacting the ball first, gain an advantage to dispose (i.e. to kick or handball) the ball without interference from the opposition. Marking is often contested by opposition players huddling in close proximity who also attempt to mark the ball. Players otherwise holding or carrying the ball can be tackled by the opposition to gain possession of the ball. During a match, players are prone to head and body impacts from multiple angles, typically resulting in orthopaedic injuries (most commonly involving hamstring, knee, calf and ankle injuries) as well as concussion, with a reported incidence of six to eight concussions per 1,000 player hours at the professional level, which equates to approximately one concussion every three matches for a team of 22 players (AFL, 2017). Video analysis of match play demonstrates concussion in Australian football commonly occurs in a marking contest (25 – 32%) and tackling situation (21 – 31%), typically from contact of another player’s shoulder (15%), knee (17%), hip (15%) and/or elbow (14%) (Makdissi & Davis, 2016b).

Best practice in the sideline management of concussion recommends the recognition and removal of concussed players from the remainder of the match (Elkington, Manzanero, & Hughes, 2017; McCrory et al., 2017). In line with other professional sports, the Australian Football League (AFL) has developed systematic multidisciplinary protocols guided by international consensus guidelines (McCrory et al., 2013) to identify and assess players after head impacts. The protocols rely on a combination of sideline clinical assessment and video footage review (Clifton, Harcourt, Gastin, & Makdissi, 2016; Makdissi & Davis, 2016b), and it is mandatory that players who demonstrate any symptoms or signs of concussion be permanently removed from that match. These protocols, however, are not routinely applied in lower levels of competition, such as community or junior league matches.

Concern remains that some players may be concussed but are not recognised by current best practice sideline concussion protocols. It has previously been reported that approximately half of concussed players do not immediately recognise or report concussion symptoms (Asken et al., 2016). The majority of players who sustain concussion show good recovery within weeks of the injury, but some may suffer ongoing somatic, cognitive and/or mood symptoms (Makdissi et al., 2017), and some evidence suggests that delayed identification of concussion is associated with protracted recovery (Asken et al., 2016). Additionally, self-report of concussion symptomatology has been shown to be unreliable as players often under-report their symptoms (Meier et al., 2015).

Development of wearable accelerometer systems over the last two decades has facilitated in vivo measurement of the head’s kinematic events (linear and angular acceleration) during sport (Duma et al., 2005; Naunheim, Standeven, Richter, & Lewis, 2000). Head acceleration events (HAEs) with accelerations of a high magnitude have been associated with elevated markers of neuronal injury in players who remain asymptomatic in the short term (Joseph et al., 2018), as well as with concussion (Brennan et al., 2016). It is important to note that a diagnosis of concussion cannot be made from the output of a wearable accelerometer (Patricios et al., 2017). Accelerometer outputs may, however, augment sideline identification of players in need of further concussion screening. At present, the most commonly used accelerometer technology to assess head kinematics in-vivo are instrumented helmets with the Head Impact Telemetry System (HITS; O'Connor, Rowson, Duma, & Broglio, 2017). This is, however, not a suitable option for non-helmeted contact sports such as basketball, soccer, or Australian football.

To date, no study has examined the utility of a wearable accelerometer to identify players for concussion screening in non-helmeted contact sport. The aim of this study was to explore the feasibility and potential utility of a non-helmeted accelerometer (X-Patch®) to identify professional male (AFL) and female (Australian Football League Women’s; AFLW) Australian football players who sustain HAEs above thresholds typically associated with concussion and may require sideline screening for possible concussion.

3.3 Method

3.3.1 Design and Sample

This prospective observational pilot study was approved by the Monash University Research Ethics Committee (Project Number: 0785). Consenting players were recruited from nine of the ten regional professional male AFL teams who competed across four weeks during the 2017 Jardine Lloyd Thompson Group (JLT) Community Series; and from all eight available professional AFLW teams who played across four weeks in the NAB (National Australia Bank) AFLW’s competition. Inclusion criteria were consent to participate in the study and consent to wear an X-Patch® for one entire match. All players participated for a single match only. Demographic information was gathered post-match or retrospectively from official league online records including age, height and player experience (combined number of years playing community and professional football). Limited records were available for weight for female players as this was the inaugural year of female player participation at the professional AFLW level.

3.3.2 Accelerometer Device

At the time of this study, the X-Patch® was the only commercially available device that could be applied to the head without need of a helmet, headband and/or mouthguard. The X-Patch® (purchased in 2015 from X2 Biosystems Inc., Seattle, WA) now owned by Prevent Biometrics® is a small (1cm x 2cm) device that contains a triaxial linear accelerometer and triaxial gyroscope sensor. This device continuously samples at a frequency of 1 kHz and is triggered to record and timestamp 100 ms of data for any HAE with peak linear accelerations (PLA) that exceed 10 *g*. We used the Impact Monitoring System (IMS; X2 Biosystems) proprietary software to obtain a timestamped data set of PLA values per accelerometer device per player. We defined HAEs above threshold as any X-Patch® recorded PLA value above 95.0 *g* for male players and 85.5 *g* for female players. The limits of the primary exposure variable were selected based on a 75% likelihood of concussion using an injury-risk curve pooled from laboratory-based biomechanical data of injured and non-injured AFL and National Football League (NFL) players and supported by findings from a meta-analysis demonstrating concussive episodes are generally associated with PLAs of this magnitude (Brennan et al., 2016; McIntosh, 2012). In addition, injury-risk curves from large-cohort studies reveal PLA magnitudes of 96 *g* and above are the most predictive of concussive injury (Broglio et al., 2010; Duma & Rowson, 2009). We selected an arbitrary 10% lower PLA threshold for female players based on current evidence suggesting that females have a greater susceptibility to concussion and concussion may be associated with lower PLAs (Dick, 2009; Wilcox et al., 2014).

Analysis of X-Patch® outputs relative to reference ground values estimating the head's kinematics (Hybrid III headform) revealed PLAs have greater reliability and lower variance when compared to PRA, and PRA was therefore excluded from the analysis (McIntosh et al., 2019; Nevins, Smith, & Kensrud, 2015; Wu et al., 2015). The IMS in-built algorithm to identify false positive HAEs was disabled due to the lack of reliability for this software and all PLAs were therefore included for analysis (Press & Rowson, 2017; Willmott et al., 2018). Data from accelerometer devices that became detached or faulty were excluded. Extreme values were also excluded, and were defined as a frequency of HAEs measured by the X-Patch® with PLAs above 10 *g* per player that exceeded *n* = 150 (Willmott et al., 2018). All X-Patch® accelerometers were tested for basic functionality (e.g., battery life) prior to use. The devices were applied using the prescribed instructions: placed on the skin behind the ear over the mastoid process using double-sided adhesives and counterbalancing the application of the patch between the left and right side of the participant. To further secure the X-Patch®, a strip of BodyPlus® sports strapping tape was placed across the device.

3.3.3 Primary Outcome

The primary outcome variable was removal of players from the match due to suspected concussion. Concussion screening was conducted independently by medically qualified club personnel according to the AFL concussion management guidelines in keeping with the international concussion in sports group (CISG) consensus statement (McCrory et al., 2013). This consists of the sideline detection of any incident potentially resulting in concussion (e.g., visible head impact during skill execution) and use of the Head Injury Assessment form (HIAf; Clifton et al., 2016) to assist club personnel identify and remove players suspected of concussion who are observed to have concussive signs (e.g., balance disturbance, no protective action in fall to ground, loss of consciousness) and/or report symptoms (e.g., memory impairment, headache, neck pain). Players who undergo sideline screening with the HIAf are not permitted to return to the playing surface for at least 15 minutes following medical assessment (AFL Regulations, 2019).

Accelerometer outputs were not available in real time nor available to sideline personnel at any time. After the season, all HAEs above threshold were independently reviewed by two neuropsychology trainees (JR and JN) using match video provided by the AFL. The X-Patch output and video footage provided a specific date and timestamp allowing precise verification of HAEs with corresponding video footage events. All video reviews were conducted using a window of +/- one minute from the HAE timestamp to account for potential discrepancies in exact times (e.g., stoppage during match extended quarter time). Review of match footage was unlimited to optimise the verification process.

A HAE was considered verified if there was an unobstructed view of a player and direct contact was made to the player’s head by another player and/or object during the inspected timeframe consistent with previous video review methodologies (Caswell et al., 2017; Cortes et al., 2017). No single HAE was associated with more than one contact event. There was no real-time or post-match official video analysis conducted by team personnel or AFL personnel independent of the investigator team.

A sub-set of videos were randomly selected by author (JR) for review by a trained physician who routinely conducts video review (MM) for signs of concussion as per a published protocol (Makdissi & Davis, 2016a). The reviewer was blinded to PLA values and to avoid a selection bias, the sub-set of videos for review included all players removed from a match for sideline screening and all players with HAEs above threshold without sideline screening who were visible during the inspected time-frame.

3.3.4 Analysis

We analysed all data using Stata (StataCorp v11.3, College Station, Texas). As this was a pilot assessment of X-Patch® measured HAEs in a non-helmeted sport, a formal sample size calculation was not performed as there was no previous data on frequency or clinical significance of HAEs above threshold in this population. Concordance among X-Patch® recorded HAEs above threshold and player removal for sideline screening of concussion by club personnel were calculated and presented using 95% confidence intervals. Descriptive statistics for player demographics and match-related information were produced (see Table 1). Continuous variables (age in years and height in cm) were summarised using mean (standard deviation) and differences assessed using Student's *t*-test. Ordinal variables (years of player experience) were summarised using median (inter-quartile ranges) and differences assessed using the Mann Whitney U test. Proportions (level of education) were compared using the chi-square test. Statistical significance was defined as $p < 0.05$.

3.4 Results

A total of 17 clubs were observed once across 14 matches out of the total 56 matches comprising the assessed competitions (Male JLT Community Series = 27 matches; Female AFLW Competition = 29 matches). From the 409 approached to participate in the study, 354 players consented to participate though 55 players withdrew their consent on match-day (73% response rate). In addition, 86 players had patches that detached or became faulty and HAEs from these patches were excluded from further analysis. Data from three male players determined to have an extreme number of HAEs (HAEs n = 342, 301, 226 respectively) were excluded resulting in data from 210 players included for analysis (see Figure 1).

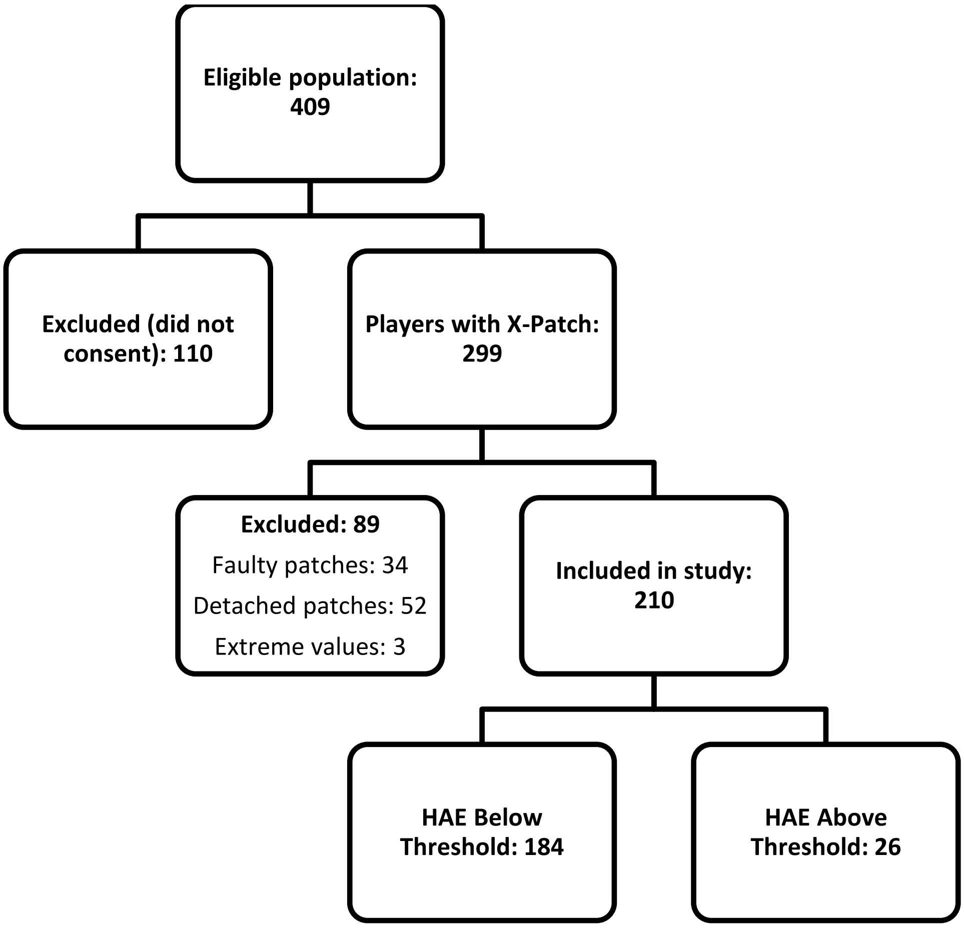

Figure 1. Participant inclusion. HAE = Head acceleration events.

There were a total of 4957 HAEs above 10 *g*. Of these, 4621 HAEs were between 10.1 *g* – 30 *g* and 336 HAEs above 30 *g* (See Figure 2). Demographics and match-related information are listed in Table 1. HAEs above threshold were recorded in 26 (12.4%; 95% CI: 8.6-17.5) players (n = 13 males and n = 13 females). Among these 26 players, only two (8%; 95% CI: 2.1-24.1) were removed from the field for concussion screening following an observable impact to the head by club personnel. Among players with recorded HAE below threshold, five players (n = 3 female and n = 2 males) were removed for concussion screening. Among these five players, HAEs were recorded for four of these players (26 *g*, 62 *g*, 75 *g* and 77 *g*) who demonstrated an impact to the head and concussive signs (n = 1 with loss of responsiveness and n = 1 with balance disturbance) or symptoms post-impact, while no HAE was recorded for one player who reported “neck pain” on screening.

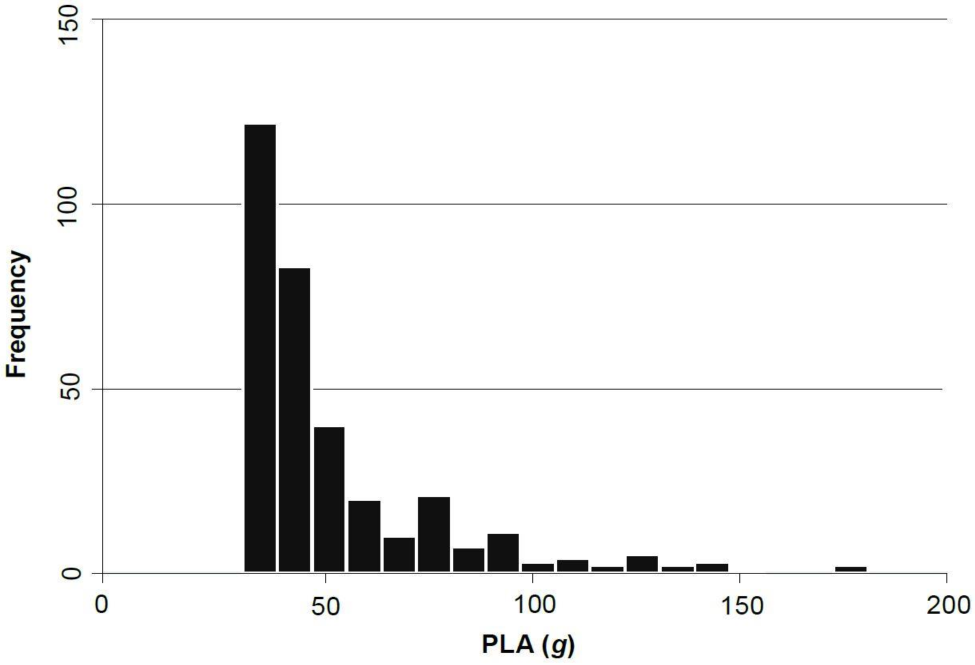

Figure 2. The frequency of head acceleration events (HAE; y-axis) according to the peak linear acceleration (PLA) for acceleration events above 30 *g* (x-axis).

Table 1. Player Demographics

Item	With HAE Above Threshold n = 26	With HAEs Below Threshold n = 184	p-value
Age at assessment (years) †	23.2 (3.6)	24.5 (4.1)	0.12
Sex			0.50
Male	13 (50%)	79 (43%)	
Female	13 (50%)	105 (57%)	
Height (cm) †	179.96 (15.0)	182.34 (61.4)	0.84
Highest Level of Education			0.84
Secondary Studies	18 (69%)	131 (71%)	
Tertiary Studies	8 (31%)	53 (29%)	
Years of player experience*			
Community level	5 (3 – 10)	6 (3 – 10)	0.56
Professional level	1 (1 – 5)	1 (1 – 5)	0.88

† Summarised using mean (standard deviation)
*Summarised using median (inter-quartile range)
HAE = Head acceleration event

On review of video footage, all seven players (n = 2 with HAE above threshold and n = 5 with HAEs below threshold) identified and removed from a match for sideline screening were confirmed on video as having sustained a direct head impact. Of the remaining 24 players with HAEs above threshold who were not identified in-match for sideline concussion screening, video analysis identified six players who sustained a direct head impact, nine players who sustained a body impact (e.g., being tackled) but no head impact could be identified, while nine players were not filmed on the match video at the relevant time points.

On assessment of videos for signs of concussion, blinded video footage review by an expert reviewer revealed that of the players with HAEs above threshold and removed from the match, two were identified as having signs of concussion (slow to get up). None of the remaining six players with HAEs above threshold were observed to have signs of concussion. Of the five players removed from match with HAEs below threshold, three were identified as having signs of concussion.

3.5 Discussion

This is the first report to explore the utility of HAEs above thresholds typically associated with concussion among professional AFL players to identify players for further concussion screening. HAEs above threshold were identified in 12.4% of players during a match. A key finding from this study was that players identified by experts in the field as having suspected concussion sustained HAEs as recorded by the X-Patch well below the acceleration threshold utilised in the current study, thereby confirming that current practice of sideline screening by medical personnel and video review remains essential for identification of players with suspected concussion. Suspected concussion in the setting of HAEs below threshold has been previously reported and is consistent with the community sport guidelines by the National Athletic Trainers' Association (NATA) which recommend screening of concussion, if indicated, in the absence of overt concussive signs (Broglio et al., 2014; O'Connor et al., 2017).

While HAEs above acceleration thresholds associated with concussion were detected in 26 players, and most not identified by current best practice, the clinical utility of these HAEs as recorded by the X-Patch remains unknown. Only a small proportion of players with head impacts progress to be diagnosed with concussion. The positive predictive value of HAEs above threshold to diagnose concussion is therefore small (Patricios et al., 2017). In the current professional level of male AFL and female AFLW, where the practice of concussion screening is rigorous and guided by consensus derived guidelines (McCrory et al., 2013) in conjunction with video review during and after match by experienced clinicians (Makdissi & Davis, 2016a, 2016b), measurements of HAEs, even if reliable, may only deliver minimal marginal benefit in the overall process of detecting concussion. The potential and marginal diagnostic yield from the use of accelerometers must be balanced against cost, player and staff inconvenience and interruptions to the match.

In our study, we used a high ‘cut-off’ to define a HAEs above threshold based on the available literature and with the intent of improving sensitivity in the analysis (i.e. identifying players with clinically significant impacts). A formal analysis of sensitivity and specificity, however, was not possible in this sample as there is no gold standard of in-vivo measurement for HAEs to use as reference ground values and longer-term follow-up of players was not feasible. Further, studies with clinical assessment of all players with HAEs above threshold would add to the clinical significance of these impacts. It remains essential that measures of HAEs are not used diagnostically, but rather, considered for further investigation as a potential tool to identify players for concussion screening when combined with robust clinical assessment.

Another limitation of this study was that the researchers did not implement an additional standardized protocol for concussion screening across clubs. Our aim was to pilot the use of accelerometer technology in the context of in-vivo observational data collection to augment existing concussion detection protocols rather than implementing an additional standardized procedure. Subject to improved accelerometer output reliability, the next step would have been to evaluate such technology in the context of an interventional study with uniform protocols.

A total of 29% (n = 86) of X-Patch® data were excluded as these patches were faulty or became loose throughout the match. Consistent with previous studies, it was found the X-Patch® measurements did not differentiate between a direct head impact or an impact to the body alone (Carey et al., 2019; McIntosh et al., 2019). While body impacts may lead to inertial loading of the head and/or concussion, this is less commonly observed (Lincoln, Caswell, Almquist, Dunn, & Hinton, 2013; Makdissi & Davis, 2016b; McIntosh et al., 2019). In this study, however, there were no post-match clinical assessment of players with HAEs above threshold making conclusions difficult. Furthermore, in its current configuration the X-Patch® does not facilitate real-time, wireless communication to the sideline therefore not allowing in-match assessment.

Concussion is also considered to be caused by a combination of the head’s linear and angular kinematics, in the absence of local skull and brain deformation (Greenwald, Gwin, Chu, & Crisco, 2008; Ommaya & Gennarelli, 1974). As a result of the reduced accuracy and precision of the X-Patch® with regards to angular head kinematics, however, only PLA was considered in this study. Improvements are required in accelerometer accuracy and precision to facilitate a comprehensive measurement of head impact kinematics. Unlike other areas of impact biomechanics, where injury tolerance data and injury assessment reference values (IARVs) are based on structural injuries (e.g., fracture or contusion) concussion is predominantly a functional injury (King, 2000; Ommaya & Hirsch, 1971) with variable thresholds.

We relied on the assessment of currently available data to define the PLA threshold applied in this study. The majority of research exploring biomechanical thresholds associated with concussion has been conducted in other contact sports (e.g., North American football, ice hockey), using multi-sensor devices (e.g., HITS) fitted in protective gear which reflects a stark contrast to non-helmeted sport including Australian football (Brennan et al., 2016; McIntosh et al., 2014; O'Connor et al., 2017).

In studies predominantly using the HITS, concussion has been observed to be associated with a mean PLA of 98 *g*, but this can range from 70 *g* to 145 *g* (Brennan et al., 2016; O'Connor et al., 2017). Furthermore, there is increasing evidence to suggest the rate of head impact exposure over time leading to, or on the day of injury, is more relevant to concussion risk in comparison to use of specific or single acceleration thresholds (Broglio, Lapointe, O'Connor, & McCrea, 2017; Stemper et al., 2019). In comparison to individually-matched controls, players with concussion sustain HAEs in closer succession and these HAEs may be of the highest magnitude for the individual player suggesting there are individualised acceleration threshold for concussion (e.g. a player typically incurring PLAs between 20 *g* to 40 *g* may sustain concussion at 60 *g*, while another player typically incurring PLAs of 40 *g* to 60 *g* may sustain concussion at 80 *g*).

Emerging evidence on the importance of timely detection of concussion and expected variability in the biomechanical threshold of injury associated with concussion, therefore, may require the identification of players with potential concussion who sustain HAEs of a lower magnitude and clinical assessment (O'Connor et al., 2017). As outlined by O’Connor and colleagues, lowering such thresholds for screening players must be weighed against the increased rate of false positives, the unnecessary removal and/or assessment of players during matches and associated costs [15].

3.6 Conclusions

In professional Australian football, 12.4% of participating players recorded HAEs above threshold during a match, with few removed from the field for concussion screening by club personnel. The clinical utility of these HAE values however, remains unknown. Some players who sustained HAEs below threshold were identified as having suspected concussion. HAEs as measured by the X-Patch® accelerometer are not sufficiently reliable to be used in practice for identifying professional players for further concussion screening in Australian Football.

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3.8 References

AFL. (2017). *26th Annual AFL Injury Survey*. Melbourne, Victoria, Australia: Australian Football League (AFL).

AFL. (2019). *Laws of Australian Football*. Melbourne, Victoria, Australia: Australian Football League (AFL).

Asken, B. M., McCrea, M., Clugston, J. R., Snyder, A. R., Houck, Z. M., & Bauer, R. M. (2016). ‘‘Playing Through It’’: Delayed reporting and removal from athletic activity after concussion predicts prolonged recover. *Journal of Athletic Training, 51*(4), 329-335. doi:10.4085/1062-6050-51.5.02

Brennan, J. H., Mitra, B., Synnot, A., McKenzie, J., Willmott, C., McIntosh, A. S., . . . Rosenfeld, J. V. (2016). Accelerometers for the assessment of concussion in male athletes: A systematic review and meta-analysis. *Sports Medicine, 47*(3), 469–478. doi:10.1007/s40279-016-0582-1

Broglio, S. P., Cantu, R. C., Gioia, G. A., Guskiewicz, K. M., Kutcher, J., Palm, M., & Valovich McLeod, T. C. (2014). National Athletic Trainers' Association position statement: Management of sport concussion. *Journal of Athletic Training, 49*(2), 245-265. doi:10.4085/1062-6050-49.1.07

Broglio, S. P., Lapointe, A., O'Connor, K. L., & McCrea, M. (2017). Head impact density: A model to explain the elusive concussion threshold. *Journal of Neurotrauma, 34*(19), 2675-2683. doi:10.1089/neu.2016.4767

Broglio, S. P., Schnebel, B., Sosnoff, J. J., Shin, S., Feng, X., He, X., & Zimmerman, J. (2010). The biomechanical properties of concussions in high school football. *Medicine & Science In Sports & Exercise, 42*(11), 2064-2071. doi:10.1249/MSS.0b013e3181dd9156

Carey, L., Stanwell, P., Terry, D. P., McIntosh, A. S., Caswell, S. V., Iverson, G. L., & Gardner, A. J. (2019). Verifying head impacts recorded by a wearable sensor using video footage in rugby league: A preliminary study. *Sports Medicine Open, 5*(1), 9. doi:10.1186/s40798-019-0182-3

Caswell, S. V., Lincoln, A. E., Stone, H., Kelshaw, P., Putukian, M., Hepburn, L., . . . Cortes, N. (2017). Characterizing verified head impacts in high school girls' lacrosse. *The American Journal of Sports Medicine, 45*(14), 3374-3381. doi:10.1177/0363546517724754

Clifton, P., Harcourt, P., Gastin, T., & Makdissi, M. (2016). An investigation of the role of a rapid sideline head injury assessment form (hiaf) in the clinical diagnosis of concussion in elite australian football [Abstract 207]. *British Journal of Sports Medicine, 51*(11), A79-A79. doi:10.1136/bjsports-2016-097270.205

Cortes, N., Lincoln, A. E., Myer, G. D., Hepburn, L., Higgins, M., Putukian, M., & Caswell, S. V. (2017). Video analysis verification of head impact events measured by wearable sensors. *The American Journal of Sports Medicine, 45*(10), 2379-2387. doi:10.1177/0363546517706703

Dick, R. (2009). Is there a gender difference in concussion incidence and outcomes? *British Journal of Sports Medicine, 43*(Suppl 1), i46-i50.

Duma, S. M., Manoogian, S. J., Bussone, W. R., Brolinson, P. G., Goforth, M. W., Donnenwerth, J. J., . . . Crisco, J. J. (2005). Analysis of real-time head accelerations in collegiate football players. *Clinical Journal of Sport Medicine, 15*(1), 3-8. doi:10.1097/00042752-200501000-00002

Duma, S. M., & Rowson, S. (2009). *Every newton hertz: A macro to micro approach to investigating brain injury.* Paper presented at the Engineering in Medicine and

Biology Society, 2009. EMBC 2009. Annual International Conference of the IEEE.

Elkington, L., Manzanero, S., & Hughes, D. (2017). *Australian Institute of Sport and Australian Medical Association Concussion in Sport Position Statement* (Vol. 206): Medical Journal of Australia.

Greenwald, R. M., Gwin, J. T., Chu, J. J., & Crisco, J. J. (2008). Head impact severity measures for evaluating mild traumatic brain injury risk exposure. *Neurosurgery, 62*(4), 789-798. doi:10.1227/01.neu.0000318162.67472.ad

Joseph, J. R., Swallow, J. S., Willsey, K., Lapointe, A. P., Khalatbari, S., Korley, F., . . . Broglio, S. (2018). Elevated markers of brain injury as a result of clinically asymptomatic high-acceleration head impacts in high-school football athletes. *Journal of Neurosurgery, 130*(4), 1642-1648. doi:10.3171/2017.12.JNS172386

King, A. I. (2000). Fundamentals of impact biomechanics: Part I - Biomechanics of the head, neck, thorax. *Annual Review of Biomedical Engineering, 2.1*, 55-81.

Lincoln, A. E., Caswell, S. V., Almquist, J. L., Dunn, R. E., & Hinton, R. Y. (2013). Video incident analysis of concussions in boys' high school lacrosse. *The American Journal of Sports Medicine, 41*(4), 756-761. doi:10.1177/0363546513476265

Makdissi, M., & Davis, G. (2016a). The reliability and validity of video analysis for the assessment of the clinical signs of concussion in Australian football. *Journal Of Science and Medicine in Sport, 19*(10), 859-863. doi:10.1016/j.jsams.2016.02.015

Makdissi, M., & Davis, G. (2016b). Using video analysis for concussion surveillance in Australian football. *Journal Of Science And Medicine In Sport, 19*(12), 958-963. doi:10.1016/j.jsams.2016.02.014

Makdissi, M., Schneider, K. J., Feddermann-Demont, N., Guskiewicz, K., Hinds, S., Leddy, J. J., . . . Johnston, K. (2017). Approach to investigation and treatment of persistent symptoms following sport-related concussion: A systematic review. *British Journal Of Sports Medicine, 51*, 958-968. doi:10.1136/bjsports-2016-097470

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

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

McIntosh, A. S. (2012). Biomechanical considerations in the design of equipment to prevent sports injury. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 226*(3-4), 193-199. doi:10.1177/1754337111431024

McIntosh, A. S., Patton, D. A., Frechede, B., Pierre, P. A., Ferry, E., & Barthels, T. (2014). The biomechanics of concussion in unhelmeted football players in Australia: A case-control study. *BMJ Open, 4*(5), e005078. doi:10.1136/bmjopen-2014-005078

McIntosh, A. S., Willmott, C., Patton, D., Mitra, B., Brennan, J. H., Dimech-Betancourt, B., . . . Rosenfeld, J. V. (2019). An assessment of the utility and functionality of wearable head impact sensors in Australian Football. *Journal of Science and Medicine in Sport, 22*, 784-789. doi:10.1016/j.jsams.2019.02.004

Meier, T. B., Brummel, B. J., Singh, R., Nerio, C. J., Polanski, D. W., & Bellgowan, P. S. (2015). The underreporting of self-reported symptoms following sports-related concussion. *Journal of Science and Medicine In Sport, 18*(5), 507-511. doi:10.1016/j.jsams.2014.07.008

Naunheim, R. S., Standeven, J., Richter, C., & Lewis, L. M. (2000). Comparison of impact data in hockey, football, and soccer. *Journal of Trauma and Acute Care Surgery, 48*(5), 938-941. doi:10.1097/00005373-200005000-00020

Nevins, D., Smith, L., & Kensrud, J. (2015). Laboratory evaluation of wireless head impact sensor. *Procedia Engineering, 112*, 175-179. doi:10.1016/j.proeng.2015.07.195

O'Connor, K. L., Rowson, S., Duma, S. M., & Broglio, S. P. (2017). Head-impact–measurement devices: A systematic review. *Journal of Athletic Training, 52*(3), 206-227. doi:10.4085/1062-6050.52.2.05

Ommaya, A., & Hirsch, A. (1971). Tolerances for cerebral concussion from head impact and whiplash in primates. *Journal of Biomechanics, 4*(1), 13-21.

Ommaya, A. K., & Gennarelli, T. (1974). Cerebral concussion and traumatic unconsciousness: correlation of experimental and clinical observations on blunt head injuries. *Brain, 97*(4), 633-654.

Patricios, J., Fuller, G. W., Ellenbogen, R., Herring, S., Kutcher, J. S., Loosemore, M., . . . Schneider, K. J. (2017). What are the critical elements of sideline screening that can be used to establish the diagnosis of concussion? A systematic review. *British Journal of Sports Medicine, 51*(11), 888-894. doi:10.1136/bjsports-2016-097441

Press, J. N., & Rowson, S. (2017). Quantifying head impact exposure in collegiate women's soccer. *Clinical Journal Of Sport Medicine, 27*(2), 104-110. doi:10.1097/JSM.0000000000000313

Regulations, A. (2019). *Australian Football League Regulations*. Victoria, Australia: Australian Football League.

