A Biomechanical Assessment of Direct and Inertial Head Loading in Rugby Union

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“Knowledge is knowing that a tomato is a fruit, wisdom is knowing not to put it in a fruit salad”.

Miles Kington/Brian O’Driscoll

Declaration

I, Gregory Tierney, declare that this thesis has not been submitted as an exercise for a degree at this or any other university and it is entirely my own work.

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Abstract

Rugby union is a territorial, dynamic and high-impact collision sport. Unfortunately, due to its physical and high impact nature, the incidence of concussion is high. There is mounting evidence that repeatedly sustaining concussion injuries can lead to long-term brain health issues. Furthermore, the adverse effects of repeated sub-concussive impacts in contact sport are an emerging concept. Despite this, little research has been conducted on the regular head loading environment associated with rugby union. In particular, the magnitude and influencing factors associated with direct head impacts and inertial head loading are poorly understood. Accordingly, the aim of this thesis is to biomechanically assess direct and inertial head loading in rugby union to identify prevention strategies. The thesis is split into two main areas: direct head impacts and inertial head loading.

For direct head impacts, an initial aim was to understand how head impacts were occurring in rugby union. A general video analysis review of elite level competitions discovered that the tackle accounted for 60% of direct head impacts. The tackler was much more likely to receive a direct head impact than the ball carrier. Additional video analysis identified tackle characteristics that have a lower propensity to result in a tackler Head Injury Assessment (HIA) and a positive influence on tackle success. Specific tackler proficiency variables were identified such as "identify/track ball carrier onto shoulder", "head up and forward/face up", "shortening steps" and "head placement on correct side of ball carrier". For the ball carrier, much fewer tackle characteristics were identified, however incorrect fending was identified as a risk factor for upper body front-on tackles. A large majority (81%) of tackle related direct head impacts occurred in the second half of games. A disproportionate number of direct head impacts from upper body tackles (63%) occurred in the final quarter. However, tackling proficiency was found to remain relatively constant throughout the game. Instead, more tackles occur in the final quarter of a game. Further video analysis identified that tackling at the upper trunk accounted for nearly half (47%) of all tackler HIAs and had no greater propensity to result in tackler success outcomes. Tackling at the upper trunk and upper legs had a greater propensity to result in a tackler HIA.

MBIM is a novel approach for measuring six degree of freedom head kinematics from uncalibrated multiple camera view video footage of sporting head impacts. An assessment was conducted on the accuracy of the MBIM method. A vehicle-cadaver head-windscreen impact case was utilised. Reflective marker-based motion capture system head kinematic time-histories were available as an independent measure. The method exhibited Root Mean Square Errors (RMSE) between 10-20 mm for linear displacement and 0.01-0.03 rad for rotational displacement for reconstructing 6 degree of freedom head motion. However, the MBIM method was deemed unsuitable for measuring componential angular velocity during direct head impacts (RMSE up to 5.61 rad/s). For inertial head loading, MBIM was utilised to measure the head kinematics of a visually unaware ball carrier during an active shoulder tackle to the upper trunk. The componential head angular velocities were similar to the average values previously reported for concussive direct head impacts. This is a potentially concern. It was postulated that lower tackle heights may reduce inertial head kinematics for the ball carrier.

Staged tackles in a motion analysis laboratory and multibody modelling simulations indicated that higher tackle heights cause greater ball carrier inertial head kinematics. By tackling below the upper trunk, the multibody simulations suggest that average ball carrier peak head linear acceleration, angular acceleration and change in angular velocity values could be reduced in the tackle by 35%, 61% and 40%, respectively. Based on the staged tackles, median ball carrier peak head linear acceleration, angular acceleration and change in angular velocity values could be reduced in the tackle by 44%, 55% and 57%, respectively. The MADYMO ellipsoid human body model was assessed for reconstructing head kinematics during the abovementioned staged tackles. The results indicated that the model is currently unsuitable for detailed reconstruction of head kinematics on an individual case basis. However, the model identified the kinematic trend that upper trunk tackles cause greater ball carrier inertial head kinematics than mid/lower trunk tackles, even with significant variations in initial player-to-player configurations and speeds.

The findings from this thesis provide an evidence base, at the elite level, for coaches to develop and implement technical based concussion prevention strategies. Focus should be placed on safe and proficient tackle technique. Upper trunk tackles were identified as a risk factor for direct head impacts for tacklers and high inertial head kinematics for ball carriers. Tackling at the upper trunk of the ball carrier should be discouraged. Instead, coaching strategies should place emphasis on tackling at lower HIA risk body regions such as the mid and lower trunk.

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Abbreviations

Abbreviation	Word/Phrase
3D	3-Dimensional
ATD	Anthropomorphic Test Device
BC	Ball Carrier
CG	Centre of Gravity
CMD	Common Mental Disorder
CSF	Cerebrospinal Fluid
CTE	Chronic Traumatic Encephalopathy
DOF	Degrees of Freedom
DP	Dementia Pugilistica
ES	Effect Size
FEHM	Finite Element Head Models
FPS	Frames Per Second
GRTP	Graduated Return to Play
HIA	Head Injury Assessment
ICC	Intra-class Correlation Coefficients
IRFU	Irish Rugby Football Union
LBT	Lower Body Tackle
M/LTT	Mid/Lower Trunk Tackle
MADYMO	Mathematical Dynamic Models
MBIM	Model-Based Image-Matching
MPS	Maximal Principal Strain
NFL	National Football League
OR	Odds Ratio
RMSE	Root Mean Square Errors
RR	Relative Risk
SCAT	Sports Concussion Assessment Tool
SD	Standard Deviation
T	Tackler
UBT	Upper Body Tackle
UTT	Upper Trunk Tackle
WSTC	Wayne State Tolerance Curve

Glossary

Term	Definition
Active shoulder tackle	Tackler impedes/stops the ball carrier with the shoulder as the first point of contact whilst also executing leg drive and/or forward momentum
Acute	Short term
Aetiology	The attribution of the cause or reason for something
Anterior	Related to or situated towards the front of the body.
Arm tackle	Tackler impedes/stops ball carrier with upper limb(s)
Chronic	Long-term
Coronal plane	Any vertical plane from left to right dividing the body into ventral (front) and dorsal (back) sections.
Chronic Traumatic Encephalopathy	A progressive neurodegenerative disease of the brain that has been linked to repetitive head trauma.
Head Injury Assessment	The Head Injury Assessment is the suspected concussion assessment protocol utilised in rugby union.
Inertial	Relating to or arising from inertia
Kinematics	Description of body motion without describing the forces that caused the motion
Posterior	Related to or situated towards the back of the body.
Propensity	An inclination, disposition or tendency
Sagittal plane	Any vertical plane from ventral to dorsal dividing the body into right and left sections.
Shoulder tackle	Tackler impedes/stops ball carrier with shoulder as the first point of contact followed by use of arm(s)
Smother tackle	Tackler impedes/stops ball carrier with upper limb(s)
Transverse plane	Any horizontal plane dividing the body into superior and inferior sections.
Zygomatic processes	A protrusion of the temporal bone

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Contents

1 Introduction

Rugby union is a territorial, dynamic and high-impact collision sport [1]. One of the primary aims is to forcibly penetrate the opposition's line of defence and score a "try". The attacking team attempts to advance the ball closer to the opposition try line by carrying and/or kicking the ball. Conversely, the defending team can prevent this forward movement by tackling the ball carrier. The physical and high impact nature of rugby union has made injury and concussion a concern [2]. In the 2016-17 season, the overall incidence of match injury in English Premiership rugby union was 96 per 1000 player hours (1000 player hours = 25 matches) [3]. For the sixth consecutive season, concussion was the most commonly reported match injury for English Premiership rugby union (incidence rate of 20.9/1000 player hours, contributing to 22% of all match injuries during the 2016-17 season) [3]. A systematic review study found rugby union to have a higher concussion incidence rate than American football [4].

Despite this, there is still little knowledge on the specific motion patterns associated with concussive impacts in rugby union. There is mounting evidence that repeatedly sustaining concussion injuries can lead to long-term brain health issues and adverse effects of repeated sub-concussive impacts have been reported [5-7]. A plethora of biomechanical research has linked head kinematics to brain injury [8-12]. However, the studies focus on the magnitude of a single hit. There is also an emerging concept of neuronal vulnerability to injury due to repetitive sub-concussive loading [13-15]. Therefore, it is argued that injury thresholds should not be based on the magnitude of a single hit. Instead, the number and magnitude of hits and the time between hits should all be considered [13]. This is particularly concerning for rugby union given its high impact nature. However, insufficient research has been conducted on the regular head loading environment associated with rugby union [16]. In particular, little is known about the magnitude and influencing factors for head kinematics during regular play without any direct head contact i.e. inertial head loading.

Clearly, a greater understanding in this area is needed to guide prevention strategies. A starting point is to split this thesis into two main areas: direct head impacts and inertial head loading. An understanding of how direct head impacts are occurring within the game is critical. Once understood, specific technical aspects of the game can be further analysed to identify risk factors and preventative measures. An examination of inertial head kinematics during high impact contact events will develop an initial understanding of the regular head loading environment associated with rugby union.

2 Background

2.1 Introduction

This chapter presents a background to the content of this thesis. It will focus on (1) anatomy of the head and brain; (2) concussion and sub-concussion definitions; (3) mechanisms of concussion; (4) fundamental kinematic theory (5) long-term effects of repeated concussion and sub-concussion; (6) concussion management in rugby union. This shall provide the reader with context and understanding of the pertinent knowledge underlying this thesis.

2.2 Anatomy of the human head and brain

The brain is the most vital organ in the human body. Natural evolution has led to a range of integrated protection devices, mainly the scalp and skull [17]. Unfortunately, these structures have not fully adapted to the dynamic loading conditions associated with modern road and sports accidents [18].

2.2.1 Anatomy of the human head

The human head (cranium) is a multi-layered structure. The scalp is the outermost layer of the human head followed by the skull, the meninges and finally the brain and spinal cord (Figure 1) [19]. The thickness of the scalp is about 5-7mm and it mainly consists of hair bearing skin. Loose connective tissue below the scalp covers the bony skull [19]. The skull is a complex structure consisting of a range of bones, of varying thickness and curvature, fused together [17].

The meninges provide protection and support for the spinal cord and brain whilst separating them from surrounding bone [19]. The three membranes of the meninges are the dura mater (periosteal and meningeal), arachnoid mater and the pia mater (Figure 1). The dura mater is a tough and fibrous membrane. The arachnoid mater and pia mater are separated by the subarachnoid space [19]. The arachnoid mater is considered to resemble a spider's web. The pia mater surrounds the brain (cerebral cortex), dipping into the fissures [19]. A range of blood vessels cross the meninges to supply the brain and scalp [19].

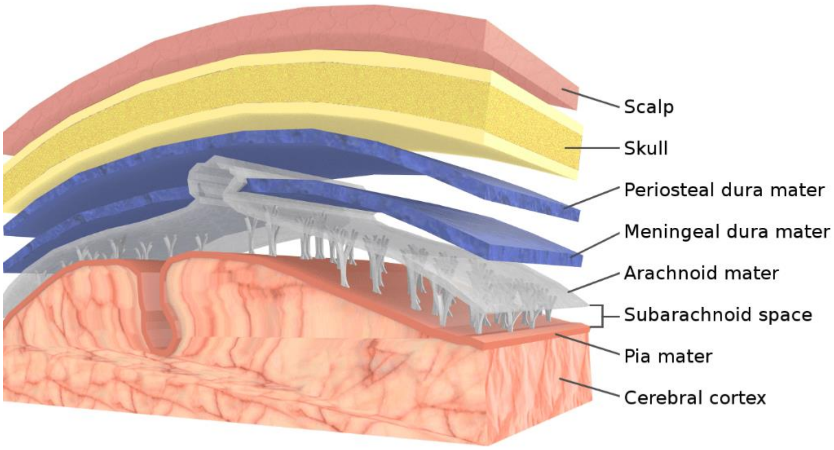

Figure 1. A subsection of the human skull and brain [20].

Cerebrospinal fluid (CSF) fills the subarachnoid space and the brains ventricles. This cushions the brain from mechanical shock [19]. CSF is constantly circulating and surrounding the brain. CSF moderates impacts to the head and supports the weight of the brain [19].

2.2.2 Anatomy of the human brain

The brain serves as the centre of the nervous system [17]. The main functions of the brain are to store, retrieve and process information. Different regions of the brain work together to react appropriately to stimuli [17]. The brain consists of three main areas (Figure 2):

- The Cerebrum
- The Cerebellum
- The Brain Stem

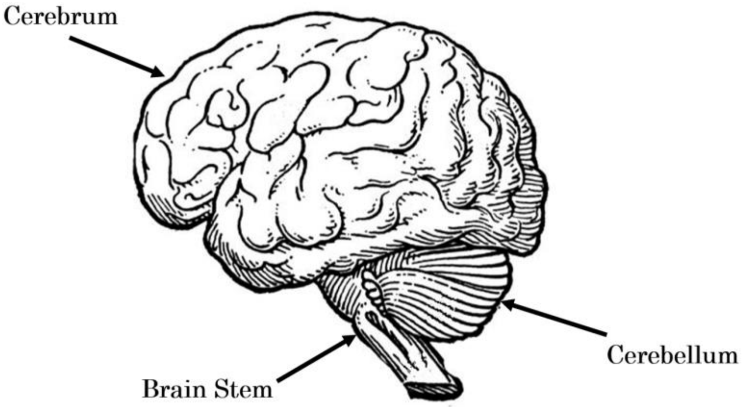

Figure 2. The three main regions of the brain.

2.2.2.1 The cerebrum

The cerebrum is the bulkiest part of the brain [18]. This is where thought processes and muscle control occur. The cerebrum is composed of two halves (left and right hemispheres [20]). Furthermore, the cerebrum is made up of two layers. The cerebral cortex (grey matter) is the outer most layer, beneath which lies a thick mass of white matter [20]. Each hemisphere is comprised of portions known as lobes (Figure 3). The corpus callosum is a large band of nerve fibres that connects the left and right cerebral hemispheres. Damage to the corpus callosum is regarded as one of the main mechanisms for concussion [21, 22].

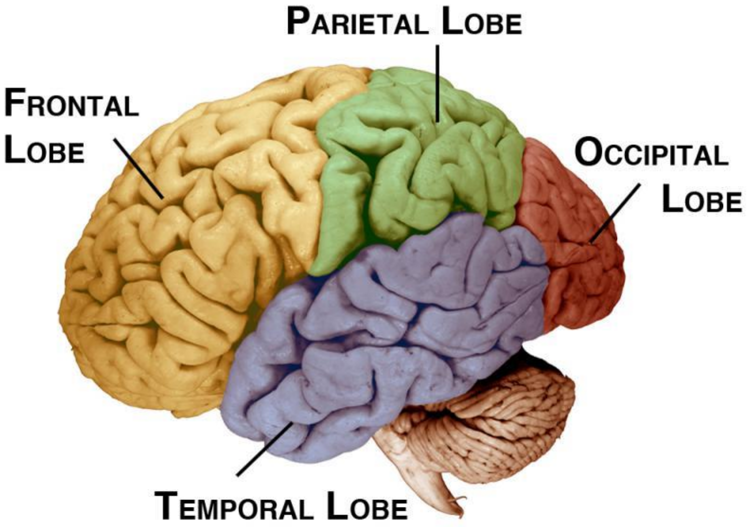

Figure 3. The four lobes which form the cerebral cortex [18].

2.2.2.2 The cerebellum

The cerebellum is located at the posterior of the brain, below the occipital lobe (Figure 3) and attached to the back of the brain stem, spinal cord and cerebrum [18]. The cerebellum is mainly associated with autonomous responses and behaviours and simple motor movement coordination. Damage to the cerebellum can have an adverse effect on the stability of posture and gait, planning and visual spatial organisation [18].

2.2.2.3 The brain stem

The brain stem is connected to the spine and located at the base of the brain. It is composed of the medulla oblongata and the pons. Most of the brain stem is composed of white matter nerve fibres that connect the cerebral and cerebellum hemispheres

[18]. The brain stem maintains basic but important body functions such as breathing, swallowing, digestion and heartbeat. Minor damage to the lower pons or upper medulla oblongata can cause vertigo, nausea and vomiting [18].

2.3 Definition and nature of concussion and sub-concussion

2.3.1 Concussion

Concussion has been defined as “a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces” [23]. Common features including clinical, pathological and biomechanical injury constructs can be used to define the nature of a concussion injury [24]. These are as follows [24]:

- A concussive head injury may be due to a direct blow to the head (direct head impact) or elsewhere on the person’s body where an impulsive load is transmitted to the head (inertial head loading).
- A typical concussion results in the quick onset of very temporary impairment of neurological function that is resolved spontaneously. However, symptoms can take up to 48 hours to become apparent [25].
- Resolution of the clinical and cognitive symptoms of concussion usually follow a sequential course.

Unlike many sport injuries, detecting a concussion is difficult as the neuropathological changes cannot be recognised on standard neuroimaging technology [26, 27]. Emphasis is placed on detecting the signs and symptoms associated with the injury.

2.3.1.1 Signs and symptoms of concussion

The diagnosis of concussion in rugby union is generally made by medical personnel. The signs and symptoms include clinical symptoms, physical signs, cognitive impairment as well as loss of consciousness. A Head Injury Assessment (see, Section 2.7) should be conducted on a player presenting any of the signs or symptoms presented in Table 1.

Table 1. The signs and symptoms of concussion [24].

Cognitive problems	Physical signs
Unaware of period, opposition, score of game	Loss of consciousness/impaired conscious state
Confusion	Poor coordination or balance
Amnesia	Concussive convulsion/impact seizure
Loss of consciousness	Gait unsteadiness/loss of balance
Typical symptoms	Slow to answer questions or follow directions
Headache or pressure in the head	Easily distracted, poor concentration
Balance problems or dizziness	Displaying inappropriate emotions—for example, laughing or crying
Nausea	
Feeling “dinged”, “foggy”, stunned, or “dazed”	Vomiting
Visual problems—for example, seeing stars or flashing lights, double vision	Vacant stare/glassy eyed
	Slurred speech
Hearing problems. For example, ringing in the ears	Personality changes
Irritability or emotional changes	Inappropriate playing behavior. For example, running in the wrong direction
Feeling of slowness and fatigue	
	Significantly decreased playing ability

2.3.2 Sub-concussion

Sub-concussion is defined by head motion or impacts “that do not result in symptoms typically used to define concussion such as loss of consciousness, amnesia, confusion and headache” [13]. This definition presents some challenges as a lower threshold for sub-concussive impacts has not been established. However, for practical purposes, impacts that result in less than 10g head acceleration have generally not been considered in rugby union head kinematic studies [28, 29]. Head impacts under 10g have been reported for activities such as walking, jumping, running, and sitting [30] and are considered noncontact events.

Sub-concussive impacts do not necessarily require direct contact with the head [24]. For example, engaging in a tackle at speed can result in inertial head loading due to the forces and torques transmitted through the neck from an impact to the body [31, 32]. A given rugby union player can be involved in over 30 tackles per game [33]. However, little is known about this in biomechanical terms.

2.4 Mechanism of concussion

For over 70 years, biomechanical research has focused on understanding the mechanism of concussion [21, 34]. There is uncertainty throughout the literature about the mechanical aetiology of concussion. This confusion can be derived from the diverse range of head motions that can occur when the head is impacted [35]. Upon impact, there are two main components of head motion; linear and rotational, see Figure 4.

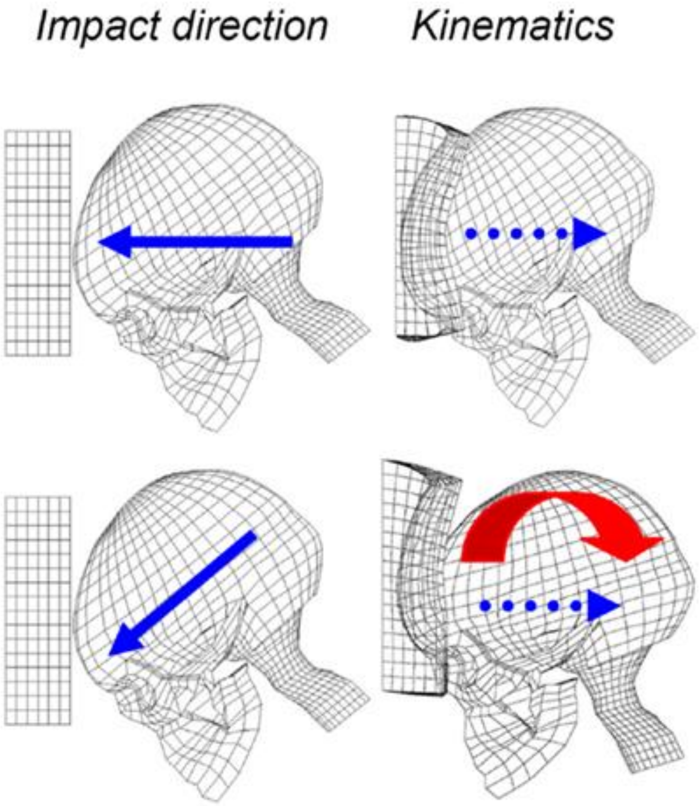

Figure 4. The effect of impact and loading direction on skull kinematics. The blue solid and dotted arrows indicate the linear head motion before and after impact, respectively. The red arrow indicates the head rotational motion after impact. [36].

2.4.1 Linear motion

As a result of an impact, the brain and skull move relative to each other [37, 38]. The difference in response is caused by a rise in pressure at the impact site with the skull pressing against the brain (coup). At the opposite end there is a drop in pressure as the brain lags behind the moving skull (contre coup) [39] (Figure 5).

2.4.2 Rotational motion

Concussion is a diffuse brain injury [40]. As the name suggests, diffuse brain injuries are distributed across the brain and not localised to one area (focal injuries) [40]. It is believed that linear motion causes focal injuries whereas rotational motion can cause both focal and diffuse injuries [41].

The brain has a high bulk modulus but low shear modulus [42]. The bulk modulus is an extension of Young's modulus to three dimensions [42]. Therefore, the brain has a high ability to resist changes in volume (high bulk modulus) but a poor ability to resist changes in shape (low shear modulus). The bulk modulus of brain tissue is roughly five to six times greater in magnitude than the shear modulus [36]. This means that the brain tends to deform primarily in shear when the head is impacted [36, 43]. Therefore, brain strain has a large sensitivity to rotational loading and a small sensitivity to linear [36]. Thus, it is suggested that rotational kinematics are a greater indicator of brain injury risk than linear [36].

Rapid head rotations result in shear forces throughout the brain [36]. This causes deformation and shear induced tissue damage (Figure 5) [36]. Many studies report rotational motion as the main mechanism for concussion [44-46]. One study on primates found that if head motion does not include any rotational movement and is purely linear, it is difficult to cause unconsciousness [47]. However, including rotational movement after impact significantly increased the possibility of unconsciousness [47]. A concussion injury in rugby union does not have to involve the player being unconscious [24]. Given that the concussion injury mechanism is still debated and not yet fully understood, both linear and rotational motion should be considered during analysis.