Stemper, B. D., Shah, A. S., Harezlak, J., Rowson, S., Mihalik, J. P., Duma, S. M., . . . McCrea, M. (2019). Comparison of head impact exposure between concussed football athletes and matched controls: Evidence for a possible second mechanism of sport-related concussion. *Annals of Biomedical Engineering, 47*(10), 2057-2072. doi:10.1007/s10439-018-02136-6

Wilcox, B. J., Machan, J. T., Beckwith, J. G., Greenwald, R. M., Burmeister, E., & Crisco, J. J. (2014). Head-impact mechanisms in men's and women's collegiate ice hockey. *Journal Of Athletic Training, 49*(4), 514-520. doi:10.4085/1062-6050-49.3.19

Willmott, C. M., McIntosh, A. S., Howard, T., Mitra, B., Dimech-Betancourt, B., Donovan, J., & Rosenfeld, J. V. (2018). SCAT3 changes from baseline and associations with X2 patch measured head acceleration in amateur Australian football players. *Journal of Science and Medicine in Sport, 21*(5), 442-446. doi:10.1016/j.jsams.2017.09.591

Wu, L. C., Nangia, V., Bui, K., Hammoor, B., Kurt, M., Hernandez, F., . . . Camarillo, D. B. (2015). In vivo evaluation of wearable head impact sensors. *Annals of Biomedical Engineering, 44*(4), 1234-1245.

Chapter Four:

Concussion Screening in Community-Level Football: The Association Between Observable Signs of Concussion, SCAT3 and Cogstate Performance

Original Article

Concussion Screening in Community-Level Football: The Association Between Observable Signs of Concussion, SCAT3 and Cogstate Performance

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This chapter constitutes a manuscript submitted (and under review) with the *Journal of Science and Medicine in Sport* and was therefore formatted in accordance with the journal requirements. Sections of the chapter below, however, were formatted in a manner consistent with the remainder of this thesis.

4.1 Abstract

Objectives: The Head Injury Assessment form (HIAf) facilitates identification of early clinical features of concussion and rapid on-field screening. It typically relies on video review by experienced medical staff and has not been evaluated for community live sideline observations where video footage is not available. This study explored the utility of the HIAf items to identify Australian community male and female football players with possible concussion.

Design: Prospective cohort study.

Methods: Non-expert personnel with basic training conducted live match observations across a season (60 matches) using the HIAf. Players identified to have positive concussive signs on the HIAf checklist (HIAf+ve) were compared to players without these signs (HIAf-ve). Both the Sport Concussion Assessment Tool (SCAT3) and Cogstate were administered as outcome measures at baseline and post-match.

Results: HIAf+ve (n = 22) and HIAf-ve (n = 61) groups were matched with respect to age, sex, education, baseline mood, and concussion history. Among HIAF+ve players, 100% (95% CI: 84%- 100%) demonstrated clinically-significant deficits in the SCAT3 or Cogstate tasks, compared to 59% (95% CI: 46% to 71%) of HIAF-ve players. All HIAf+ve players demonstrating a blank/vacant look had clinically-significant decline on the Standardized Assessment of Concussion (SAC).

Conclusions: Use of the HIAf represents a rapid, real-time method to screen players suspected of concussion in community sports where video technology and medical personnel are rarely present. Consistent with community guidelines, it is recommended that all HIAf+ve players are immediately removed from play for further concussion screening.

Keywords: Athletic Injuries; Australian Football; Brain Concussion; Head; Signs and Symptoms; Sport Concussion Assessment Tool.

4.2 Introduction

Review of video footage for detection of players with observable concussive signs to facilitate concussion screening is becoming widely established across various professional sporting bodies [1]. Studies in professional Australian football have demonstrated that having a *blank/vacant look* or *balance/motor incoordination* post-head impact are among the most common concussive signs displayed by players with concussion [2]. Specific concussive signs are reported to have high predictive value for concussion diagnosis and may have potential utility in screening players suspected of concussion who require further assessment [2-4].

At the community level, advanced video technology (e.g. HawkEye Innovations systems®) and medically-trained personnel are seldom present. Concussion detection therefore relies on team personnel with limited concussion expertise. Despite recent advances in the training of coaching staff, many do not receive sufficient concussion education and few talk to their players about concussion safety [5]. In a survey of community level Australian football and rugby coaches, 40% incorrectly identified reasons (e.g. “whether player wants to come off”) to consider when removing a player with suspected concussion [6].

Furthermore, qualified personnel are required to interpret the Sport Concussion Assessment Tool (SCAT) and Cogstate, as detection of concussive symptoms and/or decrement in cognitive performance with these tools can be influenced by other factors including mood [7, 8], fatigue and pain [9-11]. Concussion screening is therefore complex for inexperienced team personnel. The Australian Football League (AFL) community guidelines for concussion management advise the use of the Head Injury Assessment form (HIAf) to help identify and remove players suspected of concussion who are observed to have concussive signs and/or report symptoms [12]. Symptom report, however, has been demonstrated to be unreliable and subject to individual bias [13, 14].

At the professional level in rugby, Gardner et al. examined the relationship between observable concussive signs in video footage and clinical outcomes of concussion using the SCAT3 [15]. Players demonstrating loss of responsiveness performed poorly on the modified Balance Error Scoring System (mBESS) and the Standardized Assessment of Concussion (SAC), as well as reporting greater symptom severity in comparison to players without this sign. To date, no study has explored the use of observable concussive signs to identify community-level players with suspected concussion.

The aim of this study was to explore the utility of items in the HIAf to help identify community-level male and female Australian football players with poorer performance on concussion assessment measures. Players demonstrating positive signs on the HIAf were expected to exhibit poorer performance on the SCAT3 and Cogstate in comparison to players without observable signs, and experience clinically-significant declines at post-match assessment compared to baseline.

4.3 Method

Player were recruited from one male (Division 2, Victoria Amateur Football Association) and female (Division 1, Victorian Women's Football League) senior and reserve teams competing in 2017. Inclusion criteria were player membership with the football club. There were no exclusion criteria. All participating players provided informed consent in this study approved by the Monash University Human Research Ethics Committee (Project Number: 0785).

Use of the HIAf recommends that players who demonstrate one or more concussive sign(s)(see Table 1) are removed from play and seek medical attention [12]. Variables B to E are reported to have high (93% – 100%) concussion specificity while variable A is reported to have less specificity (75%) suggesting probable concussion [2, 4]. Variables F and G are reported to be difficult to assess objectively (Davis et al., 2019) and were treated as one item in the present study.

Table 1
Observable Concussive Signs as per the Head Injury Assessment Form (HIAf)

Concussive Sign	Observation
a) LOC or prolonged immobility (> 2 seconds)	Lying on ground without moving, does not appear to react or reply to others around
b) No protective action in fall to ground	Loss of muscular control, does not use protective manoeuvres as they fall to ground (e.g. does not extend arms to protect self)
c) Impact seizure	Tonic posturing or clonic movements
d) Balance disturbance (loss of control over movements)	Appears 'clumsy' or to have 'rubbery legs', unsteady on their feet, walking in staggered fashion
e) Dazed or blank and vacant stare	Demonstrates no facial expression or emotion in response to the environment
f) Unusual behaviour change for player	Demonstrates odd or unusual behaviour that is not typical of the player
g) Confusion or disorientation	Appears confused and/or disoriented in response to surrounding environment (e.g., player attempting to mark ball when ball is not in vicinity)

The SCAT3 [16] was administered with the iPad-based X2 Interactive Concussion Examination (as commercially available in 2017 through X2 Biosystems®). Baseline and post-match index scores were: *Symptom Total* (0 to 22), total *Symptom Severity* (0 to 132), *SAC Total Score* (0 to 30) and *mBESS Total Errors* (0 to 30). The SAC examines orientation, concentration, immediate and delayed recall with use of alternate word and digits lists at re-test. The mBESS was conducted on a hard surface (e.g., concrete) without shoes.

Cogstate [17] is a 10 – 15 minute computerized test comprising three tasks assessing performance speed (msec): Detection (psychomotor speed), Identification (attention), One-Back (working memory), and one task assessing accuracy: One-Card Learning (visual learning). Four baseline and post-match Cogstate index scores were computed.

The Depression, Anxiety and Stress Scale-21 Item (DASS21) [18] consists of three 7-item scales that measure the extent to which symptoms have been experienced over the past two weeks, with greater total scale scores reflecting greater psychological distress (Cronbach's Alpha = 0.93) [19].

The Brief Pain Inventory (BPI) [20] measures pain intensity and interference with activity. Self-rated post-match pain intensity (which could compromise cognitive performance) was provided on a four-item scale of "no pain" (0) to "pain as bad as you can imagine" (10) (Cronbach's Alpha = 0.82 – 0.89) [21].

To mimic the real-world application of the HIAf, trained personnel with no previous experience in detection of sport-related concussion conducted all observations live from the sideline without video footage use. All personnel received training in SCAT3 and Cogstate administration as well as 1.5 hours of training with use of the HIAf and recognition of concussive signs. This included detailed knowledge with regards to observation of concussive signs, and operating procedures of the HIAf, including use of record keeping features (e.g., player ID, quarter, time, notes regarding injury/event, record of single or multiple signs, etc.) per player per observer. All 60 seasonal matches were monitored by three personnel who were stationed at opposite ends of the field and conducted observations of head impacts independent of the clubs' standard policy for concussion management. Head impacts were defined as any observable impact to the head by another player and/or object.

Participating players underwent one pre-season baseline assessment after a mid-week training session. Throughout the season, players who demonstrated a concussive sign(s) post-head impact underwent post-match assessment on the day (HIAf+ve group). Players who demonstrated no concussive signs following a head impact underwent a brief follow-up post-match. These players were excluded if they reported symptoms and/or memory difficulties on the basis that these features are not observable from the sideline and can only be elicited from the player. Players who did not demonstrate any concussive signs or report any concussive symptoms (HIAf-ve group) were scheduled to receive a post-match assessment at one of four different time points throughout the season. All assessments were conducted in semi-private rooms following 10 minutes of rest and no more than one hour.

SCAT3 and Cogstate post-match performance were the primary outcomes. Normality was assessed (Appendix A) and only players with complete data were analysed. Nominal and ordinal variables were summarized using proportions and assessed using a chi-square or Fisher's exact test. Discrete variables were summarized using median (IQR) and assessed with a Mann-Whitney U Test. Continuous normal or near normally distributed variables were summarized using mean (SD) and assessed using between-groups Student's t-test or within-groups Paired Sample's t-test. Skewed continuous variables were primarily assessed with non-parametric tests and secondarily with parametric tests to determine if the outcome was the same.

Change scores (baseline minus post-match index scores) for both groups were produced. Group-level differences in post-match index scores were conducted using one-way analyses of covariance (ANCOVAs) while controlling for individual baseline [22]. HIAf+ve and HIAf-ve players were compared on sex, age, education level, concussion history, time from baseline to post-match assessment and baseline DASS21 in order to identify potential covariates for group analyses. For HIAf+ve players, post-match outcomes (SCAT3 and Cogstate) and post-match BPI scores were assessed using Pearson's *r* for correlations.

SCAT3 clinically-significant decline was determined using an increase of 2.14 mBESS points and/or a decrease of 2.13 SAC points from baseline at post-match testing (i.e. one-tailed 95% confidence or ≤ 5th percentile) [23]. For Cogstate, a criterion of 1.65 SD units more (for Detection, Identification and One-Back tasks) or less (for One Card Learning) from the mean of normative values was used [24]. Statistical significance was defined as $p < 0.05$ with Bonferroni corrections where appropriate. All data were analysed using SPSS (IBM Version 25, Armonk, NY).

4.4 Results

Of n = 104 consenting players (64% response rate), n = 4 players reported symptoms and/or memory difficulties and were excluded, while n = 83 were included in the final analysis (see Appendix B for sample bias assessment). Player reports of medical history show n = 17 (20.5%) had a hospital presentation for concussion in a previous season, n = 12 (14.5%) had history of depression/anxiety, while n = 9 (10.8%) had a history of headaches/migraines.

HIAf+ve (n = 22) and HIAF-ve (n = 61) players were well matched demographically (see Table 2). Among HIAF+ve players, 31.8% (n = 7) demonstrated

Table 2
Demographic Comparison Between Players Without Observable Concussive Signs (HIAf-ve) and With Observable Concussive Signs (HIAf+ve)

Item	HIAf-ve n = 61	HIAf+ve n = 22	p
Age at Baseline (years)[a]	26.09 (3.65)	26.49 (5.52)	.76
Sex[c]			
Female	20 (32.8)	9 (40.9)	.49
Dominant Hand[c]			
Right	56 (91.8)	22 (100)	.17
Concussion History[c]			
No Concussions	21 (34.4)	4 (18.2)	.41
One Concussion	12 (19.7)	5 (22.7)	
Two or More	28 (45.9)	13 (59.1)	
Highest Level of Education[c]			
Secondary Studies	19 (31.1)	4 (18.2)	.24
Tertiary Studies	42 (68.9)	18 (81.8)	
Player Position[c]			
Forward	19 (31.1)	8 (36.4)	.41
Midfield	29 (47.5)	7 (31.8)	
Defender	13 (21.3)	7 (31.8)	
Years of Player Experience[b]			
Under 18s Division	2 (0 – 7)	2 (0 – 5)	.98
Over 18s Division	5 (3 – 8)	7 (2 – 10)	.19
DASS21 Total Score[a]	16.89 (11.24)	17.36 (15.32)	.88
Median Time (days) From Baseline[b]	74 (42 – 97)	83 (63 – 112)	.26

Abbreviations: p, p-value with significance set at $p < .05$.

[a] Summarised using mean (standard deviation)

[b] Summarised using median (inter-quartile range)

[c] Summarised using proportions

two or more observable signs. Six (27%) HIAf+ve players were not removed from the field and five HIAF-ve players were removed from play due to orthopaedic injury.

Complete SCAT3 assessments were available for n = 62 players (n = 17 lost due to technical error, n = 4 were incomplete). Compared to baseline, the HIAf-ve group symptom total, t (42) = 3.23, p = 0.001, and symptom severity**,** t (42) = 3.56, p = 0.002, were significantly higher at post-match (see Table 3), while no significant differences were evident in mBESS total errors, p = 0.44, or SAC total score, p = 0.41. The HIAf+ve group symptom total, t (18) = 5.99, p < 0.001, and symptom severity, t (18) = 3.86, p = 0.001, were significantly higher, and SAC total scores were significantly lower, t (18) = 4.63, p < 0.001, at post-match testing when compared to baseline, while mBESS total errors were not significantly different, p = 0.26.

When HIAf+ve players were compared to HIAf-ve players, the HIAf+ve group demonstrated a greater change in symptom total, t (60) = 2.87, p = 0.006, symptom severity, t (60) = -2.51, p = 0.020, and SAC total scores, t (60) = 3.84, p < 0.001. No significant difference in mBESS total errors change score was observed across the groups, p = 0.14 (see Table 3).

After controlling for individual baseline scores, one-way ANCOVAs revealed significant HIAf+ve and HIAf-ve group differences in symptom total, F (1, 59) = 8.11, p = 0.006, η_p^2= 0.121, symptom severity, F (1, 59) = 10.92, p = 0.002, η_p^2= 0.156, and SAC total scores, F (1, 59) = 18.48, p < 0.001, η_p^2= 0.238, while there was no significant difference for mBESS total errors, F (1, 59) = 2.29, p = 0.135, η_p^2 = 0.037. In comparison to HIAf-ve players, HIAf+ve players, on average, endorsed more symptoms by 3.55 (95% CI: 1.06 – 6.04), reported higher symptom severity by 12.20 (95% CI: 4.81 – 19.58), and performed worse on the SAC by 1.71 (95% CI: 0.91 – 2.50).

Complete Cogstate assessments were available for n = 75 players (n = 8 were invalid). Compared to baseline, the HIAf-ve group performance in Detection, t (54) =

3.75, p < 0.001, and Identification, t (54) = 5.62, p < 0.001, were significantly worse at post-match (see Table 3), while no significant differences were evident in One-Card Learning, p = 0.18, or One-Back tasks, p = 0.90. The HIAf+ve group performance in Detection, t (19) = 4.41, p < 0.001, Identification, t (19) = 6.53, p < 0.001, and One-Back tasks, t (19) = 2.85, p = 0.010, were significantly worse at post-match testing in comparison to baseline, while One-Card Learning performances were not significantly

Table 3
SCAT3 & Cogstate Summary of Baseline, Post-Match and Change Score for HIAf-ve and HIAf+ve Groups, M (SD)

	HIAf-ve			HIAf+ve			HIAf-ve	HIAf+ve	
	B	PM	p	B	PM	p	Change Score		p
SCAT	n = 43			n = 19			n = 43	n = 19	
Symptom Total	3.81 (4.19)	6.07 (5.91)	.001	3.52 (4.00)	9.13 (5.58)	<.001	2.26 (4.58)	5.79 (4.21)	.006
Symptom Severity	5.12 (6.05)	10.53 (12.01)	.002	5.43 (8.58)	20.22 (20.11)	.001	5.40 (9.93)	17.21 (19.45)	.020
BESS Total Errors	3.64 (2.79)	3.30 (2.39)	.44	3.43 (2.78)	4.13 (2.83)	.26	0.33 (2.75)	0.89 (3.46)	.14
SAC Total Score	28.29 (1.52)	28.53 (1.44)	.41	28.39 (1.37)	26.83 (1.75)	<.001	0.23 (1.85)	1.63 (1.54)	<.001
Cogstate	n = 55			n = 20			n = 55	n = 20	
Detection[a]	2.45 (0.07)	2.49 (0.08)	<.001	2.43 (0.06)	2.53 (0.09)	<.001	0.04 (0.09)	0.10 (0.10)	.015
Identification[a]	2.62 (0.06)	2.66 (0.07)	<.001	2.64 (0.05)	2.72 (0.07)	<.001	0.04 (0.05)	0.08 (0.06)	.001
One-Card Learning[b]	0.86 (0.13)	0.83 (0.13)	.18	0.81 (0.11)	0.76 (0.14)	.28	0.03 (0.15)	0.05 (0.20)	.65
One-Back[a]	2.79 (0.10)	2.79 (0.09)	.90	2.79 (0.08)	2.84 (0.09)	.010	0.00 (0.08)	0.05 (0.08)	.014

All index scores are presented in the Cogstate recommended transformed state.
[a] Log10-transformation of the mean response time.
[b] Accuracy is provided by the arcsine transformation of the square root.
B = Baseline
PM = Post-Match

different, $p = 0.28$.

When HIAf+ve players were compared to HIAf-ve players, the HIAf+ve group demonstrated a significantly greater change in reaction time of Detection, $t(73) = 2.49$, $p = 0.015$, Identification, $t(73) = 3.62$, $p = 0.001$, and One-Back, $t(73) = 2.52$, $p = 0.014$. No significant difference in One-Card Learning change score was observed across the groups, $p = 0.65$ (see Table 3).

After controlling for individual baseline scores, one-way ANCOVAs revealed significant HIAf+ve and HIAf-ve group differences in performance of Detection, $F(1, 72) = 5.61$, $p = 0.021$, $\eta_p^2 = 0.072$, Identification, $F(1, 72) = 14.65$, $p < 0.001$, $\eta_p^2 = 0.169$, and One-Back tasks, $F(1, 72) = 7.64$, $p = 0.007$, $\eta_p^2 = 0.096$, while there was no significant difference for the One-Card Learning task, $F(1, 72) = 3.12$, $p = 0.08$, $\eta_p^2 = 0.041$. In comparison to HIAf-ve players, HIAf+ve players, on average, demonstrated significantly slower reaction time in Detection (0.05, 95% CI: 0.01 - 0.09), Identification (0.05 units, 95% CI: 0.02 - 0.08) and One-Back tasks (0.05, 95% CI: 0.01 - 0.09).

For HIAf+ve players, there was no significant association between self-rating of pain intensity and any SCAT3 (symptom total, $p = 0.12$, symptom severity, $p = 0.13$, mBESS total errors, $p = 0.76$, or SAC total score, $p = 0.65$) or Cogstate (Detection, $p = 0.16$, Identification, $p = 0.56$, One-Card Learning, $p = 0.06$, or One-Back task, $p = 0.41$) outcome.

The proportion of HIAf+ve players (100%; 95% CI: 84% - 100%) who demonstrated a clinically-significant decline in at least one SAC, mBESS or Cogstate task was significantly higher than the proportion of HIAf-ve players (59%; 95% CI: 46% - 71%), $\chi^2 = 12.90$, $p < 0.001$. Significant decline in either mBESS or SAC were evident in a greater proportion of HIAf+ve players (74%; 95% CI: 49% - 91%) compared to HIAf-ve players (43%; 95% CI: 28% - 59%), $\chi^2 = 4.99$, p = 0.021. Similarly, the proportion of players with significant decline in at least two or more Cogstate tasks was greater in HIAf+ve players (50%; 95% CI: 27% - 73%) compared to HIAf-ve players (25%; 95% CI: 15% - 39%), $\chi^2 = 4.06$, p = 0.044.

With regards to observable signs with high concussion specificity (signs B to E) [2, 4] among the HIAf+ve group, 100% (n = 5) of players with no protective action in fall to ground (sign B) demonstrated a significant decline in SAC and 56% (5/9) of players with balance disturbance (sign D) demonstrated a significant decline in three or more Cogstate tasks, while 50% (3/6) of players with a blank/vacant stare (sign E) demonstrated significant decline in two or more Cogstate tasks.

4.5 Discussion

This study was the first to explore the utility of items in the HIAf to help identify community male and female Australian football players with a possible concussion. HIAf+ve players demonstrated significantly worse orientation, concentration and recall (SAC) as well as reaction time on psychomotor speed, attention and working memory tasks (Cogstate) and greater symptom reporting (SCAT3) when compared to matched HIAf-ve players. There were no significant group differences in performance on balance (mBESS) or visual learning (Cogstate) tasks. A significantly greater proportion of HIAf+ve players were characterised by clinically-significant decline in at least one of SAC, mBESS or Cogstate tasks, and all players who were observed to have no protective action in fall to ground post-head impact, demonstrated cognitive decline in SAC. These results support the routine use of the

HIAf in community football to help identify players with a possible concussion who require removal from play and a formal concussion assessment.

The observation of concussive signs in professional sports is facilitated using advanced video technology and review by experienced medical professionals [1]. Community personnel, however, do not have these resources or expertise [6]. In this study, non-expert personnel with basic training and use of the HIAf detected HIAf+ve players live from the sideline in keeping with a real world-application. Only four players were detected for further concussion screening on the basis of symptom report and/or memory difficulties alone. By observing concussive signs, an additional 22 players were identified for further screening, supporting previous research that suggests symptom reporting alone is not always reliable in screening possible concussion [13, 14]. Furthermore, six HIAf+ve players were not removed from the field despite recommendations for their immediate removal suggesting limited translation of community concussion guidelines [6].

In the absence of experienced medical personnel, the HIAf represents a rapid and real-time method to facilitate concussion recognition in community sports by non-expert personnel. Players with positive signs should be removed from play and sent for medical assessment. Basic training of the HIAf use should be combined with education programs (for coaches, trainers and players) to improve the recognition of signs and reporting of symptoms.

While the HIAf+ve sample size was limited, there was preliminary evidence suggesting that specific concussive signs highly predictive of concussion diagnosis (signs B to E) are associated with worse cognitive outcomes. For example, 100% of players who were observed to have *no protective action in fall to ground* (sign B) also demonstrated significant cognitive decline in the SAC, while 50% of players with either a *balance disturbance* (sign D) or a *dazed or blank and vacant stare* (sign E) demonstrated significant cognitive deficits in at least two or more Cogstate tasks. In this sample, no players were observed to have an impact seizure (sign C) which is not uncommon [3, 4].

This study, however, did not provide an independent medical assessment to establish concussion diagnoses (see section 5.3 and 5.4 for further discussion). Not all players with concussive signs have concussion and not all players with a concussion necessarily exhibit concussive signs [3, 4]. In this study, a proportion of HIAf-ve players were also characterised by poor performance on concussion assessment. It remains possible some concussive signs were missed, however there was no use of video to review this potential confound. An independent concussion medical assessment with concurrent video footage review in a research context could therefore establish the HIAf sensitivity and specificity in community sports. Video footage could also help establish inter-rater agreement among non-expert observers in order to inform future training protocols for community personnel (see section 5.3 for further discussion).

Sex-based differences in sport-related injury assessment are critically relevant in light of increased female participation in Australian football. It was not possible, however, to statistically compare cognitive outcomes between male and female players of the HIAf+ve group due to the small sample. An important component of future work in this field will be to explore differential effects of concussive signs on cognitive outcomes between the sexes.

This was the first study to explore the utility of the HIAf to monitor observable concussive signs in community-level players. Use of the HIAf represents a quick and real time method to screen players suspected of concussion at community-level sports, where advanced video technology and expert medically-qualified personnel are seldom present. It is recommended that all HIAf+ve players are immediately removed from play for further concussion assessment. Post-match medical assessment and long-term follow up of HIAf+ve players present areas for further research to inform the predictive utility of specific concussive signs.

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4.7 References

1. Davis GA, Makdissi M, Bloomfield P et al. International consensus definitions of video signs of concussion in professional sports. *Br J Sports Med* 2019; 0:1-4.
2. Davis GA, Makdissi M. Use of video to facilitate sideline concussion diagnosis and management decision-making. *J Sci Med Sport* 2016; 19(11):898-902.
3. Gardner AJ, Iverson GL, Stanwell P et al. A Video Analysis of Use of the New 'Concussion Interchange Rule' in the National Rugby League. *Int J Sports Med* 2016; 37(4):267-273.
4. Makdissi M, Davis G. The reliability and validity of video analysis for the assessment of the clinical signs of concussion in Australian football. *J Sci Med Sport* 2016; 19(10):859-863.
5. Sullivan L, Molcho M. What do coaches want to know about sports-related concussion? A needs assessment study. *J Sport Health Sci* 2018; 7(1):102-108.
6. White PE, Newton JD, Makdissi M et al. Knowledge about sports-related concussion: is the message getting through to coaches and trainers? *Br J Sports Med* 2014; 48(2):119-124.
7. Houck Z, Asken B, Bauer R et al. Predictors of post-concussion symptom severity in a university-based concussion clinic. *Brain Inj* 2019; 33(4):480-489.
8. McAllister TW, Wall R. Neuropsychiatry of sport-related concussion. *Handb Clin Neurol* 2018; 158:153-162.

9. Lee JH, Howell DR, Meehan WP et al. Effects of exercise on sport concussion assessment tool-third edition performance in professional athletes. *Orthop J Sports Med* 2017; 5(9):2325967117727261.

10. Moore DJ, Keogh E, Eccleston C. Headache impairs attentional performance. *Pain* 2013; 154(9):1840-1845.

11. Sanchez CA. Working through the pain: working memory capacity and differences in processing and storage under pain. *Memory* 2011; 19(2):226-232.

12. Davis GA, Makdissi M, Harcourt P et al. *The management of concussion in Australian football with specific provisions for children aged 5-17 years*, Victoria, Australia, Australian Football League, 2017.

13. Asken BM, McCrea M, Clugston JR et al. ‘‘Playing Through It’’: Delayed reporting and removal from athletic activity after concussion predicts prolonged recover. *J Athl Train* 2016; 51(4):329-335.

14. McCrea M, Hammeke T, Olsen G et al. Unreported concussion in high school football players: implications for prevention. *Clin J Sport Med* 2004; 14(1):13-17.

15. Gardner AJ, Wojtowicz M, Terry DP et al. Video and clinical screening of national rugby league players suspected of sustaining concussion. *Brain Inj* 2017; 31(13-14):1918-1924.

16. McCrory P, Meeuwisse WH, Aubry M et al. Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport held in Zurich, November 2012. *Br J Sports Med* 2013; 47(5):250-258.

17. Collie A, Maruff P, Makdissi M et al. CogSport: reliability and correlation with conventional cognitive tests used in postconcussion medical evaluations. *Clin J Sport Med* 2003; 13(1):28-32.

18. Lovibond PF, Lovibond SH. The structure of negative emotional states: Comparison of the depression anxiety stress scales (DASS) with the beck depression and anxiety inventories. *Behav Res Ther* 1995; 33(3):335-343.

19. Henry JD, Crawford JR. The short-form version of the Depression Anxiety Stress Scales (DASS-21): construct validity and normative data in a large non-clinical sample. *Br J Clin Psychol* 2005; 44(Pt 2):227-239.

20. Cleeland CS, Ryan KM. Pain assessment: Global use of the Brief Pain Inventory. *Ann Acad Med Singapore* 1994; 23(2):129-138.

21. Keller S, Bann CM, Dodd SL et al. Validity of the brief pain inventory for use in documenting the outcomes of patients with noncancer pain. *Clin J Pain* 2004; 20(5):309-318.

22. Vickers AJ, Altman DG. Analysing controlled trials with baseline and follow up measurements. *BMJ* 2001; 33:1123-1124.

23. Chin EY, Nelson LD, Barr WB et al. Reliability and Validity of the Sport Concussion Assessment Tool-3 (SCAT3) in High School and Collegiate Athletes. *Am J Sports Med* 2016; 44(9):2276-2285.

24. Louey AG, Cromer JA, Schembri AJ et al. Detecting cognitive impairment after concussion: sensitivity of change from baseline and normative data methods using the CogSport/Axon cognitive test battery. *Arch Clin Neuropsychol* 2014; 29(5):432-441.

4.8 Appendix

4.8.1 Appendix A Normality Assessment

Normality Results. Normality for SCAT3 index scores was acceptable (Kurtosis = 0.23 – 1.11, SE = 0.71 – 1.01; Skewness = 0.30 – 1.09, SE = 0.36 - .052), except for symptom total and symptom severity (Kurtosis = 2.18 – 2.40; Skewness = 1.09 – 1.64). Normality for Cogstate index scores was acceptable (Kurtosis = -0.01 – 2.07, SE = 0.63 – 0.99; Skewness = -0.02 – 1.25, SE = 0.32 - .051).

4.8.2 Appendix B Sample Bias Assessment

Reason for exclusion. Of n = 21 players excluded from the sample (see Figure 1), n = 13 players (62%) did not participate in a single match throughout the season, n = 3 players (14%) only participated in the first two rounds of the season, while n = 4 (19%) reported concussive symptoms and/or memory difficulties without showing concussive signs and n = 1 (5%) did not complete the post-match testing due to laceration of forehead and seeking medical care immediately.

The excluded sample (n = 21) was comparable to the included sample (n = 83) with regards to demographics (Table 1), except for player positions as shown in the table below. Only one player of the excluded sample did not provide their medical history. The remaining n = 20 players demonstrated a similar medical history in comparison to the included sample for: past hospital presentation for a head injury (n = 5, 24%, p = .12), past diagnosis of headaches or migraines (n = 2, 10%, p = .14), or past diagnosis of depression or anxiety (n = 5, 24%, p = .07).

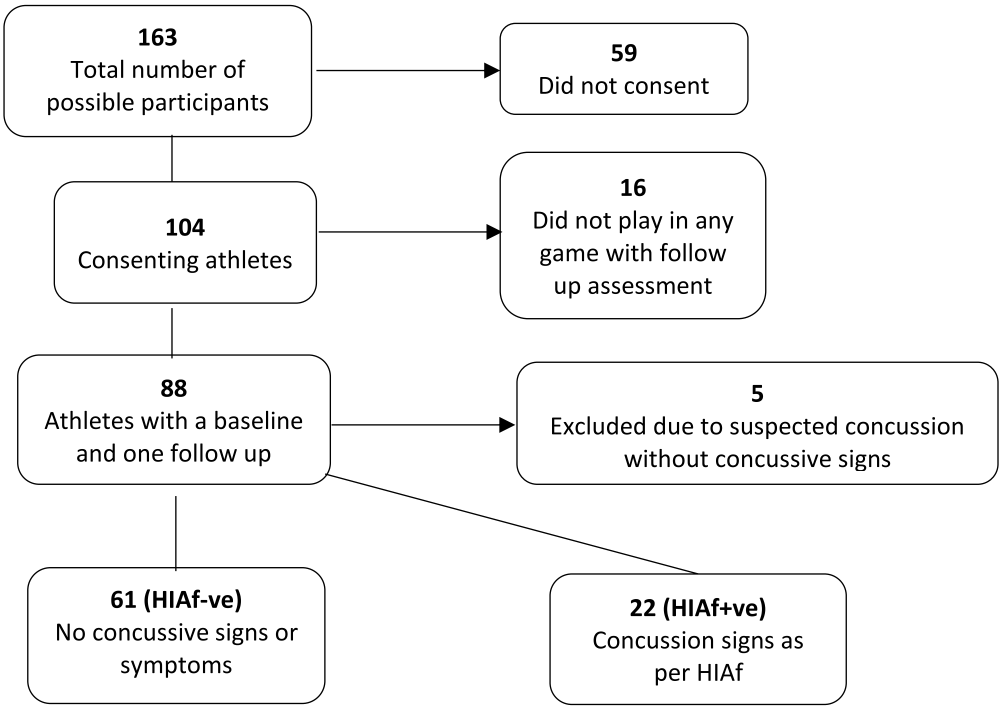

Figure 1**.** Participant flowchart.