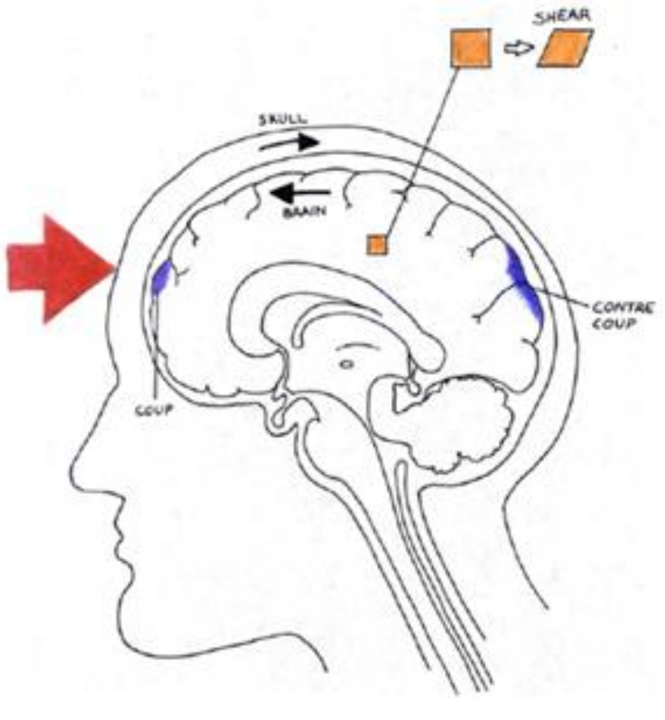

Figure 5. Coup/contre coup and shearing mechanism of the brain due to impact [36].

2.5 Rotational kinematics

2.5.1 Successive rotation angles and the rotation matrix

Successive rotation angles are a way of representing the spatial orientation of a coordinate system. Successive rotation angles are a composition of three elemental successive rotations beginning from a known standard orientation, often known as the global coordinate system [48]. In multibody kinematics, the rotated coordinate system is often assumed to be attached to a rigid body and is known as the local coordinate system of that body. The local coordinate system therefore represents the orientation of that body with respect to the global coordinate system. This orientation can be expressed by a 3x3 matrix, known as the rotation matrix.

The rotation matrix can be developed using successive rotation angles [49, 50]. Rotations in three dimensions are dependent on the successive rotation order. The Yaw- Pitch-Roll (Z-Y-X) successive rotation sequence is one of the most widely used [49] and will be utilised in this thesis. The Yaw-Pitch-Roll successive rotation order is; Yaw (ψ) - rotation about Z-axis (Z- global coordinate system); Pitch (θ) - rotation about new Y-axis (Y' – 1st frame); Roll (ϕ) - rotation about new, new X-axis (X"-2nd frame), see Figure 6.

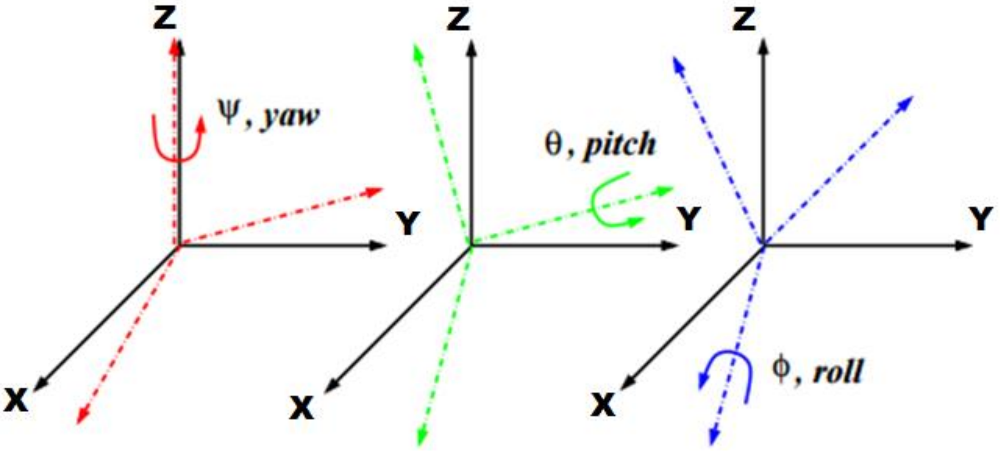

Figure 6. Schematic of the Yaw-Pitch-Roll cardan angle sequence

2.5.2 Angular velocity and acceleration

At any moment, the angular velocity vector in the body local coordinate system can be described by its three components ($\omega_x, \omega_y, \omega_z$). These are related to the yaw (ψ), pitch (θ) and roll (ϕ) angles and their time derivatives [49, 50] (Equation 1).

$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = \begin{bmatrix} 1 & 0 & -sin\theta \\ 0 & cos\phi & cos\theta cos\phi \\ 0 & -sin\phi & cos\theta cos\phi \end{bmatrix} \begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} \qquad \text{Equation 1}$$

Where $\dot{\phi}$, $\dot{\theta}$ and $\dot{\psi}$ represent the time derivatives of the roll, pitch and yaw angles respectively (SI Units = rad/s). ω_x, ω_y and ω_z represent the angular velocity vector in the body local X, Y and Z axes respectively (SI Units = rad/s). The angular acceleration of an object is defined as the rate of change of its angular velocity (SI Units = rad/s^2). At any moment, angular acceleration can be described by its three vector components resolved in a given coordinate system (usually the body local or global) coordinate system.

2.6 Long-term effects of repetitive concussion and sub-concussion

2.6.1 Concussion

Chronic Traumatic Encephalopathy (CTE) [51] is a progressive degenerative disease of the brain believed to be linked with repetitive head trauma [51, 52]. Initial symptoms include memory difficulties, cognitive difficulties, depression, behavioural problems and dementia [53]. The sufferer can exhibit Parkinsonism tendencies, speech problems and paranoia [54]. CTE is believed to be linked to participation in contact sports such as boxing, American football and ice hockey [53]. Symptoms tend to appear years after player retirement [53]. Dementia Pugilistica (DP) is the former name of Chronic Traumatic Encephalopathy [52] as it was mainly associated with boxers (pugil). A study on boxers found DP to develop progressively over a long period of time, usually 10-20 years [52]. Repetitive concussive and sub-concussive impacts were believed to be the cause of the condition [52]. Significant epidemiological evidence supports traumatic brain injury as a risk factor for the development of dementia [55]. Identification of CTE in a small sample of athletes, from American football, has sparked considerable public interest in the area [55]. However, significantly more work is required to clearly define CTE as a disease both pathologically and clinically [55]. Risk factors for CTE development such as mechanism, frequency and severity remain largely unknown [55]. One study [56] of 576 former male professional athletes (mean professional sports career of 10 years) found that athletes with a reported history of four or five career concussions were roughly 1.5 times more likely to report symptoms of Common Mental Disorders (CMDs). This rose to a two- to four-fold increase in athletes reporting a history of six or more sports career-related concussions. These CMDs included symptoms of distress, anxiety/depression, sleep disturbance and adverse alcohol use. Reduced processing speeds and cognitive function have been shown in rugby players who suffered 3 or more concussions in their playing career in comparison to those who suffered none [57]. Professional rugby union players have been forced to retire early due to repeatedly sustaining concussion injuries, however the overall brain health of these players has not been reported in the literature [16].

2.6.2 Sub-concussion

Repeated sub-concussive head impacts in sports, such as boxing and soccer, have already been associated with acute changes in brain function using functional magnetic resonance imaging techniques [6, 7], structural white matter changes using diffusion tensor imaging [58-62], biomarkers of neuronal injury [63-66] and short term cognitive impairments [67]. Sub-concussive impacts have also been associated with long term white matter changes [68, 69], lower brain volume [70] and long term cognitive defects [71, 72]. Although the long-term effects are not yet fully understood, it is believed that repeatedly engaging in sub-concussive impacts can lead to long term neurodegeneration and may play a role in the pathogenesis of CTE [53, 73]. Some studies have shown that rugby players, even those without a history of concussion, have reduced visuomotor processing speeds [74] and short term visual memory [75] in comparison to athletes from non-contact sport controls. Hume et al. [76] found that rugby players, including those without a history of concussion, have worse reaction times, psychomotor speeds and visual and verbal memory in comparison to age matched norms. On the contrary, a study on retired rugby league players identified no significant differences in measures of depression, anxiety or cognitive function when compared with controls [77]. A recent systemic review of long-term brain health in retired rugby players highlighted the need for prospective longitudinal studies taking into account both concussion history and overall head impact exposure [16].

2.7 Concussion management in rugby union

If a player is diagnosed with a concussion, they must follow the Graduated Return to Play (GRTP) protocol (Table 2). A player cannot move to the next stage until they have been symptom free during the entire period of each stage. Most players' symptoms resolve over a small time period, however for some it is a gradual and lengthy recovery [51, 78, 79]. The Irish Rugby Football Union (IRFU) strengthened its medical opinion on concussion injuries and published concussion guides targeted at amateur players, officials and parents [80]. It is now compulsory that all accredited rugby coaches must complete a World Rugby concussion module. The IRFU has implemented that any player, under the age of 20, who is diagnosed with a concussion must be removed from play for a minimum of 23 days, based on the GRTP protocols. Any amateur player above the age of 20 is removed from play for a minimum of 21 days [80]. The protocol encompasses six sequential stages: (1) physical and cognitive rest until asymptomatic; (2) light aerobic exercise; (3) sport specific exercise; (4) non-contact training drills; (5) full contact practice; (6) return to play. Professional players can progress through each stage if they remain asymptomatic for an unbroken period of 24 hours and can return to play in as little as 6 days [2].

Table 2. The Graduated Return to Play (GRTP) protocol [80].

Rehabilitation stage	Exercise at each stage of rehabilitation	Objective of stage	Adult (Amateur)	U6's - U20's
Rest	None	Rest	14 days	14 days
1. No activity	Complete physical and mental rest without symptoms	Recovery	1 day	14 days
2. Light aerobic exercise	Walking, swimming or stationary cycling keeping intensity <70% maximum predicted heart rate (Max predicted heart rate = 220 – Player Age). No resistance training	Increase heart rate	1 day	2 days
3. Rugby-specific exercise	Running drills. No impact activities	Add movement	1 day	2 days
4. Non-contact training drills	Progression to more complex training drills e.g. passing drills. May start progressive resistance training	Exercise, coordination and mental load	1 day	2 days
5. Following medical clearance, full contact practice	May participate in normal training activities	Restore confidence and assess functional skills by coaching staff	2 days	2 days
6. After 24 hours, return to play	Player rehabilitated	Recovered	2 days	23 days

2.7.1 The Head Injury Assessment and Sport Concussion Assessment Tool

World Rugby states that if a player is concussed in a match, they must be removed from the game immediately and not allowed to return to the field of play. In 2012, World Rugby introduced the Pitch-side Suspected Concussion Assessment (PSCA) trial. Any player who was suspected of sustaining a concussion was taken off the field and given a five-minute medical assessment [81]. As of June 2014, the length of time permitted to undertake the PSCA was extended to 10 minutes [82]. The PSCA was renamed the Head Injury Assessment (HIA) in July 2014.

The aim of the HIA and Sports Concussion Assessment Tool (SCAT) is to create a standardised tool for the medical assessment of concussion in rugby union during and after a game, respectively [24]. The HIA and SCAT assess a range of concussive symptoms including memory difficulties, cognitive ability, balance and player discomfort. The HIA and SCAT have been evaluated and validated on a wide range of scientific literature [83]. It has been acknowledged that the content of the HIA and SCAT will be modified as research around concussion diagnosis evolves [25]. A player enters the HIA protocol by displaying on-field signs and symptoms of concussion [24]. If a player fails any area of the HIA, they are removed from play and must follow the return to play protocol. Even if the player passes the HIA, the team doctor can overrule it. After the game, the player is medically assessed using the SCAT. This is a more rigorous assessment for evaluating concussion.

2.8 Conclusion

Concussion is an injury of the brain for which a wide range of signs and symptoms exist. Sideline medical staff utilise these to identify a suspected concussion on the field. Suspected players are removed from play and further assessed using the HIA protocol. There is a growing body of evidence suggesting that repeated concussive impacts can lead to long-term brain issues. Clearly a reduction in concussion incidence would benefit rugby union as a sport. Rugby players without a concussion history are exhibiting reduced cognitive ability. Therefore, the regular sub-concussive loading environment associated with the game may be adversely affecting long-term brain function.

3 Literature review

3.1 Introduction

This chapter gives a detailed overview of the applicable literature surrounding concussion. The literature review focuses on six main areas: (1) Injury definition and research approach; (2) Concussion epidemiology in rugby union; (3) Head protection equipment and strategies in rugby union; (4) Methodological approaches to concussion injury research; (5) Relationship between brain injury and mechanical metrics.

3.2 Injury definition and research approach

In sports injury research, inconsistent results and conclusions can be achieved by variations in injury definition [84, 85]. Fuller et al. [86] developed a consensus statement regarding injury definitions and collection procedures for soccer. The statement provided other sports (including rugby union) with a basis for universal injury definitions and collection procedures. An injury was defined as, "Any physical complaint sustained by a player that results from a football match or football training, irrespective of the need for medical attention or time loss from football activities [86]." When a player's condition is assessed by a qualified medical doctor/physiotherapist, this is referred to as "medical attention." Any injury that results in a player not fully taking part in future training or match play is referred to as a "time loss injury [86]." Fuller et al. [86] defined injury severity as, "The number of days that have elapsed from the date of injury to the date of the player's return to full participation on team training and availability for match selection [86]." The classification of time loss injuries based on days absent from training and/or match play can be seen in Table 3. In some sports, other injury parameters can be used to describe injury severity such as rehabilitation costs, duration of injury and quality of life [86, 87].

Table 3. Time loss injury classification [88].

Severity Classification	Days absent from training and/or match play
Slight	0
Minimal	1-3
Mild	4-7
Moderate	8-28
Severe	>28
Career Ending	N/A

3.2.1 Epidemiology

The objective of carrying out epidemiological research is to prevent injuries occurring in the future [84]. The first step is to carry out injury surveillance to classify the magnitude of the problem. The main questions asked at this stage are:

- What is the incidence of injury?
- What injury occurs most frequently and at what location?
- How severe is this injury?

The second step is to identify the risk factors and mechanisms that play a role in the occurrence of the injury. The main questions asked at this stage are:

- What is causing the injury?
- Why and how does this injury occur?

The third step is to develop measures that potentially decrease the risk and/or severity of the injury in the future. To introduce effective prevention strategies, it is important that this step is based on reliable and valid data collected in the first two stages. The main questions asked at this stage are:

- How can this injury be prevented?
- How much can the risk and/or severity of this injury be reduced?

The fourth step is to evaluate the efficacy of the measures taken by repeating step one. A flow chart of this process can be seen in Figure 7.

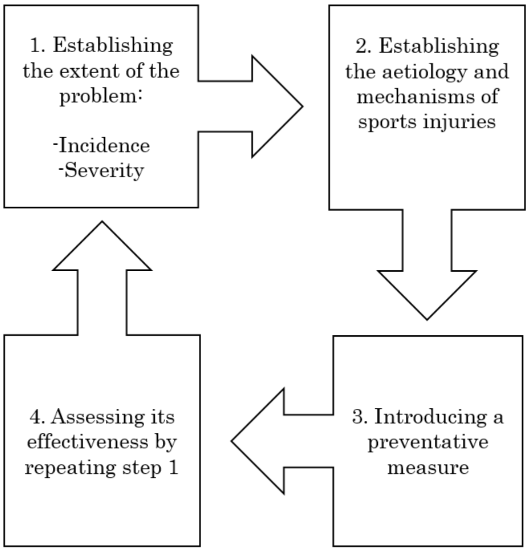

Figure 7. The four main steps to injury prevention research adapted from [84].

The complicated interaction between internal (individual-related) and external (environmental-related) risk factors must be understood when assessing injury aetiology [89]. Age, gender, skill level and physical fitness are examples of internal risk factors. Pitch conditions, weather conditions and protective equipment are examples of external risk factors. The combination and interaction of these risk factors can influence player susceptibility to injury.

However, an inciting event is required for an injury to occur. The inciting event is usually regarded as the "injury mechanism." Though, the term is used widely and not well defined [88]. A detailed and precise description of the inciting event is critical [90]. There are several factors that constitute the inciting event [90]. These factors are essential for understanding injury mechanisms and prevention (Figure 8). To identify the mechanism responsible for injury, non-injury scenarios must also be assessed [91]. This acts as a control for the study and helps distinguish the critical components of the injury mechanism.

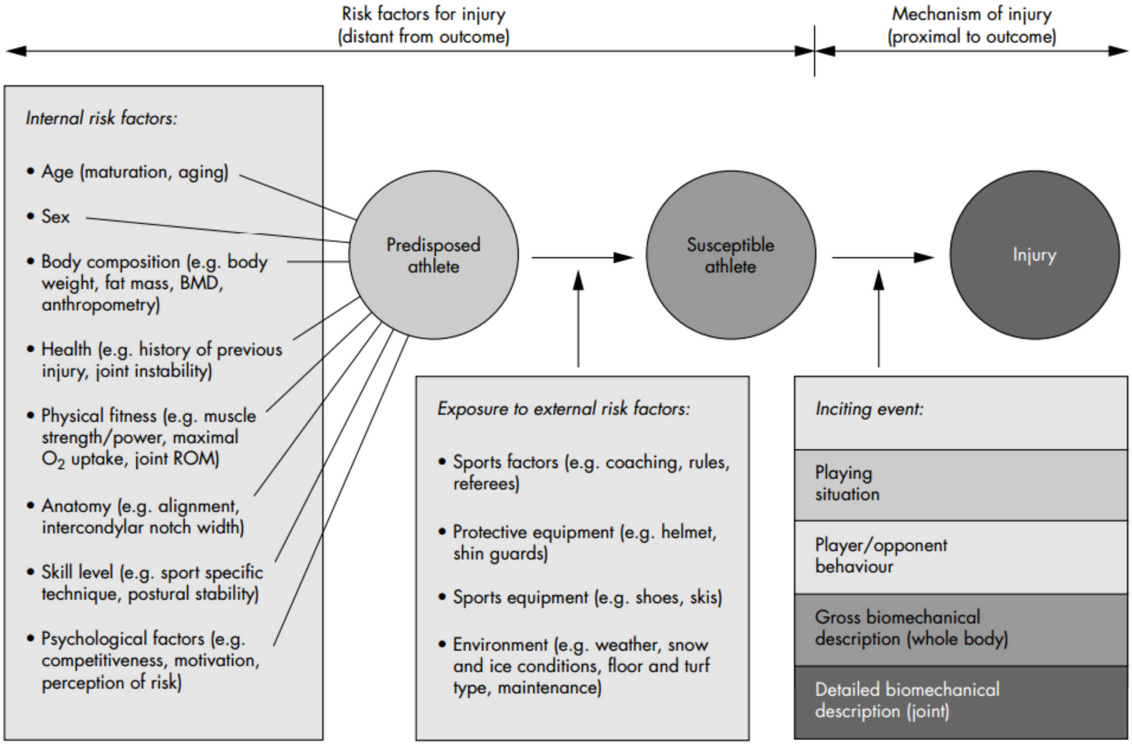

Figure 8. Comprehensive model for injury causation [90].

The McIntosh et al. [92] multifactorial biomechanically focused injury model indicates that acute injury can occur by a single inciting event when a body part's injury tolerance levels are surpassed. An example of this would be an ankle break from a sliding tackle in soccer. The model also indicates that chronic injury can develop by a body part's injury tolerance level decreasing, through repetitive loading and micro-trauma, to the point where normal loads can no longer be tolerated [92]. An example of this is tennis elbow [92]. For rugby union, Hendricks et al. [93] postulated that an upper limit exists for a player's ability to repeatedly engage in high energy impact tackles. Furthermore, this limit is higher for elite level players. Hendricks et al. [93] also postulated that once this upper limit is surpassed, player injury risk significantly increases. Previous studies found that the number of tackles a rugby player engages in is related to markers of muscle damage [94, 95]. This may also be the case with the brain. A tackler's shoulder can experience contact forces over 3500 N [96]. This may result in considerable inertial head loading and micro-trauma to the brain during a tackle event. However, this has never been evaluated.

3.3 Concussion epidemiology in rugby union

3.3.1 Demographic data

Professional rugby union players are generally tall and heavy (Table 4). Players are becoming heavier mainly due to the professional development of the sport [97, 98].

Table 4. Player demographics (mean ± SD) of Irish provincial club players. Each team number represents a provincial club team in Ireland [99].

	Team 1 (n = 36)	Team 2 (n = 49)	Team 3 (n = 50)	Team 4 (n = 37)
Age (years)	24.97 ± 4.11	24.51 ± 3.89	23.44 ± 2.91	24.46 ± 3.78
Height (ms)	1.85 ± 0.06	1.85 ± 0.09	1.87 ± 0.07	1.86 ± 0.08
Weight (kg)	100.00 ± 12.11	101.18 ± 11.71	101.24 ± 11.78	101.47 ± 12.20
Experience (years)	13.49 ± 5.79	15.14 ± 4.37	14.98 ± 4.22	14.19 ± 4.62
Forwards/Backs	18/18	20/29	19/31	13/24

3.3.2 Concussion incidence

A review study on collegiate level sport found that the concussion incidence in rugby union is higher than that of American football [4]. Lacerations and concussions are considered the most common head injuries in rugby union [100]. Concussion incidence at the Rugby World Cup has increased successively since 2007 (Table 5) [101-103]. However, studies utilising retrospective questionnaires discovered that concussion injuries had a history of going unreported due to insufficient knowledge of concussion symptoms, not wanting to be removed from the game and/or a delay in diagnosis [99, 104]. Therefore, a number of concussion injuries remained unreported, undetected and unmanaged. Improvements in concussion awareness and guidelines are believed to have improved this issue [105].

Table 5. The number of concussion injuries reported at the previous three Rugby World Cups [101-103].

Rugby World Cup Year	Number of Concussions Reported
2015	20
2011	15
2007	5
2003	4

Over three seasons (2002/03, 2003/04 and 2005/06), a detailed epidemiological study was conducted to define the incidence, nature, severity and causes of head injuries in professional rugby union. A total of 757 male participants, from 13 English Premiership clubs were utilised [106]. For match play, 6.6 head injuries per 1000 player-hours occurred resulting in 14 days lost-time on average. Concussion injuries contributed to 4.1 injuries per 1000 player-hours and were the third most commonly reported match injury for English Premiership rugby union. More recently, an English professional rugby union injury surveillance report [3] found that concussion injuries contributed to 20.9 injuries per 1000 player-hours in the 2016/17 season (contributing to 22% of all match injuries). This was a significant increase to that reported by Kemp et al. [106]. The report also stated that for the sixth consecutive season, concussion was the most commonly reported match injury for English Premiership rugby union [3]. At school level, a prospective injury surveillance study on Ulster schoolboys rugby found the head/face as the most common site for injury (23.9%) [107]. Concussion was the second most reported injury (19%) behind muscle sprains (31.2%) [107].

3.3.3 High risk concussion phases

Tackling is the most common cause of contact in rugby union [108]. Unfortunately, it is also the main cause of injury and concussion [101, 103, 109-114]. Studies show that proficient tackle technique is important for safe participation in rugby union [93, 115], and poor tackle technique is a reported risk factor for injury [116, 117].

3.3.3.1 Tackle technique

Fuller et al. [118] defined the following for arm, shoulder and smother tackles in rugby union (Figure 9); Arm Tackle - "Tackler impedes/stops ball carrier with upper limb(s)"; Shoulder tackle - "Tackler impedes/stops ball carrier with shoulder as the first point of contact followed by use of arm(s)"; Smother tackle - "Tackler uses chest and wraps both arms around ball carrier." Furthermore, McIntosh et al. [119] defined active shoulder tackles as the tackler impedes/stops the ball carrier with the shoulder as the first point of contact whilst also executing leg drive and/or forward momentum (Table 6).

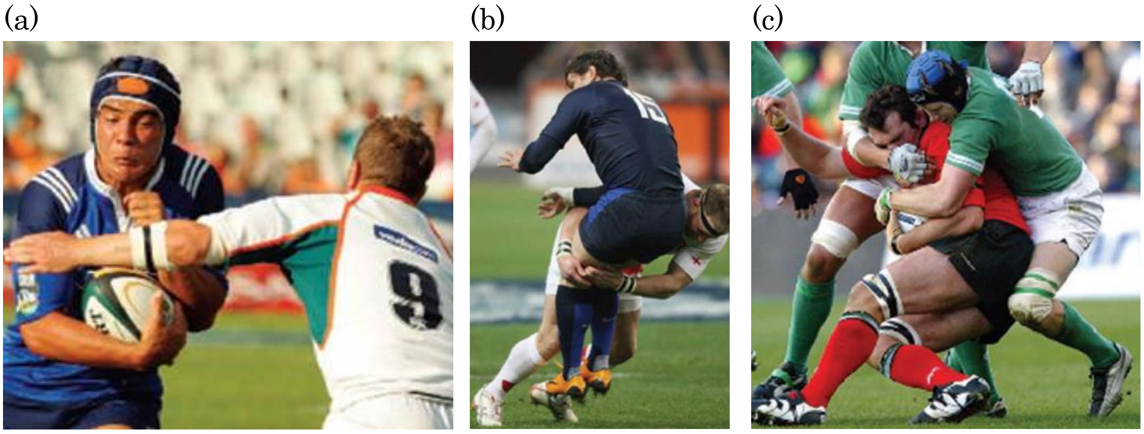

Figure 9. Examples of an (a) arm tackles, (b) shoulder tackle and (c) smother tackle [118].

Burger et al. [116] conducted an in-depth video analysis study on South African youth level rugby union players. Technical based criteria were created for assessing ball carrier and tackler proficiency in front- and side-on tackles. The criteria were based on studies that examined tackling proficiency in collision sports [1, 120-122] and tackle technique guidelines from the South African Rugby Union [123]. The criteria were appraised by a group of rugby union coaches, medical personnel and sport scientists. Accordingly, detailed technical criteria for both the tackler (Table 6) and ball carrier (Table 7) for front- and side-on tackles were proposed. Any tackle initiated outside the ball carrier's estimated peripheral vision was considered a side-on tackle [32, 116]. Burger et al [116] focused on general tackle injuries in a youth level rugby union competition. However, the mechanism of injury may not be the same for all tackle-related injuries [90]. It is possible that specific tackling characteristics are linked to concussion injury aetiology but the details are currently unknown.

3.3.3.2 Contemporaneous tackle technique literature

Several video analysis studies on tackle technique have been conducted since the publication of the journal articles associated with this thesis. The studies correlated various aspects of the tackle (e.g. speed, head positioning and proficiency) to direct head impact risk. The approaches and outcomes of the studies are similar to those presented in this thesis. Therefore, the studies will be discussed in detail in the discussion sections of the associated study chapters (Section 5.4 and 7.4).

Table 6. Tackler proficiency characteristics utilised by Burger et al. [116] (adapted from Hendricks and Lambert [115]) for front- and side-on tackles (f.o. pertains to only front-on tackles; s.o. pertains to only side on tackles).

Tackler proficiency characteristic	Description
Identify/track ball carrier onto shoulder	Identify ball carrier and position to ensure shoulder contact is made.
Body position - Upright to low	Reposition from an upright to crouched/bent at the waist body position i.e. lower centre of gravity.
Straight back, centre of gravity forward of support base	Exhibit a straight back with centre of gravity forward of the support base (point of contact the tackler's feet make with the ground).
Square to ball carrier (f.o.)	Align body position with ball carrier.
Boxer stance (elbows close, hands up) (f.o.)	Bend elbows with hands raised above the level of the elbow.
Head up and forward/face up	Manoeuvre head to face towards ball carrier.
Shortening steps	Exhibit shorter and faster steps when approaching ball carrier (feet remain active).
Approach from front/oblique (f.o.)	Approach ball carrier from front-on or at an oblique angle.
Explosiveness on contact	Execute rapid movement to maintain contact.
Contact with shoulder opposite leading (f.o.)	Contact ball carrier with opposite shoulder to leading leg.
Contact in centre of gravity	Contact ball carrier in centre of gravity (upper pelvis/lower torso).
Head placement on correct side of ball carrier	Place head beside or behind ball carrier's body.
Shoulder usage (drive into contact)	Manoeuvre shoulder to disrupt ball carrier.
Arm usage (punch forward and wrap i.e. hit-and-stick)	Wrap arms around ball carrier and maintain hold.
Leg drive on contact	Engage and drive the legs (lift knees).
Pull ball carrier with arms to ground (s.o.)	Bring ball carrier to ground using the arms.
Release ball carrier and compete for possession	Release ball carrier, get back onto feet and compete for possession.

Table 7. Ball carrier proficiency characteristics utilised by Burger et al. [116] (adapted from Hendricks and Lambert [115]) for front- and side-on tackles (f.o. pertains to only front-on tackles; s.o. pertains to only side on tackles).

Ball carrier proficiency characteristic	Description
Eyes Focused on tackler (f.o.)	Focus eyes towards tackler.
Aware of tackler (attunement) (s.o.)	Obtain visual awareness of tackler.
Shifting the ball away from contact	Move the ball away from the point of contact.
Body position - Upright to low	Reposition from upright to crouched/bent at the waist body position i.e. lower centre of gravity.
Body Position-Straight back	Exhibit a straight back.
Head up and forward, eyes open	Manoeuvre head to face towards tackler.
Shuffle or evasive manoeuvre	Shuffle, side-step or change direction to attempt contact evasion.
Fending into/away from contact	Utilise arm to contact/repel the tackler.
Side-on into contact (f.o.)	Contact side-on with hard parts of the body i.e. shoulders and hips.
Explosiveness on/away from contact	Execute rapid movement to break contact.
Body position- from low body position up into contact (f.o.)	Drive the body upwards into contact from a crouched/bent at the waist body position.
Ball protection	Ensure ball remains secure in possession.
Leg drive on contact	Engage and drive the legs (lift knees).
Arm and shoulder usage (f.o.)	Manoeuvre arm and shoulder to disrupt tackler.
Go to ground and present ball/offload	Go to ground and present ball in the ruck or pass ball to teammate.

3.3.4 High risk concussion positions

Kemp et al. [106] found that the midfield backs (Fly half (#10), inside centre (#12) and outside centre (#13)) were at highest risk of sustaining a concussion. Brooks et al. [113] and Quarrie and Hopkins [110] state that backs suffer from a greater number of concussions due to the high-speed nature of their role. On the contrary, reports have shown that forwards are more likely to sustain concussion [101, 109, 112]. Forwards engage in potentially more dangerous aspects of the game such as rucks and mauls.

In the 2011 Rugby World Cup, forwards suffered 8.8 concussion injuries per 1000 player-hours in comparison to backs who suffered 6.7 [102]. The mean severity of concussion injuries for forwards was 12.8 days, more than double that of backs (6.2 days) [102].

Fraas et al. [99] conducted an in depth epidemiological study on professional Irish rugby players from all four provincial teams. The study determined the self-reported rates of concussion in Irish rugby during the 2010-2011 season. 172 players participated in the study with an average age of 24.97 ± 4.11 years and average playing experience of 13.49 ± 5.79 years. 45% of players reported at least one concussion that season. The number of concussion injuries reported was greater for backs, but the injury severity was higher for forwards. Table 8 illustrates that all positions in rugby union are susceptible to sustaining a concussion.

Table 8. Number of concussions reported per position [99].

Player position	Number (%) of concussions
Prop	9 (9.8%)
Hooker	6 (6.5%)
Lock	12 (13.0%)
Flanker	20 (21.7%)
No. 8	4 (4.3%)
Scrumhalf	11 (12.0%)
Flyhalf	4 (4.3%)
Centre	15 (16.3%)
Wing	8 (8.7%)
Fullback	3 (3.3%)
Total	92 (100%)

3.4 Current head protection equipment and strategies

3.4.1 Padded headgear

Headgear is not compulsory in rugby union. It is postulated that players who wear hard shell headgear have a greater tendency to play more aggressively, and thus sustain more head impacts [124]. One study found that 67% of youth rugby union players (under 15 years old) felt a greater ability to tackle harder when wearing headgear [125]. The headgear currently used in rugby union consists of soft polyethylene foam padding (Figure 10).

Figure 10. The headgear currently used in rugby union [126].

McIntosh et al. [127] conducted a controlled trial on the effectiveness of padded headgear in preventing head injury and concussion in rugby union. 1493 participants (10,650 player-hours) were in the control group (no headgear). 1128 participants (8170 player-hours) were in the standard headgear group. 1474 participants (10,650 player-hours) were in the modified headgear group (Figure 11). The study found that concussion rates were not lower in the padded headgear groups. Therefore, headgear could not be recommended for concussion prevention [127]. The findings agree with a laboratory study that demonstrated the limited potential for standard headgear to attenuate impact and reduce head accelerations to tolerable limits [128]. However, a laboratory study showed that modified headgear (Figure 11), with more padding in susceptible areas, has greater potential to attenuate impacts than standard headgear [124]. Overall, padded headgear appears to offer insufficient protection against concussion in rugby union. However, headgear is recommended for laceration and abrasion prevention [124].

Figure 11. Modified honeycomb headgear model [124].

A recent review study [129] found that equipment-based approaches (helmets, mouthguards etc) in contact sports (American football, rugby union, Australian rules football and ice hockey) were insufficient for reducing concussion risk. The study stated that the most effective method to prevent concussion is to minimise the likelihood and/or severity of a head impact. Therefore, to prevent concussion in rugby union, a focus should be placed on preventing direct head contact [130]. However, Quarrie and Hopkins [110] emphasise the importance of not drastically changing the contact nature of the sport. Quarrie and Hopkins [110] recommend further educating players about safe tackle technique and slightly reducing the tackle height law to prevent general injury.

3.4.2 Neck strengthening

Viano et al. [131] found that a stronger neck resulted in a reduction in head acceleration, change in head linear velocity and displacement for direct head impacts in American football using Hybrid III dummies, see Section 3.5.3. Viano et al. [131] also stated that athletes who regularly experience concussion may benefit from preventative exercise programs tailored towards neck strengthening.

However, the 4th consensus statement on concussion in sport [23] stated that no evidence was provided to suggest an association between neck strength and concussion risk reduction. Neck strength was not mentioned in the 5th consensus statement on concussion in sport [132].

3.5 Methodological approaches to concussion injury research

Multiple approaches have been utilised to assess the mechanism of concussion. Observational approaches can be used to analyse the inciting event in terms of injury scenario and player characteristics. Observational approaches include:

- Retrospective interviews and questionnaires
- Video analysis

Biomechanical approaches can be used to measure and understand the brain and head’s response to impact. Biomechanical approaches include:

- Anthropomorphic Test Devices (ATD)
- Multibody simulations

- Finite Element Head Models (FEHM)
- Instrumented wearable devices
- Motion analysis laboratory trials

Both observational and biomechanical methodologies can help build evidence on the mechanism of concussion. However, there are advantages and disadvantages to each approach.

3.5.1 Retrospective interview and questionnaires

Retrospective interviews and questionnaires are a common way to study injury mechanisms in sport [133, 134]. This approach allows the inciting event prior to, at the time of and after the injury to be described. The data is relatively straightforward to retrieve.

An interview takes place between researchers and the injured player and/or the team coaches/medical staff [133]. The recall bias of the player, coach or medical team can limit the information gained. However, this can usually be improved by a video review of the event [133]. Nonetheless, the useful information gained is based on the interviewee's ability to recall the event. The longer the time between the injury and interview, the less likely the player will be able to recall the exact mechanisms of the injury [88].

3.5.2 Video analysis

3.5.2.1 Generalised video analysis

Detailed information on the injury mechanism can be gained from general video analysis [133]. Furthermore, critical characteristics of the inciting event can be identified when distinguishing between injury and non-injury cases [91]. This is particularly useful for developing injury prevention strategies. Analysis of match video evidence has been used to identify injury risk factors in rugby union [110, 116, 118] as well as concussion risk [103, 117, 135]. General video analysis has also been used for analysing concussion injuries in rugby league [136], ice hockey [137] and soccer [138].

3.5.2.2 Two-dimensional kinematic video analysis

Two-dimensional video analysis can allow one/two-dimensional kinematic estimates to be achieved from single camera view video footage. Out of plane movements cannot be accounted for [9]. An early two-dimensional single camera view study was conducted on concussion events in Australian rules football and rugby union [139]. The approach enabled closing speed and change in head linear velocity estimates to be obtained, see section 3.6.5.

3.5.2.3 Three-dimensional kinematic video analysis

Several three-dimensional video analysis studies have been conducted on head impact events in American football [131, 140, 141]. These approaches use multiple camera view video footage (Figure 12) and a prospective grid, based on the field dimensions, to estimate linear impact speed and head impact location. A linear impactor and Anthropometric Test Dummy (ATD) reconstruction approach (Section 3.5.3) is then utilised to extract 6 Degree-of-Freedom (DOF) head kinematic data. Many studies have used this method for gaining 6 DOF input parameters for Finite Element Head Model (FEHM) simulations (Section 3.5.6) [41, 142, 143]. However, one study concluded that this method is insufficient for gaining FEHM input parameters [142]. The approach relies heavily on ATD biofidelity and a non-validated linear impactor approach for 6 DOF head kinematic measurement.

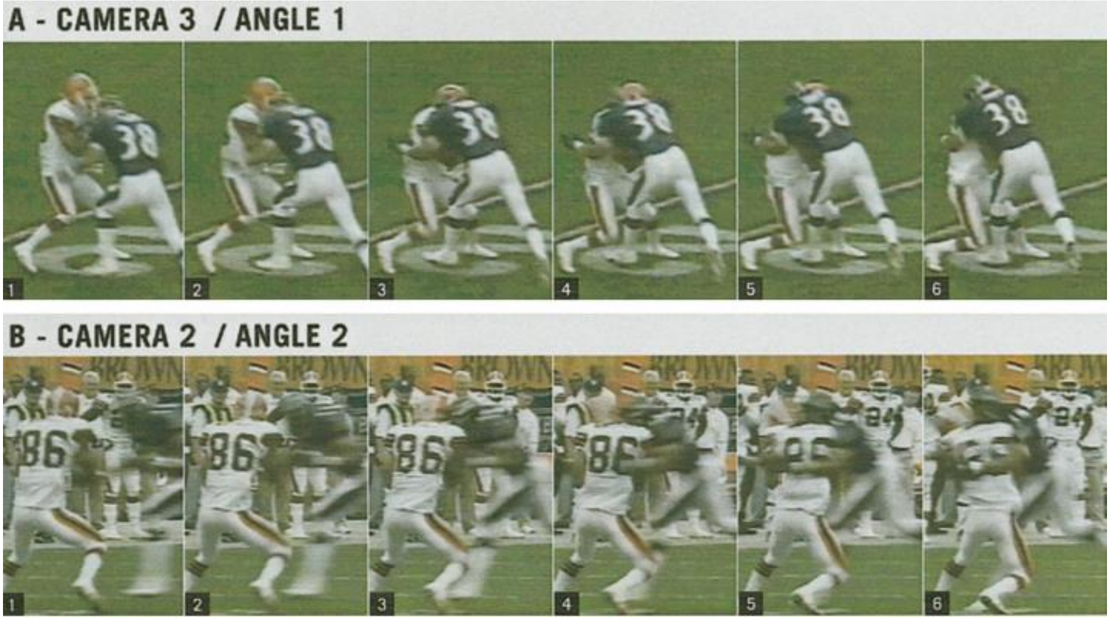

Figure 12. Two camera view time-lapse of a head impact in American football [140].

Model-Based Image-Matching (MBIM) is an approach that can be used to measure 6 DOF head motion directly from un-calibrated video data [144, 145]. The abovementioned methods were limited to extracting only linear motion and require further impact reconstruction to gain 6 DOF estimates [131, 139-141].

The method is performed using 3-D animation software Poser 4 and Poser Pro Pack (Curious Labs Inc, Santa Cruz, California). The surroundings are built into a virtual environment based on the real dimensions of the sport field. A skeleton model from Zygote Media Group Inc (Provo, Utah) is then used for skeleton matching. The skeleton model is manipulated to fit the player's anthropometry in each video frame thus allowing player kinematics, based on the video frame rate, to be calculated. The model has 21 segments (fore foot, rear foot, lower leg, thigh, pelvis, abdomen, chest, neck, head, collar, upper arm, forearm and hand) and 57 degrees of freedom.

The MBIM method has been successfully used in a range of sports to assess injury mechanisms [146, 147], such as ankle sprain (Figure 13). The method has been applied to a single head injury case in alpine skiing [145], however the accuracy of the measurement was never assessed.

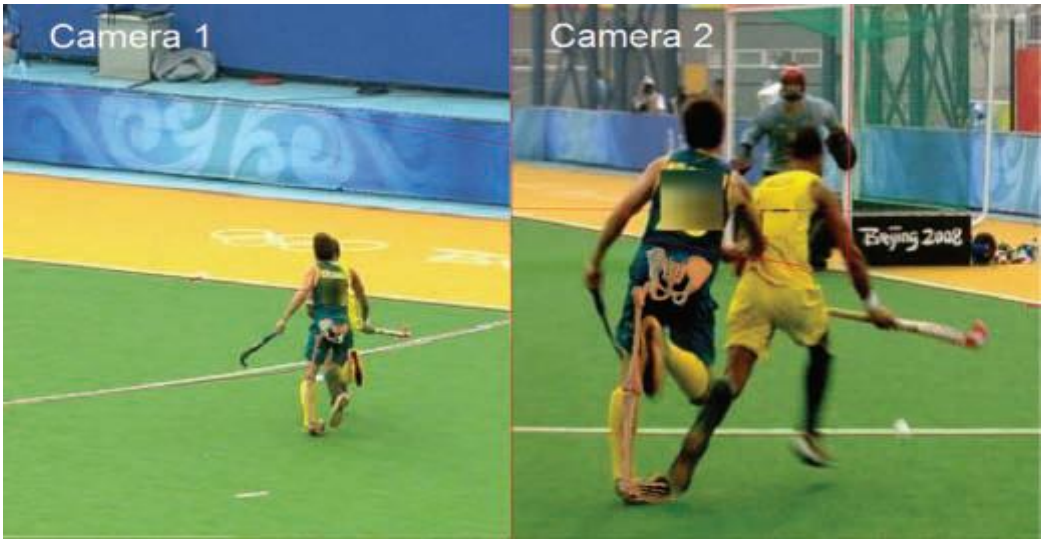

Figure 13. Captured image at the point of maximum inversion angle for an ankle sprain in field hockey using the MBIM technique [147].

3.5.3 Anthropomorphic Test Devices (ATD)

Anthropomorphic Test Devices (ATD), better known as crash test dummies, are full scale test devices that represent the dimensions, weight proportions and articulation of the human body. They are widely used in the sports industry when designing protective equipment [148].

Impact scenarios can be reconstructed with these devices (Figure 14). In-built sensors within the ATD can measure and record the dynamic behaviour of the impacted head

[148]. ATDs have no ethical issues, great repeatability and a range of dummy sizes are available. However, there can be issues with biofidelity and cost [149].

Figure 14. Laboratory reconstruction of a concussion event with a linear impactor and ATD head and neck model [148].

3.5.4 Multibody simulations

Previous studies on concussion in unhelmeted sports have utilised multibody model simulations to computationally reconstruct impact scenarios [8, 9, 150]. The studies are based on single camera view video evidence (Figure 15). Reconstructions are typically simulated using MADYMO (MAthematical DYnamic MOdels) human body models.

The outer geometry of MADYMO human body models are usually modelled using ellipsoids and/or facets. The models have numerous input parameters e.g. geometry, mechanical/structural properties, contact characteristics and initial conditions. Assumptions regarding these input parameters strongly influence the results of simulations [9, 150]. Deformation of soft tissues (flesh and skin) is represented by force-penetration based contact characteristics (stiffness, damping, hysterisis). The contact characteristics for various model body parts (e.g. pelvis, abdomen, thorax and shoulder) are based on data found in the literature and were optimised using various blunt impact tests [151-154]. The models have also been validated based on leg shear and bending tests [155, 156].

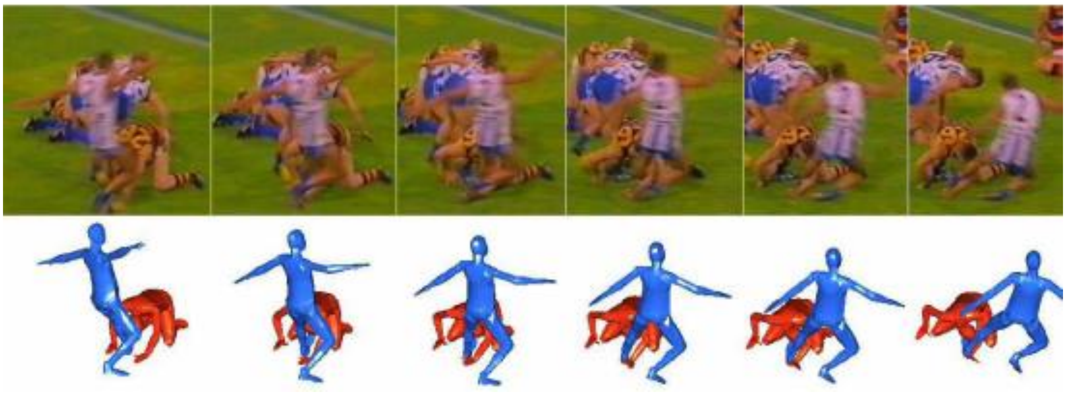

Figure 15. Simulation of an Australian rules football impact using the MADMYO facet human body model [150].

A sensitivity analysis of the facet human body model was conducted for the abovementioned concussion studies [8, 9, 150]. However, their predictive capacity for head impact reconstruction in sport was not formally assessed. This is largely because direct validation data for sport impacts were not available. The predictive capacity of the models are generally validated based on staged vehicle-cadaver impact tests [157, 158].