Table 4
Comparisons Between Included and Excluded Sample

Item	Included n = 83	Excluded n = 21	p
Age at Baseline (Years)[a]	25.48 (5.02)	26.86 (5.04)	.27
Dominant Hand			
Right	78 (94.0)	18 (85.7)	.20
Left	5 (6.0)	3 (14.3)	
Concussion History			
No Concussions	25 (30.1)	6 (28.6)	.26
One Concussion	17 (20.5)	4 (19.0)	
Two or More	41 (49.4)	10 (47.6)	
Unknown	0 (0)	1 (4.8)	
Highest Level of Education			
Secondary Studies	23 (27.7)	8 (38.1)	.35
Tertiary Studies	60 (72.3)	13 (61.9)	
Player Position			
Forward	27 (32.5)	9 (42.9%)	.013
Midfield	36 (43.4)	3 (14.3)	
Defender	20 (24.1)	7 (33.3)	
Emergency/Unknown	0 (0)	2 (9.6)	
Years of Player Experience[b]			
Under 18s Divison	2 (0 – 7)	0 (0 – 4)	.14
Over 18s Division	5 (3 – 8)	5 (3 – 8)	.92

Abbreviations: p, p-value with signficance set at $p < .05$.

[a]Summarised using mean (standard deviation)

[b]Summarised using median (inter-quartile range)

Chapter Five:

General Discussion

5.1 Overview of Findings

The timely detection of concussion is of the utmost importance to avoid risk of repeat injury and prolonged recovery (Asken et al., 2016; Cross et al., 2016; Guskiewicz et al., 2003). Identification of players who require concussion assessment relies upon detection of either signs or symptoms associated with concussion and to some extent, on symptom report by the player which is subject to individual bias (McCrea et al., 2004; White et al., 2016).

The in-vivo measurement of HAEs by use of wearable accelerometers is a potential method to objectively identify players who may be at risk of concussion and who require further concussion screening assessment. Very few studies using accelerometers, however, had been conducted among sports in which both sexes participate and none in the non-helmeted sport of professional Australian football (O'Connor, Rowson, et al., 2017). In professional Australian football, there was very little, if any, published data on the determinants of frequency and magnitude of HAEs across sex, player position or experience, nor information pertaining to the match situations and phases of play in which head impacts occur. In addition, no study to date had explored the potential utility of acceleration thresholds typically associated with concussion to identify players who may require further concussion assessment at the professional level of Australian football. This information was crucially needed to guide match development and policy to improve player safety going forward.

Within Australian football, the HIAf is a resource provided by the AFL that has been developed to identify observable concussive signs and facilitate rapid on-field concussion screening with greater objectivity. It typically relies on video review and presence of experienced medical staff at the professional level of sports (Clifton et al., 2016; Davis et al., 2017). No study to date, however, had explored the utility of these variables on the HIAf to identify community players with poorer performance on concussion assessment measures who may be suspected of concussion.

In view of the highlighted gaps in the literature to date, the first aim of this thesis was to quantify exposure to HAEs in professional male and female Australian football players, and explore the association between HAEs and sex, player position and player experience as well as to characterise the situations in which HAEs occur as outlined in Chapter Two. The second aim of this thesis was to explore the potential utility of the X-Patch output to augment current best practice in concussion screening as depicted in Chapter Three. The availability of advanced technology and personnel with specific expertise in concussion diagnosis and management are rarely present at community sports, where the appropriate detection of concussion remains equally important. Therefore, the final aim of this thesis, as per Chapter Four, was to explore the utility of the HIAf to identify male and female community Australian football players with observable concussive signs and poorer performance on SCAT3 and Cogstate, while accounting for important factors known to influence outcomes on these measures.

In Chapter Two, a non-wearable accelerometer was utilised to quantify exposure to HAEs and assess the association with demographics, player experience and player position among professional Australian football players. The principal findings revealed male players have an elevated exposure to HAEs both in number of HAEs and the maximum PLAs incurred during a match when compared to female players. This is consistent with studies exploring sex-based differences in head impact exposure across a range of contact sports (Brainard et al., 2012; Mihalik et al., 2019; Wilcox et al., 2014; Willmott et al., 2018).

In contrast to previous studies, player position and player experience were not associated with the frequency or magnitude of HAEs in Australian football. Players in midfield positions (e.g., centre, wing, rover, ruck rover) typically achieve greater ground coverage and greater involvement in the match, which is suggested to be associated with an increased likelihood of injury (Braham, Finch, McIntosh, et al., 2004; Dawson, Hopkinson, Appleby, Stewart, & Robers, 2004; Gabbe et al., 2002; Wisbey et al., 2010). Only one study to date, however, had explored positional exposure to non-verified HAEs among 23 community male Australian football players with the X-Patch and found midfielders incurred more HAEs per player per match in comparison to defenders and forwards (King, Hecimovich, Clark, & Gissane, 2017). Conversely, our findings revealed forwards sustained greater median and maximum PLAs in comparison to midfield and defender positions, although this was not statistically significantly.

There is also evidence to suggest that appropriate skill execution (e.g., safe tackling, proper headers) and greater situational awareness are associated with reduced exposure to HAEs across a range of contact sports including North American football, ice hockey and soccer (Harriss et al., 2019; Lamond et al., 2018; Mihalik et al., 2010; Schmidt, Pierce, et al., 2016; Swartz et al., 2019). In this study however, the total number of years playing Australian football stratified into four categories (0 to 5, 6 to 10, 11 to 15, > 15 years) as a marker of player experience, was not associated with HAEs. This suggests other match-related factors (e.g., player activity profiles, match status) which more closely reflect involvement in the match (Black et al., 2019;

Gastin, Hunkin, Fahrner, & Robertson, 2019; Gronow, Dawson, Heasman, Rogalski, & Peeling, 2014) may better account for differential exposure to HAEs in this sporting code. The association between these factors and impact exposure remains to be investigated.

In Chapter Two, inciting events in which verified HAEs occurred were also characterised allowing the following observations: an elevated exposure to PLAs was primarily evident during the second half of the match and players typically incurred HAEs during a phase of play with limited or no control of the ball (i.e., contested play), while executing skills under considerable physical pressure and limited control of their environment (i.e., contesting a ball along the ground, marking contest). When stratifying direct head impacts by sex, females demonstrated twice the head impact rate per marking contest (16 per 100) in comparison to males (8 per 100).

Among players with injury-related HAEs, two male players were diagnosed with concussion in association with PLAs of 62 *g* and 75 *g* respectively. Current evidence suggests concussion is typically associated with a mean PLA of 100 *g*, however this value can range from 70 *g* to 145 *g* (Brennan et al., 2016; O'Connor, Rowson, et al., 2017). While accelerometer output has very limited diagnostic value for concussion diagnosis which requires clinical assessment and formulation (Patricios et al., 2017), it remains unknown to what extent these values aid in the process of identifying players who require further screening for possible concussion.

To counteract deficiencies in self-reporting, Chapter Three explored the potential utility of accelerometer output to augment concussion screening in professional AFL. For this study, acceleration thresholds previously associated with concussion were defined for male (above 95 *g*) and female (above 85.5 *g*) players

(Brennan et al., 2016; Broglio et al., 2013; Duma & Rowson, 2009; Funk, Duma, Manoogian, & Rowson, 2007; McIntosh, 2012). The proportion of players who were identified to have HAEs above these acceleration thresholds were compared to players detected by current best practice and video review for concussion screening. The results revealed that use of these acceleration thresholds did not reliably identify all players who required further concussion screening in comparison to current best practice at the professional AFL. While professional sports often have the necessary resources to provide optimal concussion detection and management, this is not always the case in community sports (Baugh et al., 2015; Kroshus et al., 2017; Putukian et al., 2009; Wicker & Breuer, 2015).

Given current accelerometers outputs were found to be unreliable and video monitoring not feasible at the community level, Chapter Four explored the efficacy of items in the HIAf to help identify players with reduced performance on concussion assessments. Our findings revealed that HIAf+ve players with observable concussive signs demonstrated post-match deficits in cognitive measures of orientation, concentration and recall (SAC), as well as reaction time (Cogstate), and greater symptom severity (SCAT), in comparison to HIAf-ve players. Both groups were matched on factors which potentially influence these outcome measures such as age, sex, mood, and time from baseline to post-match assessment (Covassin, Elbin, Harris, et al., 2012; Nelson, Guskiewicz, et al., 2016; Van Pelt et al., 2019). In addition, there was no evidence to suggest performance on primary outcome measures among HIAf+ve players were influenced by acute pain post-match, thereby controlling for this potential confound (Moore et al., 2013; Sanchez, 2011).

Only four players were identified for post-match concussion screening assessment on the basis of symptom report relative to a further 22 players identified for post-match assessment on the basis of demonstrating concussive signs on the HIAf. These findings are consistent with previous evidence suggesting monitoring players with observable concussive signs can augment the overall process of concussion screening (Davis & Makdissi, 2016; Makdissi & Davis, 2016a). Players who were observed have concussive signs were characterised by reduced performance on concussion assessment measures in comparison to players without such signs, suggesting possible concussion and need for further assessment.

Moreover, there was preliminary evidence to suggest that specific concussive signs (i.e., no protective action in fall to ground, balance disturbance) were associated with worse clinical outcomes, in line with previous findings (Gardner, Wojtowicz, et al., 2017). In this sample, not all HIAf+ve players with observable concussive signs were removed from the field, suggesting limited translation of current concussion management guidelines at community Australian football (Kemp et al., 2016; White et al., 2014). These findings together suggest the HIAf, in the absence of medical personnel, can be used to facilitate recognition of concussion in community sports. Use of the HIAf should be implemented in conjunction with education programs for community-based personnel (coaches, trainers) to improve concussion recognition and management (as later discussed in section 5.2.2).

5.2 Implications

5.2.1 Head Impact Exposure in Professional Australian Football: New Insights

The use of accelerometer technology to quantify head impacts in contact sports endeavours to: 1) provide a better understanding of the kinematic insult associated with concussion and 2) assist sport physicians and other professionals make important decisions regarding sporting policy (e.g., rule modification and use of protective gear) and the development of interventional strategies (e.g., identification of high-risk sporting situations, skill development), with the overall aim to mitigate the risk of concussion. While accelerometer technology has limited value in the clinical process of making a concussion diagnosis (Patricios et al., 2017), it remains useful to estimate head impact exposure within real-life dynamics of the match.

In this research program, professional male Australian football players incurred more HAEs, with a greater maximum PLA, compared to females during a match. One possible explanation for the greater number of HAEs in males is differences in match duration, with male (80 minutes) exceeding female (60 minutes) exposure (Laws of the Game; AFL, 2019). Sex differences, however, were also evident in the PLA magnitude of HAEs. While sex-based differences in exposure to HAEs at the professional level of Australian football are broadly consistent with previous literature, differing methodologies limit comparisons (e.g., King et al., 2015; King et al., 2018; Reynolds et al., 2016). Findings that significant differences were evident in maximum, and not median, PLAs indicate that analyses of mid-point estimates may be misleading or fail to capture important group differences. Eckner et al. (2018) instrumented ice hockey players with the X-Patch and found statistical – though clinically limited – differences in mean PLA between females (19 *g*) and male players (17 *g*). An analysis of the upper percentiles by these authors, however, revealed clinically-relevant differences in exposure between sex for the top 5% (57 *g* vs. 47 *g*) and 1% (85 *g* vs. 77 *g*) of PLAs. In Chapter Two of this thesis, analysing maximum PLA values similarly revealed important difference between the sexes. It was found male

Australian football players frequently incurred PLAs (median of 62 *g*) bordering the lower range of PLAs (i.e., 70 *g*) previously related to concussion (Broglio et al., 2010; Duma & Rowson, 2009; O'Connor, Rowson, et al., 2017).

5.2.1.1 Sex and Other Player-Related Factors Underpinning Exposure

Acceleration – as detected by wearable accelerometer technology – measures the change in velocity of the cranium and not the force of impact. According to Newton’s second law of motion, the magnitude of force (F) is equal to mass (m) of an object multiplied by acceleration (a) of the object. In the context of sport, it can be argued that as the application of force from a striking player increases, so does the acceleration of the head of the struck player given that the mass of the head is a static value (Broglio, Eckner, & Kutcher, 2012).

Mass, however, can actively contribute to acceleration through its relationship with energy. In the most simplistic depiction of real-world impacts in sport, a collision involves the transference of kinetic energy between two players following the application of force by one player to another. Kinetic energy is the energy an object (player) has because of its motion, and it depends on the mass and speed achieved by the object. In previous research, both greater body mass or muscle size and travelling speed have been associated with a greater magnitude of HAEs (Brainard et al., 2012; Cobb et al., 2013; Schmidt et al., 2014; Withnall, Shewchenko, Gittens, & Dvorak, 2005). If the mass and speed of professional male players is greater, on average, in comparison to professional female players (Black et al., 2019; Clarke et al., 2018; Delaney, Thornton, Burgess, Dascombe, & Duthie, 2017; Gronow et al., 2014;

Kempton, Sullivan, Bilsborough, Cordy, & Coutts, 2015), then the transference of energy during a collision may also be greater among male players.

The mass of a player, however, does not solely act as a single rigid object at the time of impact. The body is comprised of multiple rigid objects (e.g., bones) linked together at the joints by soft tissue (e.g., muscle, ligaments) which provide limited stabilization of the joints at the moment of impact thereby allowing the mass from multiple segments to be summed. If a striking player contracts their neck muscles and aligns their head, neck and spine before a tackle, the effective mass of the striking player is likely to be the sum of their full body weight (e.g., 100 kg) in comparison to a striking player with less neck muscle contraction whose effective mass might be the sum of their head (e.g., 4 kg) and torso (e.g., 79 kg) only (Broglio, Eckner, et al., 2012).

Most male players at the professional level of Australian football have typically participated in the sport since early childhood through their involvement in junior league programs (e.g., AUS Kick) and also have long standing careers (e.g., 10 years or more) participating in the AFL. Female players, by contrast, have had limited junior league involvement in Australian football and have typically migrated from other sporting codes to compete at the AFL. Generally male players have therefore received additional training in safer gameplay and practices within this sport to date. This additional practice may allow the striking male player to exercise better body preparedness by bracing before impacts in comparison to the striking female player. In addition, better bracing before impacts (e.g., contracting neck muscles) might generate situations wherein males' effective mass is greater than females' during collisions and potentially lead to HAEs with greater accelerations incurred by the struck player. The implication, however, is two-fold. Numerous studies have demonstrated that the ability of a struck player to mitigate HAEs post-impact is proportionally related to several anthropometric features (e.g., greater isometric neck strength, head-neck stiffness) underpinning the body's preparedness for impact (Bretzin et al., 2017; Eckner, Oh, et al., 2014) and ability to mitigate the risk of concussion (Hrysomallis, 2016).

Another likely factor underpinning sex differences in exposure to HAEs might be differing levels of risk compensation. In the context of sport, risk compensation proposes that players endorse a certain level of risk and will exercise risk-taking behaviour in accordance with their perception of risk reductions until they breach their perceived risk tolerance (Hagel & Willem, 2004; Hedlund, 2000). In professional Australian football, male players who have long-standing, full-time careers participating in the sport might form the belief they are better protected from injury by their experience and skill development thereby engaging in more intensive and forceful impacts. By contrast female players who are relatively new to the sporting code may not form the same belief or endorse the extent of risk-taking behaviour that males have (Barr Jr. et al., 2015; Van Leijenhorst, Westenberg, & Crone, 2008) thereby avoiding forceful impacts which are proportionally related to acceleration.

In addition, it is important to consider that these factors, such as body composition (e.g., mass and anthropometric features) and trait-based characteristics (e.g., risk-taking behaviour), are not inherent qualities of sex. Consequently, these factors should be treated as separate and independent internal risk factors to injury, which could likely underpin the observed sex differences in exposure to HAEs in this research program and the wider literature (Bahr & Krosshaug, 2005; Brainard et al., 2012; Van Pelt et al., 2019; Wilcox et al., 2014).

5.2.1.2 Match-Related Factors Underpinning Exposure

At the professional level of Australian football, there are also other internal (e.g., physical fitness, activity profile) and external (e.g., match status, opposition ranking) risk factors that may better account for exposure to HAEs in contrast to player position and player experience. When investigating activity profiles using global positioning systems, it was revealed that defenders and midfielders spent the longest time conducting high intensity acceleration and deceleration efforts, which have been previously associated with post-match elevated markers of muscle damage (i.e., creatine kinase; Gastin et al., 2019; Johnston, Watsford, Austin, Pine, & Spurrs, 2015). This suggests that deceleration induced tissue damage, likely arising from intense eccentric muscle contraction while braking abruptly, can lead to injuries (e.g., knee, thigh, ankle) among players with specific activity profiles (Gastin et al., 2019; Hoffman, Dwyer, Tran, Clifton, & Gastin, 2019)**.**

Activity demands, however, interact with match status. Gronow et al. (2014) demonstrated that time spent conducting high-speed running (14.4 km/h) is greater among forwards whilst in possession of the ball (i.e., offensive play) and greater among defenders whilst not in possession of the ball (i.e., defensive play) suggesting a winning or losing team will require efforts from each respective player thereby increasing their chances of potential injury. This is the case for defenders whose activity demands are greater when competing against top-ranked opposition teams (Black et al., 2019). Individual differences in physical fitness (i.e., agility, athletic ability) are also a source of considerable variability in activity profiles (Haycraft, Kovalchik, Pyne, & Robertson, 2019). As the match progresses, however, player efforts in high and very-high running acceleration-deceleration are reduced, suggesting performance reductions in sprinting which could be decisive in critical match-related activities to avoid possible injury (e.g., decelerating rapidly to avoid collision; Clarke et al., 2018; Cochrane, Lloyd, Buttfield, Seward, & McGivern, 2007; Donnan, Pizzari, O'Dwyer, & Edwards, 2018; Harper, Carling, & Kiely, 2019). When analysing the incidence of injury by time in other sports, most injuries occur towards the second half of the match possibly as fatigue increases, suggesting a reduced capacity to avoid collision with potential for injury (Chahla et al., 2018; Chalmers et al., 2013; Gardner et al., 2015; King, Hume, & Clark, 2012; Stevens, Lassonde, de Beaumont, & Keenan, 2008). Therefore positional designation on the field and total number of years playing football may not sufficiently reveal player vulnerabilities to HAEs in comparison to more specific match-related factors that better reflect involvement in the match and likelihood of injury. While many of these factors may predispose a player towards injury, it is the inciting event that precipitates injury (Bahr & Krosshaug, 2005).

In this research program, most verified HAEs (52%, *n* = 110) occurred during a contested phase of play, which typically accounts for the greatest proportion of match-play (Rennie, Watsford, Spurrs, Kelly, & Pine, 2018). When stratifying HAEs by skill, most HAEs occurred while the player was executing skills under considerable physical pressure (i.e., contesting a ball along the ground) and while having very limited control of their environment (i.e., marking contest). An elevated burden of HAEs during these situations may reflect player efforts to gain possession of the ball despite the individual cost of incurring a head impact. Concussion in sport primarily occurs following a direct impact to the head and less commonly, following an impact to the body (Lincoln, Caswell, Almquist, Dunn, & Hinton, 2013; Makdissi & Davis, 2016b; McIntosh, McCrory, & Comeford, 2000). In this study, most verified HAEs were observed following a direct head impact (*n* = 74; Carey et al., 2019; Caswell et al., 2017; Nevins et al., 2019) and predominantly following contact to the side of the head (*n* = 38), which is commonly associated with concussion in Australian football (McIntosh et al., 2014). When stratified by sex, it was revealed that female players demonstrated twice the exposure to head impacts (16 per 100) than male players (8 per 100) in marking situations, which are commonly associated with concussion (Makdissi & Davis, 2016b) as per the two players in Chapter Two.

5.2.1.3 Acceleration Events and Detection of Concussion

With this in mind, it was a subsequent aim of the research program to explore the utility of an acceleration threshold to identify players with need for further concussion assessment. It was revealed that cases of suspected concussion (e.g., 77 *g*) and concussion diagnoses (i.e., 62 *g* and 75 *g*) were evident in association with HAEs below acceleration thresholds previously associated with concussion (i.e., above 85.5 or 95 *g*). There is emerging evidence to suggest that despite attempts to determine PLA thresholds in association with concussion, considerable variability remains suggesting cohort-derived values have limited utility in the context of concussion (O'Connor, Rowson, et al., 2017; Rowson et al., 2018). In one the largest samples of concussions (*n* = 105) and related measurements of HAEs to date, it was revealed concussion was associated with a mean acceleration of 103 *g* (*SD* = 34 *g*), however this value ranged from 29 *g* to 205 *g,* thereby including the above mentioned PLAs in this study (Beckwith, Greenwald, Chu, Crisco, Rowson, Duma, Broglio, McAllister, Guskiewicz, & Mihalik, 2013; Broglio et al., 2010). Differences in response to HAEs and related concussion may be due to differential levels of individual exposure to HAEs prior to the time of injury. For instance, when comparing exposure profiles between concussed players and individually-matched controls over the same period of time, it is revealed that concussed players sustain a greater frequency of HAEs within closer succession. This suggests that repeated exposure over a short period of time may be more relevant to the risk of concussion than the occurrence of a single HAE with a PLA above a certain threshold (Broglio, Lapointe, O'Connor, & McCrea, 2017; Rowson et al., 2019).

At the individual level, it has also been found that concussed players sustain the highest or second highest frequency of HAEs on the date of injury or season-to-date of injury in comparison to matched controls (Stemper et al., 2019). Interestingly, the authors found over half (56%, *n* = 28) of concussions were associated with HAEs that had less than 1% risk of injury according to previous injury-related PLAs derived from risk curves to predict concussion (Rowson & Duma, 2013). Instead, it is evident that concussion is associated with HAEs that are among the most severe for each individual player, likely reflecting individual variations in the biological properties of the body and/or head to sustain impacts (Cormier et al., 2011; Rowson et al., 2018; Schmidt et al., 2014).

This is in keeping with the pathophysiological model of concussion and risk of repeated injury. Concussion can lead to primary and secondarily cascading metabolic disruptions, which maximise intra-cellular energy production and resource allocation in order to re-establish homeostasis (Barkhoudarian et al., 2016; Romeu-Mejia et al., 2019). If a secondary concussion occurs before homeostasis is reached, the metabolic disruptions are compounded further and recovery is delayed. This “window of vulnerability” can vary in time as it is likely subject to individual differences in several of the underpinning biological factors that determine recovery (Eckner et al., 2011; Giza & Hovda, 2001; Hovda et al., 1999; Vagnozzi et al., 2008).

This model, however, may be extended to the underpinning process by which repetitive head impacts lead to concussion. Broglio, Lapointe, et al. (2017) suggest that the degree to which the concussive-related threshold decreases after an impact is dependent on the magnitude of HAEs, while the time it takes for the concussion thresholds to return to baseline is dependent on the frequency of HAEs. In this sense, each HAE with an elevated magnitude alters the concussion-relative threshold in a downward manner, while a shorter time between HAEs places the player further away from their baseline (or homeostasis).

It is therefore individual exposure profiles to HAEs and the incidence of HAEs weighted by time are becoming more relevant in the context of concussion. Presently, there is evidence to suggest that repeated HAEs are associated with alterations in cerebral white matter (Bazarian et al., 2014; Davenport et al., 2014; McAllister et al., 2014; Merchant-Borna et al., 2016) and positive neuropathological markers of injury (Joseph et al., 2018; Poole et al., 2015; Talavage et al., 2014). The link between repeated HAEs and neurocognitive outcomes, however remains mixed (Gysland et al., 2012; McAllister et al., 2012; Willmott et al., 2018) and two possible explanations are proposed. Firstly, there are limitations with the methodology of the abovementioned studies including the time interval between the player’s last exposure to contact and player assessment (up to 3-4 weeks), thereby attenuating the optimal sensitivity of the concussion assessment measures employed (e.g., ImPACT, ANAM) across this time span (Gysland et al., 2012; McAllister et al., 2012); as well as the limited sampling of participants (*n* = 4; Talavage et al., 2014) or exposure to the match (match n = 1; Willmott et al., 2018) thereby making it difficult to detect a possible relationship. Secondly, the association between exposure to HAEs and clinical outcomes has been conducted using cohort-level analyses (e.g., relationship between group exposure both in terms of frequency and magnitude, as well as clinical outcomes) with metrics of impact exposure not weighted for time between HAEs. With increasing evidence of differences in individual-specific tolerance values and importance of time between successive HAEs, the relationship between exposure profiles and clinical outcomes should be examined accordingly.

If an individual incurs repeated HAEs that are uniquely severe relative to their normative exposure profile, the individual threshold for injury might be exceeded. Physiologically, this might represent the inability of the brain to reach homeostasis with repeated exposure during this “window of vulnerability” (Giza & Hovda, 2001; Hovda et al., 1983; Hovda et al., 1999). Clinically, this might represent the short-term deterioration in reaction time or attention thereby reducing the player’s ability to respond effectively to their environment and increasing the likelihood of secondary head impacts and/or concussion. When analysing the data of this player in conjunction with the exposure profiles and clinical outcomes of more resilient players, the findings might be obscured thereby insufficiently defining individual trajectories to concussive injury.

5.2.1.4 How to Mitigate Exposure?

If indeed the risk of concussive injury increases as a function of repeated exposure to HAEs, and PLAs uniquely contribute toward the risk of concussive injury at the individual level, then several implications follow from the current findings. Independent risk factors, in addition to sex, were proposed to likely interact with an elevated exposure to HAEs in sport. In professional Australian football, players frequently incur head impacts during situations with limited control of the ball or under considerable external physical pressure. The identification of players exhibiting high risk-taking behaviour (e.g., contesting ball along with the head down) or inappropriate skill execution (e.g., tackling without bracing for impact) might aid team personnel to provide personalised interventions and mitigate the severity of HAEs during these situations (Hrysomallis, 2016; Swartz et al., 2019).

This is perhaps additionally pertinent for female players who are relatively new to the professional level of Australian football and may require greater reinforcement of skill development and execution for specific skills (e.g., marking contests) with a high-risk of concussion (Makdissi & Davis, 2016b). Both speed and overall mass of the striking player might be important determinants of impact severity, however further research is required before recommendations can be made with regards to rule modification (e.g., limitations with the permissible distance before collision is permitted; Schmidt, Guskiewicz, et al., 2016) or change of player tactics (e.g., coach matching players to opposition players of similar height and weight).

Both positional designations and number of years playing football may not be sufficiently sensitive to capture the variability in exposure to HAEs. Other predisposing risk factors, such as activity profiles might provide better estimates of exposure risk to HAEs, which could help inform both team tactics and mitigate further exposure to HAEs. If player activity profiles reduce with increasing fatigue during a match, thereby limiting their response time to avoid collisions, and this occurs towards the second half of the match (when injury rates are reported to increase), then rotating players more frequently throughout the second half of the match in order to avoid player exhaustion might be important to mitigate HAEs of higher magnitude (as observed in this study during the second half of the match).

Evidence that concussion is more closely associated with: a) the cumulative exposure of the individual to HAEs prior to injury, and b) the individual tolerance to injury further support the need to identify the above mentioned risk factors predisposing players to HAEs. At present, the non-helmeted X-Patch in its current state, is not recommended for use in daily practice of identifying players for further concussion screening. The implementation of such system, subject to improved reliability and measurement accuracy, would require: 1) routine use of the device in all players, 2) real-time data processing and provision to sideline staff, and 3) the identification of players who incur HAEs of a greater magnitude relative to their non-injurious HAEs (e.g., player who routinely incurs PLAs of 20 *g* to 40 *g* is flagged at 60 *g*). Implementation of such a system, however, must be weighed against staff cost and inconvenience to the match and provide an added benefit in addition to current protocols for concussion screening in professional sports (e.g., medically qualified personnel with expert background in concussion, World Rugby HIA protocol, standardized video review of concussive signs; Davis et al., 2019; Fuller, Kemp, & Raftery, 2017; Patricios et al., 2018).

5.2.2 Head Injury Assessment Form: Improving Concussion Screening at the Community Level

In this research program, there was preliminary evidence to suggest that concussion screening at community football can be facilitated by identifying players with observable concussive signs as per the recommended use of the HIAf (Clifton et al., 2016; Davis et al., 2017). Much of the literature supporting the utility of concussive signs to identify players for further concussion assessment, however, has been conducted in professional level sports with use of advanced video technology by highly experienced personnel (C. W. Fuller et al., 2017; Gardner, Howell, et al., 2017; Makdissi & Davis, 2016a). Further, these resources and expertise are not present at community football where concussion detection is limited to the awareness and knowledge of concussion among players and club personnel (Kemp et al., 2016; White et al., 2016; White et al., 2014). In this research program, use of the HIAf represented a rapid and real-time method to identify players with concussive signs who warrant further assessment as per community concussion guidelines (Davis & Makdissi, 2016; Davis et al., 2017).

5.2.2.1 Real-World Applications

The AFL and Australian Institute of Sport provide multiple recommendations and online resources for the appropriate detection and management of concussion in sport that are consistent with the recommendations from the CISG (Davis et al., 2017; Elkington et al., 2019). Among these recommendations by the AFL, is the recommendation for the routine use of the HIAf which provides a basic triage system to aid community personnel identify and immediately remove players for medical assessment once they are observed to demonstrate concussive signs such as balance disturbance, no protective action in fall to ground, blank or vacant stare (as in section 1.1.4) and/or report concussion symptoms (See Appendix; Clifton et al., 2016; Davis et al., 2017). The HIAf is therefore targeted for use by community personnel with limited experience in concussion detection and live from the sideline in the absence of video technology as seen in professional sports.

In the current study, personnel with no previous experience in concussion detection and only basic training, conducted observations live from the sideline without video footage review, thereby mimicking the real-world application of the HIAf. These findings suggest that basic and limited training could be effectively delivered to community personnel with non-expert background in concussion detection and help them better recognise players with observable concussive signs (Echemendia, Bruce, et al., 2017; Gardner, Levi, et al., 2017) who may demonstrate poor neurocognitive and balance performance on concussion assessment measures.

5.2.2.2 Objectivity

The current study purposely focused on the use of HIAf items with observable concussive signs and not items of symptom reporting and/or memory difficulties, which has important implications. Investigating the utility of observable concussive signs as an objective method to identify players for further concussion assessment – as per the aim of this thesis – would be confounded by the inclusion of otherwise standard methods of player identification. Such methods of identification are based on presence of symptom report and/or memory difficulties which must elicited from the player and cannot be directly observed. While psychometric properties of symptom assessment are largely forgiving (Guskiewicz et al., 2013), and it is well established that symptom report is a primary method by which to detect possible concussion, it remains subject to individual bias and player motivations to remain on the field (McCrea et al., 2004; Meier, Brummel, et al., 2015). By contrast, very few studies have explored the utility of observable concussive signs in the overall process of screening for concussion, which provide greater objectivity (e.g., is the player exhibiting motor imbalance?) relative to symptom reporting. In this study, an additional 22 players were identified for further concussion assessment on the basis of demonstrating observable concussive signs, relative to only four players identified for further assessment on the basis of symptom report. While all HIAf+ve players reported a significantly greater frequency and severity of symptoms post-match assessment, this assessment was primarily triggered by the observation of concussion signs. It is unknown, however, how many HIAf+ve players would have presented for further assessment on their own accord without having been identified by this process.

5.2.2.3 Feasibility

The objectivity provided by use of observable concussive signs in the HIAf may also address individual bias in the decision-making process of player removal and management following suspected concussion in the absence of experienced medical personnel. It is reported that community staff incorrectly weigh in factors (e.g., “how tough the player is”) or pressure from other staff (e.g., resistance from parents/trainers) when making decisions to remove players suspected of concussion (Kemp et al., 2016; White et al., 2014)**.** Instead, the HIAf represents a standardised method to screen concussion by promoting a definitive decision-making process with distinct dichotomous outcomes (e.g., player has concussive signs = remove for further assessment).

Additionally, use of the HIAf at community sports might require designated personnel. For example, survey data (*n* = 118) within community rugby suggests personnel (e.g., parents, coaches, referees, management) have very poorly defined roles and responsibilities with regards to concussion management, with only 29% becoming involved in this process (Clacy, Goode, Sharman, Lovell, & Salmon, 2019). Perhaps a similar protocol to that implemented in the professional level of the NFL and NHL might aid concussion screening in community football. This could involve dedicated third-party *spotters* or personnel who have designated roles to monitor concussive signs and detect possible concussion from the sideline independent of the coach and/or trainer (Echemendia, Comper, et al., 2019; Ellenbogen et al., 2018). At the level of the AFL, dedicated spotters were trialled in 2019 and will be expanded in 2020, however, this model remains in its preliminary stages with no reportable protocols or outcomes yet published. Such information will inform the efficacy of such models at lower competition levels of the game where certain modifications will be required.