Elliot et al. [158] reconstructed ATD, cadaver and real vehicle collisions to assess the validity of the human body ellipsoid model. Head contact on a vehicle for a typical pedestrian collision usually takes about 100 ms [159]. Head motion prior to vehicle contact is entirely inertial loading through the neck. Elliot et al. [158] validated the model for head translations (average error of 10%), rotations (based on head impact location with the windscreen), head impact time (average error of 7%) and head impact velocity (average error of 15%). An ATD test reconstruction using the ellipsoid model (mechanical properties modified to match the dummy) reproduced a similar peak acceleration value (within 17%) to that of the ATD [160]. Further evaluation of the models for application to rugby union is clearly needed. However, the MADYMO human body models can be considered suitable for preliminary impact analysis in rugby union, with a focus more on trends than on absolute values of kinematic and dynamic predictions.

3.5.5 Finite Element Head Models

Finite Element Head Models (FEHM) are computational tools for examining intracranial stresses and tissue deformations during a head impact. Head impact kinematics are utilised as initial conditions to drive the models and thus, the mechanical loading and response of the brain tissue is computed. Concussion injury likelihood can then be inferred from the brain tissue response [142, 161-163]. The models rely on accurate material properties and detailed geometric representation [22, 142]. The model outputs would benefit from a reliable means of measuring head kinematics and patient specific customisation due to the natural variation in these parameters [40].

3.5.6 Instrumented wearable devices

Instrumented wearable devices include headgear, mouthguards (Figure 16) and skin patches instrumented with gyroscopes and/or accelerometer arrays. This enables head linear and rotational kinematics to be measured during direct head impact and inertial head loading cases [28]. Head acceleration data is recorded and stored, subject to a minimum threshold (usually 10g) being exceeded on one or more accelerometer [164]. The devices are designed to monitor and record the direction and magnitude of head impacts in real time [165].

Figure 16. An instrumented mouthguard [166].

Factors such as fit, adhesion, soft tissue elasticity and hair/scalp properties can influence device coupling and coherence [167]. This can result in measurement inaccuracies and over-predictions [167]. The wearable skin patch device [29] has previously been used in a rugby union match play study. However, the same device demonstrated high false-positive rates (up to 68%) in a study on lacrosse i.e. the sensors identified head impacts that could not be verified by video footage or were not part of match play [168]. False-positives were not evaluated in the abovementioned rugby union study. Furthermore, in human volunteer soccer heading laboratory trials, the wearable skin patch overpredicted peak linear and angular acceleration [169]. The instrumented mouthguard (Figure 16) appears to demonstrate the greatest validity.

This is due to mouthguards having the tightest coupling to the human skull in comparison to headgear and skin patch devices [169]. The mouthguard is commercially unavailable at present and requires further validation. For example, human mandible interactions with the sensor have not been assessed using human volunteer-based trials [170].

3.5.7 Motion analysis laboratory trials

Motion analysis laboratories capture 3D motion data by utilising marker-based optoelectronic systems. Within a calibrated volume, multiple infrared cameras record the motion of spherical retro-reflective markers. The marker-based system combines this information from all cameras to record the motion of each individual marker [171]. Using an instrumented testing device, Richards [172] reported Root Mean Square Errors (RMSE) of 1mm or less for marker tracking using the Vicon marker-based motion capture system. The retro-reflective markers are generally attached to human subjects. By placing them on certain bony landmarks, 3D human body segment motion can be measured by applying a human body model to the marker data. Motion analysis laboratory trials have not been used to study concussion before. Direct head impacts cannot be ethically reconstructed voluntarily. However, staged 3D motion analysis trials have been utilised to assess tackle technique in rugby union, see Figure 17 [173].

Figure 17. A staged shoulder tackle on an instrumented tackle bag in a motion analysis laboratory [173]. Both the tackler and tackle bag were instrumented with retro-reflective markers. The black arrows illustrate the force plate measures.

3.6 Mechanical metrics to predict concussion injury likelihood

To measure the response of the head to impact and establish tolerance limits is a key objective for impact biomechanics researchers [174]. An acute injury is a result of an exceeded tissue tolerance to a specific load. Ideally, for concussion, brain tissue deformation could be measured directly. However, this is not possible [18]. Therefore, emphasis is placed on identifying injury metrics that evaluate concussion risk. Criteria for assessing concussion injuries function on the basis that head kinematics are correlated with concussion injury likelihood.

Meaney et al. [40] states that factors such as normal variation in brain shape and material properties can result in significant differences in brain deformation for a given head impact event [40]. Therefore, Meaney et al. [40] indicates that concussion thresholds are illusive, particularly if previous impacts have occurred in a game. There is an emerging concept of neuronal vulnerability to injury due to repetitive sub-concussive loading if the time between hits is sufficiently small (up to 24 hours) [13-15]. This has been identified using advanced medical imaging techniques. Therefore, Merchant-Borna et al. [13] argues that injury thresholds should not be based on the magnitude of a single hit. Instead, the magnitude and number of hits and the time between hits should all be considered.

Current research debates the most significant biomechanical metrics associated with concussion injuries: acceleration vs velocity, linear vs. rotational, etc. At present, researchers are focusing on which of these parameters are most significant [41, 175].

3.6.1 Impact Time

Research in American football suggests that direct head impacts occur over 15 milliseconds (ms) [176]. Impact compliance differs when headgear is worn. Headgear reduces peak linear acceleration however increases the duration of the impulse [18]. Rousseau [18] found that the peak linear and angular accelerations were similar on average for concussion cases and non-injury cases in ice hockey impacts. However, impulse duration was greater for the concussion group [18]. This complies with the Wayne State University Tolerance curve (Section 3.6.3). King et al. [28] found, using instrumented mouthguards (minimum threshold of 10g), that the average (±1 Standard Deviation (SD)) head impact duration (including inertial loading cases) for rugby union was 12 ±9 ms.

3.6.2 Impact Location

McIntosh et al. [8] found significant differences in the distribution of head impact locations for concussive and non-injury head impact events in rugby and Australian rules football. It appears that most concussive impacts occur to the temporal region of the head (Figure 18). It is possible that the concussed player is less aware of the impending contact during temporal cases in comparison to frontal/facial contact.

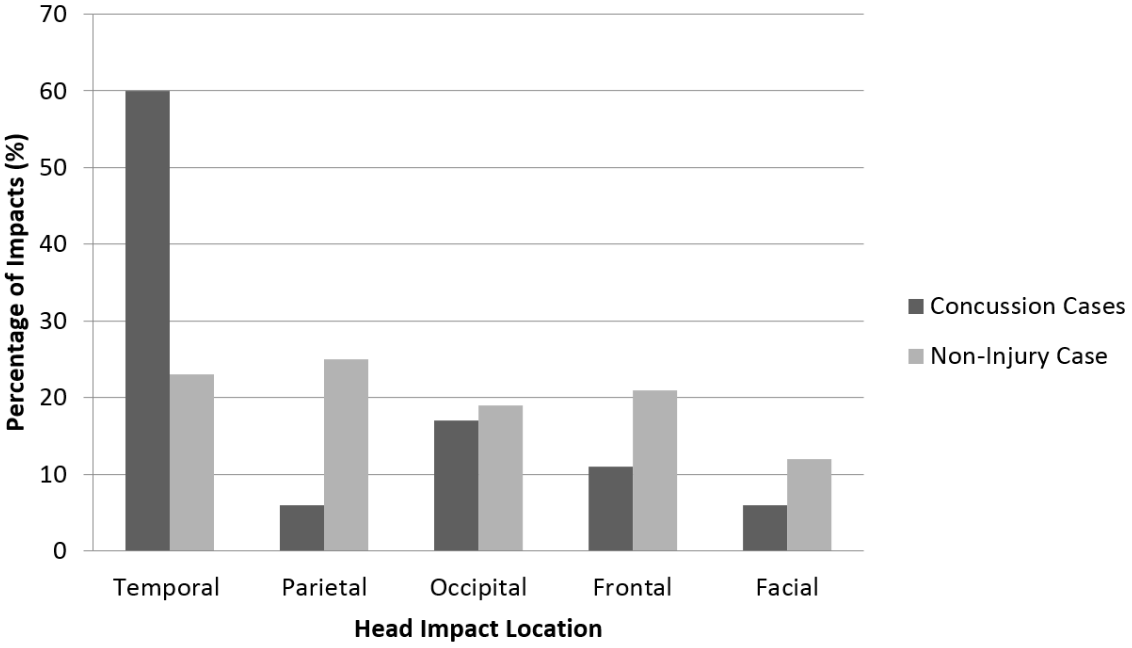

Figure 18. The distribution of head impact location which resulted in concussive and non-injury cases [8].

An example of the impact locations recorded by King et al. [28] using an instrumented mouthguard for a single player in one amateur rugby union match can be seen in Figure 19. King et al. [28] reported that inertial head loading most likely accounted for a high proportion of these large head kinematic values recorded. However, no further assessment was conducted. Therefore, it is unclear what proportion of these were direct or inertial head loading cases [28]. There appears to be a high number of head loading cases for a single game (Figure 19). A synchronised video review to identify false-positive sensor readings was not conducted in the study. Therefore, it is possible that many of these impacts did not occur. On average, players are involved in 21±11 breakdown exertions (rucks, mauls and scrums) and make 9±6 tackles per game [177].

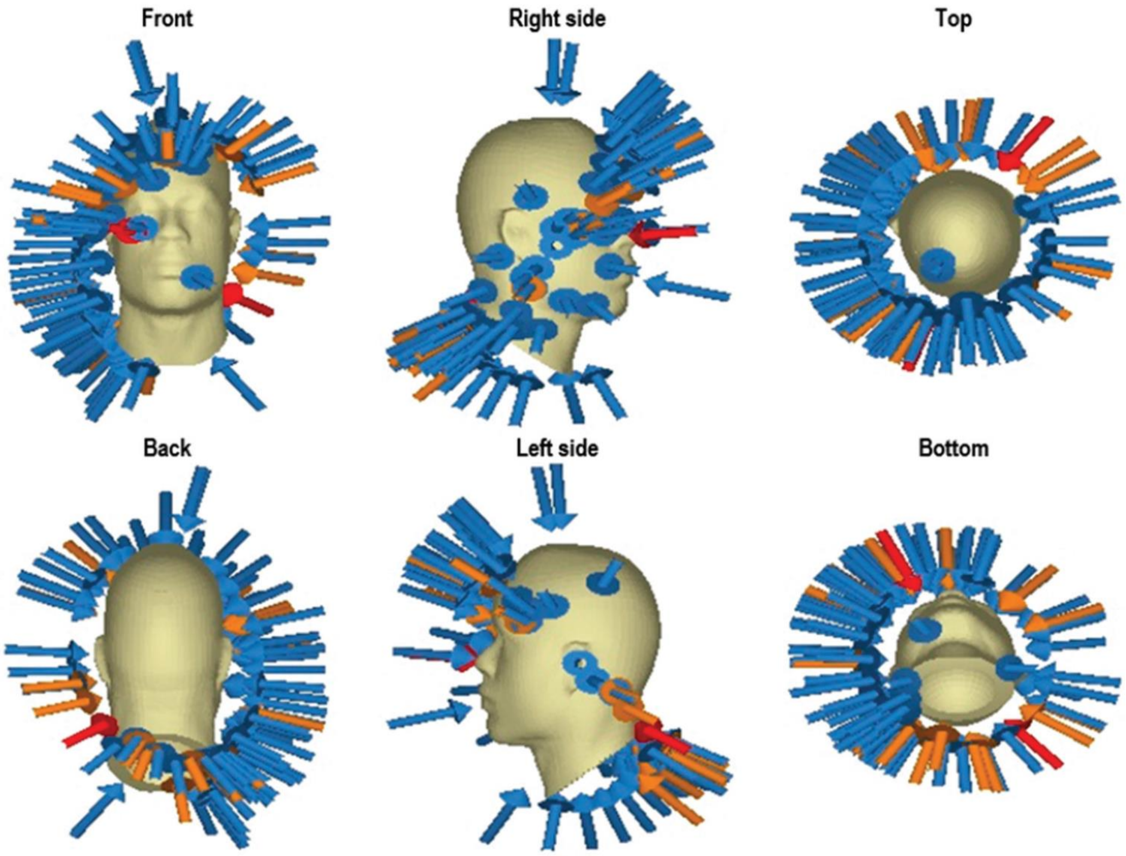

Figure 19. Example of the head impact locations for 1 player wearing an instrumented mouthguard during a single amateur rugby union game (Peak acceleration values: Blue, 10-30g; orange, 40-60g; and red, >70g) [28].

3.6.3 Linear acceleration

Linear acceleration is a common parameter used in engineering. Linear acceleration is commonly reported in g (9.807 m/s^2). Due to the low shear modulus of the brain, rotational kinematics are believed to correlate better with concussion injury predictions [36, 41]. Linear acceleration is believed to correlate better with other head injuries such as skull fracture [178, 179].

The time dependency of skull fracture to linear acceleration is the basis of the the Wayne State Tolerance Curve (WSTC) [180, 181]. The WSTC illustrates the relationship between average head acceleration, impact duration and the possibility of skull fracture (Figure 20) [182]. It is believed that by measuring the tolerance of the skull to fracture loads, one is effectively deducing the tolerance to brain injury [19].

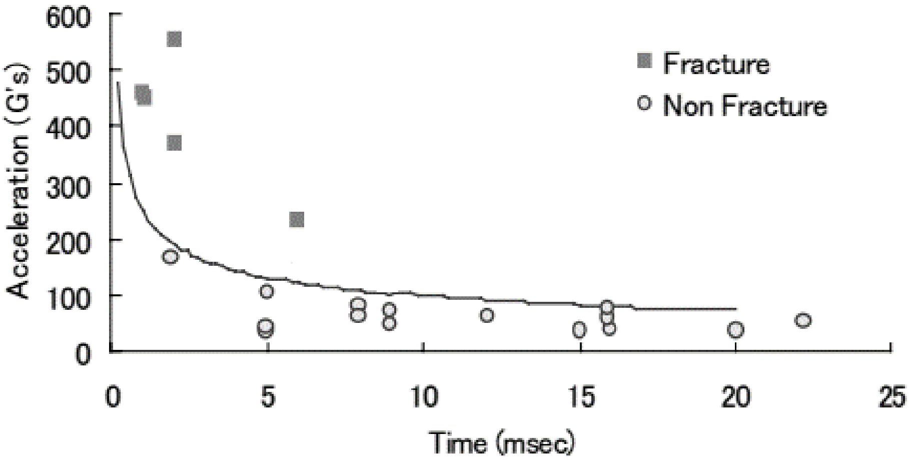

Figure 20. The Wayne State Tolerance Curve [183].

The curve shows that the skull is capable of withstanding high accelerations for short impact durations but is vulnerable to long impulse durations. The WSTC has many limitations for brain injury prediction. The criterion is mainly based on the response of the skull rather than the brain, focus was placed on frontal impacts and the curve has not been validated for living human beings [184].

American football studies have shown links between concussion injury likelihood and head linear acceleration. However, threshold values can vary significantly. Newman et al. [12] found that the mean peak acceleration value for concussive impacts in National Football League (NFL) players was roughly 98 g. Yet, Funk et al. [185] reported an average value of 151 g for collegiate players. Potentially age may affect concussion threshold values [186]. Both studies had different research methodologies. Newman et al. [12] used a video-based approach and ATD reconstruction. Funk et al. [185] used instrumented helmets.

This indicates the importance of validating techniques for real world application before reporting concussion injury thresholds. Figure 21 and Table 9 illustrate a comparison of the average peak resultant head linear acceleration values for concussion and non-injury cases reported in the literature.

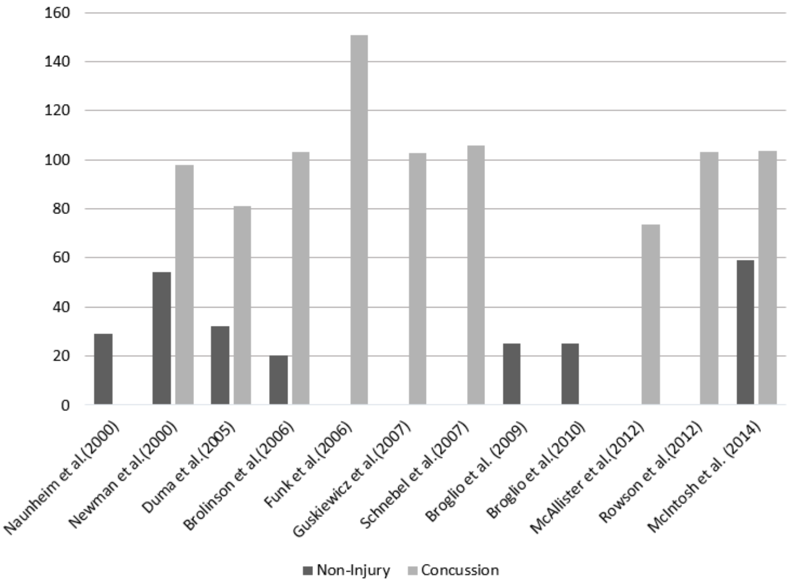

Figure 21. Average peak resultant head linear acceleration (g) for non-injury and concussion cases.

Table 9. The average peak resultant head linear acceleration, for concussion and non-injury cases, reported in the literature.

Study	Average peak resultant head acceleration (g) Non-Injury	Concussion	Number of Cases Non-Injury	Concussion	Sport	Level	Method
Naunheim et al. [187]	29.2	–	132	0	American football	High school	Instrumented helmets
Newman et al. [12]	54.3	97.9	33	25	American football	Professional	Anthropomorphic Test Dummy (ATD)
Duma et al. [188]	32.0	81	3311	1	American football	Collegiate	Instrumented helmets
Bronlinson et al. [186]	20.1	103.3	11601	3	American football	Collegiate	Instrumented helmets
Funk et al. [185]	–	151	22 701	3	American football	Collegiate	Instrumented helmets
Guskiewicz et al. [189]	–	102.8	0	13	American football	Collegiate	Instrumented helmets
Schnebel et al. [190]	–	105.9	0	3	American football	High school, collegiate	Instrumented helmets
Broglio et al. [191]	25.0	–	19224	0	American football	High school	Instrumented helmets
Broglio et al. [165]	25.1	–	54247	0	American football	High school	Instrumented helmets
McAllister et al. [192]	–	73.6	0	10	American football, ice hockey	High school, collegiate	Instrumented helmets
Rowson et al. [164]	–	103	300977	57	American football	Collegiate	Instrumented helmets
McIntosh et al. [8]	59.0	103.4	13	27	Australian rules football, rugby	Professional	Multibody simulations

3.6.4 Angular acceleration

Angular Acceleration is another well-known parameter in engineering. It is argued to be the predominant mechanism for causing concussion injuries [193, 194]. Brain tissue has a high ability to resist volume change (bulk modulus) but a poor ability to resist a change in shape (shear modulus) [36]. This led to the idea that shear stress from rotational forces was the true cause of brain injury [34, 195]. Many tests on the relationship between rotational acceleration and brain injury have been carried out [45, 196-199]. As a result, it is considered the main mechanism of concussion, diffuse axonal injury and subdural hematoma [45, 196-199]. One lab-based experiment applied controlled sagittal plane head motions to primates. The study identified that purely translational head motion could not cause concussion in the primates whereas rotational head motion could [200]. Studies observed that rotational head kinematics are the most significant factor in determining intracranial strain whereas linear kinematics determine intracranial pressure [142, 143, 201]. McIntosh et al. [8] utilised a passive MADYMO facet human body model approach to calculate 6 DOF head kinematics from concussive and non-concussive direct head impacts in unhelmeted sports. The study found that angular acceleration of the head in the coronal plane had the greatest association with concussion. Tentative threshold values of 1747 rad/s^2 and 2296 rad/s^2 were reported for a 50% and 75% chance of concussion, respectively. Figure 22 and Table 10 illustrate a comparison of the average peak resultant head angular acceleration values for concussion and non-injury cases reported in the literature.

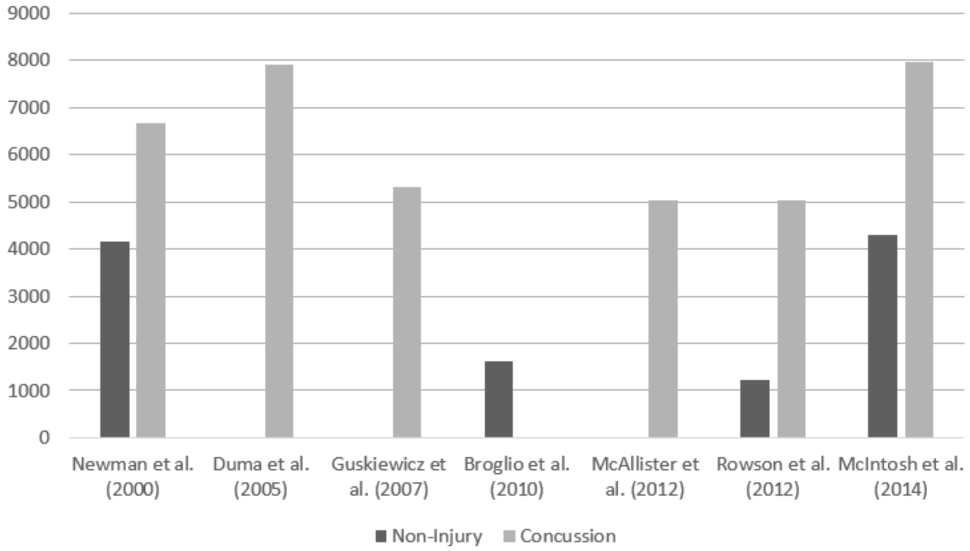

Figure 22. Average Peak Resultant Angular Head Acceleration (rad/s^2) for non-injury and concussion cases.

Table 10. A comparison of the average peak resultant head angular accelerations, for concussion and non-injury cases, reported in the literature.

	Average peak resultant angular acceleration (rad/s^2)		Number of Cases				
Study	**Non-Injury**	**Concussion**	**Non-Injury**	**Concussion**	**Sport**	**Level**	**Method**
Newman et al. [12]	4159	6664	33	25	American football	Professional	ATD
Duma et al. [188]	–	7912	3311	1	American football	Collegiate	Instrumented helmets
Guskiewicz et al. [189]	–	5312	0	13	American football	Collegiate	Instrumented helmets
Broglio et al. [165]	1627	–	54247	0	American football	High school	Instrumented helmets
McAllister et al. [192]	–	5025	0	10	American football, ice hockey	High school, collegiate	Instrumented helmets
Rowson et al. [164]	1230	5022	300977	57	American football	Collegiate	Instrumented helmets
Patton et al. [22]	-	4500	-	27	Australian rules football, rugby	Professional	Multibody simulations/Finite Element Head Model
McIntosh et al. [8]	4300	7951	13	27	Australian rules football, rugby	Professional	Multibody simulations

3.6.5 Changes in head linear and angular velocity

In the NFL, concussion impacts were found to have mean player closing speeds of 9.3 m/s resulting in a mean change in head linear velocity of 7.2 m/s [140]. McIntosh et al [139] found an average change in head linear velocity of 4m/s for concussive impacts in rugby and Australian rules football. The average closing speed for tackles in elite level rugby union is 10.4 m/s [202].

A FEHM study [22], using the input conditions determined by McIntosh et al [139], found an average maximum change in head angular velocity of 33 rad/s for concussive head impacts. McIntosh et al. [8] utilised multibody simulations to estimate an average maximum change in resultant head angular velocity of 36 rad/s for concussive head impacts. Average values of 23, 14 and 22 rad/s for coronal, sagittal and transverse directions were also reported, respectively. Tentative threshold values, based on peak change in resultant head angular velocity, of 22.2 rad/s and 27.5 rad/s were reported for a 50% and 75% chance of concussion, respectively. For the coronal plane, tentative threshold values of 10.8 rad/s and 15.9 rad/s were reported for a 50% and 75% chance of concussion, respectively.

3.7 Conclusion

Epidemiological studies identify the tackle as the most dangerous phase of play in rugby union. However, the specific motion patterns and key kinematic scenarios leading to a concussion have not yet been studied in detail. This needs to be addressed. Protective equipment and increased neck strength appear insufficient for reducing concussion risk considerably. Therefore, technique-based prevention strategies should be explored.

The variation in reported average concussive peak values for both angular acceleration and linear acceleration in sport are significant, 4500-7951 rad/s^2 and 71-151g respectively. This may be due to limited sample sizes, differences in methodologies, lack of methodology validation and/or the limited viability of linear and rotational acceleration in predicting brain injury. Although these reported thresholds cannot be considered as a gold standard for concussion injury prediction, they can be used for comparison against relevant rugby union impact scenarios.

The predictive capacity of multibody models in sporting impacts has not been formally assessed. Specifically, no direct validation for reconstructing head kinematics exists. Largely because direct validation data for sporting impacts is not available. Nonetheless, MADYMO multibody modelling can be considered suitable for preliminary rugby union impact analysis. Focus should be placed more on trends than on absolute values of kinematic predictions.

The relationship between contact technique and inertial head loading is not well understood. Motion analysis laboratory trials would enable staged impacts to be reconstructed with human volunteers. The approach could assess inertial head kinematics during specific rugby union phases of play. The nature of these impacts would differ from those of a real-match scenario. However, head kinematic measurement from real-match impacts can be achieved using Model-Based Image-Matching. Though, a validation assessment is needed first.

4 Project approach

4.1 Background

Epidemiological research on concussion injuries has been carried out in rugby union [105, 109, 110, 130]. However, there is little knowledge on specific player techniques, motion patterns and key kinematic scenarios that are leading to direct head impacts in rugby union.

Insufficient research has been conducted on the regular head loading environment associated with rugby union [16]. In particular, little is known about the magnitude and influencing factors for head kinematics during regular play without any direct head contact. An examination on the biomechanics of tackling and its influence on inertial head kinematics would be beneficial for developing prevention strategies.

4.2 Project Aim

To biomechanically assess direct and inertial head loading in rugby union to identify prevention strategies.

4.3 Project Objectives

4.3.1 Part 1. Direct head impacts

Chapters 5-8. To collect head impact video data from elite level rugby union games. The data is analysed to identify key factors and characteristics that are causing head impacts to occur. Focus is given to the main phase of play causing head impacts. Performance analysis is also conducted on these key factors and characteristics. This can allow head impact prevention strategies to be developed that are both safe and effective.

Chapter 9. To assess the validity of the Model-Based Image-Matching (MBIM) technique for estimating head kinematics during a vehicle-cadaver head-windscreen impact. If successful, the method could be used on direct head impact cases in rugby union.

4.3.2 Part 2. Inertial head loading

Chapter 10. To utilise the MBIM technique to measure inertial head kinematics during a legal high tackle in rugby union.

Chapter 11. To utilise multibody simulations and staged tackles in a 3D motion analysis laboratory to identify if a lower tackle height would reduce ball carrier inertial head kinematics.

Chapter 12. To assess the validity of the MADYMO human body ellipsoid model for predicting head kinematic values and trends during rugby union tackles. The abovementioned 3D motion data is utilised.

A flow chart of the thesis can be seen in Figure 23.

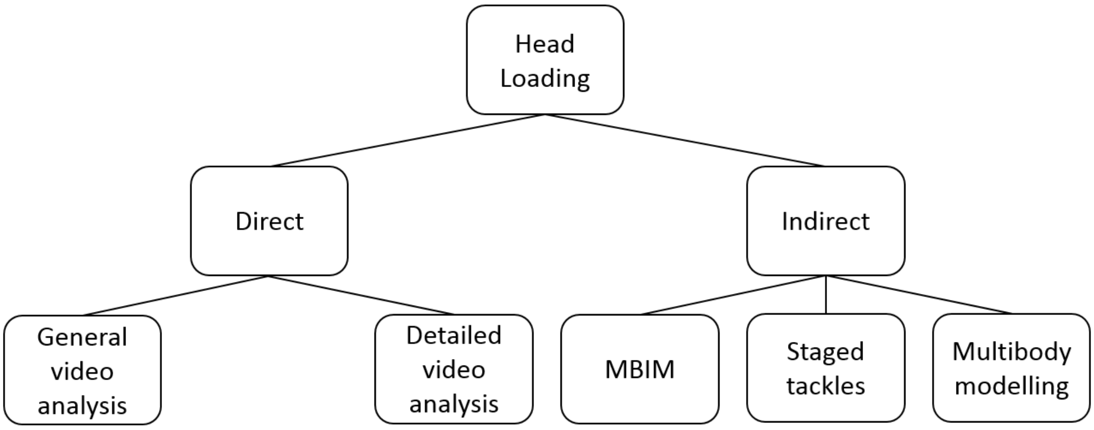

Figure 23. Thesis flow chart

5 Player movement patterns leading to direct head impacts

Related publication. Tierney GJ, Lawler J, Denvir K, McQuilkin K, Simms CK. Risks associated with significant head impact events in elite rugby union. Brain Injury. 2016;30(11):1350-61.

5.1 Introduction

Impacts are integral to rugby union but head impacts can result in concussion injuries [23]. Some epidemiological head injury specific research has been carried out in elite level rugby union [103, 105, 130]. However, there is still little documented knowledge on the specific elite player motion patterns, just before and during direct head impact events. This knowledge is needed to guide prevention strategies in rugby union.

Accordingly, the aim of this study is to utilise video data to analyse direct head impact events in elite rugby union games. Focus will be placed on the main phase of play that is causing head impacts to occur. A direct head impact was defined as contact to the head that required on-field medical treatment and/or a Head Injury Assessment (HIA). A non-direct head impact was defined as the player contacted another player but did not receive direct contact to the head. Non-direct head impacts have been associated with concussion injuries [23]. However, this analysis is aimed at providing an evidence base for player actions to decrease the risk of direct head impacts.

5.2 Methods

5.2.1 Data collection

Video data was collected by retrospectively reviewing game footage of international test rugby union matches from 2014 and 2015. This dataset was compiled of all matches from the RBS 6 Nations 2014, Guinness Autumn Test Series 2014, RBS 6 Nations 2015, Rugby World Cup warm up games 2015 (Home nation games only) and the Rugby World Cup 2015 (all games). A total of 52 direct head impact cases, of which 48 resulted in HIA, were identified.

5.2.2 Direct head impacts

5.2.2.1 General

Two reviewers independently viewed and analysed the video data. The videos were viewed using VLC media player software. The software allowed frame-by-frame viewing of the videos. Differences between reviewers were resolved by a review and discussion of the footage until a consensus was reached. A tackle was defined as either an upper- or lower body tackle (Table 11). The initial analysis focused on finding the general cause of the direct head impact event. Five main categories were identified:

- Head Impact from an upper body tackle
- Head Impact from a lower body tackle
- Head Impact in a ruck
- Head Impact from a dive
- Head Impact with the ground

No direct head impact events occurred from a maul. Further analysis was carried out for each category following a series of discussions involving elite level (Pro 12) rugby union personnel including a coach, physiotherapist, video analyst and referee (Table 11 and 12).

5.2.2.2 Tackles

A Tackle was defined as "when the ball-carrier was contacted (hit and/or held) by an opponent without reference to whether the ball-carrier went to ground" [110]. To aid the analysis, two-dimensional representations of the players at the point of impact were created (Figure 24). The approach allowed for upper- and lower body tackles and player speed to be distinguished.

5.2.2.2.1 Upper body tackles

For upper body single tackles (one tackler), the tackle variables were grouped into three main categories: tackler and ball carrier data (retrieved from freely available online player profiles), pre-tackle and tackle (Table 11). For upper body double tackles (two tacklers), the type of tackle, impacting player, striking body region and time in game were analysed (Table 11).

5.2.2.2.2 Lower body tackles

All lower body tackles involved single tackles (one tackler). For lower body tackles, the tackle variables were grouped into three main categories; tackler and ball carrier data (retrieved from online player profiles), pre-tackle and tackle.

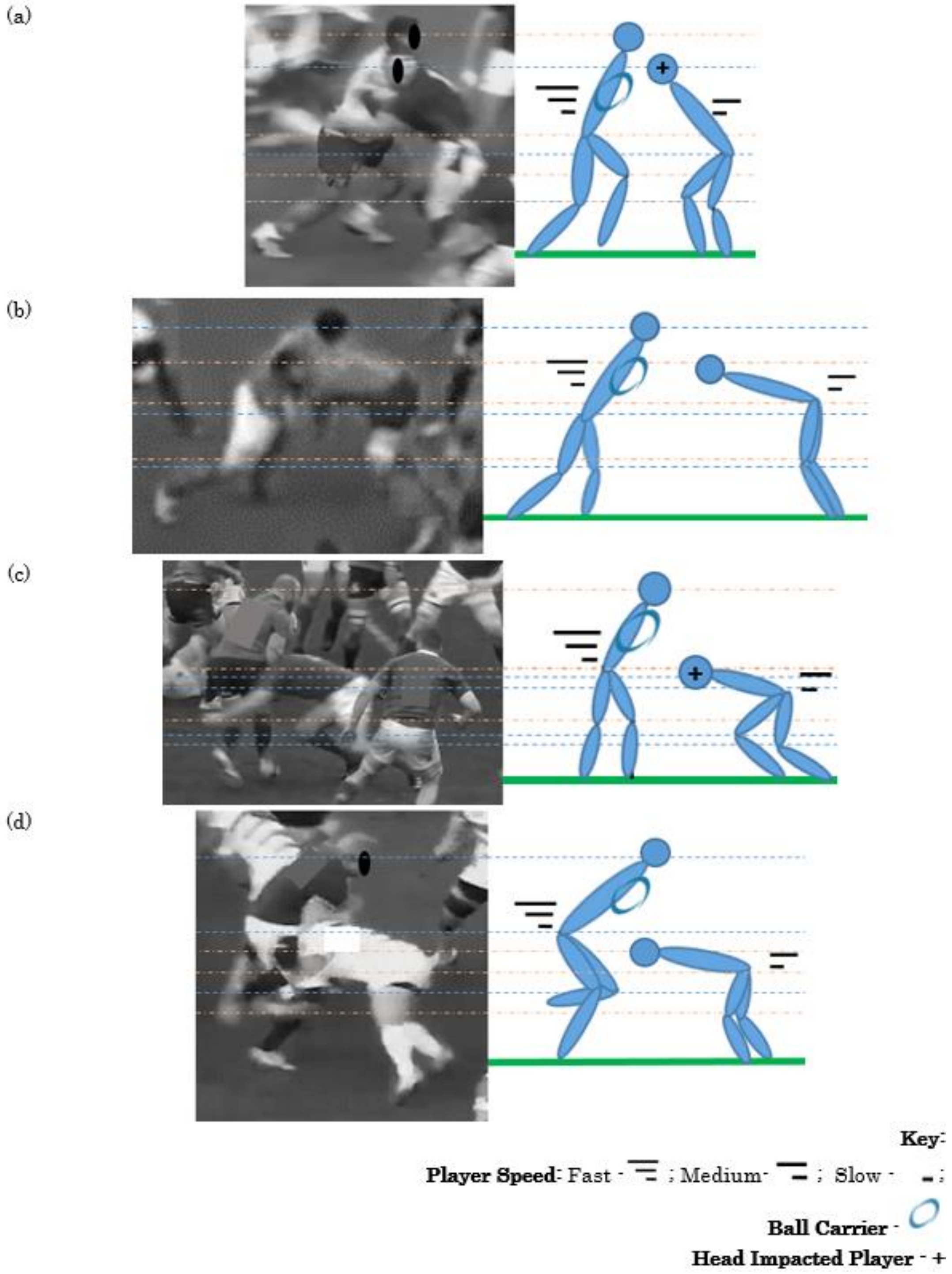

Figure 24. Representative cases of the multibody model method applied to a (a) direct head impact from an upper body tackle; (b) non-direct head impact from an upper body tackle; (c) direct head impact from a lower body tackle (d) non-direct head impact from a lower body tackle.

Table 11. Single tackle variables with corresponding description developed during the discussions with elite level rugby union personnel.

Variable	Description
Tackler and Ball Carrier (BC) Data	
Playing Position	Front Row; Second Row; Back Row; Scrum Half; Midfield Backs; Back Three
Pre-tackle	
Speed [118]	
Fast	Tackler/Ball carrier was running/sprinting into tackle
Slow	Tackler/Ball carrier was jogging/side shuffling/walking into tackle
Stationary	Tackler/Ball carrier was standing/minimal movement into tackle
Acceleration/Deceleration	
Speeding up	Visible increase in tackler/ball carrier speed before committing to the tackle
Slowing Down	Visible decrease in tackler/ball carrier speed before committing to the tackle
Change in direction	Change in ball carrier direction once tackler has committed to the tackle
Leading with arm/shoulder	Ball carrier leading with arm/shoulder (applied to upper body tackles only)
Upper arm raise	Ball carrier raises upper arm (applied to upper body tackles only)
Foot planting	Tackler planting foot when committing to the tackle or at the time of impact
Tackler Head Placement	
In front of BC	Head placed in front of ball carrier
Side of BC	Head placed to the side of ball carrier
Behind BC	Head placed behind ball carrier
Tackle	
Type of Tackle	
Upper body tackle	Intended primary contact being above the ball carrier's hip
Lower body tackle	Intended primary contact being at or below the ball carrier's hip
Number of tacklers	Number of players tackling the ball carrier
Time in Game	
1st , 2nd, 3rd or 4th Quarter	0 - ≤20 mins, >20 - ≤40 mins, >40 - ≤60 mins, >60 - ≤80 mins
Head Impacted Player	
Tackler	Tackler received direct head impact
Ball Carrier	Ball carrier received direct head impact
Impacting Player	
Tackler	Tackler impacted ball carrier's head
Ball Carrier	Ball carrier impacted tackler's head
Teammate	Tackler from own team impacted either ball carrier or tackler's head
Striking Body Region	
Head	Impacting player's head struck the head impacted player's head
Shoulder	Impacting player's shoulder struck the head impacted player's head
Arm	Impacting player's arm struck the head impacted player's head
Back	Impacting player's back struck the head impacted player's head
Hip	Impacting player's hip struck the head impacted player's head
Thigh	Impacting player's thigh struck the head impacted player's head
Knee	Impacting player's knee struck the head impacted player's head
Foot	Impacting player's foot struck the head impacted player's head

5.2.2.3 Ruck, dive and ground impact analysis

This analysis was conducted when a player received a direct head impact from a ruck, diving towards the ground or directly impacting their head with the ground. The variables for this analysis were grouped into a framework involving three main categories: main cause, striking body region and time in game (Table 12).

Table 12. Ruck, dive and ground variables with corresponding description

Variable	Description
Ruck	
Main Cause	
Opposing player entry	Player received head impact by opposing player's entry into the ruck
Own entry	Player received head impact by their own entry into the ruck
Teammate entry	Player received head impact by their own teammate's entry into the ruck
Striking Body Region	
Head	Player's head struck the head impacted player's head
Shoulder	Player's shoulder struck the head impacted player's head
Knee	Player's knee struck the head impacted player's head
Foot	Player's foot struck the head impacted player's head
Time in Game	
1st , 2nd, 3rd or 4th Quarter	0 - ≤20 mins, >20 - ≤40 mins, >40 - ≤60 mins, >60 - ≤80 mins
Dive	
Main Cause	
Loose ball	Player received head impact by attempting to retrieve a loose ball either on the ground or in the air
Try	Player received head impact by diving forward to score a try
Striking Body Region	
Knee	Player's knee struck the head impacted player's head
Foot	Player's foot struck the head impacted player's head
Time in Game	
1st , 2nd, 3rd or 4th Quarter	0 - ≤20 mins, >20 - ≤40 mins, >40 - ≤60 mins, >60 - ≤80 mins
Ground	
Main Cause	
Tackle made	Player's head impacted the ground after making a tackle
Tackle Received	Player's head impacted the ground after receiving a tackle
Air contest	Player's head impacted the ground after contesting a high ball.
Time in Game	
1st , 2nd, 3rd or 4th Quarter	0 - ≤20 mins, >20 - ≤40 mins, >40 - ≤60 mins, >60 - ≤80 mins

5.2.3 Non-direct head impacts

Video data from a total of 40 non-direct head impact single tackle cases (20 upper body tackles and 20 lower body tackles) from two randomly chosen Rugby World Cup 2015 games were also analysed. This allowed key differences in tackle configuration between direct and non-direct head impact cases to be identified. Head impacted player, impacting player and striking body region, see Table 11, were not applicable for non-direct head impact cases.

5.2.4 Statistical analysis

For single tackle cases, the Relative Risk (RR), 95% Confidence Interval (CI) and probability (*p*) values were calculated for the pre-tackle variables [203]. The RR for each variable was calculated by comparing the frequency of occurrence for the direct head impact cases with the frequency of occurrence in the non-direct head impact cases, similar to Fuller et al. [118].

An RR=1 indicates that the variable has no greater propensity to cause a direct head impact than that anticipated by chance; an RR>1 and RR<1 indicates that the variable has a greater and lesser propensity to cause a direct head impact than expected by chance, respectively [118]. In cases where frequency of occurrence was zero, RR was calculated acording to Pagano et al. [204] i.e. 0.5 was added into each cell of the 2x2 table. A variable was considered to have statistical significance if the 95% CI for the RR value did not include 1 and the *p*-value was <0.05.

5.3 Results

5.3.1 General

Tackles accounted for 31 of the 52 direct head impacts (60%). Upper- and lower body tackles accounted for 19 (37%) and 12 (23%) cases respectively (Figure 25). Within upper body tackles, single tackles (one tackler) accounted for 15 direct head impacts whereas double tackles (two tacklers) accounted for 4. None of the tackler related direct head impacts were regarded as foul play by the referee. A large majority (n=25; 81%) of tackle-related direct head impacts occurred in the second half of the game. A disproportionate number of direct head impacts from upper body tackles (n=12; 63%) occurred in the final quarter (Figure 26).

Rucks, dives and ground head impacts accounted for 10 (19%), 7 (13%) and 4 (8%) direct head impacts respectively. Rucks, dives and ground head impacts occurred with a relatively even distribution with respect to time in the game (Figure 26). One ruck related direct head impact was regarded as foul play by the referee in the game.

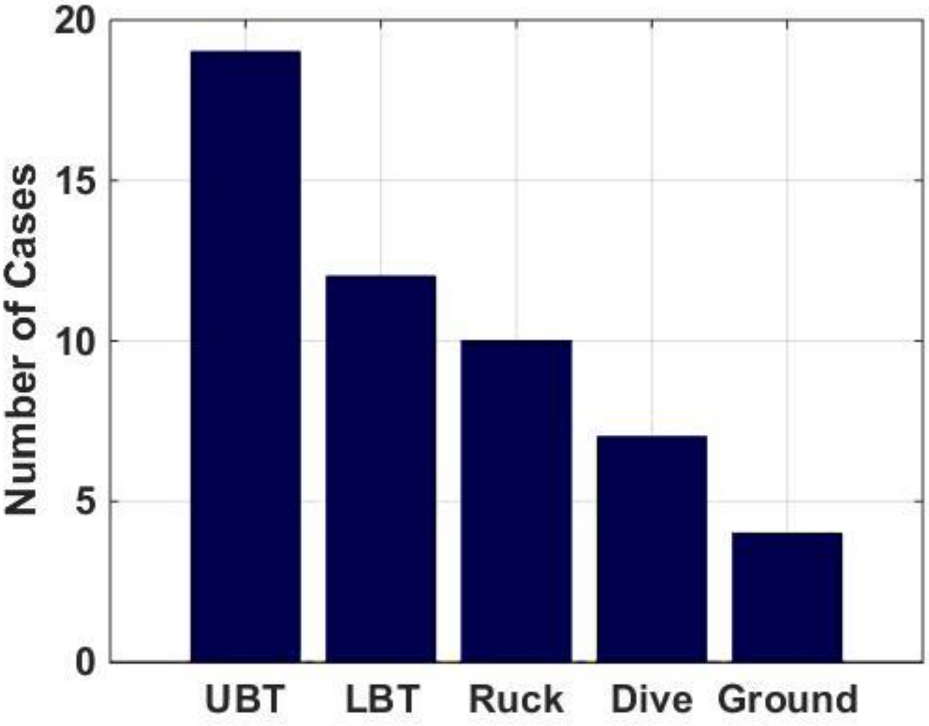

Figure 25. Categories of direct head impacts from all cases. UBT – Upper Body Tackle; LBT – Lower Body Tackle.

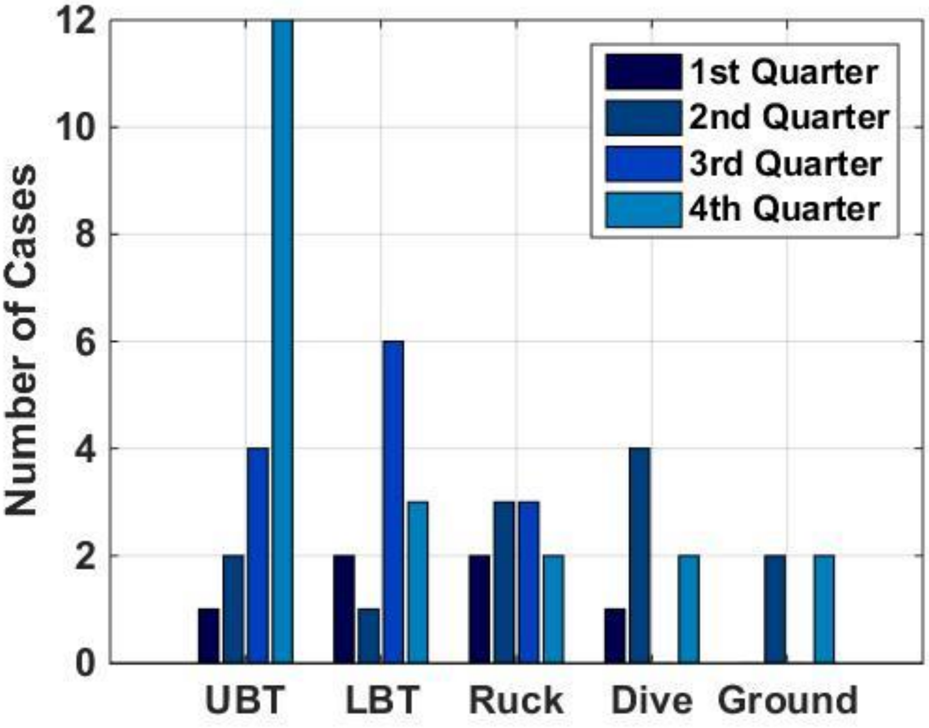

Figure 26. Quarter of the game at which direct head impacts occurred. UBT – Upper Body Tackle; LBT – Lower Body Tackle.