For instance, in community Australian football, this model might be implemented at a volunteer-service capacity in light of limited resources (Baugh et al., 2015; Kroshus et al., 2017; Putukian et al., 2009; Wicker & Breuer, 2015). It should be noted that most team personnel and players of the participating teams, however, were not familiar with the HIAf protocol thereby suggesting limited translation and training with regards to community concussion safety guidelines. Indeed, it was found that not all HIAf+ve players (27%) were removed from the field contrary to HIAf recommendations. Routine use of the HIAf by designated spotters at community sports, therefore might also require the delivery of cost-effective training and educational programs highlighting the benefits of timely concussion detection and management, which is demonstrated to have positive effects in concussion management (Hotz et al., 2018; Kerr et al., 2015).

The successful dissemination of concussion protocols, including training and education as well as compliance, however, require a careful consideration of the targeted context (e.g., community level) and the hierarchical levels (e.g., parents/players, coaches/trainers, club management) within this context (Finch & White, 2017). For key organisations (e.g., Sport and Recreation Victoria, Sports Medicine Australia, AFL) for example, research which provides practical or “easy-to-digest” resources to end users at community sport clubs can facilitate translation by such organisations involved in this process (Bekker, Paliadelis, & Finch, 2017). At community sports club, however, coaches and sport trainers are considered to be the primary programme adopters and implementers even if they are not necessarily the target end user or beneficiaries (i.e., players) of the program (Donaldson, Lloyd, Gabbe, Cook, & Finch, 2017)

An important step in this process is therefore to identify potential barriers and/or facilitators to the success of the programme in group discussion with personnel who are also involved in match-day protocols (e.g., secondary coach, first aid; O’Brien, Finch, Pruna, & McCall, 2018)**.** In their study describing the implementation of exercise programs, Donaldson et al. (2017) describe the considerable challenges related to the seasonal and volunteer nature of community

Australian football. The authors found most key stakeholders did not wish to meet pre-season in lieu of other commitments and were under considerable time pressure with administrative/coaching tasks during the season, thereby making regular meetings difficult**.** It was suggested that having high-profile local sports medicine physicians or league representatives invited to the community club or specifying the limited/brief time demands of the programme with the option to communicate via telephone or email can be helpful.

Other methods to effectively deliver a training program to volunteer staff also include the use of online training modules, which are easily accessible, economical, flexible to individual time-commitments and are demonstrated to be efficacious with regards to improving concussion knowledge and awareness (Daugherty, DePadilla, & Sarmiento, 2019; Glang, Koester, Beaver, Clay, & McLaughlin, 2010; Parker, Gilchrist, Schuster, Lee, & Sarmiento, 2015).

5.2.2.4 Utility of Variables

All 22 HIAf+ve players demonstrated clinically-significant decline in post-match assessments of mBESS, SAC or Cogstate tasks utilising validated methods to establish decline from baseline and normative values (Chin et al., 2016; Louey et al., 2014). The SCAT3 and Cogstate are widely used measures to detect and assess the extensive range of possible multisystem sequelae with concussion (Echemendia, Broglio, et al., 2017; Feddermann-Demont et al., 2017; Moody et al., 2019; Nelson, LaRoche, et al., 2016). Several demographic and match-related factors as outlined below need to be considered when administering and interpreting clinical outcomes on these measures, thereby limiting their utility among non-experience personnel. In this study, both HIAf+ve and HIAf-ve groups were matched on age (Covassin, Elbin, Larson, & Kontos, 2012; Echemendia, Broglio, et al., 2017), sex (Cottle et al., 2017; Covassin, Elbin, Larson, et al., 2012; Dougan et al., 2014; Houck et al., 2019), education level (Chin et al., 2016; Donders & Stout, 2019; Oldenburg et al., 2016), and baseline mood (Kontos, Covassin, et al., 2012; Weber et al., 2018) in order to control for these potential confounds. While there is currently not sufficient evidence to suggest a history of concussion is associated with long-term cognitive deficits (Alsalaheen, Stockdale, Pechumer, Giessing, et al., 2017; Brooks et al., 2016; Brooks et al., 2018; Gardner et al., 2019) groups were also matched on this variable and no player reported having concussion within the same year. Furthermore, there was no evidence to suggest post-match outcomes among HIAf+ve players were influenced by acute pain (Higgins, Martin, Baker, Vasterling, & Risbrough, 2018; Moore et al., 2013; Sanchez, 2011).

These findings demonstrate that interpretation of these measures requires careful consideration and adjustment for possible confounding factors, supporting concussion guidelines which do not advise use of these measures by non-qualified personnel (McCrory, Meeuwisse, et al., 2017). In contrast, a significantly greater proportion of HIAf+ve players, compared to HIAf-ve players, showed poorer performance on these assessment measures. This suggests the HIAf might be a suitable and rapid alternative in the overall process of screening concussion when qualified staff and resources (e.g., computer or licence to administer Cogstate) are not available.

Lastly, there was preliminary evidence to suggest specific concussive signs are associated with worse cognitive and balance performance, which may have implications for recovery and indicate need for long-term follow-up. Previous research suggests certain concussive signs (e.g., blank or vacant look; motor imbalance, other) have greater utility in predicting concussion diagnosis (Davis & Makdissi, 2016). To the best of the author's knowledge, very few studies have explored the clinical outcomes associated with specific concussive signs. In a mixed sample of NRL players with and without concussion diagnosis (Gardner, Wojtowicz, et al., 2017) findings revealed signs of *loss of responsiveness* (including *no protective action in fall to ground*) and a *blank or vacant stare* were associated with worse balance performance. In the current study, 50% of HIAf+ve players with *balance disturbance* or *blank and vacant stare* had cognitive deficits on at least two or more Cogstate tasks, while 100% of players with *no protective action in fall to ground* had deficits on the SAC. While it is recommended that all players with observable concussive signs are immediately removed from play for further concussion assessment (Davis & Makdissi, 2016; Davis et al., 2017), players with these specific concussive signs may also have an elevated risk of poorer outcomes post-match.

5.3 Strengths and Limitations

The studies in Chapter Two and Chapter Three of this research program were characterised by novel findings and certain methodological strengths. To date, there has been very limited research attention paid to exploring head impact exposure among professional male and female Australian football players by quantifying and characterising HAEs within the real-life dynamics of this sporting code. This necessitated use of wearable non-helmeted accelerometer. At the time this research program began, the first generation X-Patch (X2 Biosystems now incorporated by Prevent Biometrics®) was the only suitable device for this cohort as other devices such as instrumented mouthguard or helmets were not viable options. Several publications thereafter, however, revealed important caveats with use of the X-Patch (Cummiskey et al., 2017; McIntosh et al., 2019; Press & Rowson, 2017). Multiple measures were thus implemented in order to optimise the accuracy of the X-Patch output in the current study, demonstrating methodological advantages in comparison to previous studies with use of this device (Eckner et al., 2018; King et al., 2018; Reynolds et al., 2017a). These actions included: a) disabling the in-built algorithm that was initially developed to detect false positives in order to avoid excluding true events, b) the use of video footage to verify HAEs and avoid over estimating exposure, c) exclusion of PRA data which is reported to have significant variability and measurement error and d) exclusion of HAEs below 30 *g* which are associated with a very low likelihood of concussion and mostly associated with non-contact events (e.g., jumping, running, landing). Thus far, this is first study that has explored the in-vivo kinematics of the head in the setting of professional Australian football, with both male and female players. In addition, the sample size was sufficiently large to achieve a power of at least 80% to detect statistical significance at conventional levels (*p* = 0.05) and was representative of both male and female leagues.

These studies however, were not without limitations. With regards to the X-Patch output, whilst both PLA and PRA were able to be calculated form the data collection, only PLA was utilised as PRA is reported to have a large margin of measurement error (Cummiskey et al., 2017; McIntosh et al., 2019; Siegmund et al., 2016). Since the seminal work of Holbourn (1943), rotational acceleration-deceleration is known to be an important contributor to concussion related pathophysiology (e.g., shear strain of white matter tissue) in combination with linear acceleration-deceleration. In North American football, concussion is reported to occur in association with mean PRA values of 3,977 *rad/s*^{2} (Beckwith, Greenwald, Chu, Crisco, Rowson, Duma, Broglio, McAllister, Guskiewicz, & Mihalik, 2013; Broglio et al., 2010) while limited data from female (ice hockey) players (*n* = 4) suggests mean PRA values of 4,030 *rad/s*^{2} (Wilcox et al., 2015). Moreover, PRA is not linearly related to PLA (Broglio, Lapointe, et al., 2017) and PRA is similarly subject to variability based on individual levels of tolerance to injury (Broglio, Lapointe, et al., 2017; Rowson et al., 2019; Stemper et al., 2019). In accurate and reliable accelerometer systems, PRA values provide considerable additional information above and beyond PLA values.

Furthermore, data collection was limited to matches only and practice sessions were not observed. While head impact exposure mostly occurs during match sessions, head impacts remain evident during practice sessions (Campolettano et al., 2019). In addition, both play and regulations during practice sessions are heterogonous and largely synthetic due to differences in drill strategies and coach instructions compared to match play (Dawson, Hopkinson, Appleby, Stewart, & Roberts, 2004). The focus of the study, was therefore to conduct measurements of head impact exposure during sessions that reflect the most realistic dynamics of this sporting code. As the X-Patch had received limited field testing at the time this research program began, seasonal observations could not be justified empirically without first conducting a pilot observation.

Players were therefore monitored for the duration of one match only (i.e., across a total of 14 matches). While incidence rate analyses were conducted for the basis of these matches, it was not possible to calculate head impact exposure per player per match over the season, thereby making comparison to other sporting codes not possible. Two widely used denominators in the process of calculating incidence rates are player hours (i.e., total number of hours played) or athletic exposures (i.e., total number of sessions played). While it is possible to gather the total number of seasonal player hours and athletic exposures from official online league records, thereby providing realistic denominators, the numerator in this calculation would need to be extrapolated from observations of one match only and would therefore be largely artificial.

The study constituting Chapter Four was also characterised by several strengths and limitations. This was the first study – to the author's knowledge – to explore the utility of the observable concussive signs as a method to identify community Australian football players for further concussion assessment. The study design provided ecological validity by mimicking the real-world application of the HIAf. In addition, two male and female teams were monitored across the entire winter season (60 matches) by trained personnel at each match to optimise the detection of concussive signs. All players underwent baseline assessment with the use of sideline and computerised assessment tools in order to improve the detection of possible sequelae associated with suspected concussion (Feddermann-Demont et al., 2017). For HIAf+ve players, assessments were conducted on the day post-match in order to optimise the detection of possible cognitive and balance deficits (Broglio et al., 2019). All HIAf-ve players, by contrast, received in-season follow-ups in order to represent the time span between baseline and post-match assessment evident in the HIAf+ve group. A brief screen of mood (DASS21) and pain post-match (BPI-Short Form) were utilised to control for these potential confounds, as well as matching groups on several demographic factors (e.g., sex, age, education).

There were, however, no independent medical assessments by trained clinicians to diagnose or exclude concussion. While there are specific concussive signs that are highly indicative of a concussion diagnosis (e.g., no protective action in fall to ground; Davis & Makdissi, 2016) not all players who are observed to have concussive signs receive a concussion diagnosis (Bruce et al., 2017; Echemendia, Bruce, et al., 2017; Gardner, Howell, et al., 2017). In addition, not all players who sustain concussion necessarily exhibit concussive signs. It is therefore difficult to exclude suspected concussion among the HIAf-ve group, which was characterised by a proportion of players with reduced performance in concussion assessment measures.

In addition, the SCAT3 was revised during the course of this research program to the SCAT5 in 2017 (McCrory, Meeuwisse, et al., 2017; McCrory et al., 2013). While many important elements of concussion assessment in the SCAT3 were maintained in the SCAT5 (e.g., mBESS), modifications were made in order to improve the SCAT5's sensitivity. One limiting factor of the SCAT3 was the prevalent ceiling effects for the immediate recall component of the SAC, which now includes an optional 10-word list for recall in the SCAT5 (Echemendia, Meeuwisse, et al., 2017). Additionally, the SCAT3 graded symptom scale required participants to report symptoms based on their current (e.g., "how they feel now") rather than their general state (e.g., "how they typically feel") as per the SCAT5, which provides a more accurate characterisation of the respondent's 'non-concussed' state at baseline (Asken, Houck, Bauer, & Clugston, 2019). While presently there is scant research with the SCAT5, preliminary evidence suggests use of the 10-word list eliminates ceiling effects among diverse populations including male and female players thereby improving its' clinical utility (Black et al., 2020; Norheim, Kissinger-Knox, Cheatham, & Webbe, 2018).

It also remained possible that some HIAf-ve players exhibited concussive signs and these were missed by the observers. The study did not employ video footage review of these matches, thereby making a formal verification of the absence of these signs not possible. Video footage review can also be used to assess agreement between raters and assess performance in detection of signs between expert reviewers and naïve reviewers (Echemendia, Bruce, et al., 2017; Gardner, Levi, et al., 2017), which could potentially inform future training protocols. The combination of video footage review and independent medical assessment of players suspected of concussion can then help provide a formal assessment of sensitivity and specificity of the HIAf and further inform practice of concussion screening at community sports. For example, it may be possible that specific concussive signs are more subjective and have inferior discriminant ability, thereby indicating a revision of the HIAf and included items to aid concussion screening for the naïve user.

Lastly, HIAf+ve and HIAf-ve groups were matched on sex, thereby further controlling for possible differential effects of sex on measures of cognitive and balance performance (Cottle et al., 2017; Covassin, Elbin, Larson, et al., 2012; Dougan et al., 2014; Houck et al., 2019). Due to a limited HIAF+ve sample however, it was not possible to make comparison between male and female player outcomes within this group. Evidence from the literature suggests females are more susceptible to the deleterious consequences of concussion (O'Connor, Baker, et al., 2017; Van Pelt et al., 2019) and this bias may be reflected with experience of specific concussive signs.

5.4 Future Directions

Future research directions have been outlined in previous sections of this thesis, however, a summary of the key recommendations is presented in this section.

Over the past two decades, multiple studies with use of wearable accelerometer devices have offered novel insights of the exposure to head impacts and possible concussion within the real-life dynamics of sport. There remains, however, considerable heterogeneity in the methodology of studies employing accelerometer technology which may attenuate comparison across different sports. For example, the minimal recording threshold used to measure HAEs can vary between studies with threshold values recording acceleration from above 10 *g* (Mihalik et al., 2019; Nevins et al., 2019; Reynolds et al., 2017a; Vollavanh et al., 2018), 15 *g* (Broglio et al., 2010; Eckner et al., 2011; O'Day et al., 2017), 20 *g* (Carey et al., 2019; Caswell et al., 2017) or 30 *g* (McIntosh et al., 2019; Willmott et al., 2018). Similarly, ‘high-magnitude’ HAEs can be recorded from 40 *g* (Alois et al., 2019; Gellner, Campolettano, Smith, & Rowson, 2019), 60 *g* (Poole et al., 2015) or 70 *g* and above (Joseph et al., 2018; Kindschi, Higgins, Hillman, Penczek, & Lincoln, 2017). There is evidence to suggest that studies which employ lower recording thresholds measure more HAEs and will produce lower average magnitudes than studies with higher recording thresholds thereby producing a significant source of bias in the literature (King et al., 2016). It is therefore, that an important step to unify such efforts in future will require the development of standardised or consensus-based protocols for the use accelerometer technology. This could also include criterion for consistent use of recording thresholds (e.g., above 30 *g*), validation methods (e.g., field testing as per X-Patch and HITS) and qualification techniques (e.g., criteria for video review of playing situations) thereby making comparisons between studies more accurate (King et al., 2016; McIntosh et al., 2019).

A further point to consider, is that players from the studies in Chapter Two and Chapter Three were observed during a match, and not across the season. Seasonal observations, however, are important in order to attain more realistic estimates of head impact exposure per player per match thereby allowing comparisons of head impact exposure between sports. To date, the HITS remains the most reliable and well-validated system in use, however, it is fitted in hard-shell helmets and therefore not a viable option for use in non-helmeted sports, such as Australian football (Laws of the Game; AFL, 2019). The development of a modified HITS, fitted into padded headgear as previously accomplished for boxers (Beckwith et al., 2007; Stojsih et al., 2010) might provide more reliable estimates of head impact exposure in non-helmeted sports such as Australian football, where padded headgear is optional.

In section 5.2.1 of this chapter, several other predisposing factors of head impact exposure in sport were proposed in addition to sex, player position, and player experience. One such factor was activity profiles. It would be interesting to explore if high-intensity acceleration-deceleration running is associated with a greater exposure to HAEs. At the professional level of Australian football, players routinely wear global positioning systems thereby providing indices of speed and total distance covered throughout the match (Black et al., 2019; Kempton et al., 2015). This analysis would require a consideration of interacting effects between other intrinsic (e.g., body mass, anthropometric features, risk-taking behaviour, physical fitness, skill execution) and extrinsic (e.g., match status, opposition ranking) factors. In turn, this may provide a more detailed appraisal of match situations that represent potential risk of head impacts and inform match-day protocols (e.g., enforce greater interchange rotations of players during high-risk situations). For example, while observations were limited to one match in this pilot study (Chapter Two), it was evident male players had greater exposure to HAEs than female players. By accounting for skill execution, however, it was found that female players incurred twice the head impact rate during specific skill execution in comparison to male players (e.g., marking contest). This identified playing situations with an elevated risk of exposure to head impacts for a specific groups of players (e.g., females). Importantly, with increasing evidence of individual-specific tolerance limits for injury, the analysis abovementioned might be of further use when explored at the individual level. Exposure profiles to HAEs may be examined in relation to activity profiles across the match or season for each individual player, rather than the cohort level thereby accounting for individual variability across these factors (Broglio, Lapointe, et al., 2017; Rowson et al., 2018; Stemper et al., 2019).

Lastly, while there is evidence to suggest exposure to HAEs may be associated with positive neuropathological markers of injury (Joseph et al., 2018; Poole et al., 2015; Talavage et al., 2014), there is limited evidence to support a relationship between exposure to HAEs and neurocognitive function (Gysland et al., 2012; McAllister et al., 2012; Willmott et al., 2018). More recent evidence, however, suggests exposure profiles to HAEs are associated with concussion at the individual level. Of note, these studies have not examined the relationship between formal performance (neurocognitive, balance) on concussion assessment measures (e.g., ImPACT, Cogstate, SCAT) and individual exposure profiles of HAEs among concussed and matched controls thereby highlighting an important area for future research. These findings might have important implications for screening players for suspected concussion who are demonstrated to have an elevated exposure to HAEs within a short-period of time relative to their individual normative exposure. These players may also have concomitant short-term reductions in visuomotor speed, reaction time and attention thereby reducing their ability to respond efficiently to their environment.

The findings of Chapter Four revealed preliminary evidence that use of the HIAf can augment screening of players in need of further concussion assessment. Future work in this field, however, should take note of several considerations in order to help establish effective concussion screening in community football. Firstly, it would be important to determine how many players with observable concussive signs receive a concussion diagnosis. This would require qualified personnel to be present and/or available on site to make such assessments, with use of consistent concussion criteria and assessment tools (Feddermann-Demont et al., 2017; McCrory, Meeuwisse, et al., 2017). Having qualified personnel on site might also aid concussion screening of players who have concussion and do not necessarily exhibited concussive signs. In this way, the study design is providing more rigorous control of excluding suspected concussion among the control sample. This information would form the basis for a discriminant analysis of the HIAf items to screen concussion successfully at community football.

An important component of this work would also involve exploring the relationship, if any, between protracted recovery and specific concussive signs. Players could be stratified into comparison groups in order to compare short-term outcomes and recovery between players with: a) concussive signs and concussion; b) concussive signs and no concussion; c) no concussive signs and concussion and d) no concussive signs and no concussion (i.e., controls).

In addition, video recordings of matches across the season might facilitate the verification of observed concussive signs. Furthermore, this may enable the characterisation of surrounding situations in which these signs commonly occur, and provide the basis for analysis of inter-rater and intra-rater agreement in detecting these signs. This information would have important implications for developing training protocols for the use of the HIAf among community sport staff. For example, it remains unknown which concussive signs are determined to be *objective* (i.e., high inter-rater agreement) or subjective (i.e., low inter-rater agreement) to the rater and therefore require further explanation when developing training programs.

Lastly, the efficacy of such an effort would require an investigation of current concussion knowledge and potential barriers to the translation of concussion guidelines at community sports (Kemp et al., 2016; White et al., 2016). After all, the utility of the HIAf and training protocols for wider distribution would depend on the overall receptiveness and compliance among community personnel. Using objective standardised protocols for concussion screening might help overcome such potential barriers and facilitate the adoption of these protocols, thereby improving concussion detection at this level.

5.5 Final Remarks

The overarching aim of this thesis was to identify methods that could augment concussion screening in professional and community Australian football. While the acute clinical presentation of concussion is multifaceted, non-specific and influenced by a host of individual factors thereby requiring clinical formulation following comprehensive assessment, methods to identify players with concussion remain subject to individual bias. In this thesis, two distinct methods were proposed to have greater objectivity in the overall process of identifying and characterising risk of possible concussion within contact sport. The findings from three studies undertaken to explore these methods provide novel insights with regards to the real-life dynamics of head impact exposure among professional Australian football players, as well as the utility and feasibility of using observable concussive signs for concussion screening among community Australian football players.

Several proposals were made that could optimise future research ventures in this field and more generally within clinical practice. A unifying concept which forms the core basis of this thesis reflects the ongoing pursuit noted in the wider literature – that being – the prevention and timely identification of concussion in sport to prevent further harm to the player and provide appropriate care. This research program, however, could not have been accomplished without the vast efforts of the multiple authorities in the field which have propelled our knowledge of concussion to date, thereby allowing this research program to serve as a small stepping stone towards safe participation in contact sports for players at both community and professional level sports.

References

Abeare, C., Messa, I., Whitfield, C., Zuccato, B., Casey, J., Rykulski, N., & Erdodi, L. (2019). Performance Validity in Collegiate Football Athletes at Baseline Neurocognitive Testing. *Journal of Head Trauma Rehabilitation, 34*(4), E20-E31. doi:10.1097/HTR.0000000000000451

AFL. (2017). *26th Annual AFL Injury Survey*. Melbourne, Victoria, Australia: Australian Football League (AFL).

AFL. (2019). *Laws of Australian Football*. Melbourne, Victoria, Australia: Australian Football League (AFL).

Ahmed, O. H., & Hall, E. E. (2017). "It was only a mild concussion": Exploring the description of sports concussion in online news articles. *Physical Therapy in Sport, 23*, 7-13. doi:10.1016/j.ptsp.2016.07.003

Alla, S., Sullivan, S. J., Hale, L., & McCrory, P. (2009). Self-report scales/checklists for the measurement of concussion symptoms: a systematic review. *British Journal of Sports Medicine, 43*(Suppl 1), i3-i12. doi:10.1136/bjsm.2009.058339

Alla, S., Sullivan, S. J., & McCrory, P. (2012). Defining asymptomatic status following sports concussion: fact or fallacy? *British Journal of Sports Medicine, 46*(8), 562-569. doi:10.1136/bjsm.2010.081299

Alois, J., Bellamkonda, S., Campolettano, E. T., Gellner, R. A., Genemaras, A., Beckwith, J. G., . . . Crisco, J. J. (2019). Do American youth football players intentionally use their heads for high-magnitude impacts? *The American Journal of Sports Medicine, 47*(14), 3498-3504. doi:10.1177/0363546519882034

Alsalaheen, B., Stockdale, K., Pechumer, D., Broglio, S. P., & Marchetti, G. F. (2017). A comparative meta-analysis of the effects of concussion on a computerized neurocognitive test and self-reported symptoms. *Journal of Athletic Training, 52*(9), 834-846. doi:10.4085/1062-6050-52.7.05

Alsalaheen, B., Stockdale, K., Pechumer, D., Giessing, A., He, X., & Broglio, S. P. (2017). Cumulative effects of concussion history on baseline computerized neurocognitive test scores: Systematic review and meta-analysis. *Sports Health, 9*(4), 324-332. doi:10.1177/1941738117713974

ANAM4. (2010). *ANAM4 Sports Medicine Battery: Automated Neuropsychological Assessment Metrics*. Oklahoma, United States: Center for the Study of Human Operator Performance.

Anderson, T., Heitger, M., & Macleod, A. D. (2006). Concussion and mild head injury. *Practical Neurology, 6*(6), 342-357. doi:10.1136/jnnp.2006.106583

APA. (2013). *Diagnostic and Statistical Manual of Mental Disorders* (5th ed.). Washington, DC: American Psychiatric Publishing, Inc.

Arbour, C., Khoury, S., Lavigne, G. J., Gagnon, K., Poirier, G., Montplaisir, J. Y., . . . Gosselin, N. (2015). Are NREM sleep characteristics associated to subjective sleep complaints after mild traumatic brain injury? *Sleep Medicine, 16*(4), 534-539. doi:10.1016/j.sleep.2014.12.002

Arndt, S. R., Cargill, R. S., & Hammoud, S. (2004). *Head accelerations experienced during everyday activities and while riding roller coasters.* Paper presented at the Proceedings Of The Human Factors And Ergonomics Society 48th Annual Meeting, Los Angeles, CA.

Asken, B. M., DeKosky, S. T., Clugston, J. R., Jaffee, M. S., & Bauer, R. M. (2018). Diffusion tensor imaging (DTI) findings in adult civilian, military, and sport-related mild traumatic brain injury (mTBI): a systematic critical review. *Brain Imaging and Behavior, 12*(2), 585-612. doi:10.1007/s11682-017-9708-9

Asken, B. M., Houck, Z. M., Bauer, R. M., & Clugston, J. R. (2019). SCAT5 vs. SCAT3 symptom reporting differences and convergent validity in collegiate athletes. *Archives of Clinical Neuropsychology, Epub ahead of print*, 1-11. doi:10.1093/arclin/acz007

Asken, B. M., McCrea, M., Clugston, J. R., Snyder, A. R., Houck, Z. M., & Bauer, R. M. (2016). ‘‘Playing Through It’’: Delayed reporting and removal from athletic activity after concussion predicts prolonged recover. *Journal of Athletic Training, 51*(4), 329-335. doi:10.4085/1062-6050-51.5.02

Bahr, R., & Krosshaug, T. (2005). Understanding injury mechanisms: A key component of preventing injuries in sport. *British Journal of Sports Medicine, 39*(6), 324-329. doi:10.1136/bjsm.2005.018341

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

Bailey, C. M., & Arnett, P. A. (2006). Chapter 4: Motivation and the assessment of sports-related concussion. In S. Slobounov & W. Sebastianelli (Eds.), *Foundations of Sport-Related Brain Injuries* (pp. 171-193). Boston, MA: Springer.

Bailey, C. M., Echemendia, R. J., & Arnett, P. A. (2006). The impact of motivation on neuropsychological performance in sports-related mild traumatic brain injury.

Journal of the International Neuropsychological Society, 12(4), 475-484. doi:10.1017/s1355617706060619

Balasundaram, A. P., Athens, J., Schneiders, A. G., McCrory, P., & Sullivan, S. J. (2016). The influence of psychological and lifestyle factors on the reporting of postconcussion-like symptoms. *Archives of Clinical Neuropsychology, 31*, 197-205. doi:10.1093/arclin/acw001

Balasundaram, A. P., Athens, J., Schneiders, A. G., McCrory, P., & Sullivan, S. J. (2017). Do post-concussion-like symptom responses change following exercise or sports participation in a non-concussed cohort? *Scandinavian Journal of Medicine & Science in Sports, 27*(12), 2002-2008. doi:10.1111/sms.12844

Balasundaram, A. P., Sullivan, J. S., Schneiders, A. G., & Athens, J. (2013). Symptom response following acute bouts of exercise in concussed and non-concussed individuals - A systematic narrative review. *Physical Therapy in Sport, 14*(4), 253-258. doi:10.1016/j.ptsp.2013.06.002

Barkhoudarian, G., Hovda, D. A., & Giza, C. C. (2016). The molecular pathophysiology of concussive brain injury - an update. *Physical Medicine and Rehabilitation Clinics, 27*(2), 373-393. doi:10.1016/j.pmr.2016.01.003

Barr Jr., G. C., Kane, K. E., Barraco, R. D., Rayburg, T., Demers, L., Kraus, C. K., . . . Kane, B. G. (2015). Gender differences in perceptions and self-reported driving behaviors among teenagers. *Journal of Emergency Medicine, 48*(3), 366-370 e363. doi:10.1016/j.jemermed.2014.09.055

Barr, W. B., & McCrea, M. (2001). Sensitivity and specificity of standardized neurocognitive testing immediately following sports concussion. *Journal of the*

International Neuropsychological Society, 7(6), 693-702. doi:10.1017/s1355617701766052

Barth, J. T., Alves, W., Ryan, T., Macciocchi, S. N., Rimel, R. W., Jane, J. J., & Nelson, W. (1989). Mild head injury in sports: Neurospychological sequelae and recovery of function. In H. S. Levin, J. Eisenberg, & A. Benton (Eds.), *Mild Head Injury* (pp. 257-275). New York: Oxford Univeristy Press.

Basser, P. J., Mattiello, J., & LeBIhan, D. (1994). MR diffusion tensor spectroscopy and imaging. *Journal of Biophysiology, 66*(1), 259-267. doi:10.1016/S0006-3495(94)80775-1

Baugh, C. M., Kroshus, E., Daneshvar, D. H., Filali, N. A., Hiscox, M. J., & Glantz, L. H. (2015). Concussion management in United States college sports: Compliance with National Collegiate Athletic Association concussion policy and areas for improvement. *The American Journal of Sports Medicine, 43*(1), 47-56. doi:10.1177/0363546514553090

Bazarian, J. J., Zhu, T., Blyth, B., Borrino, A., & Zhong, J. (2012). Subject-specific changes in brain white matter on diffusion tensor imaging after sports-related concussion. *Magnetic Resonance Imaging, 30*(2), 171-180. doi:10.1016/j.mri.2011.10.001

Bazarian, J. J., Zhu, T., Zhong, J., Janigro, D., Rozen, E., Roberts, A., . . . Blackman, E. G. (2014). Persistent, long-term cerebral white matter changes after sports-related repetitive head impacts. *PLoS One, 9*(4), e94734. doi:10.1371/journal.pone.0094734

Beckwith, J. G., Chu, J. J., & Greenwald, R. M. (2007). Validation of a noninvasive system for measuring head acceleration for use during boxing competition. *Journal of Applied Biomechanics, 23*(3), 238-244. doi:10.1123/jab.23.3.238

Beckwith, J. G., Greenwald, R. M., & Chu, J. J. (2012). Measuring head kinematics in football: Correlation between the head impact telemetry system and Hybrid III headform. *Annals of Biomedical Engineering, 40*(1), 237-248. doi:10.1007/s10439-011-0422-2

Beckwith, J. G., Greenwald, R. M., Chu, J. J., Crisco, J. J., Rowson, S., Duma, S. M., . . . Mihalik, J. P. (2013). Timing of concussion diagnosis is related to head impact exposure prior to injury. *Medicine and Science In Sports and Exercise, 45*(4), 747-754. doi:10.1249/MSS.0b013e3182793067

Beckwith, J. G., Greenwald, R. M., Chu, J. J., Crisco, J. J., Rowson, S., Duma, S. M., . . . Collins, M. W. (2013). Head impact exposure sustained by football players on days of diagnosed concussion. *Medicine & Science in Sports & Exercise, 45*(4), 737-746. doi:10.1249/MSS.0b013e3182792ed7

Bekker, S., Paliadelis, P., & Finch, C. F. (2017). The translation of sports injury prevention and safety promotion knowledge: insights from key intermediary organisations. *Health Research Policy and Systems, 15*(1), 25. doi:10.1186/s12961-017-0189-5

Belanger, H. G., Vanderploeg, D. R., & McAllister, D. T. (2016). Subconcussive blows to the head: A formative review of short-term clinical outcomes. *Journal of Head Trauma Rehabilitation, 31*(3), 159-166. doi:10.1097/HTR.0000000000000138

Belanger, H. G., & Vanderploeg, R. D. (2005). The neuropsychological impact of sports-related concussion: A meta-analysis. *Journal of the International Neuropsychological Society, 11*(4), 345-357. doi:10.1017/s1355617705050411

Bell, D. R., Guskiewicz, K. M., Clark, M. A., & Padua, D. A. (2011). Systematic review of the balance error scoring system. *Sports Health, 3*(3), 287-295. doi:10.1177/1941738111403122

Bellamkonda, S., Woodward, S. J., Campolettano, E., Gellner, R., Kelley, M. E., Jones, D. A., . . . Crisco, J. J. (2018). Head impact exposure in practices correlates with exposure in games for youth football players. *Journal of Applied Biomechanics, 34*(5), 354-360. doi:10.1123/jab.2017-0207

Benzel, E. C., Miele, V., Bartsch, A., & Gilbertson, L. G. (2015). U.S. 9,149.227 B2. Cleveland, OH, United States of America.