5.3.2 Tackles

5.3.2.1 Upper body tackles

The tackler was the head impacted player in 18 (95%) cases. The ball carrier was the impacting player for 14 cases (Table 13). The 4 remaining cases involved double tackles (two tacklers) where the head impacted player's team-mate was the impacting player. In these 4 cases, the head was the striking body region (Figure 27). The most common upper body tackle related direct head impact scenario was a single tackler event in which the tackler was the head impacted player, with the ball carrier as the impacting player and the shoulder as the striking body region (Figure 27).

Table 13. The head impacted player, impacting player and striking body region for upper body tackle direct head impacts.

Variable	No of event in group (%)
Head Impacted Player	
Tackler	18
Ball Carrier	1
Impacting Player	
Tackler	1
Ball Carrier	14
Teammate	4
Striking Body Region	
Head	8
Shoulder	7
Arm	3
Back	1

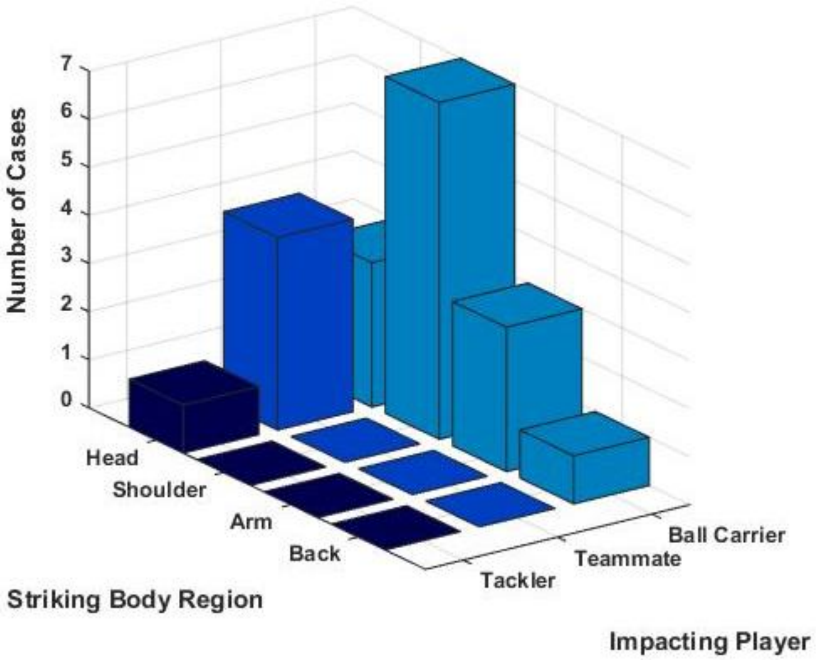

Figure 27. The number of upper body tackle direct head impacts based on striking body region and impacting player.

At least one player entering the tackle fast (*p*=0.03), tackler head placement in front of the ball carrier (*p*<0.01) and tackler foot planting (*p*=0.02) had a higher propensity to cause a direct head impact (Table 14). Tackler head placement to the side of the ball carrier (*p*<0.01) had a higher propensity to prevent a direct head impact.

Table 14. Relative Risk (RR) of direct head impact as a function of upper body tackle (one tackler) pre-tackle variables.

	No of events in group (%)			
	Direct Head Impact (n=15)	**Non-Direct Head Impact (n=20)**	**RR (95% CI)**	***p* value**
General				
One Player Fast	13 (87%)	10 (50%)	1.73 (1.07 to 2.80)	**0.03**
Ball Carrier				
Position				
Front Row	4 (27%)	2 (10%)	2.67 (0.56 to 12.7)	0.22
Second Row	2 (13%)	1 (5%)	2.67 (0.27 to 26.7)	0.40
Back Row	3 (20%)	8 (40%)	0.70 (0.22 to 2.25)	0.55
Scrum Half	0 (0%)	1 (5%)	0.44 (0.02 to 10.0)	0.61
Midfield Back	4 (27%)	3 (15%)	1.78 (0.47 to 6.78)	0.40
Back three	2 (13%)	5 (25%)	0.53 (0.12 to 2.38)	0.41
Speed				
Fast	11 (73%)	9 (45%)	1.63 (0.92 to 2.89)	0.09
Slow	4 (27%)	8 (40%)	0.67 (0.24 to 1.81)	0.43
Stationary	0 (%)	3 (15%)	0.19 (0.01 to 3.38)	0.26
Acceleration/ Deceleration				
Speeding up	6 (40%)	4 (20%)	2.00 (0.68 to 5.85)	0.21
Slowing down	0 (0%)	0 (0%)	0 (-)	-
Change in direction	2 (13%)	3 (15%)	0.89 (0.17 to 4.67)	0.89
Leading with arm/shoulder	8 (53%)	7 (35%)	1.52 (0.71 to 3.27)	0.28
Upper Arm Raise	8 (53%)	7 (35%)	1.52 (0.71 to 3.27)	0.28
Tackler				
Position				
Front Row	4 (27%)	6 (30%)	0.88 (0.30 to 2.60)	0.83
Second Row	0 (0%)	1 (5%)	0.44 (0.02 to 10.0)	0.61
Back Row	0 (0%)	3 (15%)	0.19 (0.01 to 3.38)	0.26
Scrum Half	0 (0%)	0 (0%)	0 (-)	0.00
Midfield Back	9 (60%)	7 (35%)	1.71 (0.83 to 3.54)	0.15
Back three	2 (13%)	3 (15%)	0.89 (0.17 to 4.67)	0.89
Speed				
Fast	4 (27%)	1 (5%)	5.33 (0.66 to 43.0)	0.12
Slow	7 (46%)	14 (70%)	0.67 (0.36 to 1.23)	0.19
Stationary	4 (27%)	5 (25%)	1.07 (0.34 to 3.31)	0.91
Acceleration				
Speeding up	1 (7%)	2 (10%)	0.67 (0.07 to 6.68)	0.73
Slowing down	7 (47%)	5 (25%)	1.87 (0.73 to 4.74)	0.19
Head Placement				
In front of BC	14 (93%)	2 (10%)	9.33 (2.49 to 35.0)	**<0.01**
Side of BC	1 (7%)	18 (90%)	0.07 (0.01 to 0.49)	**<0.01**
Foot Planting	9 (60%)	3 (15%)	4.00 (1.30 to 12.3)	**0.02**

5.3.2.2 Lower body tackles

In all 12 lower body tackle cases, the tackler was the head impacted player and the ball carrier was the impacting player. The knee was the main striking body region and accounted for 5 direct head impacts (42%) The hip accounted for 4 cases (33%), see Figure 28.

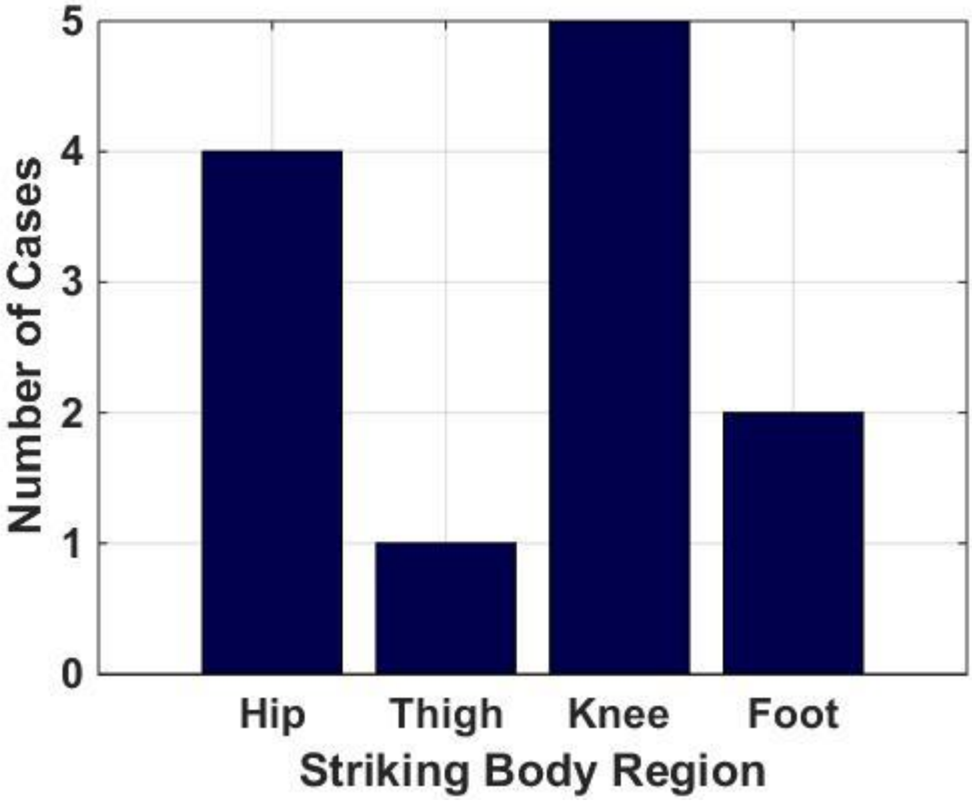

Figure 28. The number of lower body tackles with direct head impacts based on striking body region.

At least one player entering the tackle at fast speed (p=0.02), tackler head placement in front of the ball carrier (p<0.01) and ball carrier change in direction (p=0.04) had a higher propensity to cause a direct head impact (Table 15). Tackler head placement to the side of the ball carrier (p=0.02) had a higher propensity to avoid a direct head impact. Front row players received 4 (33%) direct head impacts. Midfield backs and back three players received 3 (25%) each.

5.3.3 Ruck, dive and ground

The main causes and striking body region for ruck, dive and ground direct head impacts are presented in Table 16. For rucks, an opposing player entering the ruck was the main cause (70%, n=7) of direct head impacts. Diving for a loose ball (spilled or in the air) was the main cause of dive related direct head impacts (86%, n=6). Impacting the head off the ground after making a tackle (50%) was the main cause of ground related direct head impacts. The knee was the predominant striking body region for both ruck (50%) and dive (57%) related direct head impacts.

Table 15. Relative Risk (RR) of direct head impact as a function of lower body tackle pre-tackle variables.

	No of event in group (%)			
	Direct Head Impact (n=12)	**Non-Direct Head Impact (n=20)**	**RR (95% CI)**	***p* value**
General				
One Player Fast	11 (92%)	11 (55%)	1.67 (1.08 to 2.57)	**0.02**
Ball Carrier				
Position				
Front Row	2 (17%)	4 (20%)	0.83 (0.18 to 3.88)	0.82
Second Row	2 (17%)	3 (15%)	1.11 (0.22 to 5.73)	0.90
Back Row	1 (8%)	6 (30%)	0.28 (0.04 to 2.04)	0.21
Scrum Half	0 (0%)	1 (5%)	0.54 (0.02 to 12.3)	0.70
Midfield Back	3 (25%)	4 (20%)	1.25 (0.34 to 4.66)	0.74
Back three	4 (33%)	2 (10%)	3.33 (0.72 to 15.5)	0.13
Speed				
Fast	9 (75%)	9 (45%)	1.67 (0.93 to 2.99)	0.09
Slow	3 (25%)	7 (35%)	0.71 (0.23 to 2.25)	0.57
Stationary	0 (0%)	4 (20%)	0.18 (0.01 to 3.07)	0.24
Acceleration				
Speeding up	3 (25%)	3 (15%)	1.67 (0.40 to 6.97)	0.48
Slowing down	0 (0%)	1 (5%)	0.54 (0.02 to 12.26)	0.70
Change in direction	7 (58%)	4 (20%)	2.92 (1.07 to 7.92)	**0.04**
Tackler				
Position				
Front Row	4 (33%)	2 (10%)	3.33 (0.72 to 15.5)	0.13
Second Row	1 (8%)	1 (5%)	1.67 (0.11 to 24.3)	0.71
Back Row	0 (0%)	6 (30%)	0.12 (0.01 to 2.03)	0.14
Scrum Half	1 (8%)	1 (5%)	1.67 (0.11 to 24.3)	0.71
Midfield Back	3 (25%)	8 (40%)	0.63 (0.20 to 1.91)	0.41
Back three	3 (25%)	2 (10%)	2.50 (0.49 to 12.9)	0.27
Speed				
Fast	5 (42%)	4 (20%)	2.08 (0.69 to 6.28)	0.19
Slow	4 (33%)	12 (60%)	0.56 (0.23 to 1.33)	0.19
Stationary	3 (25%)	4 (20%)	1.25 (0.34 to 4.66)	0.74
Acceleration				
Speeding up	1 (8%)	1 (5%)	1.67 (0.11 to 24.26)	0.71
Slowing down	3 (25%)	5 (25%)	1.00 (0.29 to 3.45)	1.00
Head Placement				
In front of BC	10 (83%)	1 (5%)	16.7 (2.43 to 114)	**<0.01**
Side of BC	0 (0%)	19 (95%)	0.04 (<0.01 to 0.63)	**0.02**
Behind BC	2 (17%)	0 (0%)	8.08 (0.42 to 155)	0.17
Foot Planting	4 (33%)	5 (25%)	1.33 (0.44 to 4.02)	0.61

Table 16. Main causes and striking body region for direct head impacts from ruck, dive and ground impacts.

Variable	No of event in group (%)
Ruck (n=10)	
Main Cause	
Opposing player entry	7 (70%)
Own entry	2 (20%)
Teammate entry	1 (10%)
Striking Body Region	
Head	2 (20%)
Shoulder	3 (30%)
Knee	4 (50%)
Foot	1 (10%)
Dive (n=7)	
Main Cause	
Loose ball	6 (86%)
Try	1 (14%)
Striking Body Region	
Shoulder	2 (14%)
Knee	4 (57%)
Foot	1 (29%)
Ground (n=4)	
Main Cause	
Tackle made	2 (50%)
Tackle Received	1 (25%)
Air contest	1 (25%)

5.4 Discussion

5.4.1 General

This study set out to identify the general cause of direct head impacts in elite level rugby union. The findings agree with previous literature that identified the tackle as the main cause of concussion in rugby union [103, 106, 110]. The study then set out to establish the player configurations and characteristics just before and during tackle-related direct head impacts. Most tackle-related direct head impacts occurred in the second half of the game and a disproportionate number of upper body tackle-related direct head impacts occurred in the last quarter (Figure 26). Assuming the player played from the beginning of the game, this potentially illustrates the influence of repeated impacts and player fatigue on tackling technique and general injury risk [92, 93]. However, players may also place themselves in high risk scenarios when the end of a game is near.

Recently, Tucker et al. [205, 206] conducted two video analysis studies on HIA risk in rugby union from professional competitions during 2013 and 2015 (Six Nations, Rugby Championship, Rugby World Cup, England Premiership, Super Rugby, Top 14, Pro 12 and European Champions Cup). In one of the studies [205], tackles were identified as the main cause of HIAs (76%). Furthermore, the tackler sustained 72% of tackle-related HIAs. Although the percentages differ to those reported in the current study, the principal findings are the same. Tucker et al. [205] reported that HIAs appear to occur relatively evenly throughout the game. However, phase of play specific findings were not reported. The second study by Tucker et al. [206] focused on tackle technique. The study identified that an upright tackler (indicative of an upper body tackle) and high-speed tackles were a risk factor for HIAs [206]. This agrees with the current findings. Tucker et al. [206] did not distinguish between upper- and lower body tackles. However, the study found that head-to-head and shoulder-to-head contact were the two main striking body regions for tackle-related HIAs, respectively. The findings of the current study identified the reverse order for upper body tackles i.e. shoulder-to-head as the main cause with head-to-head second.

5.4.2 Tackles

5.4.2.1 Player speed

At least one player entering the tackle at speed had a higher propensity to cause a direct head impact for upper and lower body tackles. For prevention strategies, player speed would be difficult to limit. Recently, Cross et al. [207] identified tackling at high speed as a risk factor for concussion.

5.4.2.2 Head placement

For upper and lower body tackles, placing the head in front of the ball carrier was a substantial risk factor for causing direct head impacts. This is similar to the findings of Hendricks et al. [117] for amateur players. When the head was placed in front of the ball carrier, it was generally in line with the ball carrier's trajectory and thus impacted. These findings suggest that tackler head placement to the side of the ball carrier and not in line with the ball carrier's trajectory is an effective means to prevent direct head impacts. When the tackler's head was placed to the side of the ball carrier, it was generally not in line with the ball carrier's trajectory. However, changes in ball carrier direction/side shuffling when the tackler has committed to the tackle could place the head in line with the ball carrier's trajectory. This could explain why a visible change in ball carrier direction had a greater propensity to cause a direct head impact for lower body tackles. In a small number of non-direct head impact cases, the tackler placed the head in front of the ball carrier. Either a change in direction of the ball carrier or the ball carrier's speed being slow/stationary prevented the occurrence of a direct head impact. Sobue et al. [208] recently illustrated that tackling with incorrect head position relative to the ball carrier resulted in a higher tackler concussion risk.

5.4.2.3 Foot planting

For upper body tackles, tackler foot planting pre-contact had a greater propensity to cause a direct head impact (Table 14). Foot planting could compromise the tackler's technique and timing. This could potentially lead to the tackler being unable to place their head safely in the tackle.

5.4.2.4 Change in direction

For lower body tackles, a visible change in ball carrier direction once the tackler had committed to the tackle had a greater propensity to cause a direct head impact. A change in ball carrier direction is generally used to evade contact with the tackler. However, in the direct head impact cases, the change in ball carrier direction generally placed the tackler's head in the trajectory of the ball carrier.

5.4.3 Limitations

The study was based on all direct head impacts identified in the games reviewed, as defined in the methodology section. It is possible that other direct head impacts occurred in the games reviewed. These direct head impacts were potentially not reported in the video footage or happened off-screen. The assessments remain partially subjective and only semi-quantitative (acceleration/deceleration estimates etc). The sample size could be considered small given the level of analysis conducted. However, the abovementioned studies with similar results support the current findings. Tucker et al. [206] utilised a sample size of 464 tackle related HIAs which is considerably larger than the current study. Therefore, it is suggested that the striking body region finding that conflicts with Tucker et al. [206] is interpreted with caution.

The study analysed international rugby union games. The results are therefore applicable to the elite game. It is possible that the results are applicable to amateur and youth level rugby union. However, further research in these areas would be needed to conclude this. Only 40 cases were utilised as a control in this study. This is small compared to other video analysis-based studies [116]. Future work should use sample sizes similar to those utilised in the literature [116].

5.5 Conclusion

The tackle is a major cause of direct head impacts in elite level rugby union. The tackler is much more likely to receive a direct head impact than the ball carrier. A number of tackle related variables that increased the risk of a direct head impact were identified. Direct head impact tackles generally had at least one player entering the tackle at speed. Most tackle-related direct head impacts occurred in the second half of the game. The majority of upper body tackle related direct head impacts occurred in the final quarter. For upper and lower body tackles, tackler head placement was the most influencing factor for direct head impact risk. This was potentially affected by tackler foot planting for upper body tackles and ball carrier change in direction for lower body tackles.

Additional contributor. John Lawlor was the second reviewer involved in the study.

6 A performance assessment of tackle technique in elite level rugby union

Related publications. Tierney GJ, Denvir K, Farrell G, Simms CK. Does player time-in-game affect tackle technique in elite level rugby union? Journal of Science and Medicine in Sport. 2018;21(2):221-5.

Tierney GJ, Denvir K, Farrell G, Simms CK. The effect of technique on tackle gainline success outcomes in elite level rugby union. International Journal of Sports Science & Coaching. 2018;13(1):16-25.

6.1 Introduction

Tackling is a major component of rugby union. Effective attacking and defensive play are essential for game outcomes [1, 115, 209]. In rugby union, the gainline is an imaginary line that intersects the middle of a set piece or breakdown (e.g. ruck) width-wise across the field [209]. Similarly, a tackle gainline can be defined as an imaginary line width-wise across the field at the point of contact for each tackle. This approach can assess whether the ball carrier advances beyond the tackle gainline or conversely, whether the tackler prevents the ball carrier from advancing beyond the tackle gainline. In Chapter 5, the tackle was identified as a major cause of direct head impacts. To develop concussion prevention strategies that also improve performance would be particularly encouraging to players and coaches. Therefore, a first step is to identify player techniques that have a positive influence on tackle performance.

At the elite level, players must have a high physical tolerance to fatigue to repeatedly engage in tackles safely and effectively throughout the game [93]. Some players can make over 30 tackles per game [33]. Previous studies identified that the number of tackles a player engages in is related to markers of muscle damage in rugby union [94, 95]. In rugby league, it has been reported that tackling proficiency, based on a one-on-one tackling drill, decreases as fatigue levels increase in sub-elite players [122]. It has been hypothesised that fatigue may be a major factor in tackle related injury risk in rugby union [93, 96]. Hence, more injuries may occur in the later stages of a game [93, 96]. Hendricks and Lambert [93] proposed that an upper limit exists for a player's ability to repeatedly engage in high energy impact tackles. In theory, elite players who are well-conditioned and have a high level of tackle skill may never reach the upper limit. However, players who are unconditioned and technically poor may reach the upper limit during a match or over the course of a season. Hendricks and Lambert [93] suggest that once the upper limit is surpassed, the risk of injury significantly increases and tackle proficiency noticeably decreases. However, this theory has not been confirmed using match data. In Chapter 5, most tackle-related direct head impacts occurred in the second half of a game. Thus, player time-in-game was considered to have influenced direct head impact causation. This requires further investigation. Burger et al. [116] conducted a detailed video analysis of youth level rugby union games. Specific ball carrier and tackler proficiency characteristics that influence tackle injury risk were identified.

Accordingly, the aim of this study is to identify changes in ball carrier or tackler proficiency characteristics as player time-in-game increases. The tackle-based proficiency characteristics developed by Burger et al. [116] and match video footage of elite level European Rugby Champions Cup games will be utilised. A deterioration in tackle technique would indicate an increase in injury risk, based on the findings of Burger et al. [116]. A secondary aim is to assess tackle count variation between quarters of a game. This can further explore the finding that most head impacts occur in the last quarter. Finally, a third aim is to identify tackle technique characteristics that have a positive influence on tackler or ball carrier success in the tackle.

6.2 Methods

6.2.1 Definitions and data collection

A tackle was defined as “when the ball-carrier was contacted (hit and/or held) by an opponent without reference to whether the ball-carrier went to ground” [110]. Missed tackles where no contact was made with the ball carrier were excluded from the analysis. However, tackles where the ball carrier either loses the ball (dropped or ripped), breaks the tackle or offloads post-contact were included. The tackle gainline was considered to exist width wise across the field at the point of contact for each tackle. Ball carrier success was defined by the ball carrier advancing beyond the tackle gainline. Conversely, tackler success was defined by the tackler preventing the ball carrier from advancing beyond the tackle gainline. If a ball carrier entered a tackle, went over the gainline, but lost the ball (dropped or ripped), this was defined as tackler success.

Three randomly selected 2014/15 European Rugby Champions Cup games involving an Irish club were selected for analysis. These games occurred about halfway through the playing season. Each game of the 2014/15 European Rugby Champions Cup was assigned a number. A random number generator (http://www.random.org/) then selected 3 games. Only tackles involving a tackler from the chosen Irish club were selected for the analysis (ball carrier and tackler technique were analysed for each tackle). Analysis was only conducted on players who started and remained on the field for the entire game. Tackles involving ball carriers from the opposing team who were substitution players were excluded. A tackle initiated outside the peripheral vision of the ball carrier was considered a side-on tackle [32, 116]. A total of 122 front-on tackles and 111 side-on tackles were analysed for tackler proficiency characteristics. 113 front-on tackles and 98 side-on tackles were analysed for ball carrier proficiency characteristics.

6.2.2 Technical proficiency criteria

Technical tackle-based criteria developed by Burger et al. [116] for ball carrier and tackler proficiency in front- and side-on tackles were utilised for the analysis. The criteria were developed by a group of rugby union coaches, physicians and sport scientists. The group appraised studies assessing tackling proficiency in rugby union and league [1, 120-122] and recommendations from the South African Rugby Union [123].

Sports Code video software (Version 8) was utilised to analyse each video clip. The software enables frame by frame viewing. Two coders analysed each video together. The coders were at liberty to watch each clip as many times as needed. The video data were recorded at 25 fps. At least two camera views of each tackle were available. The tackle was divided into three stages: pre-contact, contact and post-contact. Technical proficiency characteristics were assigned to each stage. For each technical proficiency characteristic, a player scored 1 or 0 based on whether the characteristic was exhibited or not. Furthermore, each tackle was defined as tackler success or ball carrier success based on the abovementioned tackle gainline definition.

6.2.3 Time distribution of tackles

A separate analysis was conducted on 10 randomly selected 2014/15 European Rugby Champions Cup/Pro 12 games (using the same random number generator method as above). This analysis assessed the time distribution of tackles throughout a game by counting the number of tackles in each quarter (including those made by substitute/substituted players).

6.2.4 Statistical Analysis

6.2.4.1 Technical proficiency criteria

Statistical analysis was conducted using SPSS (IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp.). A Chi-Square test was conducted to identify any significant differences ($p<0.05$) for technical proficiency characteristics between quarters. If significant differences between quarters were identified, post-hoc testing using the SPSS adjusted z-tests with Bonferroni correction ($p<0.01$) was conducted [210]. A Chi-Square test was also conducted to identify differences in tackle characteristics for tackler or ball carrier success. Effect Sizes (ES) were assessed using Phi and Cramer's V. A Phi and Cramer's V value less than 0.1, between 0.1 and less than 0.3, between 0.3 and less than 0.5 and 0.5 or greater were considered indicative of a trivial, small, moderate and large effect sizes respectively [211].

6.2.4.2 Time distribution of tackles

A Shapiro-Wilk test confirmed that the tackle count data for each quarter was normally distributed. A one-way way ANOVA with Tukey post-hoc testing was conducted to identify significant differences ($p<0.05$) in the number of tackles occurring in each quarter of the game [212]. Effect Sizes (ES) were assessed using Cohen's d. A Cohen's d value less than 0.2, between 0.2 and less than 0.5, between 0.5 and less than 0.8 and 0.8 or greater were considered indicative of a trivial, small, moderate and large effect sizes respectively [211].

6.2.4.3 Reliability

A random number generator chose 20 tackles (10 front-on and 10 side-on) for the reliability analysis. For intra-rater reliability, the two reviewers conducted the analysis at least one week after the initial set of tackles were analysed. For inter-rater reliability, an external coder conducted the analysis on the 20 selected cases. Cohen's Kappa (K) was calculated to assess intra- and inter-rater reliability. Cohen's Kappa values of 0.83 and 0.84 were calculated for intra- and inter-rater reliability for front-on tackler proficiency characteristics, respectively, as well as 0.96 and 0.84 for side-on tackler proficiency characteristics, respectively. Cohen's Kappa values of 0.94 and 0.81

were also calculated for intra- and inter-rater reliability for front-on ball carrier proficiency characteristics, respectively, as well as 0.98 and 0.86 for side-on ball carrier proficiency characteristics, respectively. A Cohen's Kappa value greater than 0.8 is indicative of almost perfect agreement [213].

6.3 Results

6.3.1 Technical proficiency criteria

6.3.1.1 Tackler

For front-on tackles, "explosiveness on contact" had a significant difference (p=0.04) in occurrence between quarters for tackler proficiency criteria (Table 17). Post-hoc testing identified that this characteristic was exhibited by tacklers more in the second (p<0.01; ES=0.38) and fourth quarter (p<0.01; ES=0.32) than in the third quarter. For side-on tackles, only "straight back, centre of gravity forward of support base" had a significant difference (p=0.02) in occurrence between quarters for tackler proficiency criteria (Table 18). Post-hoc testing identified that this characteristic was exhibited by tacklers more in the third quarter than in the second (p<0.01; ES=0.37).

During front-on tackles (Table 19), all 3 phases had characteristics that influenced tackler success. "Body position - upright to low" (p=0.03, ES=Small), "straight back centre of gravity forward of support base" (p<0.01, ES=Moderate) and "shortening steps" (p=0.03, ES=Small) all had a higher propensity to enable tackler success for the pre-contact phase. In the contact phase, "explosiveness on contact" (p<0.01, ES=Small) was significant. All post-contact tackle characteristics positively influenced tackler success. For side-on tackles (Table 20), the post-contact characteristic "shoulder usage (drive into contact)" had a higher propensity to enable tackler success.

Table 17. Tackler front-on tackle proficiency results based on quarter in game.

Tackler Front-on	1st Quarter (n=23)		2nd Quarter (n=21)		3rd Quarter (n=39)		4th Quarter (n=39)		p value
	n	%	n	%	n	%	n	%	
Pre-contact									
Identify/track ball carrier onto shoulder	21	(91%)	20	(95%)	39	(100%)	37	(95%)	0.41
Body position - upright to low	12	(52%)	9	(43%)	16	(41%)	19	(49%)	0.79
Straight back, centre of gravity forward of support base	8	(48%)	5	(33%)	13	(46%)	14	(54%)	0.79
Square to ball carrier	20	(87%)	20	(95%)	34	(87%)	33	(85%)	0.70
Boxer stance (elbows close, hands up)	18	(78%)	9	(43%)	23	(59%)	25	(64%)	0.10
Head up and forward/face up	21	(91%)	20	(95%)	38	(97%)	36	(92%)	0.79
Shortening steps	17	(74%)	11	(52%)	16	(41%)	25	(64%)	0.08
Approach from front/oblique	23	(100%)	20	(95%)	39	(100%)	39	(100%)	0.22
Contact									
Explosiveness on contact	5	(22%)	6	(29%)	2	(5%)	9	(23%)	**0.04**
Contact with shoulder opposite leading	13	(57%)	10	(48%)	22	(56%)	27	(69%)	0.56
Contact in centre of gravity	8	(35%)	4	(19%)	10	(26%)	11	(28%)	0.69
Head placement on correct side of ball carrier	87	(87%)	91	(91%)	97	(97%)	95	(95%)	0.20
Post-contact									
Shoulder usage (drive into contact)	7	(30%)	5	(24%)	9	(23%)	10	(26%)	0.90
Arm usage (punch forward and wrap i.e. hit-and-stick)	14	(61%)	14	(67%)	24	(62%)	24	(62%)	0.88
Leg drive on contact	1	(9%)	4	(19%)	6	(15%)	4	(10%)	0.11
Release ball carrier and compete for possession	2	(9%)	4	(19%)	6	(15%)	4	(10%)	0.75

Table 18. Tackler side-on tackle proficiency results based on quarter in game.

Tackler Side-on	1st Quarter (n=23)		2nd Quarter (n=23)		3rd Quarter (n=38)		4th Quarter (n=27)		p value
	n	%	n	%	n	%	N	%	
Pre-contact									
Identify/track ball carrier onto shoulder	22	(96%)	23	(100%)	37	(97%)	26	(96%)	0.77
Body position - upright to low	9	(52%)	7	(43%)	17	(41%)	6	(49%)	0.07
Straight back, centre of gravity forward of support base	4	(17%)	1	(4%)	13	(34%)	5	(19%)	**0.02**
Head up and forward/face up	22	(96%)	23	(100%)	37	(97%)	26	(96%)	0.67
Shortening steps	12	(52%)	10	(44%)	19	(50%)	12	(44%)	0.72
Contact									
Explosiveness on contact	1	(4%)	1	(4%)	4	(11%)	3	(11%)	0.68
Contact in centre of gravity	6	(26%)	8	(35%)	8	(21%)	6	(22%)	0.78
Head placement on correct side of ball carrier	22	(96%)	22	(96%)	37	(97%)	25	(93%)	0.83
Post-contact									
Shoulder usage (drive into contact)	3	(13%)	2	(9%)	6	(16%)	4	(15%)	0.63
Arm usage (punch forward and wrap i.e. hit-and-stick)	16	(70%)	18	(78%)	30	(79%)	21	(78%)	0.90
Pull ball carrier with arms to ground	18	(78%)	20	(87%)	30	(79%)	20	(74%)	0.74
Release ball carrier and compete for possession	2	(9%)	2	(9%)	4	(11%)	2	(7%)	0.98

Table 19. Tackler front-on proficiency results for tackler success vs ball carrier success (includes % occurrence, p values, Phi and Cramer's V and interpretations).

Tackler Front-on	Tackler Success (n=48)	Ball Carrier Success (n=74)	p value	Phi and Cramer's V	Interpretation
Pre-contact					
Identify/track ball carrier onto shoulder	46 (96%)	71 (96%)	0.98	<0.01	Trivial
Body position - upright to low	28 (58%)	28 (38%)	**0.03**	0.20	Small
Straight back, centre of gravity forward of support base	24 (50%)	16 (22%)	**<0.01**	0.30	Small
Square to ball carrier	45 (94%)	62 (84%)	0.10	0.15	Small
Boxer stance (elbows close, hands up)	32 (67%)	43 (58%)	0.34	0.09	Trivial
Head up and forward/face up	44 (92%)	71 (96%)	0.32	0.09	Trivial
Shortening steps	33 (69%)	36 (49%)	**0.03**	0.20	Small
Approach from front/oblique	48(100%)	73 (99%)	0.42	0.07	Trivial
Contact					
Explosiveness on contact	15 (31%)	7 (10%)	**<0.01**	0.28	Small
Contact with shoulder opposite leading	33 (69%)	39 (53%)	0.08	0.16	Small
Contact in centre of gravity	17 (35%)	16 (22%)	0.09	0.15	Small
Head placement on correct side of ball carrier	45 (94%)	69 (93%)	0.91	0.01	Trivial
Post-contact					
Shoulder usage (drive into contact)	19 (40%)	12 (16%)	**<0.01**	0.26	Small
Arm usage (punch forward and wrap i.e. hit-and-stick)	36 (75%)	40 (54%)	**0.02**	0.21	Small
Leg drive on contact	11 (23%)	4 (5%)	**<0.01**	0.26	Small
Compete for possession	11 (23%)	5 (7%)	**0.01**	0.23	Small

Table 20. Tackler side-on proficiency results for tackler success vs ball carrier success (includes % occurrence, p values, Phi and Cramer's V and interpretations).

Tackler Side-on	Tackler Success (n=28)	Ball Carrier Success (n=83)	p value	Phi and Cramer's V	Interpretation
Pre-contact					
Identify/track ball carrier onto shoulder	28(100%)	80 (96%)	0.31	0.10	Small
Body position - upright to low	12 (43%)	27 (33%)	0.32	0.09	Trivial
Straight back, centre of gravity forward of support base	8 (29%)	15 (18%)	0.24	0.11	Small
Head up and forward/face up	28(100%)	80 (96%)	0.31	0.10	Small
Shortening steps	17 (61%)	36 (43%)	0.11	0.15	Small
Contact					
Explosiveness on contact	4 (14%)	5 (6%)	0.17	0.13	Small
Contact in centre of gravity	7 (25%)	21 (25%)	0.98	<0.01	Trivial
Head placement on correct side of ball carrier	26 (93%)	80 (96%)	0.44	0.07	Trivial
Post-contact					
Shoulder usage (drive into contact)	7 (25%)	8 (10%)	**0.04**	0.20	Small
Arm usage (punch forward and wrap i.e. hit-and-stick)	24 (86%)	61 (74%)	0.19	0.13	Small
Pull ball carrier with arms to ground	24 (86%)	64 (77%)	0.33	0.09	Trivial
Compete for possession	2 (7%)	8 (10%)	0.69	0.04	Trivial

6.3.1.2 Ball carrier

For front-on tackles, no ball carrier technical proficiency characteristic showed a significant difference in occurrence between quarters (Table 21). However, for side-on tackles, “explosiveness away from contact” had a significant difference (p=0.02) in occurrence between quarters (Table 22). Post-hoc testing indicated that this characteristic was exhibited by ball carriers more in the second quarter than in the first (p<0.01; ES=0.43).

For front-on tackles, only two of the three tackle phases (contact and post-contact) influenced ball carrier success (Table 23). In the contact phase, “fending into contact” (p=0.01, ES=Small), “explosiveness on contact” (p<0.01), ES=Moderate) and “ball protection” (p=0.03, ES=Small) positively influenced ball carrier success. In the post-contact phase, “leg drive on contact” (p<0.01, ES=Moderate) was significant. For side-on tackles, the post-contact characteristic “leg drive on contact” was the only characteristic with a higher propensity to enable ball carrier success (Table 24). Surprisingly, no pre-contact characteristics influenced ball carrier success in front- or side-on tackles.

Table 21. Ball carrier front-on tackle proficiency results based on quarter in game.

Ball Carrier Front-on	1st Quarter (n=23)		2nd Quarter (n=21)		3rd Quarter (n=36)		4th Quarter (n=33)		p value
	n	%	n	%	n	%	N	%	
Pre-contact									
Eyes focused on tackler	21	(91%)	18	(86%)	29	(81%)	26	(79%)	0.61
Shifting the ball away from contact	13	(56%)	15	(71%)	17	(47%)	12	(36%)	0.08
Body position - upright to low	11	(48%)	7	(33%)	17	(47%)	16	(49%)	0.69
Body position- straight back	17	(74%)	18	(86%)	30	(83%)	28	(85%)	0.69
Head up and forward, eyes open	16	(70%)	15	(71%)	25	(69%)	23	(70%)	0.99
Shuffle or evasive manoeuvre	4	(17%)	5	(24%)	11	(31%)	8	(24%)	0.72
Contact									
Fending into contact	5	(22%)	3	(14%)	5	(14%)	3	(9%)	0.62
Side-on into contact	2	(9%)	4	(19%)	5	(14%)	9	(27%)	0.29
Explosiveness on contact	7	(30%)	8	(38%)	11	(31%)	9	(27%)	0.87
Body position- from low body position up into contact	6	(26%)	3	(14%)	9	(25%)	3	(9%)	0.26
Ball protection	22	(96%)	21	(100%)	36	(100%)	31	(94%)	0.35
Post-contact									
Leg drive on contact	14	(61%)	10	(48%)	18	(50%)	12	(36%)	0.34
Arm and shoulder usage	10	(44%)	8	(38%)	8	(22%)	16	(49%)	0.13
Go to ground and present ball/offload	22	(96%)	20	(95%)	35	(97%)	31	(94%)	0.93

Table 22. Ball carrier side-on tackle proficiency results based on quarter in game.

Ball Carrier Side-on	1st Quarter (n=23)		2nd Quarter (n=22)		3rd Quarter (n=35)		4th Quarter (n=18)		p value
	n	%	n	%	n	%	N	%	
Pre-contact									
Aware of tackler (attunement)	13	(57%)	19	(86%)	21	(60%)	12	(67%)	0.13
Shifting the ball away from contact	10	(44%)	13	(59%)	17	(49%)	11	(61%)	0.60
Body position - upright to low	5	(22%)	1	(5%)	5	(14%)	4	(22%)	0.34
Body Position- straight back	19	(96%)	21	(95%)	32	(91%)	17	(94%)	0.44
Head up and forward, eyes open	19	(83%)	20	(91%)	30	(86%)	14	(78%)	0.70
Shuffle or evasive manoeuvre	7	(30%)	8	(36%)	12	(34%)	6	(33%)	0.98
Contact									
Fending away from contact	5	(22%)	7	(32%)	6	(17%)	4	(22%)	0.64
Explosiveness away from contact	4	(17%)	13	(59%)	10	(29%)	6	(33%)	**0.02**
Ball protection	20	(87%)	20	(91%)	33	(94%)	16	(89%)	0.64
Post-contact									
Leg drive on contact	7	(30%)	14	(64%)	12	(34%)	8	(44%)	0.06
Go to ground and present ball/offload	20	(87%)	20	(91%)	34	(97%)	15	(83%)	0.35

Table 23. Ball carrier front-on proficiency results for tackler success vs ball carrier success (includes % occurrence, p values, Phi and Cramer's V and interpretations).

Ball Carrier Front-on	Tackler Success (n=48)	Ball Carrier Success (n=74)	p value	Phi and Cramer's V	Interpretation
Pre-contact					
Eyes focused on tackler	39 (81%)	64 (86%)	0.44	0.07	Trivial
Shifting the ball away from contact	25 (52%)	36 (49%)	0.71	0.03	Trivial
Body position - upright to low	23 (48%)	34 (46%)	0.83	0.02	Trivial
Body position-straight back	39 (81%)	62 (84%)	0.72	0.03	Trivial
Head up and forward, eyes open	34 (71%)	52 (70%)	0.95	<0.01	Trivial
Shuffle or evasive manoeuvre	9 (19%)	20 (27%)	0.29	0.09	Trivial
Contact					
Fending into contact	2 (4%)	15 (20%)	**0.01**	0.23	Small
Side-on into contact	10 (21%)	10 (14%)	0.29	0.01	Trivial
Explosiveness on contact	6 (13%)	30 (41%)	**<0.01**	0.30	Moderate
Body position-from low body position up into contact	6 (13%)	16 (22%)	0.20	0.12	Small
Ball protection	45 (94%)	74(100%)	**0.03**	0.20	Small
Post-contact					
Leg drive on contact	12 (25%)	47 (64%)	**<0.01**	0.38	Moderate
Arm and shoulder usage	19 (40%)	25 (34%)	0.52	0.06	Trivial
Present ball/offload/break tackle	44 (77%)	73 (80%)	0.73	0.03	Trivial

Table 24. Ball carrier side-on proficiency results for tackler success vs ball carrier success (includes % occurrence, p values, Phi and Cramer's V and interpretations).

Ball Carrier Side-on	Tackler Success (n=28)	Ball Carrier Success (n=83)	p value	Phi and Cramer's V	Interpretation
Pre-contact					
Aware of tackler (attunement)	18 (64%)	56 (68%)	0.76	0.03	Trivial
Shifting the ball away from contact	17 (61%)	43 (52%)	0.41	0.08	Trivial
Body position - upright to low	4 (14%)	13 (16%)	0.86	0.02	Trivial
Body Position-straight back	25 (89%)	76 (92%)	0.72	0.04	Trivial
Head up and forward, eyes open	21 (75%)	73 (88%)	0.10	0.16	Small
Shuffle or evasive manoeuvre	8 (29%)	29 (35%)	0.54	0.06	Trivial
Contact					
Fending away from contact	5 (18%)	19 (23%)	0.58	0.05	Trivial
Explosiveness away from contact	7 (25%)	31 (37%)	0.23	0.11	Small
Ball protection	25 (89%)	75 (90%)	0.87	0.02	Trivial
Post-contact					
Leg drive on contact	6 (21%)	39 (47%)	**0.02**	0.23	Small
Present ball/offload/break tackle	23 (82%)	76 (92%)	0.17	0.13	Small

6.3.2 Time distribution of tackles

The number of tackles occurring in each quarter appears to differ (Table 25). Tukey HSD post-hoc testing indicated that significantly more tackles occurred in the final quarter than the first (p=0.04; ES=1.36) and second (p<0.01; ES=1.93) quarter.

Table 25. The average tackle count per game quarter with standard deviation and p value.

	1st Quarter	2nd Quarter	3rd Quarter	4th Quarter	p value
Tackle Count	55 (±14)	50 (±12)	57 (±17)	73 (±11)	**<0.01**

6.4 Discussion

6.4.1 Technical proficiency criteria

6.4.1.1 Player time-in-game

The results show that player time-in-game did not affect tackle proficiency for both the ball carrier and tackler at the elite level. The distribution of tackle based technical characteristics occurred relatively evenly in each quarter. Even the significant results did not indicate a trend of deterioration in ball carrier or tackler proficiency with increased player time-in-game. For example, “straight back, centre of gravity forward of support base” was exhibited by tacklers more in the third quarter than in the second for side-on tackles (Table 18). Furthermore, no deterioration was found in the high injury risk tackle proficiency characteristics identified by Burger et al. [116]. The results support the theory that elite players do not reach the upper limit for repeatedly engaging in high energy impact tackles during the eighty minutes of a game [93]. Gabbett et al. [122] found that tackling proficiency decreases as fatigue levels increase in amateur level rugby league players. The current findings suggest that the high level of tackle-based training, fitness and physical conditioning experienced by elite level players reduces their susceptibility to tackle technique deterioration. Factors that reduce tackle related injury risk in rugby league include high levels of upper body strength [214], running endurance [214] and quick decision making [215]. These are also more likely to be exhibited by an elite level player than an amateur.

6.4.1.2 Ball carrier proficiency

For front-on tackles, “explosiveness on contact” positively influenced ball carrier success and has previously been shown to help prevent the ball carrier from getting injured in a front-on tackle [116]. Therefore, “explosiveness on contact” carries the twin benefits of being an effective and safe tackle technique characteristic for the ball carrier. “Ball protection” unsurprisingly influenced ball carrier success in front-on tackles. Not protecting the ball increases the likelihood of it being ripped by the tackler or dropped by the ball carrier. “Leg drive on contact” was significant for ball carrier success. “Explosiveness on contact” and “Fending into contact” (Figure 29) were also identified. Previous studies identified fending as an effective ball carrying technique [1, 216]. The abovementioned characteristics indicate the importance of strong and powerful ball carrier play for achieving tackle gainline success. Conversely, absorbing the tackle and falling backwards/to ground is less effective. Surprisingly no pre-contact characteristics influenced ball carrier success in front- or side-on tackles. Pre-contact characteristics may have a greater influence on line-break success (ball carrier evading contact with the defence and advancing forward) [217]. Wheeler et al [217] found that executing a side-step evasive manoeuvre and then straightening the running line was associated with successfully breaking the tackle.