Black, A., Miutz, L., Kv, V., Schneider, K., Yeates, K., & Emery, C. (2020). Baseline Performance of High School Rugby Players on the Sport Concussion Assessment Tool 5. *Journal of Athletic Training, in press*. doi:10.4085/1062-6050-123-19

Black, G. M., Gabbett, T. J., Naughton, G., Cole, M. H., Johnston, R. D., & Dawson, B. (2019). The influence of contextual factors on running performance in female Australian football match-play. *The Journal of Strength & Conditioning Research, 33*(9), 2488-2495. doi:10.1519/JSC.0000000000002142

Bland, J. M., & Altman, D. G. (1996). Meaurement error. *British Medical Journal, 312*(7047), 1654. doi:10.1136/bmj.312.7047.1654

Bleiberg, J., Cernich, A. N., Cameron, K., Sun, W., Peck, K., Ecklund, P. J., . . . Warden, D. L. (2004). Duration of cognitive impairment after sports concussion. *Neurosurgery, 54*(5), 1073-1078. doi:10.1227/01.NEU.0000118820.33396.6A

Braham, R., Finch, C., & McCrory, P. (2004). The incidence of head/neck/orofacial injuries in non-elite Australian football. *Journal of Science And Medicine in Sport, 7*(4), 451-453. doi:10.1016/S1440-2440(04)80263-9

Braham, R., Finch, C. F., McIntosh, A., & McCrory, P. (2004). Community level australian football: A profile of injuries. *Journal of Science And Medicine in Sport, 7*(1), 96-105. doi:10.1016/S1440-2440(04)80048-3

Brainard, L. L., Beckwith, J. G., Chu, J. J., Crisco, J. J., McAllister, T. W., Duhaime, A.-C., . . . Greenwald, R. M. (2012). Gender differences in head impacts sustained by collegiate ice hockey players. *Medicine and Science In Sports and Exercise, 44*(2), 297-304. doi:10.1249/MSS.0b013e31822b0ab4

Breedlove, K. M., Ortega, J. D., Kaminski, T. W., Harmon, K. G., Schmidt, J. D., Kontos, A. P., . . . Buckley, T. A. (2019). King-Devick Test reliability in national collegiate athletic association athletes: A national collegiate athletic association-department of defense concussion assessment, research and education report. *Journal of Athletic Training, 54*(12), 1241-1246. doi:10.4085/1062-6050-219-18

Brennan, J. H., Mitra, B., Synnot, A., McKenzie, J., Willmott, C., McIntosh, A. S., . . . Rosenfeld, J. V. (2016). Accelerometers for the assessment of concussion in male athletes: A systematic review and meta-analysis. *Sports Medicine, 47*(3), 469–478. doi:10.1007/s40279-016-0582-1

Bretzin, A. C., Mansell, J. L., Tierney, R. T., & McDevitt, J. K. (2017). Sex differences in anthropometrics and heading kinematics among division I soccer athletes. *Sports Health, 9*(2), 168-173. doi:10.1177/1941738116678615

Broglio, S. P., Cantu, R. C., Gioia, G. A., Guskiewicz, K. M., Kutcher, J., Palm, M., & Valovich McLeod, T. C. (2014). National Athletic Trainers' Association position statement: Management of sport concussion. *Journal of Athletic Training, 49*(2), 245-265. doi:10.4085/1062-6050-49.1.07

Broglio, S. P., Eckner, J. T., & Kutcher, J. S. (2012). Field-based measures of head impacts in high school football athletes. *Current Opinion in Pediatrics, 24*(6), 702-708. doi:10.1097/MOP.0b013e3283595616

Broglio, S. P., Eckner, J. T., Martini, D., Sosnoff, J. J., Kutcher, J. S., & Randolph, C. (2011). Cumulative head impact burden in high school football. *Journal of Neurotrauma, 28*(10), 2069-2078. doi:10.1089/neu.2011.1825

Broglio, S. P., Ferrara, M. S., Macciocchi, S. N., Baumgartner, T. A., & Elliot, R. (2007). Test-retest reliability of computerized concussion assessment programs. *Journal of Athletic Training, 42*(4), 509-514.

Broglio, S. P., Harezlak, J., Katz, B., Zhao, S., McAllister, T., & McCrea, M. (2019). Acute sport concussion assessment optimization: A prospective assessment from the CARE consortium. *Sports Medicine, 49*(12), 1977-1987. doi:10.1007/s40279-019-01155-0

Broglio, S. P., Katz, B. P., Zhao, S., McCrea, M., & McAllister, T. (2018). Test-retest reliability and interpretation of common concussion assessment tools: Findings from the NCAA-DoD CARE consortium. *Sports Medicine, 48*(5), 1255-1268. doi:10.1007/s40279-017-0813-0

Broglio, S. P., Lapointe, A., O'Connor, K. L., & McCrea, M. (2017). Head impact density: A model to explain the elusive concussion threshold. *Journal of Neurotrauma, 34*(19), 2675-2683. doi:10.1089/neu.2016.4767

Broglio, S. P., Macciocchi, S. N., & Ferrara, M. S. (2007). Sensitivity of the concussion assessment battery. *Neurosurgery, 60*(6), 1050-1057. doi:10.1227/01.NEU.0000255479.90999.C0

Broglio, S. P., Martini, D., Kasper, L., Eckner, J. T., & Kutcher, J. S. (2013). Estimation of head impact exposure in high school football: Implications for regulating contact practices. *The American Journal Of Sports Medicine, 41*(12), 2877-2884. doi:10.1177/0363546513502458

Broglio, S. P., McCrea, M., McAllister, T., Harezlak, J., Katz, B., Hack, D., & Hainline, B. (2017). A national study on the effects of concussion in collegiate athletes and us military service academy members: The NCAA-DoD Concussion Assessment, Research and Education (CARE) consortium structure and methods. *Sports Medicine, 47*(7), 1437-1451. doi:10.1007/s40279-017-0707-1

Broglio, S. P., Schnebel, B., Sosnoff, J. J., Shin, S., Feng, X., He, X., & Zimmerman, J. (2010). The biomechanical properties of concussions in high school football. *Medicine & Science In Sports & Exercise, 42*(11), 2064-2071. doi:10.1249/MSS.0b013e3181dd9156

Broglio, S. P., Sosnoff, J. J., & Ferrara, M. S. (2009). The relationship of athlete-reported concussion symptoms and objective measures of neurocognitive function and postural control. *Clinical Journal of Sport Medicine, 19*(5), 377-382. doi:10.1097/JSM.0b013e3181b625fe

Broglio, S. P., Sosnoff, J. J., Shin, S., He, X., Alcaraz, C., & Zimmerman, J. (2009). Head impacts during high school football: A biomechanical assessment. *Journal of Athletic Training, 44*(4), 342-349. doi:10.4085/1062-6050-44.4.342

Broglio, S. P., Surma, T., & Ashton-Miller, J. A. (2012). High school and collegiate football athlete concussions: A biomechanical review. *Annals of Biomedical Engineering, 40*(1), 37-46. doi:10.1007/s10439-011-0396-0

Brooks, B. L., Mannix, R., Maxwell, B., Zafonte, R., Berkner, P. D., & Iverson, G. L. (2016). Multiple past concussions in high school football players: Are there differences in cognitive functioning and symptom reporting? *The American Journal of Sports Medicine, 44*(12), 3243-3251. doi:10.1177/0363546516655095

Brooks, B. L., Silverberg, N., Maxwell, B., Mannix, R., Zafonte, R., Berkner, P. D., & Iverson, G. L. (2018). Investigating effects of sex differences and prior concussions on symptom reporting and cognition among adolescent soccer players. *The American Journal of Sports Medicine, 46*(4), 961-968. doi:10.1177/0363546517749588

Brown, D. A., Elsass, J. A., Miller, A. J., Reed, L. E., & Reneker, J. C. (2015). Differences in symptom reporting between males and females at baseline and after a sports-related concussion: A systematic review and meta-analysis. *Sports Medicine, 45*(7), 1027-1040. doi:10.1007/s40279-015-0335-6

Bruce, J. M., & Echemendia, R. J. (2009). History of multiple self-reported concussions is not associated with reduced cognitive abilities. *Neurosurgery, 64*(1), 100-106. doi:10.1227/01.NEU.0000336310.47513.C8

Bruce, J. M., Echemendia, R. J., Meeuwisse, W., Hutchison, M. G., Aubry, M., & Comper, P. (2017). Development of a risk prediction model among professional hockey players with visible signs of concussion. *British Journal of Sports Medicine, 52*(17), 1143-1148. doi:10.1136/bjsports-2016-097091

Bussone, W. R., Moore, T. L. A., Richards, D., Bove, R. T., Scher, I., & Prange, M. T. (2009). Measurements of non-injurious head accelerations of a pediatric population. *SAE International Journal of Passenger Cars - Mechanical Systems, 2*(1), 565-586. doi:10.4271/2009-01-0383

Caccese, J. B., Buckley, T. A., Tierney, R. T., Rose, W. C., Glutting, J. J., & Kaminski, T. W. (2018). Sex and age differences in head acceleration during purposeful soccer heading. *Research in Sports Medicine, 26*(1), 64-74. doi:10.1080/15438627.2017.1393756

Caccese, J. B., Iverson, G. L., Cameron, K. L., Houston, M. N., McGinty, G. T., Jackson, J. C., . . . Buckley, T. A. (2019). Estimated age of first exposure to contact sports is not associated with greater symptoms or worse cognitive functioning in male U.S. service academy athletes. *Journal of Neurotrauma, 37*(2), 334-339. doi:10.1089/neu.2019.6571

Caeyenberghs, K., Verhelst, H., Clemente, A., & Wilson, P. H. (2017). Mapping the functional connectome in traumatic brain injury: What can graph metrics tell us? *Neuroimage, 160*, 113-123. doi:10.1016/j.neuroimage.2016.12.003

Campolettano, E. T., Rowson, S., Duma, S. M., Stemper, B., Shah, A., Harezlak, J., . . . McCrea, M. (2019). Factors affecting head impact exposure in college football practices: A multi-institutional study. *Annals of Biomedical Engineering, 47*(10), 2086-2093. doi:10.1007/s10439-019-02309-x

Cancelliere, C., Hincapie, C. A., Keightley, M., Godbolt, A. K., Cote, P., Kristman, V. L., . . . Cassidy, J. D. (2014). Systematic review of prognosis and return to play after sport concussion: Results of the international collaboration on mild traumatic brain injury prognosis. *Archives of Physical Medicine and Rehabilitation, 95*(3 Suppl), S210-229. doi:10.1016/j.apmr.2013.06.035

Carey, L., Stanwell, P., Terry, D. P., McIntosh, A. S., Caswell, S. V., Iverson, G. L., & Gardner, A. J. (2019). Verifying head impacts recorded by a wearable sensor using video footage in rugby league: A preliminary study. *Sports Medicine Open, 5*(1), 9. doi:10.1186/s40798-019-0182-3

Carroll, L., Cassidy, J. D., Holm, L., Kraus, J., & Coronado, V. (2004). Methodological issues and research recommendations for mild traumatic brain injury: The WHO collaborating centre task force on mild traumatic brain injury. *Journal of Rehabilitation Medicine, 43 Suppl*, 113-125. doi:10.1080/16501960410023877

Caswell, S. V., Lincoln, A. E., Stone, H., Kelshaw, P., Putukian, M., Hepburn, L., . . . Cortes, N. (2017). Characterizing verified head impacts in high school girls' lacrosse. *The American Journal of Sports Medicine, 45*(14), 3374-3381. doi:10.1177/0363546517724754

Cernich, A., Reeves, D., Sun, W., & Bleiberg, J. (2007). Automated Neuropsychological Assessment Metrics sports medicine battery. *Archives of Clinical Neuropsychology, 22S*, S101-S114. doi:10.1016/j.acn.2006.10.008

Chahla, J., Sherman, B., Cinque, M., Miranda, A., Garrett, W. E., Chiampas, G., . . . Mandelbaum, B. R. (2018). Epidemiological findings of soccer injuries during the 2017 gold cup. *The Orthopaedic Journal of Sports Medicine, 6*(8), 2325967118791754. doi:10.1177/2325967118791754

Chalmers, S., Magarey, M. E., Esterman, A., Speechley, M., Scase, E., & Heynen, M. (2013). The relationship between pre-season fitness testing and injury in elite junior Australian football players. *Journal of Science and Medicine in Sport, 16*(4), 307-311. doi:10.1016/j.jsams.2012.09.005

Chamard, E., Theoret, H., Skopelja, E. N., Forwell, L. A., Johnson, A. M., & Echlin, P. S. (2012). A prospective study of physician-observed concussion during a varsity university hockey season: metabolic changes in ice hockey players. Part 4 of 4. *Neurosurgical Focus, 33*(6), E4: 1-7. doi:10.3171/2012.10.FOCUS12305

Chin, E. Y., Nelson, L. D., Barr, W. B., McCrory, P., & McCrea, M. A. (2016). Reliability and validity of the Sport Concussion Assessment Tool-3 (SCAT3) in high school and collegiate athletes. *The American Journal of Sports Medicine, 44*(9), 2276-2285. doi:10.1177/0363546516648141

Chrisman, S. P. D., Mac Donald, C. L., Friedman, S., Andre, J., Rowhani-Rahbar, A., Drescher, S., . . . Rivara, F. P. (2016). Head impact exposure during a weekend youth soccer tournament. *Journal of Child Neurology, 31*(8), 971-978. doi:10.1177/0883073816634857

Chung, J. S., Zynda, A. J., Didehbani, N., Hicks, C., Hynan, L. S., Miller, S. M., . . . Cullum, C. M. (2019). Association between sleep quality and recovery following sport-related concussion in pediatrics. *Journal of Child Neurology, 34*(11), 639-645. doi:10.1177/0883073819849741

Clacy, A., Goode, N., Sharman, R., Lovell, G. P., & Salmon, P. (2019). A systems approach to understanding the identification and treatment of sport-related concussion in community Rugby Union. *Applied Ergonomics, 80*, 256-264. doi:10.1016/j.apergo.2017.06.010

Clarke, A. C., Ryan, S., Couvalias, G., Dascombe, B. J., Coutts, A. J., & Kempton, T. (2018). Physical demands and technical performance in Australian Football League Women's (AFLW) competition match-play. *Journal of Science and Medicine in Sport, 21*(7), 748-752. doi:10.1016/j.jsams.2017.11.018

Clay, M. B., Glover, K. L., & Lowe, D. T. (2013). Epidemiology of concussion in sport: A literature review. *Journal of Chiropractic Medicine, 12*(4), 230-251. doi:10.1016/j.jcm.2012.11.005

Clifton, P., Harcourt, P., Gastin, T., & Makdissi, M. (2016). An investigation of the role of a rapid sideline head injury assessment form (hiaf) in the clinical diagnosis of concussion in elite australian football [Abstract 207]. *British Journal of Sports Medicine, 51*(11), A79-A79. doi:10.1136/bjsports-2016-097270.205

Clugston, J. R., Chrisman, S. P. D., Houck, Z. M., Asken, B. M., Boone, J. K., Buckley, T. A., . . . Ortega, J. D. (2019). King-Devick test time varies by testing modality. *Clinical Journal of Sport Medicine, Epub ahead of print*. doi:10.1097/jsm.0000000000000691

Cobb, B. R., Urban, J. E., Davenport, E. M., Rowson, S., Duma, S. M., Maldjian, J. A., . . . Stitzel, J. D. (2013). Head impact exposure in youth football: Elementary school ages 9–12 years and the effect of practice structure. *Annals of Biomedical Engineering, 41*(12), 2463-2473. doi:10.1007/s10439-013-0867-6

Cochrane, J. L., Lloyd, D. G., Buttfield, A., Seward, H., & McGivern, J. (2007). Characteristics of anterior cruciate ligament injuries in Australian football. *Journal of Science and Medicine in Sport, 10*(2), 96-104. doi:10.1016/j.jsams.2006.05.015

Cogstate. (1999). *CogSport [Computer software]*. Parkville, Victoria, Australia: CogState, Ltd.

Collie, A., Makdissi, M., Maruff, P., Bennell, K., & McCrory, P. (2006). Cognition in the days following concussion: Comparison of symptomatic versus asymptomatic athletes. *Journal of Neurology, Neurosurgery & Psychiatry, 77*(2), 241-245. doi:10.1136/jnnp.2005.073155

Collie, A., Maruff, P., Makdissi, M., McCrory, P., McStephen, M., & Darby, D. (2003). CogSport: Reliability and correlation with conventional cognitive tests used in postconcussion medical evaluations. *Clinical Journal of Sport Medicine, 13*(1), 28-32. doi:10.1097/00042752-200301000-00006

Collie, A., Maruff, P., McStephen, M., & Darby, D. (2003). Are reliable change (RC) calculations appropriate for determining the extent of cognitive change in concussed athletes? *British Journal of Sports, 37*(4), 370-372. doi:10.1136/bjsm.37.4.370-a

Combs, P. R., Ford, C. B., Campbell, K. R., Carneiro, K. A., & Mihalik, J. P. (2019). Influence of self-reported fatigue and sex on baseline concussion assessment scores. *Orthopaedic Journal of Sports Medicine, 7*(1), 2325967118817515. doi:10.1177/2325967118817515

Cook, M. J., Gardner, A. J., Wojtowicz, M., Williams, W. H., Iverson, G. L., & Stanwell, P. (2019). Task-related functional magnetic resonance imaging activations in patients with acute and subacute mild traumatic brain injury: A coordinate-based meta-analysis. *Neuroimage: Clinical, 25*, 102129. doi:10.1016/j.nicl.2019.102129

Cormier, J., Manoogian, S., Bisplinghoff, J., Rowson, S., Santago, A., McNally, C., . . . Bolte, J. (2011). The tolerance of the maxilla to blunt impact. *Journal of Biomechanical Engineering, 133*(6), 064501: 064501-064505. doi:10.1115/1.4004248

Cortes, N., Lincoln, A. E., Myer, G. D., Hepburn, L., Higgins, M., Putukian, M., & Caswell, S. V. (2017). Video analysis verification of head impact events measured by wearable sensors. *The American Journal of Sports Medicine, 45*(10), 2379-2387. doi:10.1177/0363546517706703

Costello, D. M., Ernest, J., Kaye, A. H., O'Brien, T. J., & Shultz, S. R. (2018). Concussion incidence in amateur Australian rules footballers. *Journal of Clinical Neuroscience, 56*, 88-89. doi:10.1016/j.jocn.2018.07.003

Cottle, J. E., Hall, E. E., Patel, K., Barnes, K. P., & Ketcham, C. J. (2017). Concussion baseline testing: Preexisting factors, symptoms, and neurocognitive performance. *Journal of Athletic Training, 52*(2), 77-81. doi:10.4085/1062-6050-51.12.21

Cournoyer, J., & Tripp, B. L. (2014). Concussion knowledge in high school football players. *Journal of Athletic Training, 49*(5), 654-658. doi:10.4085/1062-6050-49.3.34

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

Covassin, T., Elbin, R. J., Larson, E., & Kontos, A. (2012). Sex and age differences in depression and baseline sport-related concussion neurocognitive performance and symptoms. *Clincal Journal of Sport Medicine, 22*(2), 98-104. doi:10.1097/JSM.0b013e31823403d2

Craton, N., & Leslie, O. (2014). Time to re-think the Zurich Guidelines?: A critique on the Consensus Statement on Concussion in Sport: The 4th International Conference on Concussion in Sport, held in Zurich, November 2012. *Clinical Journal of Sport Medicine, 24*(2), 93-95. doi:10.1097/JSM.0000000000000023

Crisco, J. J., Chu, J. J., & Greenwald, R. M. (2004). An algorithm for estimating acceleration magnitude and impact location using multiple nonorthogonal single-axis accelerometers. *Journal of Biomechanical Engineering, 126*(6), 849-854. doi:10.1115/1.1824135

Crisco, J. J., Fiore, R., Beckwith, J. G., Chu, J. J., Brolinson, P. G., Duma, S., . . . Greenwald, R. M. (2010). Frequency and location of head impact exposures in individual collegiate football players. *Journal of Athletic Training, 45*(6), 549-559. doi:10.4085/1062-6050-45.6.549

Crisco, J. J., Wilcox, B. J., Beckwith, J. G., Chu, J. J., Duhaime, A., Rowson, S., . . . Greenwald, R. M. (2011). Head impact exposure in collegiate football players. *Journal of Biomechanics, 44*(15), 2673-2678. doi:10.1016/j.jbiomech.2011.08.003

Crisco, J. J., Wilcox, B. J., Machan, J. T., McAllister, T. W., Duhaime, A., Duma, S. M., . . . Greenwald, R. M. (2012). Magnitude of head impact exposures in individual collegiate football players. *Journal of Applied Biomechanics, 28*(2), 174-183.

Critchely, M. (1949). *Punch-drunk syndromes: The chronic traumatic encephalopathy of boxers*. Maloine, Paris.

Cross, M., Kemp, S., Smith, A., Trewartha, G., & Stokes, K. (2016). Professional Rugby Union players have a 60% greater risk of time loss injury after concussion: A 2-season prospective study of clinical outcomes. *British Journal of Sports Medicine, 50*(15), 926-931. doi:10.1136/bjsports-2015-094982

Cummiskey, B., Schiffmiller, D., Talavage, T. M., Leverenz, L., Meyer, J. J., Adams, D., & Nauman, E. A. (2017). Reliability and accuracy of helmet-mounted and head-mounted devices used to measure head accelerations. *Journal of Sports Engineering and Technology, 231*(2), 144-153. doi:10.1177/1754337116658395

Daniel, R. W., Rowson, S., & Duma, S. M. (2012). Head impact exposure in youth football. *Annals of biomedical engineering, 40*(4), 976-981.

Daniel, R. W., Rowson, S., & Duma, S. M. (2014). Head impact exposure in youth football: Middle school ages 12 - 14 years. *Journal of Biomechanical Engineering, 136*(9), 094501. doi:10.1115/1.4027872

Dashnaw, M. L., Petraglia, A. L., & Bailes, J. E. (2012). An overview of the basic science of concussion and subconcussion: Where we are and where we are going. *Neurosurgery Focus, 33*(6), E5: 1-9. doi:10.3171/2012.10.FOCUS12284

Daugherty, J., DePadilla, L., & Sarmiento, K. (2019). Effectiveness of the US Centers for Disease Control and Prevention HEADS UP coaches' online training as an educational intervention. *Health Education Journal, 78*(7), 784-797. doi:10.1177/0017896919846185

Davenport, E. M., Whitlow, C. T., Urban, J. E., Espeland, M. A., Jung, Y., Rosenbaum, D. A., . . . Maldjian, J. A. (2014). Abnormal white matter integrity related to head impact exposure in a season of high school varsity football. *Journal of Neurotrauma, 31*(19), 1617-1624. doi:10.1089/neu.2013.3233

Davis, G. A., & Makdissi, M. (2016). Use of video to facilitate sideline concussion diagnosis and management decision-making. *Journal of Science and Medicine in Sport, 19*(11), 898-902. doi:10.1016/j.jsams.2016.02.005

Davis, G. A., Makdissi, M., Bloomfield, P., Clifton, P., Echemendia, R. J., Falvey, E. C., . . . McCrory, P. (2019). International consensus definitions of video signs of concussion in professional sports. *British Journal of Sports Medicine, 0*, 1-4. doi:10.1136/bjsports-2019-100628

Davis, G. A., Makdissi, M., Harcourt, P., Clifton, P., & McCrory, P. (2017). *The management of concussion in Australian football with specific provisions for children aged 5-17 years*. Victoria, Australia: Australian Football League.

Dawson, B., Hopkinson, R., Appleby, B., Stewart, G., & Robers, C. (2004). Player movement patterns and game activities in the Australian Football League. *Journal of Science and Medicine in Sport, 7*(3), 278-291. doi:10.1016/s1440-2440(04)80023-9

Dawson, B., Hopkinson, R., Appleby, B., Stewart, G., & Roberts, C. (2004). Comparison of training activities and game demands in the Australian Football League. *Journal of Science and Medicine in Sport, 7*(3), 292-301. doi:10.1016/S1440-2440(04)80024-0

Delaney, J. A., Thornton, H. R., Burgess, D. J., Dascombe, B. J., & Duthie, G. M. (2017). Duration-specific running intensities of Australian football match-play. *Journal of Science and Medicine in Sport, 20*(7), 689-694. doi:10.1016/j.jsams.2016.11.009

Dick, R. (2009). Is there a gender difference in concussion incidence and outcomes? *British Journal of Sports Medicine, 43*(Suppl 1), i46-i50.

Didehbani, N., Munro Cullum, C., Mansinghani, S., Conover, H., & Hart, J. (2013). Depressive symptoms and concussions in aging retired NFL players. *Archives of Clinical Neuropsychology, 28*(5), 418-424. doi:10.1093/arclin/act028

Docherty, C., McLeod, T. C. V., & Schultz, S. J. (2006). Postural control deficits in participants with functional ankle instability as measured by the balance error scoring system. *Clinical Journal of Sport Medicine, 16*(3), 203-208. doi:10.1097/00042752-200605000-00003

Dodd, A. B., Epstein, K., Ling, J. M., & Mayer, A. R. (2014). Diffusion tensor imaging findings in semi-acute mild traumatic brain injury. *Journal of Neurotrauma, 31*(14), 1235-1248. doi:10.1089/neu.2014.3337

Donaldson, A., Lloyd, D. G., Gabbe, B. J., Cook, J., & Finch, C. F. (2017). We have the programme, what next? Planning the implementation of an injury prevention programme. *Injury Prevention, 23*(4), 273-280. doi:10.1136/injuryprev-2015-041737

Donders, J., & Stout, J. (2019). The influence of cognitive reserve on recovery from traumatic brain injury. *Archives of Clinical Neuropsychology, 34*(2), 206-213. doi:10.1093/arclin/acy035

Donnan, L., Pizzari, T., O'Dwyer, N., & Edwards, S. (2018). *Fatigue induced postural changes in Australian rules football players with and without a history of hamstring injury*. Paper presented at the 36th Conference Of The International Society of Biomechanics in Sports, Auckland, New Zeland.

Dougan, B. K., Horswill, M. S., & Geffen, G. M. (2014). Athletes' age, sex, and years of education moderate the acute neuropsychological impact of sports-related concussion: A meta-analysis. *Journal of the International Neuropsychological Society, 20*(1), 64-80. doi:10.1017/S1355617712001464

Douglas, D. B., Ro, T., Toffoli, T., Krawchuk, B., Muldermans, J., Gullo, J., . . . Wintermark, M. (2019). Neuroimaging of Traumatic Brain Injury. *Medical Sciences (Basel), 7*(2). doi:10.3390/medsci7010002

Downey, R. I., Hutchison, M. G., & Comper, P. (2018). Determining sensitivity and specificity of the Sport Concussion Assessment Tool 3 (SCAT3) components in university athletes. *Brain Injury, 32*(11), 1345-1352. doi:10.1080/02699052.2018.1484166

Dretsch, M. N., Silverberg, N. D., & Iverson, G. L. (2015). Multiple past concussions are associated with ongoing post-concussive symptoms but not cognitive impairment in active-duty army soldiers. *Journal of Neurotrauma, 32*(17), 1301-1306. doi:10.1089/neu.2014.3810

Duhaime, A. C., Beckwith, J. G., Maerlender, A. C., McAllister, T. W., Crisco, J. J., Duma, S. M., . . . Greenwald, R. M. (2012). Spectrum of acute clinical characteristics of diagnosed concussions in college athletes wearing instrumented helmets: Clinical article. *Journal of Neurosurgery, 117*(6), 1092-1099. doi:10.3171/2012.8.JNS112298

Duma, S. M., Manoogian, S. J., Bussone, W. R., Brolinson, P. G., Goforth, M. W., Donnenwerth, J. J., . . . Crisco, J. J. (2005). Analysis of real-time head accelerations in collegiate football players. *Clinical Journal of Sport Medicine, 15*(1), 3-8. doi:10.1097/00042752-200501000-00002

Duma, S. M., & Rowson, S. (2009). *Every newton hertz: A macro to micro approach to investigating brain injury.* Paper presented at the Engineering in Medicine and Biology Society, 2009. EMBC 2009. Annual International Conference of the IEEE.

Eccleston, C., & Crombez, G. (1999). Pain demands attention: A cognitive-affective model of the interruptive function of pain. *Psychological Bulletin, 125*(3), 356-366. doi:10.1037/0033-2909.125.3.356

Echemendia, R. J., Broglio, S. P., Davis, G. A., Guskiewicz, K. M., Hayden, K. A., Leddy, J. J., . . . McCrory, P. (2017). What tests and measures should be added to the SCAT3 and related tests to improve their reliability, sensitivity and/or specificity in sideline concussion diagnosis? A systematic review. *British Journal of Sports Medicine, 51*(11), 895-901. doi:10.1136/bjsports-2016-097466

Echemendia, R. J., Bruce, J. M., Meeuwisse, W., Hutchison, M. G., Comper, P., & Aubry, M. (2017). Can visible signs predict concussion diagnosis in the National Hockey League? *British Journal of Sports Medicine, 52*(17), 1149-1154.

Echemendia, R. J., Comper, P., Aubry, M., Colucci, T., Terry, M., Cookson, R., . . . Kutcher, J. (2019). *Concussion Evaluation and Management Protocol*: NHL/NHLPA.

Echemendia, R. J., Herring, S., & Bailes, J. (2009). Who should conduct and interpret the neuropsychological assessment in sports-related concussion? *British Journal of Sport Medicine, 43 Suppl 1*, i32-35. doi:10.1136/bjsm.2009.058164

Echemendia, R. J., Iverson, G. L., McCrea, M., Macciocchi, S. N., Gioia, G. A., Putukian, M., & Comper, P. (2013). Advances in neuropsychological assessment of sport-related concussion. *Br J Sports Med, 47*(5), 294-298.

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

Echemendia, R. J., Putukian, M., Mackin, R. S., Julian, L., & Shoss, N. (2001). Neuropsychological test performance prior to and following sports-related mild traumatic brain injury. *Clinical Journal of Sport Medicine, 11*(1), 23-31. doi:10.1097/00042752-200101000-00005

Echemendia, R. J., Thelen, J., Meeuwisse, W., Comper, P., Hutchison, M. G., & Bruce, J. M. (2019). Testing the hybrid battery approach to evaluating sports-related concussion in the National Hockey League: A factor analytic study. *The Clinical Neuropsychologist*, 1-20. doi:10.1080/13854046.2019.1690051

Eckner, J. T., Kutcher, J. S., Broglio, S. P., & Richardson, J. K. (2014). Effect of sport-related concussion on clinically measured simple reaction time. *British Journal of Sports Medicine, 48*(2), 112-118. doi:10.1136/bjsports-2012-091579

Eckner, J. T., O'Connor, K. L., Broglio, S. P., & Ashton-Miller, J. A. (2018). Comparison of head impact exposure between male and female high school ice hockey athletes. *The American Journal of Sports Medicine, 46*(9), 2253-2262. doi:10.1177/0363546518777244

Eckner, J. T., Oh, Y. K., Joshi, M. S., Richardson, J. K., & Ashton-Miller, J. A. (2014). Effect of neck muscle strength and anticipatory cervical muscle activation on the kinematic response of the head to impulsive loads. *The American Journal of Sports Medicine, 42*(3), 566-576. doi:10.1177/0363546513517869

Eckner, J. T., Sabin, M., Kutcher, J. S., & Broglio, S. P. (2011). No evidence for a cumulative impact effect on concussion injury threshold. *Journal of Neurotrauma, 28*(10), 2079-2090. doi:10.1089/neu.2011.1910

Eckner, J. T., Wang, J., Nelson, L. D., Bancroft, R., Pohorence, M., He, X., . . . McCrea, M. (2019). Effect of routine sport participation on short-term clinical neurological outcomes: A comparison of non-contact, contact, and collision sport athletes. *Sports Medicine*, 1-12. doi:10.1007/s40279-019-01200-y

Edmed, S., & Sullivan, K. (2012). Depression, anxiety, and stress as predictors of postconcussion-like symptoms in a non-clinical sample. *Psychiatry Research, 200*(1), 41-45. doi:10.1016/j.psychres.2012.05.022

Elbin, R. J., Schatz, P., & Covassin, T. (2011). One-year test-retest reliability of the online version of ImPACT in high school athletes. *The American Journal of Sports Medicine, 39*(11), 2319-2324. doi:10.1177/0363546511417173

Elkington, L., Manzanero, S., & Hughes, D. (2019). *Concussion in sport Australia position statement*. ACT, Australia: SportAUS.

Ellemberg, D., Henry, L. C., Macciocchi, S. N., Guskiewicz, K. M., & Broglio, S. P. (2009). Advances in sport concussion assessment: From behavioral to brain imaging measures. *Journal of Neurotrauma, 26*(12), 2365-2382. doi:10.1089/neu.2009.0906

Ellenbogen, R., Batjer, H., Cardenas, J., Berger, M., Bailes, J., Pieroth, E., . . . Sills, A. (2018). National Football League head, neck and spine committee’s concussion diagnosis and management protocol: 2017-18 season. *British*

Journal of Sports Medicine, 52(14), 894-902. doi:10.1136/bjsports-2018-099203

Emery, C. A., Kang, J., Schrier, I., Goulet, C., Hagle, B. E., Benson, B. W., . . . Meeuwisse, W. (2010). Risk of injury associated with body checking among youth ice hockey players. *JAMA, 303*(22), 2265-2272. doi:10.1001/jama.2010.755

Farnsworth, J. L., 2nd, Dargo, L., Ragan, B. G., & Kang, M. (2017). Reliability of computerized neurocognitive tests for concussion assessment: A meta-analysis. *Journal of Athletic Training, 52*(9), 826-833. doi:10.4085/1062-6050-52.6.03

Feddermann-Demont, N., Echemendia, R. J., Schneider, K. J., Solomon, G. S., Hayden, K. A., Turner, M., . . . Tarnutzer, A. A. (2017). What domains of clinical function should be assessed after sport-related concussion? A systematic review. *British Journal of Sports Medicine, 51*(11), 903-918. doi:10.1136/bjsports-2016-097403

Feigenbaum, L. A., Kim, K. J., Gaunaurd, I. A., Kaplan, L. D., Scavo, V. A., Bennett, C., & Gailey, R. S. (2019). Post-concussive changes in balance and postural stability measured with Canesense™ and the Balance Error Scoring System (BESS) in division I collegiate football players: A case series. *International Journal of Sports Physical Therapy, 14*(2), 296-307. doi:10.26603/ijspt20190296

Finch, C. F., Clapperton, A. J., & McCrory, P. (2013). Increasing incidence of hospitalisation for sport-related concussion in Victoria, Australia. *The Medical Journal of Australia, 198*(8), 427-430. doi:10.5694/mja12.11217

Finch, C. F., & White, P. E. (2017). The new concussion in sport guidelines are here. But how do we get them out there? *British Journal of Sports Medicine, 51*(24), 1734-1736. doi:10.1136/bjsports-2017-098212

Finnoff, J. T., Peterson, V. J., Hollman, J. H., & Smith, J. (2009). Intrarater and interrater reliability of the Balance Error Scoring System (BESS). *PM&R, 1*(1), 50-54. doi:10.1016/j.pmrj.2008.06.002

Flik, K., Lyman, S., & Marx, R. G. (2005). American collegiate men's ice hockey: an analysis of injuries. *The American Journal of Sports Medicine, 33*(2), 183-187. doi:10.1177/0363546504267349

Fortington, L. V., Twomey, D. M., & Finch, C. F. (2015). Concussion in community Australian football - epidemiological monitoring of the causes and immediate impact on play. *Injury Epidemiology, 2*(1), 20-25. doi:10.1186/s40621-015-0052-5

Fuller, C. W., Fuller, G. W., Kemp, S., & Raftery, M. (2017). Evaluation of World Rugby’s concussion management process: results from Rugby World Cup 2015. *British Journal of Sports Medicine, 51*, 64-69. doi:10.1136/bjsports-2016-096461

Fuller, G. W., Kemp, S. P., & Raftery, M. (2017). The accuracy and reproducibility of video assessment in the pitch-side management of concussion in elite rugby. *Journal of Science and Medicine in Sport, 20*(3), 246-249. doi:10.1016/j.jsams.2016.07.008

Funk, J. R., Duma, S., Manoogian, S., & Rowson, S. (2007). Biomechanical risk estimates for mild traumatic brain injury. *Annual Proceedings Association for the Advancement of Automotive Medicine, 51*, 343-361.

Funk, J. R., Rowson, S., Daniel, R. W., & Duma, S. M. (2011). Validation of concussion risk curves for collegiate football players derived from HITS data. *Annals of Biomedical Engineering, 40*(1), 79-89. doi:10.1007/s10439-011-0400-8

Gabbe, B., Finch, C., Wajswelner, H., & Bennell, K. (2002). Australian football: Injury profile at the community level. *Journal of Science and Medicine in Sport, 5*(2), 149-160. doi:10.1016/s1440-2440(02)80036-6

Galetta, K. M., Brandes, L. E., Maki, K., Dziemianowicz, M. S., Laudano, E., Allen, M., . . . Devick, S. (2011). The King–Devick test and sports-related concussion: Study of a rapid visual screening tool in a collegiate cohort. *Journal of the Neurological Sciences, 309*(1), 34-39. doi:10.1016/j.jns.2011.07.039

Galetta, K. M., Liu, M., Leong, D. F., Ventura, R. E., Galetta, S. L., & Balcer, L. J. (2015). The King-Devick test of rapid number naming for concussion detection: Meta-analysis and systematic review of the literature. *Concussion, 1*(2). doi:10.2217/cnc.15.8

Galetta, M. S., Galetta, K. M., McCrossin, J., Wilson, J. A., Moster, S., Galetta, S. L., . . . Master, C. L. (2013). Saccades and memory: baseline associations of the King-Devick and SCAT2 SAC tests in professional ice hockey players. *Journal of the Neurological Sciences, 328*(1-2), 28-31. doi:10.1016/j.jns.2013.02.008

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

Gao, H., Han, Z., Bai, R., Huang, S., Ge, X., Chen, F., & Lei, P. (2017). The accumulation of brain injury leads to severe neuropathological and neurobehavioral changes after repetitive mild traumatic brain injury. *Brain Research, 1657*, 1-8. doi:10.1016/j.brainres.2016.11.028

Gardner, A. J., Howell, D. R., & Iverson, G. L. (2018). A video review of multiple concussion signs in National Rugby League match play. *Sports Medicine Open, 4*(1), 5. doi:10.1186/s40798-017-0117-9

Gardner, A. J., Howell, D. R., & Iverson, G. L. (2019). The association between multiple prior concussions, cognitive test scores, and symptom reporting in youth rugby league players. *Brain Injury, 34*, 224-228. doi:10.1080/02699052.2019.1683894

Gardner, A. J., Howell, D. R., Levi, C. R., & Iverson, G. (2017). Evidence of concussion signs in national rugby league match play: A video review and validation study. *Sports Medicine Open 3*(29), 1-10. doi:10.1186/s40798-017-0097-9

Gardner, A. J., Iverson, G. L., & McCrory, P. (2013). Chronic traumatic encephalopathy in sport: A systematic review. *British Journal of Sports Medicine, 48*(2), 84-90. doi:10.1136/bjsports-2013-092646

Gardner, A. J., Iverson, G. L., Quinn, T. N., Makdissi, M., Levi, C. R., Shultz, S. R., . . . Stanwell, P. (2015). A preliminary video analysis of concussion in the National Rugby League. *Brain Injury, 29*(10), 1182-1185. doi:10.3109/02699052.2015.1034179

Gardner, A. J., Iverson, G. L., & Stanwell, P. (2014). A systematic review of proton magnetic resonance spectroscopy findings in sport-related concussion. *Journal of Neurotrauma, 31*(1), 1-18. doi:10.1089/neu.2013.3079

Gardner, A. J., Iverson, G. L., Stanwell, P., Moore, T., Ellis, J., & Levi, C. R. (2016). A video analysis of use of the new 'Concussion Interchange Rule' in the National

Rugby League. *International Journal of Sports Medicine, 37*(4), 267-273. doi:10.1055/s-0035-1565203

Gardner, A. J., Kohler, R., McDonald, W., Fuller, C. W., Tucker, R., & Makdissi, M. (2018). The use of sideline video review to facilitate management decisions following head trauma in super rugby. *Sport Medicine Open, 4*(20), 1-8. doi:10.1186/s40798-018-0133-4

Gardner, A. J., Levi, C. R., & Iverson, G. L. (2017). Observational review and analysis of concussion: A method for conducting a standardized video analysis of concussion in Rugby League. *Sports Medicine Open, 3*(1), 26. doi:10.1186/s40798-017-0093-0

Gardner, A. J., Shores, E. A., Batchelor, J., & Honan, C. A. (2012). Diagnostic efficiency of ImPACT and CogSport in concussed rugby union players who have not undergone baseline neurocognitive testing. *Applied Neuropsychology: Adult, 19*(2), 90-97. doi:10.1080/09084282.2011.643945

Gardner, A. J., Wojtowicz, M., Terry, D. P., Levi, C. R., Zafonte, R., & Iverson, G. L. (2017). Video and clinical screening of national rugby league players suspected of sustaining concussion. *Brain Injury, 31*(13-14), 1918-1924. doi:10.1080/02699052.2017.1358399

Gasquoine, P. G. (1998). Historical perspectives on postconcussion symptoms. *The Clinical Neuropsychologist, 12*(3), 315-324. doi:10.1076/clin.12.3.315.1990

Gastin, P. B., Hunkin, S. L., Fahrner, B., & Robertson, S. (2019). Deceleration, acceleration, and impacts are strong contributors to muscle damage in professional Australian football. *The Journal of Strength and Conditioning Research 33*(12), 3374-3383. doi:10.1519/JSC.0000000000003023

Gaudet, C. E., & Weyandt, L. L. (2017). Immediate Post-Concussion and Cognitive Testing (ImPACT): A systematic review of the prevalence and assessment of invalid performance. *The Clinical Neuropsychologist, 31*(1), 43-58. doi:10.1080/13854046.2016.1220622

Gavett, B. E., Stern, R. A., & McKee, A. C. (2011). Chronic traumatic encephalopathy: A potential late effect of sport-related concussive and subconcussive head trauma. *Clinical Journal of Sport Medicine, 30*(1), 179-188. doi:10.1016/j.csm.2010.09.007

Gellner, R. A., Campolettano, E. T., Smith, E. P., & Rowson, S. (2019). Are specific players more likely to be involved in high-magnitude head impacts in youth football? *Journal of Neurosurgery: Pediatrics, 24*(1), 47-53. doi:10.3171/2019.2.PEDS18176

Gibbs, N., & Watsford, M. (2017). Concussion incidence and recurrence in professional Australian football match-play: A 14-year analysis. *Journal of Sports Medicine, 2017*, 2831751: 2831751-2831757. doi:10.1155/2017/2831751

Giza, C., & Hovda, D. A. (2001). The neurometabolic cascade of concussion. *Journal of Athletic Training, 36*(3), 228-235.

Giza, C., & Hovda, D. A. (2014). The new neurometabolic cascade of concussion *Neurosurgery, 75 Suppl 4*, S24-S33. doi:10.1227/NEU.0000000000000505

Giza, C., Kutcher, J., Ashwal, S., Barth, J., Getchius, T. S. D., Gioia, G. A., . . . Zafonte, R. (2013). Summary of evidence-based guideline update: Evaluation and management of concussion in sports. *Neurology, 80*(24), 2250-2257. doi:10.1212/WNL.0b013e31828d57dd

Glang, A., Koester, M. C., Beaver, S. V., Clay, J. E., & McLaughlin, K. A. (2010). Online training in sports concussion for youth sports coaches. *International Journal of Sports Science & Coaching, 5*(1), 1-12. doi:10.1260/1747-9541.5.1.1

Goodell, R. (2019). *Official playing rules of the national football league*. United States of America: The National Football League.

Gosselin, N., Lassonde, M., Petit, D., Leclerc, S., Mongrain, V., Collie, A., & Montplaisir, J. (2009). Sleep following sport-related concussions. *Sleep Medicine, 10*(1), 35-46. doi:10.1016/j.sleep.2007.11.023

Greenwald, R. M., Chu, J. J., Crisco, J. J., & Finkelstein, J. A. (2003). *Head impact telemetry system (HITs™) for measurement of head acceleration in the field*, Proceedings of the American Society of Biomechanics Annual Meeting.

Greenwald, R. M., Gwin, J. T., Chu, J. J., & Crisco, J. J. (2008). Head impact severity measures for evaluating mild traumatic brain injury risk exposure. *Neurosurgery, 62*(4), 789-798. doi:10.1227/01.neu.0000318162.67472.ad

Gronow, D., Dawson, B., Heasman, J., Rogalski, B., & Peeling, P. (2014). Team movement patterns with and without ball possession in Australian Football League players. *International Journal of Performance Analysis in Sport, 14*(3), 635-651. doi:10.1080/24748668.2014.11868749

Gurdjian, E. S., Lissner, H. R., & Evans, F. G. (1961). Intracranial pressure and acceleration accompanying head impacts in human cadavers. *Surgery, Gynecology, and Obstetrics, 112*, 185-190.

Guskiewicz, K. M. (2001). Postural stability assessment following concussion: one piece of the puzzle. *Clinical Journal of Sport Medicine, 11*(3), 182-189.

Guskiewicz, K. M. (2003). Assessment of postural stability following sport-related concussion. *Current Sports Medicine Reports, 2*(1), 24-30. doi:10.1249/00149619-200302000-00006

Guskiewicz, K. M. (2011). Balance assessment in the management of sport-related concussion. *Clinical Journal of Sport Medicine, 30*(1), 89-102. doi:10.1016/j.csm.2010.09.004

Guskiewicz, K. M., Bruce, S. L., Cantu, R. C., Ferrara, M. S., Kelly, J. P., McCrea, M., . . . McLeod, T. C. V. (2004). National Athletic Trainers' Association position statement: Management of sport-related concussion. *Journal of Athletic Training, 39*(3), 280-297.

Guskiewicz, K. M., McCrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., . . . Kelly, J. P. (2003). Cumulative effects associated with recurrent concussion in collegiate football players: The NCAA Concussion Study. *JAMA, 290*(19), 2549-2555. doi:10.1001/jama.290.19.2549

Guskiewicz, K. M., & Mihalik, J. P. (2011). Biomechanics of sport concussion: Quest for the elusive injury threshold. *Exercise and Sport Sciences Reviews, 39*(1), 4-11. doi:10.1097/JES.0b013e318201f53e

Guskiewicz, K. M., Mihalik, J. P., Shankar, V., Marshall, S. W., Crowell, D. H., Oliaro, S. M., . . . Hooker, D. N. (2007). Measurement of head impacts in collegiate football players: Relationship between head impact biomechanics and acute clinical outcome after concussion. *Neurosurgery, 61*(6), 1244-1253. doi:10.1227/01.NEU.0000280146.37163.79

Guskiewicz, K. M., Perrin, D. H., & Gansneder, B. M. (1996). Effect of mild head injury on portural stability in athletes. *Journal of Athletic Training, 31*(4), 300-306.

Guskiewicz, K. M., Register-Mihalik, J., McCrory, P., McCrea, M., Johnston, K., Makdissi, M., . . . Meeuwisse, W. (2013). Evidence-based approach to revising the SCAT2: Introducing the SCAT3. *British Journal of Sports Medicine, 47*(5), 289-293. doi:10.1136/bjsports-2013-092225

Guskiewicz, K. M., Ross, S. E., & Marshall, S. W. (2001). Postural stability and neuropsychological deficits after concussion in collegiate athletes. *Journal of Athletic Training, 36*(3), 263-273.

Guskiewicz, K. M., Weaver, N. L., Padua, D. A., & Garrett, W. E. (2000). Epidemiology of concussion in collegiate and high school football players. *The American Journal of Sports Medicine, 28*(5), 643-650. doi:10.1177/03635465000280050401

Gysland, S. M., Mihalik, J. P., Register-Mihalik, J., Trulock, S. C., Shields, E. W., & Guskiewicz, K. (2012). The relationship between subconcussive impacts and concussion history on clinical measures of neurological function in collegiate football players. *Annals of Biomedical Engineering, 40*(1), 14-22. doi:10.1007/s10439-011-0421-3

Haacke, E. M., Xu, Y., Cheng, Y. C., & Reichenbach, J. R. (2004). Susceptibility weighted imaging (SWI). *Magnetic Resonance in Medicine, 52*(3), 612-618. doi:10.1002/mrm.20198

Hagel, B., & Willem, N. (2004). Risk compensation: A "side effect" of sport injury prevention? *Clinical Journal of Sport Medicine, 14*(4), 193-197. doi:10.1097/00042752-200407000-00001

Hanlon, E., & Bir, C. (2010). Validation of a wireless head acceleration measurement system for use in soccer play. *Journal of Applied Biomechanics, 26*(4), 424-431. doi:10.1123/jab.26.4.424

Hanninen, T., Parkkari, J., Tuominen, M., Iverson, G. L., Ohman, J., Vartiainen, M., & Luoto, T. M. (2017). Interpreting change on the SCAT3 in professional ice hockey players. *Journal of Science and Medicine in Sport, 20*(5), 424-431. doi:10.1016/j.jsams.2016.09.009

Hänninen, T., Tuominen, M., Parkkari, J., Vartiainen, M., Öhman, J., Iverson, G. L., & Luoto, T. M. (2016). Sport Concussion Assessment Tool - 3rd edition - normative reference values for professional ice hockey players. *Journal of Science and Medicine in Sport, 19*(8), 636-641.

Harmon, K. G., Clugston, J. R., Dec, K., Hainline, B., Herring, S., Kane, S. F., . . . Roberts, W. O. (2019). American Medical Society for Sports Medicine position statement on concussion in sport. *British Journal of Sports Medicine, 53*(4), 213-225. doi:10.1136/bjsports-2018-100338

Harmon, K. G., Drezner, J. A., Gammons, M., Guskiewicz, K. M., Halstead, M., Herring, S. A., . . . Roberts, W. O. (2013). American Medical Society for Sports Medicine position statement: concussion in sport. *British Journal of Sports Medicine, 47*(1), 15-26. doi:10.1136/bjsports-2018-100338

Harper, D. J., Carling, C., & Kiely, J. (2019). High-intensity acceleration and deceleration demands in elite team sports competitive match play: A systematic review and meta-analysis of observational studies. *Sports Medicine, 49*(12), 1923-1947. doi:10.1007/s40279-019-01170-1

Harriss, A., Johnson, A. M., Walton, D. M., & Dickey, J. P. (2019). Head impact magnitudes that occur from purposeful soccer heading depend on the game scenario and head impact location. *Musculoskeletal Science and Practice, 40*, 53-57. doi:10.1016/j.msksp.2019.01.009

Haycraft, J. A. Z., Kovalchik, S., Pyne, D. B., & Robertson, S. (2019). Relationships between physical testing and match activity profiles across the Australian Football League participation pathway. *International Journal of Sports Physiology and Performance, 14*(6), 771-778. doi:10.1123/ijspp.2018-0488

Hedlund, J. (2000). Risky business: safety regulations, risks compensation, and individual behavior. *Injury Prevention, 6*(2), 82-90. doi:10.1136/ip.6.2.82

Heitger, M. H., Jones, R. D., Macleod, A., Snell, D. L., Frampton, C. M., & Anderson, T. J. (2009). Impaired eye movements in post-concussion syndrome indicate suboptimal brain function beyond the influence of depression, malingering or intellectual ability. *Brain, 132*(10), 2850-2870. doi:10.1093/brain/awp181

Hellebrandt, F. A., & Braun, G. (1939). The inlfuence of sex and age on the postural sway of man. *American Journal of Physical Anthropology, 24*(3), 347-359. doi:10.1002/ajpa.1330240318

Helps, Y., Henley, G., & Harrison, J. (2008). *Hospital separations due to traumatic brain injury, Australia 2004-05*. Canberra, Australia: Australian Institute of Health and Welfare.

Henn, H. (1998). Crash tests and the head injury criterion. *Teaching Mathematics and its Applications, 17*(4), 162-170. doi:10.1093/teamat/17.4.162

Herring, S. A., Cantu, R. C., Guskiewicz, K. M., Putukian, M., Kibler, W. B., Bergfeld, J. A., . . . Indelicato, P. A. (2011). Concussion (mild traumatic brain injury) and the team physician: a consensus statement - 2011 update. *Medicine & Science in Sports & Exercise, 43*(12), 2412-2422. doi:10.1249/MSS.0b013e3182342e64

Heyer, G. L., Schaffer, C. E., Rose, S. C., Young, J. A., McNally, K. A., & Fischer, A. N. (2016). Specific factors influence postconcussion symptom duration among youth referred to a sports concussion clinic. *The Journal of Pediatrics, 174*, 33-38. doi:10.1016/j.jpeds.2016.03.014

Higgins, D. M., Martin, A. M., Baker, D. G., Vasterling, J. J., & Risbrough, V. (2018). The relationship between chronic pain and neurocognitive function: A systematic review. *The Clinical Journal of Pain, 34*(3), 262-275. doi:10.1097/AJP.0000000000000536

Hildenbrand, K., & Vasavada, A. N. (2013). Collegiate and high school athlete neck strength in neautral and rotated postures. *Journal of Strength and Conditioning Research, 27*(11), 3173-3182. doi:10.1519/JSC.0b013e31828a1fe2

Hoffman, D. T., Dwyer, D. B., Tran, J., Clifton, P., & Gastin, P. B. (2019). Australian Football League injury characteristics differ between matches and training: A longitudinal analysis of changes in the setting, site, and time span from 1997 to 2016. *Orthopaedic Journal of Sports Medicine, 7*(4), 2325967119837641. doi:10.1177/2325967119837641

Holbourn, A. (1943). Mechanics of head injuries. *The Lancet, 242*(6267), 438-441.

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

Hotz, G., Crittenden, R., Pomares, B., Siegel, J., Nedd, K., & Hotz, G. A. (2018). Concussion: Video education program for high school football players. *The Sport Journal, 21*, 1-13.

Houck, Z., Asken, B., Bauer, R., & Clugston, J. (2019). Predictors of post-concussion symptom severity in a university-based concussion clinic. *Brain Injury, 33*(4), 480-489. doi:10.1080/02699052.2019.1565897

Hovda, D. A., Badie, H., Karimi, S., Thomas, S., Yoshino, A., T., K., & Becker, D. P. (1983). Concussive brain injury produces a state of vulnerability for intracranial pressure perturbation in the absence of morphological damage. In A. C. J., J. H. van Eijndhoven, A. I. Maas, & J. T. Tans (Eds.), *Intracranial Pressure VIII* (pp. 469-472). New York: Springer-Verlag.

Hovda, D. A., Prins, M., Becker, D. P., Lee, S., Bergsneider, M., & Martin, N. A. (1999). Neurobiology of Concussion. In J. E. Bailes, M. R. Lovell, & J. C. Maroon (Eds.), *Sports Related Concussion* (pp. 12-51). St. Louis: Quality Medical Publishing, Inc.

Howell, D. R., Kriz, P., Mannix, R. C., Kirchberg, T., Master, C. L., & Meehan, W. P., 3rd. (2019). Concussion symptom profiles among child, adolescent, and young adult athletes. *Clinical Journal of Sport Medicine, 29*(5), 391-397. doi:10.1097/JSM.0000000000000629

Howell, D. R., Oldham, J. R., Brilliant, A. N., & Meehan, W. P., 3rd. (2019). Trouble falling asleep after concussion is associated with higher symptom burden among children and adolescents. *Journal of Child Neurology, 34*(5), 256-261. doi:10.1177/0883073818824000

Howell, D. R., Osternig, L., Van Donkelaar, P., Mayr, U., & Chou, L. S. (2013). Effects of concussion on attention and executive function in adolescents. *Medicine & Science in Sports & Exercise, 45*(6), 1030-1037. doi:10.1249/MSS.0b013e3182814595

Howell, D. R., Osternig, L. R., & Chou, L. S. (2018). Detection of acute and long-term effects of concussion: Dual-task gait balance control versus computerized neurocognitive test. *Archives of Physical Medicine and Rehabilitation, 99*(7), 1318-1324. doi:10.1016/j.apmr.2018.01.025

Hrysomallis, C. (2016). Neck muscular strength, training, performance and sport injury risk: A review. *Sports Medicine, 46*(8), 1111-1124. doi:10.1007/s40279-016-0490-4

Hutchison, M. G., Comper, P., Meeuwisse, W. H., & Echemendia, R. J. (2014). An observational method to code concussions in the National Hockey League (NHL): the heads-up checklist. *British Journal of Sport Medicine, 48*, 125-129. doi:10.1136/bjsports-2012-092059

Hutchison, M. G., Comper, P., Meeuwisse, W. H., & Echemendia, R. J. (2015). A systematic video analysis of National Hockey League (NHL) concussions, part I: Who, when, where and what? *British Journal of Sports Medicine, 49*(8), 547-551. doi:10.1136/bjsports-2013-092235

Iverson, G. L., Brooks, B. L., Ashton, V. L., & Lange, R. T. (2010). Interview versus questionnaire symptom reporting in people with the postconcussion syndrome. *The Journal of Head Trauma Rehabilitation, 25*(1), 23-30. doi:10.1097/HTR.0b013e3181b4b6ab

Iverson, G. L., Brooks, B. L., Lovell, M. R., & Collins, M. W. (2006). No cumulative effects for one or two previous concussions. *British Journal of Sports Medicine, 40*(1), 72-75. doi:10.1136/bjsm.2005.020651

Iverson, G. L., Gardner, A. J., Terry, D. P., Ponsford, J. L., Sills, A. K., Broshek, D. K., & Solomon, G. S. (2017). Predictors of clinical recovery from concussion: a systematic review. *British Journal of Sports Medicine, 51*(12), 941-948. doi:10.1136/bjsports-2017-097729

Iverson, G. L., Keene, C. D., Perry, G., & Castellani, R. J. (2018). The need to separate chronic traumatic encephalopathy neuropathology from clinical features. *Journal of Alzheimer's Disease, 61*(1), 17-28. doi:10.3233/JAD-170654

Iverson, G. L., Luoto, T. M., Karhunen, P. J., & Castellani, R. J. (2019). Mild chronic traumatic encephalopathy neuropathology in people with no known participation in contact sports or history of repetitive neurotrauma. *Journal of Neuropathology & Experimental Neurology, 78*(7), 615-625. doi:10.1093/jnen/nlz045

Iverson, G. L., & Schatz, P. (2015). Advanced topics in neuropsychological assessment following sport-related concussion. *Brain Injury, 29*(2), 263-275. doi:10.3109/02699052.2014.965214

Jacobson, N. S., & Truax, P. (1991). Clinical significance: A statistical approach to denning meaningful change in psychotherapy research. *Jouranl of Consulting and Clinical Psychology, 59*(1), 12-19. doi:10.1037//0022-006x.59.1.12

James, S. L., Theadom, A., Ellenbogen, R. G., Bannick, M. S., Montjoy-Venning, W., Lucchesi, L. R., . . . Murray, C. J. L. (2019). Global, regional, and national burden of traumatic brain injury and spinal cord injury, 1990–2016: A systematic analysis for the Global Burden of Disease Study 2016. *The Lancet Neurology, 18*(1), 56-87. doi:10.1016/s1474-4422(18)30415-0

Johnson, E. W., Kegel, N. E., & Collins, M. W. (2011). Neuropsychological assessment of sport-related concussion. *Clinical Journal of Sport Medicine, 30*(1), 73-88. doi:10.1016/j.csm.2010.08.007

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

Johnston, R. J., Watsford, M., Austin, D. J., Pine, M. J., & Spurrs, R. W. (2015). Player acceleration and deceleration profiles in professional Australian football. *Journal of Sports Medicine and Physical Fitness, 55*, 931-939.

Joseph, J. R., Swallow, J. S., Willsey, K., Lapointe, A. P., Khalatbari, S., Korley, F., . . . Broglio, S. (2018). Elevated markers of brain injury as a result of clinically asymptomatic high-acceleration head impacts in high-school football athletes. *Journal of Neurosurgery, 130*(4), 1642-1648. doi:10.3171/2017.12.JNS172386

Kaminski, T. W., Groff, R. M., & Glutting, J. J. (2009). Examining the stability of Automated Neuropsychological Assessment Metric (ANAM) baseline test scores. *Journal of Clinical and Experimental Neuropsychology, 31*(6), 689-697. doi:10.1080/13803390802484771

Karr, J. E., Areshenkoff, C. N., & Garcia-Barrera, M. A. (2014). The neuropsychological outcomes of concussion: A systematic review of meta-analyses on the cognitive sequelae of mild traumatic brain injury. *Neuropsychology, 28*(3), 321-336. doi:10.1037/neu0000037.supp

Kashluba, S., Hanks, R. A., Casey, J. E., & Millis, S. R. (2008). Neuropsychologic and functional outcome after complicated mild traumatic brain injury. *Archives of Physical Medicine and Rehabilitation, 89*(5), 904-911. doi:10.1016/j.apmr.2007.12.029

Katz, B. P., Kudela, M., Harezlak, J., McCrea, M., McAllister, T., Broglio, S. P., & Investigators, C. C. (2018). Baseline performance of NCAA athletes on a concussion assessment battery: A report from the CARE consortium. *Sports Medicine, 48*(8), 1971-1985. doi:10.1007/s40279-018-0875-7

Kay, T., Harrington, D. E., Adams, R., Adnderson, T., Berrol, S., Cicerone, K., . . . Malec, J. (1993). Definition of mild traumatic brain injury. *Journal of Head Trauma & Rehabilitation, 8*(3), 86-87.

Kazl, C., & Torres, A. (2019). Definition, classification, and epidemiology of concussion. *Seminars in Pediatric Neurology, 30*, 9-13. doi:10.1016/j.spen.2019.03.003

Kemp, J. L., Newton, J. D., White, P. E., & Finch, C. F. (2016). Implementation of concussion guidelines in community Australian Football and Rugby League - The experiences and challenges faced by coaches and sports trainers. *Journal of Science and Medicine in Sport, 19*(4), 305-310. doi:10.1016/j.jsams.2015.03.010

Kempton, T., Sullivan, C., Bilsborough, J. C., Cordy, J., & Coutts, A. J. (2015). Match-to-match variation in physical activity and technical skill measures in professional Australian Football. *Journal of Science and Medicine in Sport, 18*(1), 109-113. doi:10.1016/j.jsams.2013.12.006

Kerr, Z. Y., Register-Mihalik, J. K., Kroshus, E., Baugh, C. M., & Marshall, S. W. (2016). Motivations associated with nondisclosure of self-reported concussions in former collegiate athletes. *The American Journal of Sports Medicine, 44*(1), 220-225. doi:10.1177/0363546515612082

Kerr, Z. Y., Roos, K. G., Djoko, A., Dalton, S. L., Broglio, S. P., Marshall, S. W., & Dompier, T. P. (2017). Epidemiologic measures for quantifying the incidence of concussion in National Collegiate Athletic Association Sports. *Journal of Athletic Training, 52*(3), 167-174. doi:10.4085/1062-6050-51.6.05

Kerr, Z. Y., Yeargin, S. W., McLeod, T. C. V., Mensch, J., Hayden, R., & Dompier, T. P. (2015). Comprehensive coach education reduces head impact exposure in American youth football. *The Orthopaedic Journal of Sports Medicine, 3*(10), 1-6. doi:10.1177/2325967115610545

Kindschi, K., Higgins, M., Hillman, A., Penczek, G., & Lincoln, A. (2017). Video analysis of high-magnitude head impacts in men's collegiate lacrosse. *BMJ Open Sport & Exercise Medicine, 3*(1), e000165. doi:10.1136/bmjsem-2016-000165

King, A. I., Ruan, J. S., Zhou, C., Hardy, W. N., & Khalil, T. B. (1995). Recent advances in biomechanics of brain injury research: A review. *Journal of Neurotrauma, 12*(4), 651-658. doi:10.1089/neu.1995.12.651

King, A. I., Yang, K. H., Zhang, L., Hardy, W., & Viano, D. C. (2003). *Is head injury caused by linear or angular acceleration.* Paper presented at the IRCOBI conference.

King, A. T., & Devick, S. (1976). *The proposed King-Devick test and its relation to the pierce saccade test and reading levels*. Chicago: Illinois College of Optometry.

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

King, D., Hume, P., Gissane, C., Brughelli, M., & Clark, T. (2016). The influence of head impact threshold for reporting data in contact and collision sports: Systematic review and original data analysis. *Sports Medicine, 46*(2), 151-169. doi:10.1007/s40279-015-0423-7

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

King, D., Hume, P. A., & Clark, T. (2012). Nature of tackles that result in injury in professional rugby league. *Research in Sports Medicine, 20*(2), 86-104. doi:10.1080/15438627.2012.660824

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

Kirov, I. I., Whitlow, C. T., & Zamora, C. (2018). Susceptibility-weighted imaging and magnetic resonance spectroscopy in concussion. *Neuroimaging Clinics of North America, 28*(1), 91-105. doi:10.1016/j.nic.2017.09.007

Klein, A. P., Tetzlaff, J. E., Bonis, J. M., Nelson, L. D., Mayer, A. R., Huber, D. L., . . . Meier, T. B. (2019). Prevalence of potentially clinically significant magnetic resonance imaging findings in athletes with and without sport-related concussion. *Journal of Neurotrauma, 36*(11), 1776-1785. doi:10.1089/neu.2018.6055

Kleiven, S. (2007). Predictors for traumatic brain injuries evaluated through accident reconstructions. *Stapp Car Crash Journal, 51*, 81-114.

Kontos, A. P., Covassin, T., Elbin, R. J., & Parker, T. (2012). Depression and neurocognitive performance after concussion among male and female high school and collegiate athletes. *Archives of Physical Medicine and Rehabilitation, 93*(10), 1751-1756. doi:10.1016/j.apmr.2012.03.032

Kontos, A. P., Elbin, R. J., Schatz, P., Covassin, T., Henry, L., Pardini, J., & Collins, M. W. (2012). A revised factor structure for the post-concussion symptom scale: baseline and postconcussion factors. *The American Journal of Sports Medicine, 40*(10), 2375-2384. doi:10.1177/0363546512455400

Kontos, A. P., Sufrinko, A., Sandel, N., Emami, K., & Collins, M. W. (2019). Sport-related concussion clinical profiles: Clinical characteristics, targeted treatments, and preliminary evidence. *Current Sports Medicine Reports, 18*(3), 82-92. doi:10.1249/JSR.0000000000000573

Kontos, A. P., Sufrinko, A., Womble, M., & Kegel, N. E. (2016). Neuropsychological assessment following concussion: An evidence ‐ based review of the role of neuropsychological assessment pre-and post-concussion. *Current Pain and Headache Reports, 20*(6), 38. doi:10.1007/s11916-016-0571-y

Krolikowski, M. P., Black, A. M., Palacios-Derflingher, L., Blake, T. A., Schneider, K. J., & Emery, C. A. (2017). The effect of the "zero tolerance for head contact" rule change on the risk of concussions in youth ice hockey players. *The American Journal of Sports Medicine, 45*(2), 468-473. doi:10.1177/0363546516669701

Kroshus, E., Kubzansky, L. D., Goldman, R. E., & Austin, S. B. (2014). Norms, athletic identity, and concussion symptom under-reporting among male collegiate ice hockey players: a prospective cohort study. *Annals of Behavioral Medicine, 49*(1), 95-103. doi:10.1007/s12160-014-9636-5

Kroshus, E., Rivara, F. P., Whitlock, K. B., Herring, S., & Chrisman, S. P. (2017). Disparities in athletic trainer staffing in secondary school sport: Implications for concussion identification. *Clinical Journal of Sport Medicine, 27*(6), 542-547. doi:10.1097/JSM.0000000000000409

Lamond, L. C., Caccese, J. B., Buckley, T. A., Glutting, J., & Kaminski, T. W. (2018). Linear acceleration in direct head contact across impact type, player position, and playing scenario in collegiate women's soccer players. *Journal of Athletic Training, 53*(2), 115-121. doi:10.4085/1062-6050-90-17

LaRoche, A. A., Nelson, L. D., Connelly, P. K., Walter, K. D., & McCrea, M. (2016). Sport-related concussion reporting and state legislative effects. *Clinical Journal of Sport Medicine, 26*(1), 33-39. doi:10.1097/JSM.0000000000000192

Leddy, J. J., Baker, J. G., & Willer, B. (2016). Active rehabilitation of concussion and post-concussion syndrome. *Physical Medicine and Rehabilitation Clinics of North America, 27*(2), 437-454. doi:10.1016/j.pmr.2015.12.003

Lee, J. H., Howell, D. R., Meehan, W. P., Iverson, G. L., & Gardner, A. J. (2017). Effects of exercise on sport concussion assessment tool-third edition performance in professional athletes. *Orthopaedic Journal of Sports Medicine, 5*(9), 2325967117727261. doi:10.1177/2325967117727261

Legarreta, A. D., Mummareddy, N., Yengo-Kahn, A. M., & Zuckerman, S. L. (2019). On-field assessment of concussion: Clinical utility of the King-Devick Test. *Open Access Journal of Sports Medicine, 10*, 115-121. doi:10.2147/oajsm.S171815

Leigh, R. J., & Zee, D. S. (2006). The saccadic system. In R. J. Leigh & D. S. Zee (Eds.), *The Neurology of Eye Movements* (4 ed., pp. 108-187). New York, NY: Oxford University Press.

Leong, D. F., Balcer, L. J., Galetta, S. L., Evans, G., Gimre, M., & Watt, D. (2015). The King-Devick Test for sideline concussion screening in collegiate football. *Journal of Optometry, 8*(2), 131-139. doi:10.1016/j.optom.2014.12.005

Lessley, D. J., Kent, R. W., Funk, J. R., Sherwood, C. P., Cormier, J. M., Crandall, J. R., . . . Myers, B. S. (2018). Video analysis of reported concussion events in the National Football League during the 2015-2016 and 2016-2017 seasons. *The American Journal of Sports Medicine, 46*(14), 3502-3510. doi:10.1177/0363546518804498

Levi, Y., Rassovsky, Y., Agranov, E., Sela-Kaufman, M., & Vakil, E. (2013). Cognitive reserve components as expressed in traumatic brain injury. *Journal of the International Neuropsychological Society, 19*(6), 664-671. doi:10.1017/S1355617713000192

Lincoln, A. E., Caswell, S. V., Almquist, J. L., Dunn, R. E., & Hinton, R. Y. (2013). Video incident analysis of concussions in boys' high school lacrosse. *The American Journal of Sports Medicine, 41*(4), 756-761. doi:10.1177/0363546513476265

Losoi, H., Silverberg, N. D., Waljas, M., Turunen, S., Rosti-Otajarvi, E., Helminen, M., . . . Iverson, G. L. (2016). Recovery from mild traumatic brain injury in previously healthy adults. *Journal of Neurotrauma, 33*(8), 766-776. doi:10.1089/neu.2015.4070

Louey, A. G., Cromer, J. A., Schembri, A. J., Darby, D. G., Maruff, P., Makdissi, M., & Mccrory, P. (2014). Detecting cognitive impairment after concussion: Sensitivity of change from baseline and normative data methods using the CogSport/Axon cognitive test battery. *Archives of Clinical Neuropsychology, 29*(5), 432-441. doi:10.1093/arclin/acu020

Lovell, M. R., Iverson, G. L., Collins, M. W., Podell, K., Johnston, K. M., Pardini, D., . . . Maroon, J. C. (2006). Measurement of symptoms following sports-related concussion: reliability and normative data for the post-concussion scale. *Applied Neuropsychology, 13*(3), 166-174. doi:10.1207/s15324826an1303_4

Lunter, C. M., Carroll, E. L., Housden, C., Outtrim, J., Forsyth, F., Rivera, A., . . . Newcombe, V. F. (2019). Neurocognitive testing in the emergency department: A potential assessment tool for mild traumatic brain injury. *Emergency Medicine Australasia, 31*(3), 355-361. doi:10.1111/1742-6723.13163

Maddocks, D. L., Dicker, G. D., & Saling, M. M. (1995). The assessment of orientation following concussion in athletes. *Clinical Journal of Sport Medicine, 5*(1), 32-35. doi:10.1097/00042752-199501000-00006

Maddocks, D. L., & Saling, M. (1996). Neuropsychological deficits following concussion. *Brain Injury, 10*(2), 99-104. doi:10.1080/026990596124584

Mainwaring, L., Pennock, K. M. F., Mylabathula, S., & Alavie, B. Z. (2018). Subconcussive head impacts in sport: A systematic review of the evidence.

International Journal of Psychophysiology, 132(Pt A), 39-54. doi:10.1016/j.ijpsycho.2018.01.007

Makdissi, M., Cantu, R. C., Johnston, K. M., McCrory, P., & Meeuwisse, W. H. (2013). The difficult concussion patient: What is the best approach to investigation and management of persistent (> 10 days) postconcussive symptoms? *British Journal Of Sports Medicine, 47*(5), 308-313. doi:10.1136/bjsports-2013-092255

Makdissi, M., Collie, A., Maruff, P., Darby, D., Bush, A., McCrory, P., & Bennell, K. (2001). Computerised cognitive assessment of concussed Australian rules footballers. *British Journal of Sports Medicine, 35*(5), 354-360. doi:10.1136/bjsm.35.5.354

Makdissi, M., Darby, D., Maruff, P., Ugoni, A., Brukner, P., & McCrory, P. R. (2010). Natural history of concussion in sport: Markers of severity and implications for management. *The American Journal of Sports Medicine, 38*(3), 464-471. doi:10.1177/0363546509349491

Makdissi, M., & Davis, G. (2016a). The reliability and validity of video analysis for the assessment of the clinical signs of concussion in Australian football. *Journal Of Science and Medicine in Sport, 19*(10), 859-863. doi:10.1016/j.jsams.2016.02.015

Makdissi, M., & Davis, G. (2016b). Using video analysis for concussion surveillance in Australian football. *Journal Of Science And Medicine In Sport, 19*(12), 958-963. doi:10.1016/j.jsams.2016.02.014

Makdissi, M., Schneider, K. J., Feddermann-Demont, N., Guskiewicz, K., Hinds, S., Leddy, J. J., . . . Johnston, K. (2017). Approach to investigation and treatment of persistent symptoms following sport-related concussion: A systematic review. *British Journal Of Sports Medicine, 51*, 958-968. doi:10.1136/bjsports-2016-097470

Mannix, R., Iverson, G. L., Maxwell, B., Atkins, J. E., Zafonte, R., & Berkner, P. D. (2014). Multiple prior concussions are associated with symptoms in high school athletes. *Annals of Clinical and Translational Neurology, 1*(6), 433-438. doi:10.1002/acn3.70

Maroon, J. C., Lovell, M. R., Norwig, J., Podell, K., Powell, D., & Hartl, R. (2000). Cerebral concussion in athletes: Evaluation and neuropsychological testing. *Neurosurgery, 47*(3), 659-672. doi:10.1097/00006123-200009000-00027

Marshall, S. W., Guskiewicz, K. M., Shankar, V., McCrea, M., & Cantu, R. C. (2015). Epidemiology of sports-related concussion in seven US high school and collegiate sports. *Injury Epidemiology, 2*(1), 13. doi:10.1186/s40621-015-0045-4

Martland, H. S. (1928). Punch drunk. *JAMA, 91*(15), 1103-1107.

Maruff, P., Thomas, E., Cysique, L., Brew, B., Collie, A., Snyder, P., & Pietrzak, R. H. (2009). Validity of the CogState brief battery: Relationship to standardized tests and sensitivity to cognitive impairment in mild traumatic brain injury, schizophrenia, and AIDS dementia complex. *Archives of Clinical Neuropsychology, 24*(2), 165-178. doi:10.1093/arclin/acp010

Maruff, P., Werth, J., Giordani, B., Caveney, A. F., Feltner, D., & Snyder, P. J. (2006). A statistical approach for classifying change in cognitive function in individuals following pharmacologic challenge: An example with alprazolam. *Psychopharmacology, 186*(1), 7-17. doi:10.1007/s00213-006-0331-5

Master, C. L., Scheiman, M., Gallaway, M., Goodman, A., Robinson, R. L., Master, S. R., & Grady, M. F. (2016). Vision diagnoses are common after concussion in adolescents. *Clinical Pediatrics, 55*(3), 260-267. doi:10.1177/0009922815594367

Mayer, A. R., Quinn, D. K., & Master, C. L. (2019). The spectrum of mild traumatic brain injury: A review. *Neurology, 89*(6), 623-632. doi:10.1212/WNL.0000000000004214

McAllister, T. W., Flashman, L. A., Maerlender, A., Greenwald, R. M., Beckwith, J. G., Tosteson, T. D., . . . Turco, J. H. (2012). Cognitive effects of one season of head impacts in a cohort of collegiate contact sport athletes. *Neurology, 78*, 1777–1784. doi:10.1212/WNL.0b013e3182582fe7

McAllister, T. W., Ford, J. C., Flashman, L. A., Maerlender, A., greenwald, R., Beckwith, J. G., . . . Jain, S. (2014). Effect of head impacts on diffusivity measures in a cohort of collegiate contact sport athletes. *Neurology, 82*(1), 63-69. doi:10.1212/01.wnl.0000438220.16190.42

McAllister, T. W., & McCrea, M. (2017). Long-term cognitive and neuropsychiatric consequences of repetitive concussion and head impact exposure. *Journal of Athletic Training, 52*(3), 309-317. doi:10.4085/1062-6050-52.1.14

McAllister, T. W., Saykin, A. J., Flashman, L. A., Sparling, M. B., Johnson, S. C., Guerin, S. J., . . . Yanofsky, N. (1999). Brain activation during working memory 1 month after mild traumatic brain injury. *Neurology, 53*, 1300-1308. doi:10.1212/wnl.53.6.1300

McAllister, T. W., & Wall, R. (2018). Neuropsychiatry of sport-related concussion. *Handbook of Clinical Neurology, 158*, 153-162. doi:10.1016/B978-0-444-63954-7.00016-1

McCrea, M. (2001). Standardized mental status assessment of sports concussion. *Clinical Journal of Sport Medicine, 11*, 176-181. doi:10.1097/00042752-200107000-00008

McCrea, M., Barr, W. B., Guskiewicz, K., Randolph, C., Marshall, S. W., Cantu, R., . . . Kelly, J. P. (2005). Standard regression-based methods for measuring recovery after sport-related concussion. *Journal of the International Neuropsychological Society, 11*(1), 58-69. doi:10.1017/S1355617705050083

McCrea, M., Guskiewicz, K., Marshall, S., Barr, W., Randolph, C., Cantu, R., & Kelly, J. (2003). Acute effects and recovery time following concussion in collegiate football players. *British Journal of Sports Medicine, 38*, 369-371. doi:10.1001/jama.290.19.2556

McCrea, M., Hammeke, T., Olsen, G., Leo, P., & Guskiewicz, K. (2004). Unreported concussion in high school football players: implications for prevention. *Clinical Journal of Sport Medicine, 14*(1), 13-17. doi:10.1097/00042752-200401000-00003

McCrea, M., Iverson, G. L., Echemendia, R. J., Makdissi, M., & Raftery, M. (2013). Day of injury assessment of sport-related concussion. *British Journal of Sports Medicine, 47*(5), 272-284. doi:10.1136/bjsports-2013-092145

McCrea, M., Kelly, J. P., Kluge, J., Ackley, B., & Randolph, C. (1997). Standardized assessment of concussion in football players. *Neurology, 48*, 586-588. doi:10.1212/wnl.48.3.586

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

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

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

McCuen, E., Svaldi, D., Breedlove, K., Kraz, N., Cummiskey, B., Breedlove, E. L., . . . Zanath, E. (2015). Collegiate women's soccer players suffer greater cumulative head impacts than their high school counterparts. *Journal of Biomechanics, 48*(13), 3720-3723. doi:10.1016/j.jbiomech.2015.08.003

McGrath, N., & Eloi, J. (2019). The role of neuropsychology in the evaluation of concussion. *Seminars in Pediatric Neurology, 30*, 83-95. doi:10.1016/j.spen.2019.03.013

McIntosh, A. S. (2012). Biomechanical considerations in the design of equipment to prevent sports injury. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 226*(3-4), 193-199. doi:10.1177/1754337111431024

McIntosh, A. S., McCrory, P., & Comeford, J. (2000). The dynamics of concussive head impacts in rugby and Australian rules football. *Medicine & Science in Sports & Exercise, 32*(12), 1980-1984. doi:10.1097/00005768-200012000-00002

McIntosh, A. S., & Patton, D. A. (2015). Boxing headguard performance in punch machine tests. *British Journal of Sports Medicine, 49*(17), 1108-1112. doi:10.1136/bjsports-2015-095094

McIntosh, A. S., Patton, D. A., Frechede, B., Pierre, P. A., Ferry, E., & Barthels, T. (2014). The biomechanics of concussion in unhelmeted football players in Australia: A case-control study. *BMJ Open, 4*(5), e005078. doi:10.1136/bmjopen-2014-005078

McIntosh, A. S., Willmott, C., Patton, D., Mitra, B., Brennan, J. H., Dimech-Betancourt, B., . . . Rosenfeld, J. V. (2019). An assessment of the utility and functionality of wearable head impact sensors in Australian Football. *Journal of Science and Medicine in Sport, 22*, 784-789. doi:10.1016/j.jsams.2019.02.004

McKee, A. C., Cairns, N. J., Dickson, D. W., Folkerth, R. D., Keene, C. D., Litvan, I., . . . Gordon, W. A. (2016). The first NINDS/NIBIB consensus meeting to define neuropathological criteria for the diagnosis of chronic traumatic encephalopathy. *Acta Neuropathologica, 131*(1), 75-86. doi:10.1007/s00401-015-1515-z

McKee, A. C., Cantu, B., Nowinski, C. J., Hedley-Whyte, E. T., gavett, B. E., Budson, A. E., . . . Stern, R. A. (2009a). Chronic traumatic encephalopathy in athletes: Progressive tauopathy after repetitive head injury. *Journal of Neuropathology & Experimental Neurology, 68*(7), 709-735. doi:10.1097/NEN.0b013e3181a9d503

McKee, A. C., Cantu, R. C., Nowinski, C. J., Hedley-Whyte, E. T., Gavett, B. E., Budson, A. E., . . . Stern, R. A. (2009b). Chronic traumatic encephalopathy in athletes: progressive tauopathy after repetitive head injury. *Journal of Neuropathology & Experimental Neurology, 68*(7), 709-735.

Mclntosh, A. S., Frechede, B., McCrory, R., Ferry, E., Oberst, T., & Pierre, P. (2010). Biomechanics of concussion in sport - Differences between injury and non-injury cases [Abstract 377]. *Journal of Science and Medicine in Sport, 12*, e179-e180. doi:10.1016/j.jsams.2009.10.378

McNamee, M. J., Partridge, B., & Anderson, L. (2015). Concussion in sport: Conceptual and ethical issues. *Kinesiology Review, 4*(2), 190-202. doi:10.1123/kr.2015-0011

Meeuwisse, W. H., Schneider, K. J., Dvorak, J., Omu, O. T., Finch, C. F., Hayden, K. A., & McCrory, P. (2017). The Berlin 2016 process: A summary of methodology for the 5th International Consensus Conference on Concussion in Sport. *British Journal of Sports Medicine, 51*(11), 873-876. doi:10.1136/bjsports-2017-097569

Meier, T. B., Bellgowan, P. S., Singh, R., Kuplicki, R., Polanski, D. W., & Mayer, A. R. (2015). Recovery of cerebral blood flow following sports-related concussion. *JAMA Neurology, 72*(5), 530-538. doi:10.1001/jamaneurol.2014.4778

Meier, T. B., Brummel, B. J., Singh, R., Nerio, C. J., Polanski, D. W., & Bellgowan, P. S. (2015). The underreporting of self-reported symptoms following sports-related concussion. *Journal of Science and Medicine In Sport, 18*(5), 507-511. doi:10.1016/j.jsams.2014.07.008

Meier, T. B., Giraldo-Chica, M., Espana, L. Y., Mayer, A. R., Harezlak, J., Nencka, A. S., . . . McCrea, M. A. (2019). Resting-state fMRI metrics in acute sport-related concussion and their association with clinical recovery: A study from the NCAA-DOD CARE consortium. *Journal of Neurotrauma, 37*(1), 152-162. doi:10.1089/neu.2019.6471

Merchant-Borna, K., Asselin, P., Narayan, D., Abar, B., Jones, C. M., & Bazarian, J. J. (2016). Novel method of weighting cumulative helmet impacts improves correlation with brain white matter changes after one football season of sub-concussive head blows. *Annals of Biomedical Engineering, 44*(12), 3679-3692. doi:10.1007/s10439-016-1680-9

Mertz, H. J. (1985). Biofidelity of the Hybrid III head. *SAE Transactions*, 97-105.

Mertz, H. J., Prasad, P., & Nusholtz, G. (1996). Head injury risk assessment for forehead impacts. *SAE transactions*, 26-46. doi:10.4271/960099

Mihalik, J. P., Bell, D. R., Marshall, S. W., & Guskiewicz, K. M. (2007). Measurement of head impacts in collegiate football players: An investigation of positional and event-type differences. *Neurosurgery, 61*(6), 1229-1235. doi:10.1227/01.neu.0000306101.83882.c8

Mihalik, J. P., Blackburn, J. T., Greenwald, R. M., Cantu, R. C., Marshall, S. W., & Guskiewicz, K. M. (2010). Collision type and player anticipation affect head impact severity among youth ice hockey players. *Pediatrics, 125*(6), e1394-e1401. doi:10.1542/peds.2009-2849

Mihalik, J. P., Guskiewicz, K. M., Marshall, S. W., Blackburn, J. T., Cantu, R. C., & Greenwald, R. M. (2012). Head impact biomechanics in youth hockey:

comparisons across playing position, event types, and impact locations. *Annals of Biomedical Engineering, 40*(1), 141-149. doi:10.1007/s10439-011-0405-3

Mihalik, J. P., Wasserman, E. B., Teel, E. F., & Marshall, S. W. (2019). Head impact biomechanics differ between girls and boys youth ice hockey players. *Annals of Biomedical Engineering, 48*(1), 104-111. doi:10.1007/s10439-019-02343-9

Millspaugh, J. A. (1937). Dementia pugilistica. *US Nav Med Bull, 35*, 297-303.

Moats, R. A., Watson, L., Shonk, T., Tokuyama, S., Braslau, D., Eto, R., . . . Ross, B. D. (1995). Added value of automated clinical proton MR spectroscopy of the brain. *Journal of Computer Assissted Tomography, 19*(3), 480-491. doi:10.1097/00004728-199505000-00025

Mollayeva, T., Colantonio, A., Cassidy, J. D., Vernich, L., Moineddin, R., & Shapiro, C. M. (2017). Sleep stage distribution in persons with mild traumatic brain injury: A polysomnographic study according to American Academy of Sleep Medicine standards. *Sleep Medicine, 34*, 179-192. doi:10.1016/j.sleep.2017.02.021

Molloy, J. H., Murphy, I., & Gissane, C. (2017). The King–Devick (K–D) test and concussion diagnosis in semi-professional rugby union players. *Journal of Science and Medicine in Sport, 20*(8), 708-711. doi:10.1016/j.jsams.2017.02.002

Montenigro, P. H., Baugh, C. M., Daneshvar, D. H., Mez, J., Budson, A. E., Au, R., . . . Stern, R. A. (2014). Clinical subtypes of chronic traumatic encephalopathy: Literature review and proposed research diagnostic criteria for traumatic encephalopathy syndrome. *Alzheimer's Research and Therapy, 6*(5), 68. doi:10.1186/s13195-014-0068-z

Moody, J. R., Feiss, R. S., & Pangelinan, M. M. (2019). A systematic review of acute concussion assessment selection in research. *Brain Injury, 33*(8), 967-973. doi:10.1080/02699052.2019.1617897

Moore, D. J., Keogh, E., & Eccleston, C. (2013). Headache impairs attentional performance. *Pain, 154*(9), 1840-1845. doi:10.1016/j.pain.2013.06.006

Moore, R. D., Lepine, J., & Ellemberg, D. (2017). The independent influence of concussive and sub-concussive impacts on soccer players' neurophysiological and neuropsychological function. *International Journal of Psychophysiology, 112*, 22-30. doi:10.1016/j.ijpsycho.2016.11.011

Morgan, C. D., Zuckerman, S. L., Lee, Y. M., King, L., Beaird, S., Sills, A. K., & Solomon, G. S. (2015). Predictors of postconcussion syndrome after sports-related concussion in young athletes: A matched case-control study. *Journal of Neurosurgery Pediatrics, 15*(6), 589-598. doi:10.3171/2014.10.PEDS14356

Moser, R. S., Iverson, G. L., Echemendia, R. J., Lovell, M. R., Schatz, P., Webbe, F. M., . . . Broshek, D. K. (2007). Neuropsychological evaluation in the diagnosis and management of sports-related concussion. *Archives of Clinical Neuropsychology, 22*(8), 909-916. doi:10.1016/j.acn.2007.09.004

Mucha, A., Collins, M. W., Elbin, R. J., Furman, J. M., Troutman-Enseki, C., DeWolf, R. M., . . . Kontos, A. P. (2014). A brief Vestibular/Ocular Motor Screening (VOMS) assessment to evaluate concussions: Preliminary findings. *The American Journal of Sports Medicine, 42*(10), 2479-2486. doi:10.1177/0363546514543775

Munce, T. A., Dorman, J. C., Thompson, P. A., Valentine, V. D., & Bergeron, M. F. (2015). Head impact exposure and neurologic function of youth football players. *Medicine & Science in Sports & Exercise, 47*(8), 1567-1576. doi:10.1249/MSS.0000000000000591

Murray, N. G., Reed-Jones, R. J., Szekely, B. J., & Powell, D. W. (2019). Clinical assessments of balance in adults with concussion: An update. *Speech Language Pathology, 40*(1), 48-56. doi:10.1055/s-0038-1676451

Naidu, D., Borza, C., Kobitowich, T., & Mrazik, M. (2018). Sideline concussion assessment: The King-Devick Test in Canadian professional football. *Journal of Neurotrauma, 35*(19), 2283-2286. doi:10.1089/neu.2017.5490

Nelson, L. D., Guskiewicz, K. M., Barr, W. B., Hammeke, T. A., Randolph, C., Ahn, K. W., . . . McCrea, M. A. (2016). Age differences in recovery after sport-related concussion: A comparison of high school and collegiate athletes. *Journal of Athletic Training, 51*(2), 142-152. doi:10.4085/1062-6050-51.4.04

Nelson, L. D., LaRoche, A. A., Pfaller, A. Y., Lerner, E. B., Hammeke, T. A., Randolph, C., . . . McCrea, M. A. (2016). Prospective, head-to-head study of three computerized neurocognitive assessment tools (CNTs): Reliability and validity for the assessment of sport-related concussion. *Journal of the International Neuropsychological Society, 22*(1), 24-37. doi:10.1017/S1355617715001101

Nevins, D., Hildenbrand, K., Vasavada, A., Kensrud, J., & Smith, L. (2019). In-game head impact exposure of male and female high school soccer players. *Athletic Training & Sports Health Care, 11*(4), 174-182. doi:10.3928/19425864-20180802-02

Nevins, D., Smith, L., & Kensrud, J. (2015). Laboratory evaluation of wireless head impact sensor. *Procedia Engineering, 112*, 175-179. doi:10.1016/j.proeng.2015.07.195

Newman, J. A., Beusenberg, M. C., Shewchenko, N., Withnall, C., & Fournier, E. (2005). Verification of biomechanical methods employed in a comprehensive study of mild traumatic brain injury and the effectiveness of American football helmets. *Journal of Biomechanics, 38*(7), 1469-1481. doi:10.1016/j.jbiomech.2004.06.025

Norheim, N., Kissinger-Knox, A., Cheatham, M., & Webbe, F. (2018). Performance of college athletes on the 10-item word list of SCAT5. *BMJ Open Sport & Exercise Medicine, 4*(1), e000412. doi:10.1136/bmjsem-2018-000412

O'Connor, K. L., Baker, M. M., Dalton, S. L., Dompier, T. P., Broglio, S. P., & Kerr, Z. Y. (2017). Epidemiology of sport-related concussions in high school athletes: National Athletic Treatment, Injury and Outcomes Network (NATION), 2011-2012 through 2013-2014. *Journal of Athletic Training, 52*(3), 175-185. doi:10.4085/1062-6050-52.1.15

O'Connor, K. L., Rowson, S., Duma, S. M., & Broglio, S. P. (2017). Head-impact–measurement devices: A systematic review. *Journal of Athletic Training, 52*(3), 206-227. doi:10.4085/1062-6050.52.2.05

O'Day, K. M., Koehling, E. M., Vollavanh, L. R., Bradney, D., May, J. M., Breedlove, K. M., . . . Bowman, T. G. (2017). Comparison of head impact location during games and practices in division III men's lacrosse players. *Clinical Biomechanics, 43*, 23-27. doi:10.1016/j.clinbiomech.2017.01.013

O’Brien, J., Finch, C. F., Pruna, R., & McCall, A. (2018). A new model for injury prevention in team sports: The Team-Sport Injury Prevention (TIP) cycle. *Science and Medicine in Football, 3*(1), 77-80. doi:10.1080/24733938.2018.1512752

Oldenburg, C., Lundin, A., Edman, G., Nygren-de Boussard, C., & Bartfai, A. (2016). Cognitive reserve and persistent post-concussion symptoms - A prospective mild traumatic brain injury (mTBI) cohort study. *Brain Injury, 30*(2), 146-155. doi:10.3109/02699052.2015.1089598

Oliver, J. M., Jones, M. T., Kirk, K. M., Gable, D. A., Repshas, J. T., Johnson, T. A., . . . Zetterberg, H. (2016). Effect of Docosahexaenoic Acid on a biomarker of head trauma in American football. *Medicine & Science in Sports & Exercise, 48*(6), 974-982. doi:10.1249/MSS.0000000000000875

Omalu, B. I., DeKosky, S. T., Minster, R. L., Kamboh, M. I., Hamilton, R. L., & Wecht, C. H. (2005). Chronic traumatic encephalopathy in a National Football League player. *Neurosurgery, 57*(1), 128-134. doi:10.1227/01.neu.0000163407.92769.ed

Omalu, B. I., Fitzsimmons, R. P., Hammers, J., & Bailes, J. (2010). Chronic traumatic encephalopathy in a professional American wrestler. *Journal of Forensic Nursing, 6*(3), 130-136. doi:10.1111/j.1939-3938.2010.01078.x

Ommaya, A. K., & Hirsch, A. E. (1971). Tolerances for cerebral concussion from head impact and whiplash in primates. *Journal of Biomechanics, 4*(1), 13-21.

Ommaya, A. K., Hirsch, A. E., Flamm, E., & Mahone, R. (1966). Cerebral concussion in the monkey: an experimental model. *Science, 153*(3732), 211-212.

Onate, J. A., Guskiewicz, K. M., Riemann, B. L., & Prentice, W. E. (2000). A comparison of sideline versus clinical cognitive test performance in collegiate athletes. *Journal of Athletic Training, 35*(2), 155-160.

Oride, M., Marutani, J. K., Rouse, M. W., & Deland, P. N. (1986). Reliability study of the Pierce and King-Devick saccade tests. *American Journal of Optometry and Physiological Optics, 63*(6), 419-424. doi:10.1097/00006324-198606000-00005

Parker, E. M., Gilchrist, J., Schuster, D., Lee, R., & Sarmiento, K. (2015). Reach and knowledge change among coaches and other participants of the online course: "Concussion in sports: what you need to know". *Journal of Head Trauma Rehabilitation, 30*(3), 198-206. doi:10.1097/HTR.0000000000000097

Parker, H. L. (1934). Traumatic encephalopathy ('punch drunk') of professional pugilists. *Journal of Neurology and Psychopathology, 15*, 20-28.

Parrington, L., Fino, P. C., Swanson, C. W., Murchison, C. F., Chesnutt, J., & King, L. A. (2019). Longitudinal assessment of balance and gait after concussion and return to play in collegiate athletes. *Journal of Athletic Training, 54*(4), 429-438. doi:10.4085/1062-6050-46-18

Patricios, J., Ardern, C. L., Hislop, M. D., Aubry, M., Bloomfield, P., Broderick, C., . . . Raftery, M. (2018). Implementation of the 2017 Berlin Concussion in Sport Group Consensus Statement in contact and collision sports: A joint position statement from 11 national and international sports organisations. *British Journal of Sports Medicine, 52*(10), 635-641. doi:10.1136/bjsports-2018-099079

Patricios, J., Fuller, G. W., Ellenbogen, R., Herring, S., Kutcher, J. S., Loosemore, M., . . . Schneider, K. J. (2017). What are the critical elements of sideline screening that can be used to establish the diagnosis of concussion? A systematic review. *British Journal of Sports Medicine, 51*(11), 888-894. doi:10.1136/bjsports-2016-097441

Patton, D. A., McIntosh, A. S., & Kleiven, S. (2013). The biomechanical determinants of concussion: Finite element simulations to investigate brain tissue deformations during sporting impacts to the unprotected head. *Journal of Applied Biomechanics, 29*(6), 721-730. doi:10.1123/jab.2014-0223

Pearce, A. J., Hoy, K., Rogers, M. A., Corp, D. T., Davies, C. B., Maller, J. J., & Fitzgerald, P. B. (2015). Acute motor, neurocognitive and neurophysiological change following concussion injury in Australian amateur football. A prospective multimodal investigation. *Journal of Science and Medicine in Sport, 18*(5), 500-506. doi:10.1016/j.jsams.2014.07.010

Pearce, K. L., Sufrinko, A., Lau, B. C., Henry, L., Collins, M. W., & Kontos, A. P. (2015). Near Point of Convergence After a Sport-Related Concussion: Measurement Reliability and Relationship to Neurocognitive Impairment and Symptoms. *The American Journal of Sports Medicine, 43*(12), 3055-3061. doi:10.1177/0363546515606430

Pervez, M., Kitagawa, R. S., & Chang, T. R. (2018). Definition of traumatic brain injury, neurosurgery, trauma orthopedics, neuroimaging, psychology, and psychiatry in mild traumatic brain injury. *Neuroimaging Clinics of North America, 28*(1), 1-13. doi:10.1016/j.nic.2017.09.010

Petraglia, A. L., Maroon, J. C., & Bailes, J. E. (2012). From the field of play to the field of combat: a review of the pharmacological management of concussion. *Neurosurgery, 70*(6), 1520-1533. doi:10.1227/NEU.0b013e31824cebe8

Ponsford, J., Nguyen, S., Downing, M., Bosch, M., McKenzie, J. E., Turner, S., . . . Green, S. (2019). Factors associated with persistent post-concussion symptoms following mild traumatic brain injury in adults. *Journal of Rehabilitation Medicine, 51*(1), 32-39. doi:10.2340/16501977-2492

Poole, V. N., Breedlove, E. L., Shenk, T. E., Abbas, K., Robinson, M. E., Leverenz, L. J., . . . Talavage, T. M. (2015). Sub-concussive hit characteristics predict deviant brain metabolism in football athletes. *Developmental Neuropsychology, 40*(1), 12-17. doi:10.1080/87565641.2014.984810

Post, A., & Hoshizaki, T. B. (2012). Mechanisms of brain impact injuries and their prediction: A review. *Trauma, 14*(4), 327-349. doi:10.1177/1460408612446573

Press, J. N., & Rowson, S. (2017). Quantifying head impact exposure in collegiate women's soccer. *Clinical Journal Of Sport Medicine, 27*(2), 104-110. doi:10.1097/JSM.0000000000000313

Prien, A., Grafe, A., Rossler, R., Junge, A., & Verhagen, E. (2018). Epidemiology of head injuries focusing on concussions in team contact sports: A systematic review. *Sports Medicine, 48*(4), 953-969. doi:10.1007/s40279-017-0854-4

Prins, M. L., Alexander, D., Giza, C. C., & Hovda, D. A. (2013). Repeated mild traumatic brain injury: mechanisms of cerebral vulnerability. *Journal of Neurotrauma, 30*(1), 30-38. doi:10.1089/neu.2012.2399

Putukian, M., Aubry, M., & McCrory, P. (2009). Return to play after sports concussion in elite and non-elite athletes? *British Journal of Sports Medicine, 43 Suppl 1*, i28-31. doi:10.1136/bjsm.2009.058230

Putukian, M., Echemendia, R., Dettwiler-Danspeckgruber, A., Duliba, T., Bruce, J., Furtdado, J. L., & Murugavel, M. (2015). Prospective clinical assessment using sideline concussion assessment tool-2 testing in the evaluation of sport-related concussion in college athletes. *Clinical Journal of Sport Medicine, 25*(1), 36-43. doi:10.1097/JSM.0000000000000102

Putukian, M., Riegler, K., Amalfe, S., Bruce, J., & Echemendia, R. (2018). Preinjury and postinjury factors that predict sports-related concussion and clinical recovery time. *Clinical Journal of Sport Medicine, Epub ahead of print*, 1-8. doi:10.1097/JSM.0000000000000705

Rabinowitz, A. R. (2019). Assessment of effort in sports concussion evaluations. In P. A. Arnett (Ed.), *Neuropsychology of sports-related concussion.* (pp. 205-223): American Psychological Association.

Reams, N., Eckner, J. T., Almeida, A. A., Aagesen, A. L., Giordani, B., Paulson, H., . . . Kutcher, J. S. (2016). A clinical approach to the diagnosis of traumatic encephalopathy syndrome: A review. *JAMA Neurology, 73*(6), 743-749. doi:10.1001/jamaneurol.2015.5015

Reed, N., Taha, T., Keightley, M., Duggan, C., McAuliffe, J., Cubos, J., . . . Montelpare, W. (2010). Measurement of head impacts in youth ice hockey players. *International Journal of Sports Medicine, 31*(11), 826-833. doi:10.1055/s-0030-1263103

Reeves, D. L., Winter, K. P., Bleiberg, J., & Kane, R. L. (2007). ANAM genogram: Historical perspectives, description, and current endeavors. *Archives of Clinical Neuropsychology, 22 Suppl 1*, S15-S37. doi:10.1016/j.acn.2006.10.013

Register-Mihalik, J. K., Guskiewicz, K. M., Mihalik, J. P., Schmidt, J. D., Kerr, Z. Y., & McCrea, M. A. (2013). Reliable change, sensitivity, and specificity of a multidimensional concussion assessment battery: Implications for caution in clinical practice. *Journal of Head Trauma Rehabilitation, 28*(4), 274-283. doi:10.1097/HTR.0b013e3182585d37

Register-Mihalik, J. K., Kontos, D. L., Guskiewicz, K., Mihalik, J., Conder, R., & Schields, E. W. (2012). Age related differences and reliability on computerized and paper-and-pencil neurocognitive assessment batteries. *Journal of Athletic Training, 47*(3), 297-305. doi:10.4085/1062-6050-47.3.13

Rennie, M. J., Watsford, M. L., Spurrs, R. W., Kelly, S. J., & Pine, M. J. (2018). Phases of match-play in professional Australian Football: Descriptive analysis and reliability assessment. *Journal of Science and Medicine in Sport, 21*(6), 635-639. doi:10.1016/j.jsams.2017.10.021

Resch, J., Driscoll, A., McCaffrey, N., Brown, C. N., Ferrara, M. S., Macciocchi, S. N., . . . Walpert, K. (2013). ImPACT test-restest reliability: Reliably unreliable? *Journal of Athletic Training 48*(4), 506-511. doi:10.4085/1062-6050-48.3.09

Reynolds, B. B., Patrie, J., Henry, E. J., Goodkin, H. P., Broshek, D. K., Wintermark, M., & Druzgal, T. J. (2016). Quantifying head impacts in collegiate lacrosse. *The American Journal of Sports Medicine, 44*(11), 2947-2956. doi:10.1177/0363546516648442

Reynolds, B. B., Patrie, J., Henry, E. J., Goodkin, H. P., Broshek, D. K., Wintermark, M., & Druzgal, T. J. (2017a). Comparative analysis of head impact in contact and collision sports. *Journal of Neurotrauma, 34*(1), 38-49. doi:10.1089/neu.2015.4308

Reynolds, B. B., Patrie, J., Henry, E. J., Goodkin, H. P., Broshek, D. K., Wintermark, M., & Druzgal, T. J. (2017b). Effects of sex and event type on head impact in collegiate soccer. *Orthopaedic Journal of Sports Medicine, 5*(4), 2325967117701708. doi:10.1177/2325967117701708

Rice, S. M., Parker, A. G., Rosenbaum, S., Bailey, A., Mawren, D., & Purcell, R. (2018). Sport-related concussion and mental health outcomes in elite athletes: A systematic review. *Sports Medicine, 48*(2), 447-465. doi:10.1007/s40279-017-0810-3

Riemann, B. L., & Guskiewicz, K. (2000). Effect of mild head injury on postural stability as measured through clinical balance testing. *Jouranl of Athletic Training, 35*(1), 19-25.

Riemann, B. L., Guskiewicz, K., & Shields, E. W. (1999). Relationship betwen clinical and forceplate measures of postural stability. *Jouranl of Sports Rehabilitation, 8*(2), 71-82. doi:10.1123/jsr.8.2.71

Roberts, A. (1969). *Brain damage in boxers: A study of prevalence of traumatic encephalopathy among exprofessional boxers*. London: Pitman Medical Scientific Publishing Co.

Rogatzki, M. J., Soja, S. E., McCabe, C. A., Breckenridge, R. E., White, J. L., & Baker, J. S. (2016). Biomarkers of brain injury following an American football game: A pilot study. *International Journal of Immunopathology and Pharmacology, 29*(3), 450-457. doi:10.1177/0394632016657091

Romeu-Mejia, R., Giza, C. C., & Goldman, J. T. (2019). Concussion pathophysiology and injury biomechanics. *Current Reviews in Musculoskeletal Medicine, 12*(2), 105-116. doi:10.1007/s12178-019-09536-8

Ross, B. D., & Michaelis, T. (1994). Clinical applications of magnetic resonance spectroscopy. *Magnetic Resonance Quarterly, 10*(4), 191-247.

Rowson, S., Campolettano, E. T., Duma, S. M., Stemper, B., Shah, A., Harezlak, J., . . . McCrea, M. (2019). Accounting for variance in concussion tolerance between individuals: Comparing head accelerations between concussed and physically matched control subjects. *Annals of Biomedical Engineering, 47*(10), 2048-2056. doi:10.1007/s10439-019-02329-7

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

Rowson, S., Duma, S. M., Stemper, B. D., Shah, A., Mihalik, J. P., Harezlak, J., . . . McCrea, M. (2018). Correlation of concussion symptom profile with head impact biomechanics: A case for individual-specific injury tolerance. *Journal of Neurotrauma, 35*(4), 681-690. doi:10.1089/neu.2017.5169

Sanchez, C. A. (2011). Working through the pain: Working memory capacity and differences in processing and storage under pain. *Memory, 19*(2), 226-232. doi:10.1080/09658211.2010.547861

Satz, P. (1993). Brain reserve capacity on symptom onset after brain injury: A formulation and review of evidence for threshold theory. *Neuropsychology Review, 7*(3), 273-295.

Schatz, P. (2009). Long-term test-retest reliability of baseline cognitive assessments using ImPACT. *The American Journal of Sports Medicine, 38*(1), 47-53. doi:10.1177/0363546509343805

Schatz, P., & Putz, B. O. (2006). Cross-validation of measures used for computer-based assessment of concussion. *Applied Neuropsychology, 13*(3), 151-159. doi:10.1207/s15324826an1303_2

Schatz, P., & Zillmer, E. A. (2003). Computer-based assessment of sports-related concussion. *Applied Neuropsychology, 10*(1), 42-47. doi:10.1207/S15324826AN1001_6

Schmidt, J. D., Guskiewicz, K. M., Blackburn, J. T., Mihalik, J. P., Siegmund, G. P., & Marshall, S. W. (2014). The influence of cervical muscle characteristics on head impact biomechanics in football. *The American Journal of Sports Medicine, 42*(9), 2056-2066. doi:10.1177/0363546514536685

Schmidt, J. D., Guskiewicz, K. M., Mihalik, J. P., Blackburn, J. T., Siegmund, G. P., & Marshall, S. W. (2016). Head impact magnitude in American high school football. *Pediatrics, 138*(2), e20154231. doi:10.1542/peds.2015-4231

Schmidt, J. D., Pierce, A. F., Guskiewicz, K. M., Register-Mihalik, J. K., Pamukoff, D. N., & Mihalik, J. P. (2016). Safe-play knowledge, aggression, and head-impact biomechanics in adolescent ice hockey players. *Journal of Athletic Training, 51*(5), 366-372. doi:10.4085/1062-6050-51.5.04

Schnebel, B., Gwin, J. T., Anderson, S., & Gatlin, R. (2007). In vivo study of head impacts in football: a comparison of National Collegiate Athletic Association division I versus high school impacts. *Neurosurgery, 60*(3), 490-496. doi:10.1227/01.NEU.0000249286.92255.7F

Schneider, K. J., Leddy, J. J., Guskiewicz, K. M., Seifert, T., McCrea, M., Silverberg, N. D., . . . Makdissi, M. (2017). Rest and treatment/rehabilitation following sport-related concussion: A systematic review. *British Journal of Sports Medicine, 51*(12), 930-934. doi:10.1136/bjsports-2016-097475

Segalowitz, S. J., Mahaney, P., Santesso, D. L., MacGregor, L., Dywan, J., & Willer, B. (2007). Retest reliability in adolescents of a computerized neuropsychological battery used to assess recovery from concussion. *NeuroRehabilitation, 22*(3), 243-251.

Sharp, D. J., & Jenkins, P. O. (2015). Concussion is confusing us all. *Practical Neurology, 15*(3), 172-186. doi:10.1136/practneurol-2015-001087

Shehata, N., Wiley, J., Richea, S., Benson, B. W., Duits, L., & Meeuwisse, W. (2009). Sport concussion assessment tool: baseline values for varsity collision sport athletes. *British journal of sports medicine, 43*(10), 730-734.

Shenton, M. E., Hamoda, H., Schneiderman, J., Bouix, S., Pasternak, O., Rathi, Y., . . . Koerte, I. (2012). A review of magnetic resonance imaging and diffusion tensor imaging findings in mild traumatic brain injury. *Brain Imaging and Behavior, 6*(2), 137-192. doi:10.1007/s11682-012-9156-5

Shumway-Cook, A., & Horak, F. B. (1986). Assessing the influence of sensory interaction on balance: Suggestion from the field. *Physical Therapy, 66*(10), 1548-1550. doi:10.1093/ptj/66.10.1548

Siegmund, G. P., Guskiewicz, K. M., Marshall, S. W., DeMarco, A. L., & Bonin, S. J. (2016). Laboratory validation of two wearable sensor systems for measuring head impact severity in football players. *Annals of Biomedical Engineering, 44*(4), 1257-1274. doi:10.1007/s10439-015-1420-6

Silverberg, N. D., & Iverson, G. L. (2013). Is rest after concussion “the best medicine?”: Recommendations for activity resumption following concussion in athletes, civilians, and military service members. *The Journal of Head Trauma Rehabilitation, 28*(4), 250-259. doi:10.1097/HTR.0b013e31825ad658

Smith, L. G. F., Milliron, E., Ho, M.-L., Hu, H. H., Rusin, J., Leonard, J., & Sribnick, E. A. (2019). Advanced neuroimaging in traumatic brain injury: an overview.

Neurosurgical Focus, 47(6), E17. doi:https://doi.org/10.3171/2019.9.FOCUS19652

Stemper, B. D., Shah, A. S., Harezlak, J., Rowson, S., Mihalik, J. P., Duma, S. M., . . . McCrea, M. (2019). Comparison of head impact exposure between concussed football athletes and matched controls: Evidence for a possible second mechanism of sport-related concussion. *Annals of Biomedical Engineering, 47*(10), 2057-2072. doi:10.1007/s10439-018-02136-6

Stenberg, J., Haberg, A. K., Follestad, T., Olsen, A., Iverson, G. L., Terry, D. P., . . . Vik, A. (2020). Cognitive reserve moderates cognitive outcome after mild traumatic brain injury. *Archives of Physical Medicine and Rehabilitation, 101*(1), 72-80. doi:10.1016/j.apmr.2019.08.477

Stern, R. A., Daneshvar, D. H., Baugh, C. M., Seichepine, D. R., Montenigro, P. H., Riley, D. O., . . . McKee, A. (2013). Clinical presentation of chronic traumatic encephalopathy. *Neurology, 81*(13), 112-1129. doi:10.1212/WNL.0b013e3182a55f7f

Stern, R. A., Riley, D. O., Daneshvar, D. H., Nowinski, C. J., Cantu, R. C., & McKee, A. C. (2011). Long-term consequences of repetitive brain trauma: Chronic traumatic encephalopathy. *PM&R, 3*(10 Suppl 2), S460-S467. doi:10.1016/j.pmrj.2011.08.008

Stevens, S. T., Lassonde, M., de Beaumont, L., & Keenan, J. P. (2008). In-game fatigue influences concussions in national hockey league players. *Research in Sports Medicine, 16*(1), 68-74. doi:10.1080/15438620701879020

Stojsih, S., Boitano, M., Wilhelm, M., & Bir, C. (2010). A prospective study of punch biomechanics and cognitive function for amateur boxers. *British Journal of Sports Medicine, 44*(10), 725-730. doi:10.1136/bjsm.2008.052845

Straume-Naesheim, T. M., Andersen, T. E., & Bahr, R. (2005). Reproducibility of computer based neuropsychological testing among Norwegian elite football players. *British Journal of Sports Medicine, 39*(Suppl 1), i64-i69. doi:10.1136/bjsm.2005.019620

Stulemeijer, M., van der Werf, S., Borm, G. F., & Vos, P. E. (2008). Early prediction of favourable recovery 6 months after mild traumatic brain injury. *Journal of Neurology, Neurosurgery, and Psychiatry, 79*(8), 936-942. doi:10.1136/jnnp.2007.131250

Sufrinko, A., McAllister-Deitrick, J., Womble, M., & Kontos, A. (2017). Do sideline concussion assessments predict subsequent neurocognitive impairment after sport-related concussion? *Journal of Athletic Training, 52*(7), 676-681. doi:10.4085/1062-6050-52.4.01

Swartz, E. E., Myers, J. L., Cook, S. B., Guskiewicz, K. M., Ferrara, M. S., Cantu, R. C., . . . Broglio, S. P. (2019). A helmetless-tackling intervention in American football for decreasing head impact exposure: A randomized controlled trial. *Journal of Science and Medicine in Sport, 22*(10), 1102-1107. doi:10.1016/j.jsams.2019.05.018

Talavage, T. M., Nauman, E. A., Breedlove, E. L., Yoruk, U., Dye, A. E., Morigaki, K. E., . . . Leverenz, L. J. (2014). Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. *Journal of Neurotrauma, 31*(4), 327-338. doi:10.1089/neu.2010.1512

Tavazzi, B., Vagnozzi, R., Signoretti, S., Amorini, A. M., Belli, A., Cimatti, M., . . . Lazzarino, G. (2007). Temporal window of metabolic brain vulnerability to concussions: Oxidative and nitrosative stresses - Part II. *Neurosurgery, 61*(2), 390-395. doi:10.1227/01.neu.0000255525.34956.3f

Teasdale, G., & Jennett, B. (1974). Assessment of coma and impaired consciousness: a practical scale. *The Lancet, 304*(7872), 81-84.

Terwilliger, V. K., Pratson, L., Vaughan, C. G., & Gioia, G. A. (2016). Additional post-concussion impact exposure may affect recovery in adolescent athletes. *Journal of Neurotrauma, 33*(8), 761-765. doi:10.1089/neu.2015.4082

Thornton, C., Sheffield, D., & Baird, A. (2019). Motor performance during experimental pain: The influence of exposure to contact sports. *European Journal of Pain, 23*(5), 1020-1030. doi:10.1002/ejp.1370

Tiernan, S., Byrne, G., & O'Sullivan, D. M. (2019). Evaluation of skin-mounted sensor for head impact measurement. *Proceedings of the Institution of Mechanical Engineers, Part H, 233*(7), 735-744. doi:10.1177/0954411919850961

Tierney, R. T., Higgins, M., Caswell, S. V., Brady, J., McHardy, K., Driban, J. B., & Darvish, K. (2008). Sex differences in head acceleration during heading while wearing soccer headgear. *Journal of Athletic Training, 43*(6), 578-584. doi:10.4085/1062-6050-43.6.578

Tierney, R. T., Sitler, M. R., Swanik, C. B., Swanik, K. A., Higgins, M., & Torg, J. (2005). Gender differences in head-neck segment dynamic stabilization during head acceleration. *Medicine & Science in Sports & Exercise, 37*(2), 272-279. doi:10.1249/01.Mss.0000152734.47516.Aa

Trinh, L. N., Brown, S. M., & Mulcahey, M. K. (2020). the influence of psychological factors on the incidence and severity of sports-related concussions: A systematic review. *The American Journal of Sports Medicine, 48*(6), 1516-1525. doi:10.1177/0363546519882626

Tsushima, W. T., Siu, A. M., Ahn, H. J., Chang, B. L., & Murata, N. M. (2019). Incidence and risk of concussions in youth athletes: Comparisons of age, sex, concussion history, sport, and football position. *Archives of Clinical Neuropsychology, 34*(1), 60-69. doi:10.1093/arclin/acy019

Tucker, R., Raftery, M., Fuller, G. W., Hester, B., Kemp, S., & Cross, M. J. (2017). A video analysis of head injuries satisfying the criteria for a head injury assessment in professional Rugby Union: A prospective cohort study. *British Journal of Sports Medicine, 51*(15), 1147-1151. doi:10.1136/bjsports-2017-097883

Urban, J. E., Kelley, M. E., Espeland, M. A., Davenport, E. M., Whitlow, C. T., Powers, A. K., . . . Stitzel, J. D. (2019). In-season variations in head impact exposure among youth football players. *Journal of Neurotrauma, 36*(2), 275-281. doi:10.1089/neu.2018.5699

Vagnozzi, R., Signoretti, S., Tavazzi, B., Floris, R., Ludovici, A., Marziali, S., . . . Lazzarino, G. (2008). Temporal window of metabolic brain vulnerability to concussion: A pilot ^{1}H-Magnetic Resonance Spectroscopic study in concussed athletes - Part III. *Neurosurgery, 62*(6), 1286-1296. doi:10.1227/01.neu.0000333300.34189.74

Vagnozzi, R., Tavazzi, B., Signoretti, S., Amorini, A. M., Belli, A., Cimatti, M., . . . Lazzarino, G. (2007). Temporal window of metabolic brain vulnerability to concussions: Mitochondrial-related impairment - Part I. *Neurosurgery, 61*(2), 379-389. doi:10.1227/01.NEU.0000280002.41696.D8

Valovich McLeod, T. C., & Hale, T. D. (2015). Vestibular and balance issues following sport-related concussion. *Brain Injury, 29*(2), 175-184. doi:10.3109/02699052.2014.965206

Valovich McLeod, T. C., & Leach, C. (2012). Psychometric properties of self-report concussion scales and checklists. *Journal of Athletic Training, 47*(2), 221-223. doi:10.4085/1062-6050-47.2.221

Valovich McLeod, T. C., Perrin, D. H., Guskiewicz, K., Shultz, S. J., Diamond, R., & Gansneder, D. R. (2004). Serial administration of clinical concussion assessments and learning effects in healthy young athletes. *Clinical Journal of Sport Medicine, 14*(5), 287-295. doi:10.1097/00042752-200409000-00007

Van Leijenhorst, L., Westenberg, P. M., & Crone, E. A. (2008). A developmental study of risky decisions on the cake gambling task: Age and gender analyses of probability estimation and reward evaluation. *Developmental Neuropsychology, 33*(2), 179-196. doi:10.1080/87565640701884287

Van Pelt, K. L., Allred, D., Cameron, K. L., Campbell, D. E., D'Lauro, C. J., He, X., . . . Broglio, S. P. (2019). A cohort study to identify and evaluate concussion risk factors across multiple injury settings: Findings from the CARE consortium. *Injury Epidemiology, 6*(1), 1. doi:10.1186/s40621-018-0178-3

VanKampen, D. A., Lovell, M. R., Pardini, J. E., Collins, M. W., & Fu, F. H. (2006). The “value added” of neurcognitive testing after sportsrelated concussion. *The American Journal of Sports Medicine, 34*(10), 1630-1635. doi:10.1177/0363546506288677

Varriano, B., Tomlinson, G., Tarazi, A., Wennberg, R., Tator, C., & Tartaglia, M. C. (2018). Age, gender and mechanism of injury interactions in post-concussion syndrome. *Canadian Journal of Neurological Sciences, 45*(6), 636-642. doi:10.1017/cjn.2018.322

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

Vollavanh, L. R., O'Day, K. M., Koehling, E. M., May, J. M., Breedlove, K. M., Breedlove, E. L., . . . Bowman, T. G. (2018). Effect of impact mechanism on head accelerations in men's lacrosse athletes. *Journal of Applied Biomechanics, 34*(5), 396-402. doi:10.1123/jab.2017-0231

Voormolen, D. C., Cnossen, M. C., Polinder, S., Gravesteijn, B. Y., Von Steinbuechel, N., Real, R. G. L., & Haagsma, J. A. (2019). Prevalence of post-concussion-like symptoms in the general population in Italy, The Netherlands and the United Kingdom. *Brain Injury, 33*(8), 1078-1086. doi:10.1080/02699052.2019.1607557

Wallace, J., Covassin, T., & Beidler, E. (2017). Sex differences in high school athletes' knowledge of sport-related concussion symptoms and reporting behaviors. *Journal of Athletic Training, 52*(7), 682-688. doi:10.4085/1062-6050-52.3.06

Wang, Y., Nelson, L. D., LaRoche, A. A., Pfaller, A. Y., Nencka, A. S., Koch, K. M., & McCrea, M. A. (2016). Cerebral blood flow alterations in acute sport-related concussion. *Journal of Neurotrauma, 33*(13), 1227-1236. doi:10.1089/neu.2015.4072

Washington State Legislature. (2009). The Zackery Lystedt law. Retrieved from https://apps.leg.wa.gov/billsummary/?BillNumber=1824&Year=2009&Initiative=false

Weber, M. L., Dean, J. L., Hoffman, N. L., Broglio, S. P., McCrea, M., McAllister, T. W., . . . Dykhuizen, B. H. (2018). Influences of mental illness, current psychological state, and concussion history on baseline concussion assessment performance. *The American Journal of Sports Medicine, 46*(7), 1742-1751. doi:10.1177/0363546518765145

West, T. A., & Marion, D. W. (2014). Current recommendations for the diagnosis and treatment of concussion in sport: A comparison of three new guidelines. *Journal of Neurotrauma, 31*(2), 159-168. doi:10.1089/neu.2013.3031

White, P. E., Donaldson, A., Sullivan, S. J., Newton, J., & Finch, C. F. (2016). Australian Football League concussion guidelines: What do community players think? *BMJ Open Sport & Exercise Medicine, 2*(1), e000169. doi:10.1136/bmjsem-2016-000169

White, P. E., Newton, J. D., Makdissi, M., Sullivan, S. J., Davis, G., McCrory, P., . . . Finch, C. F. (2014). Knowledge about sports-related concussion: Is the message getting through to coaches and trainers? *British Journal of Sports Medicine, 48*(2), 119-124. doi:10.1136/bjsports-2013-092785

WHO. (2016). *The internationl classification of diseases and related health problems 10th revision* (5 ed.). France: Wolrd Health Organization.

Wicker, P., & Breuer, C. (2015). How the economic and financial situation of the community affects sport clubs’ resources: Evidence from multi-level models. *International Journal of Financial Studies, 3*(1), 31-48. doi:10.3390/ijfs3010031

Wilcox, B. J., Beckwith, J. G., Greenwald, R. M., Chu, J. J., McAllister, T. W., Flashman, L. A., . . . Crisco, J. J. (2014). Head impact exposure in male and female collegiate ice hockey players. *Journal Of Biomechanics, 47*(1), 109-114. doi:10.1016/j.jbiomech.2013.10.004

Wilcox, B. J., Beckwith, J. G., Greenwald, R. M., Raukar, N. P., Chu, J. J., McAllister, T. W., . . . Crisco, J. J. (2015). Biomechanics of head impacts associated with diagnosed concussion in female collegiate ice hockey players. *Journal Of Biomechanics, 48*(10), 2201-2204. doi:10.1016/j.jbiomech.2015.04.005

Wilkins, J. C., McLeod, T. C. V., Perrin, D. H., & Gansneder, B. M. (2004). Performance on the balance error scoring system decreases after fatigue. *Journal of Athletic Training, 39*(2), 156-161.

Williams, D. H., Levin, H. S., & Eisenberg, H. (1990). Mild head injury classification. *Neurosurgery, 27*(3), 422-428. doi:10.1097/00006123-199009000-00014

Williamson, I., & Goodman, D. (2006). Converging evidence for the under-reporting of concussions in youth ice hockey. *British journal of sports medicine, 40*(2), 128-132.

Willmott, C. M., McIntosh, A. S., Howard, T., Mitra, B., Dimech-Betancourt, B., Donovan, J., & Rosenfeld, J. V. (2018). SCAT3 changes from baseline and associations with X2 patch measured head acceleration in amateur Australian football players. *Journal of Science and Medicine in Sport, 21*(5), 442-446. doi:10.1016/j.jsams.2017.09.591

Wisbey, B., Montgomery, P. G., Pyne, D. B., & Rattray, B. (2010). Quantifying movement demands of AFL football using GPS tracking. *Journal of Science and Medicine in Sport, 13*(5), 531-536. doi:10.1016/j.jsams.2009.09.002

Wiseman-Hakes, C., Gosselin, N., Sharma, B., Langer, L., & Gagnon, I. (2019). A longitudinal investigation of sleep and daytime wakefulness in children and youth with concussion. *ASN Neuro, 11*, 1759091418822405. doi:10.1177/1759091418822405

Withnall, C., Shewchenko, N., Gittens, R., & Dvorak, J. (2005). Biomechanical investigation of head impacts in football. *British Journal of Sports Medicine, 39*(Suppl 1), i49-i57. doi:10.1136/bjsm.2005.019182

Worts, P. R., Schatz, P., & Burkhart, S. O. (2018). Test performance and test-retest reliability of the Vestibular/Ocular Motor Screening and King-Devick Test in adolescent athletes during a competitive sport season. *The American Journal of Sports Medicine, 46*(8), 2004-2010. doi:10.1177/0363546518768750

Young, T. J., Daniel, R. W., Rowson, S., & Duma, S. (2014). Head impact exposure in youth football: Elementary school ages 7-8 years and the effect of returning players. *Clinical Journal of Sport Medicine, 24*, 416-421. doi:10.1097/JSM.0000000000000055

Young, T. J., Rowson, S., & Duma, S. M. (2014). High magnitude head impacts experienced during youth football practices. *Biomedical Sciences Instrumentation, 50*, 100-105.

Appendix

COMMUNITY FOOTBALL HEAD INJURY ASSESSMENT

A. GENERAL INFORMATION

Player Name: Club:

Examiner Name: Date:

Quarter: Approximate Time in Quarter:

B. STRUCTURAL HEAD OR NECK INJURY

1. Are there clinical features of a serious or structural head and/or neck injury requiring urgent and emergency hospital transfer?[1] ☐ **Yes** ☐ No

C. REMOVAL FROM PLAY

The player **must** be removed from play with **any** of the following clinical features[2] observed directly, reported by others or from video review (if available):

	YES			NO
	Observed Directly	Reported	Video Review	
2. Loss of consciousness or prolonged immobility (> 2 seconds)	☐	☐	☐	☐
3. No protective action in fall to ground (not bracing for impact)	☐	☐	☐	☐
4. Impact seizure (stiffening arms or legs on impact)	☐	☐	☐	☐
5. Balance disturbance (loss of control over movements)	☐	☐	☐	☐
6. Dazed, blank/vacant stare or not their normal selves	☐	☐	☐	☐
7. Unusual behaviour change for the player	☐	☐	☐	☐
8. Confusion or disorientation	☐	☐		☐
9. Memory impairment (e.g. fails Maddocks questions[1])	☐	☐		☐
10. Player reports concussion symptoms[1]	☐	☐		☐

[1] Refer to the AFL Concussion Management Guidelines available on the AFL Community website: http://www.aflcommunityclub.com.au/.

[2] Example videos of each clinical feature are available on the AFL Community website.

D. OUTCOME AND ACTION

If 'Yes' is selected for question 1, it requires an ambulance to be called for immediate transfer to hospital ☐

If 'Yes' is selected for questions 2-9, it requires immediate removal from play and medical assessment[3] ☐

If 'No' is selected for questions 1-10, no criteria for removal from play for concussion[4] ☐

[5] A player who is removed from play for concussion or possible concussion must not return to play until cleared by a doctor.

[4] A player cleared to play requires regular checks at least every 30 minutes and removal from play with any deterioration.

E. SIGNATURE OF EXAMINER

Signed: _ Date: Time completed:

F. MEDICAL CLEARANCE – TO BE COMPLETED BY A MEDICAL PRACTITIONER

I have examined: following the above head injury and declared him/her medically fit[5] to train and play.

Practitioner Name: _

Medical Practice Stamp:

Signed: _

Date: _

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[5] Please refer to the medical check list over the page when assessing the player and determining his medical fitness to train and play.

NOTES FOR THE EXAMINING MEDICAL PRACTITIONER

Please refer to the AFL Concussion Management Guidelines available via the following website: http://www.aflcommunityclub.com.au/

A concussed footballer requires a medical clearance to return to training or competition.

In accordance with the current Concussion Guidelines, there is no mandatory period of time that an Australian Football player must be withheld from play following a concussion. The duration of exclusion from play is based on an individual's recovery as managed by a medical practitioner. It would not be unreasonable to clear the player to return to structured training with a second consultation to clear the player for full training/match play.

The minimum standard is that a player must be symptom free at rest and with exertion, determined to have returned to baseline level of cognitive performance, and is confident and comfortable to return to play.

Screening computerised cognitive tests provide a practical method for the assessment of cognitive recovery. A number of screening computerised cognitive test batteries have been validated for use following concussion in sport and are readily available (e.g. CogState Sport, ImPACT). Conventional imaging (e.g. CT or MRI) should be considered in cases where there is concern regarding an underlying structural injury.

The following is a guide to the medical examination of a concussed player:

- Are there any neurological symptoms on questioning or signs on examination?
- Is the player experiencing ongoing symptoms suggestive of concussion?
- Does the player experience concussion type symptoms when undertaking physical activity?
- Has the player not returned to their usual work or education?

If the answer to any of the above questions is 'Yes', the player requires further observation or a referral for specialist assessment.

If the player clears the above tests, ensure as per the AFL Community Concussion Guidelines the player complies with a graduated return to train and play protocol, with instructions for further medical assessment if the symptoms return.

Difficult or complicated cases (e.g. prolonged recovery or recurrent concussion) should be referred to a clinician or neurologist with expertise in concussion.