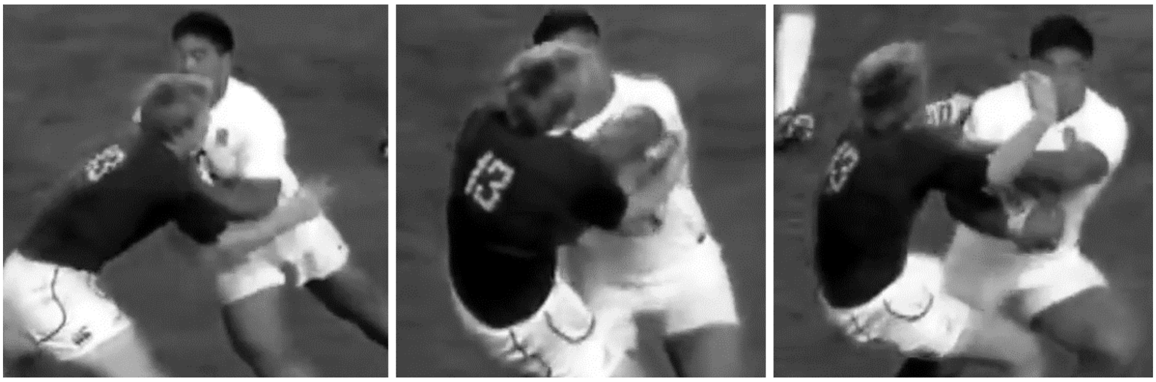

Figure 29. Ball carrier exhibiting a fend off.

6.4.1.3 Tackler proficiency

For front-on tackles, several tackler pre-contact characteristics positively influenced tackler success. “Shortening steps” ensured that the tackler kept their feet moving in the pre-contact phase of the tackle. Therefore, the tackler was better able to adapt to “shuffle/evasive manoeuvres” and/or “fending into contact” exhibited by the ball carrier. When the tackler did not exhibit “shortening steps”, they generally planted their feet. This can result in a compromised body position and an inability to time the tackle correctly or adapt to evasive ball carrier manoeuvres. “Shortening steps” has previously been shown to help to prevent the tackler from getting injured in a front-on tackle [116]. Similar to the ball carrier, the significance of “explosiveness on contact” combined with “leg drive on contact” shows the importance of strong and powerful tackler play in enabling tackle gainline success. The ability to exhibit leg drive post-contact has been previously linked to positive tackler outcomes in Super 14 rugby union games [1]. For front-on tackles, “body position - upright to low” and “straight back, centre of gravity forward of support base” (Figure 30) have a higher propensity to enable tackler success. This agrees with previous findings [218] that a more effective tackle is executed when the tackler leaned forward with the torso.

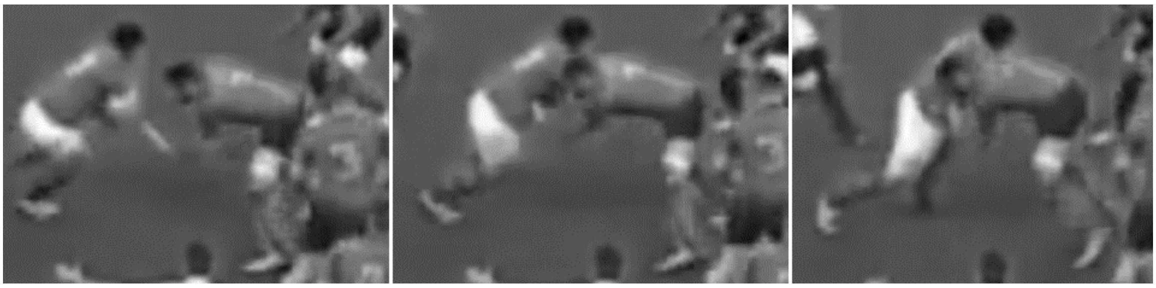

Figure 30. Tackler (right) executing a straight back with centre of gravity forward of support base.

6.4.2 Time distribution of tackles

Significantly more tackles occurred in the final quarter of the game than the first (p=0.04; ES=1.36) and second (p<0.01; ES=1.93). In the final quarter, teams may have a greater tendency to maintain possession, carry the ball and play more attacking-based rugby to win the game/secure a bonus point. Some studies propose that more tackle related injuries occur in the later stages of a game because of fatigue [93, 96]. This study provides an alternative explanation. It may be due to more tackles occurring in the final quarter. However, this is still not proportionate to the large number of upper body tackle related direct head impacts that occur in the final quarter (Chapter 5).

6.4.3 Limitations

The tackle is an open phase of play (high variability) and this must be appreciated when assessing technical criteria [32, 116]. Speed was not assessed in the current study and may have influenced tackle gainline success outcomes. Elite club level rugby union games were analysed. However, the results may be applicable to both youth and amateur level rugby union. Further research is needed to clarify this. Tackles from only three games were used in the analysis. Hence, only a small number of teams were analysed. For tackler proficiency characteristics, just one team was analysed. This could make the data susceptible to outliers. Further monitoring of other teams should be pursued.

The players analysed remained on the field throughout the entire game. These players may have higher performance capabilities than players who were substituted. Selection bias may be an issue as substituted players were not included in the study. These may be the players involved in the most tackles during the game. Further work should conduct similar analysis on substituted players. For the time-in-game analysis, a chi-square test was used to identify significant differences (p<0.05) for technical proficiency characteristics between quarters. This data was non-independent [219]. A chi-square test runs the risk of omitting significant results for non-independent data [219]. However, even the results close to significance (p<0.10) did not indicate a trend of deterioration with player time-in-game. A Cochran's Q test was not selected as some players conducted more tackles in some quarters than others. This prevented the calculation from being conducted.

The time distribution analysis utilised partially overlapping samples (i.e. dependent and independent samples) as tackles involving substitute/substituted players were included [220]. Utilising a one-way ANOVA is common in this scenario but runs the risk of omitting significant results [220].

6.5 Conclusion

Player time-in-game does not appear to affect tackler or ball carrier tackle technique proficiency at the elite level. The proposed upper limit for a player's ability to repeatedly engage in high energy impact tackles does not appear to be reached during the eighty minutes of a game. Analysis of the time distribution of tackles identified that significantly more tackles occurred in the final quarter of the game than the first ($p=0.04$; ES=1.36) and second ($p<0.01$; ES=1.93) quarter. This provides an alternative explanation to player time-in-game causing more head impacts to occur in the later stages of a game. Instead, it may be partially due to more tackles occurring in the final quarter.

Several tackle characteristics with a higher propensity towards tackle gainline success for the ball carrier and tackler were identified. For both the ball carrier and tackler, characteristics that were indicative of strong and powerful tackle technique were effective. The findings provide evidence, at the elite level, for coaches to develop and implement technical based performance strategies for tackling. These technical criteria should now be utilised to identify tackle characteristics that influence direct head impact risk.

Additional contributor. Karl Denvir was the second reviewer involved in this study.

7 The effect of technique on tackler head injury assessment risk in elite level rugby union

Related publications. Tierney GJ, Denvir K, Farrell G, Simms CK. The effect of tackler technique on head injury assessment risk in elite rugby union. Medicine and Science in Sports and Exercise. 2018;50(3):603-8.

Tierney GJ, Denvir K, Farrell G, Simms CK. Does ball carrier technique influence tackler head injury assessment risk in elite rugby union? Journal of Sports Sciences. 2018:1-6.

7.1 Introduction

Tackles account for the majority of direct head impacts in elite level rugby union (Chapter 5). In Chapter 5, legal tackles were categorised as either upper or lower body tackles. An upper body tackle was defined by the tackler's intended primary contact being above the ball carrier's hip. A lower body tackle was defined as the tackler's intended primary contact being at or below the ball carrier's hip. Chapter 5 demonstrated that tacklers were at most risk of sustaining a direct head impact. Tackle technique characteristics associated with general injury have previously been identified by Burger et al [116]. However, the study focussed on general injury even though the mechanism of injury is not the same for all types [90]. Specific tackle characteristics may be associated with concussion risk but the details are unknown. Therefore, the aim of this study is to use match video evidence to identify tackler and ball carrier characteristics, for both lower- and upper body tackles, that result in a Head Injury Assessment (HIA) for the tackler. A reduction in tackle-related HIAs would have a strong influence on concussion injury reduction. The approach for this study utilises the tackle based technical criteria lists created by Burger et al. [116].

7.2 Methods

7.2.1 Definitions and data collection

A tackle was defined as "when the ball-carrier was contacted (hit and/or held) by an opponent without reference to whether the ball-carrier went to ground" [110]. A HIA tackle was defined as when a tackler received a direct/indirect head impact in the tackle and was subsequently removed from play for a HIA and did not return to play for the remainder of the game. A non-HIA tackle was defined as when a player did not receive an injury/head impact in the tackle and was not removed from play for the remainder of the game. To provide non-HIA cases as a control cohort, the tackle technique data from Chapter 6 was utilised. In brief, this data consists of tackles from three randomly selected 2014/15 European Champions Cup games involving an Irish professional club team. A total of 92 upper body and 30 lower body front-on tackles and 75 upper body and 36 lower body side-on tackles were analysed as control cases.

To obtain tackle-related HIA cases, all Pro 12 and European Rugby Champions Cup games from 2014-2017 of the same Irish professional rugby club team were reviewed. This approach resulted in a low HIA sample size (n=19). To increase this sample size, additional video data was collected by retrospectively reviewing international test rugby union matches. This subset was compiled of all matches from the RBS 6 Nations 2014-2017, Guinness Autumn Test Series 2013-2016, Rugby World Cup warm-up games 2015 (Home nation games only), the Rugby World Cup 2015 (all games) and the British and Irish Lions Tour 2017. A total of 74 HIA cases were identified (19 upper body and 19 lower body front-on tackles and 23 upper body and 13 lower body side-on tackles). This video data was obtained from freely available online resources. Although a HIA can occur from an impact to the body [24], a direct head impact was identified in every video.

7.2.2 Technical proficiency criteria

The tackle technique characteristics are based on the work of Burger et al. [116] who developed technical criteria for tackle proficiency in front- and side-on tackles. Any tackles initiated outside the ball carrier's estimated peripheral vision were considered side-on tackles [32, 116].

Two reviewers analysed each video together. Any cases involving uncertainty between reviewers were resolved by a discussion until a consensus was reached. The videos were analysed using Sports Code (Version 8). Sports Code enabled frame-by-frame viewing of the tackles. Reviewers could watch the clips as many times as necessary. A minimum of two camera view videos (25 fps) were available for each tackle. The tackle was split into three main phases [1]; pre-contact (0.5 s preceding contact), contact (first instance of contact) and post-contact. Technical proficiency characteristics were assigned to these phases. A player was scored either 1 or 0 for each technical proficiency characteristic depending on whether or not they exhibited that particular characteristic.

7.2.3 Statistical Analysis

All statistics were calculated using SPSS (IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp.). For each tackle proficiency characteristic, Chi-Square and Phi and Cramer's V calculations were conducted [203]. Statistical significance was set at $p<0.05$. A Phi and Cramer's V value less than 0.1, between 0.1 and less than 0.3, between 0.3 and less than 0.5 and 0.5 or greater were considered indicative of a trivial, small, moderate and large Effect Sizes (ES) respectively [211].

7.2.4 Reliability

Fifteen front-on and fifteen side-on tackles (including HIA and non-HIA cases) were randomly selected using a random number generator (http://www.random.org/). The two reviewers conducted the reliability analysis at least one week after conducting the initial set of cases. To assess for inter-rater reliability, an external reviewer conducted the analysis on the same 30 cases. Inter- and intra-rater reliability was assessed using Cohen's Kappa (K). A Cohen's Kappa value greater than 0.8 indicates almost perfect agreement [213]. For front-on tackles, a Cohen's Kappa of 0.87 and 0.86 were calculated for intra- and inter-rater reliability for tackler characteristics, respectively. For side-on tackles, a Cohen's Kappa of 0.96 and 0.86 were calculated for intra- and inter-rater reliability for tackler characteristics, respectively. For front-on tackles, a Cohen's Kappa of 0.93 and 0.81 were calculated for intra- and inter-rater reliability for ball carrier characteristics, respectively. For side-on tackles, a Cohen's Kappa value of 0.95 and 0.86 were calculated for intra- and inter-rater reliability for ball carrier characteristics, respectively.

7.3 Results

7.3.1 Tackler

7.3.1.1 Upper body tackles

For front-on upper body tackles, the main tackle phase that influenced HIA causation for the tackler was the pre-contact phase (Table 26). The tackler characteristics "identify/track ball carrier onto shoulder" ($p<0.01$, ES=Moderate), "head up and forward/face up" ($p<0.01$; ES=Large) and "shortening steps" ($p<0.01$; ES=Small) had a lower propensity to result in a HIA for the tackler. In the contact phase, "head placement on correct side of ball carrier" ($p<0.01$; ES=Large) had a lower propensity to result in a HIA for the tackler. This was also the case for "arm usage (punch forward and wrap i.e. hit-and-stick)" ($p<0.01$; ES=Moderate) in the post-contact phase.

Similarly, for side-on upper body tackles, "identify/track ball carrier onto shoulder" ($p<0.01$, ES=Moderate), "head up and forward/face up" ($p<0.01$; ES=Large) and "shortening steps" ($p<0.01$; ES=Moderate) had a lower propensity to result in a HIA for the tackler in the pre-contact phase (Table 27). This was similar for "head placement on correct side/behind ball carrier" ($p<0.01$; ES=Large) in the contact phase. Differences were observed for "arm usage (punch forward and wrap i.e. hit-and-stick)" and "pull ball carrier with arms to ground" (both $p<0.01$; ES=Large) between HIA and non-HIA cases in the post-contact phase. In 35% (n=8) of side-on upper body tackles, it was another tackler from the same team that impacted the tackler's head. This was due to both team mates tackling the same ball carrier. In one case, both tacklers received HIAs.

7.3.1.2 Lower body tackles

For front-on lower body tackles, "straight back, centre of gravity forward of support base" ($p=0.04$; ES=Small), "head up and forward/face up" ($p<0.01$; ES=Large) and "head placement on correct side of ball carrier" ($p<0.01$; ES=Large) had a lower propensity to result in a HIA for the tackler (Table 28). Differences were observed on "arm usage (punch forward and wrap i.e. hit-and-stick)" ($p<0.01$; ES=Moderate) between HIA and non-HIA cases in the post-contact phase.

For side-on lower body tackles, "identify/track ball carrier onto shoulder" ($p<0.01$; ES=Moderate), "head up and forward/face up" ($p<0.01$; ES=Large) and "head placement on correct side/behind ball carrier" ($p<0.01$; ES=Large) had a lower propensity to result in a HIA for the tackler (Table 29). Differences were observed for "arm usage (punch forward and wrap i.e. hit-and-stick)" ($p=0.02$; ES=Moderate) and "pull ball carrier with arms to ground" ($p=0.01$; ES=Moderate) between HIA and non-HIA cases in the post-contact phase. In one side-on lower body tackle, it was another tackler from the same team that impacted the tackler's head. This was due to both team mates tackling the same ball carrier.

Table 26. Tackler upper body tackle front-on proficiency results for HIA and non-HIA tackles (includes % occurrence, p values, Phi and Cramer's V and interpretations).

	HIA (n=19)	Non-HIA (n=92)	p value	Phi and Cramer's V	Interpretation
Pre-contact					
Identify/track ball carrier onto shoulder	11 (58%)	89 (97%)	**<0.01**	0.49	Moderate
Body position - upright to low	7 (37%)	29 (32%)	0.65	0.04	Trivial
Straight back, centre of gravity forward of support base	5 (26%)	27 (29%)	0.79	0.03	Trivial
Square to ball carrier	14 (74%)	81 (88%)	0.11	0.15	Small
Boxer stance (elbows close, hands up)	8 (42%)	58 (63%)	0.09	0.16	Small
Head up and forward/face up	11 (58%)	90 (98%)	**<0.01**	0.53	Large
Shortening steps	4 (21%)	56 (61%)	**<0.01**	0.29	Small
Approach from front/oblique	19 (100%)	91 (99%)	0.65	0.04	Trivial
Contact					
Explosiveness on contact	5 (26%)	16 (17%)	0.37	0.09	Trivial
Contact with shoulder opposite leading	8 (42%)	49 (53%)	0.38	0.17	Small
Head placement on correct side of ball carrier	3 (16%)	86 (94%)	**<0.01**	0.73	Large
Post-contact					
Shoulder usage (drive into contact)	2 (11%)	23 (25%)	0.17	0.13	Small
Arm usage (punch forward and wrap i.e. hit-and-stick)	4 (21%)	56 (61%)	**<0.01**	0.30	Moderate
Leg drive on contact	0 (0%)	9 (10%)	0.16	0.14	Small
Release ball carrier and compete for possession	0 (0%)	15 (16%)	0.06	0.18	Small

Table 27. Tackler upper body tackle side-on proficiency results for HIA and non-HIA tackles (includes % occurrence, p values, Phi and Cramer's V and interpretations).

	HIA (n=23)	Non-HIA (n=75)	p value	Phi and Cramer's V	Interpretation
Pre-contact					
Identify/track ball carrier onto shoulder	14 (61%)	73 (97%)	<0.01	0.49	Moderate
Body position - upright to low	2 (9%)	9 (12%)	0.66	0.04	Trivial
Straight back, centre of gravity forward of support base	1 (4%)	8 (10%)	0.36	0.09	Trivial
Head up and forward/face up	16 (70%)	75(100%)	<0.01	0.50	Large
Shortening steps	2 (9%)	38 (51%)	<0.01	0.36	Moderate
Contact					
Explosiveness on contact	3 (13%)	5 (7%)	0.33	0.10	Small
Head placement on correct side/behind ball carrier	9 (39%)	74 (99%)	<0.01	0.70	Large
Post-contact					
Shoulder usage (drive into contact)	3 (13%)	6 (8%)	0.46	0.07	Trivial
Arm usage (punch forward and wrap i.e. hit-and-stick)	5 (22%)	60 (80%)	<0.01	0.52	Large
Pull ball carrier with arms to ground	5 (22%)	60 (80%)	<0.01	0.52	Large
Release ball carrier and compete for possession	0 (0%)	8 (11%)	0.10	0.17	Small

Table 28. Tackler lower body tackle front-on proficiency results for HIA and non-HIA tackles (includes % occurrence, p values, Phi and Cramer's V and interpretations).

	HIA (n=19)	Non-HIA (n=30)	p value	Phi and Cramer's V	Interpretation
Pre-contact					
Identify/track ball carrier onto shoulder	17 (89%)	28 (93%)	0.63	0.07	Trivial
Body position - upright to low	18 (95%)	27 (90%)	0.56	0.08	Trivial
Straight back, centre of gravity forward of support base	3 (16%)	13 (43%)	**0.04**	0.29	Small
Square to ball carrier	13 (68%)	26 (87%)	0.12	0.22	Small
Boxer stance (elbows close, hands up)	8 (42%)	17 (57%)	0.32	0.14	Small
Head up and forward/face up	2 (11%)	25 (83%)	**<0.01**	0.71	Large
Shortening steps	5 (26%)	13 (43%)	0.23	0.17	Small
Approach from front/oblique	19 (100%)	30 (100%)	1.00	0.00	Trivial
Contact					
Explosiveness on contact	1 (5%)	6 (20%)	0.15	0.20	Small
Contact with shoulder opposite leading	11 (58%)	23 (77%)	0.17	0.20	Small
Head placement on correct side of ball carrier	2 (11%)	28 (93%)	**<0.01**	0.83	Large
Contact in centre of gravity	9 (47%)	19 (63%)	0.27	0.16	Small
Post-contact					
Shoulder usage (drive into contact)	1 (5%)	8 (27%)	0.06	0.27	Small
Arm usage (punch forward and wrap i.e. hit-and-stick)	4 (21%)	20 (67%)	**<0.01**	0.45	Moderate
Leg drive on contact	1 (5%)	6 (20%)	0.15	0.21	Small
Release ball carrier and compete for possession	0 (0%)	1 (3%)	0.42	0.12	Small

Table 29. Tackler lower body tackle side-on proficiency results for HIA and non-HIA tackles (includes % occurrence, p values, Phi and Cramer's V and interpretations).

	HIA (n=13)	Non-HIA (n=36)	p value	Phi and Cramer's V	Interpretation
Pre-contact					
Identify/track ball carrier onto shoulder	8 (62%)	35 (97%)	<0.01	0.48	Moderate
Body position - upright to low	11 (85%)	30 (83%)	0.92	0.02	Trivial
Straight back, centre of gravity forward of support base	3 (23%)	15 (42%)	0.23	0.17	Small
Head up and forward/face up	3 (23%)	33 (92%)	<0.01	0.69	Large
Shortening steps	5 (39%)	15 (42%)	0.84	0.03	Trivial
Contact					
Explosiveness on contact	2 (15%)	4 (11%)	0.69	0.06	Trivial
Head placement on correct side/behind ball carrier	5 (39%)	32 (89%)	<0.01	0.52	Large
Contact in centre of gravity	6 (46%)	17 (47%)	0.95	0.01	Trivial
Post-contact					
Shoulder usage (drive into contact)	2 (15%)	9 (25%)	0.48	0.10	Small
Arm usage (punch forward and wrap i.e. hit-and-stick)	4 (31%)	25 (69%)	0.02	0.35	Moderate
Pull ball carrier with arms to ground	5 (39%)	28 (78%)	0.01	0.37	Moderate
Release ball carrier and compete for possession	0 (0%)	2 (6%)	0.39	0.12	Small

7.3.2 Ball Carrier

7.3.2.1 Upper body tackles

For front-on upper body tackles, only the contact phase of the tackle influenced tackler HIA risk (Table 30). The ball carrier characteristics "fending into contact" ($p<0.01$, ES=Moderate) and "explosiveness on contact" ($p=0.03$; ES=Moderate) had a higher propensity to result in a HIA for the tackler. No characteristics for side-on upper body tackles influenced tackler HIA risk (Table 31).

7.3.2.2 Lower body tackles

For front-on lower body tackles, only “explosiveness on contact” (p=0.04; ES=Moderate) had a higher propensity to result in a HIA for the tackler (Table 32). No characteristics for side-on lower body tackles influenced tackler HIA risk (Table 33).

Table 30. Ball carrier upper body tackle front-on proficiency results for HIA and non-HIA tackles (includes % occurrence, p values, Phi and Cramer's V and interpretations).

	HIA (n=19)	Non-HIA (n=92)	p value	Phi and Cramer’s V	Interpretation
Pre-contact					
Eyes focused on tackler	13 (68%)	76 (83%)	0.16	0.13	Small
Shifting the ball away from contact	5 (26%)	43 (47%)	0.10	0.16	Small
Body position - upright to low	6 (31%)	44 (48%)	0.20	0.12	Small
Body position- straight back	15 (79%)	73 (79%)	0.97	<0.01	Trivial
Head up and forward, eyes open	14 (74%)	59 (64%)	0.42	0.08	Trivial
Shuffle or evasive manoeuvre	3 (16%)	19 (21%)	0.63	0.05	Trivial
Contact					
Fending into contact	9 (47%)	14 (15%)	**<0.01**	0.30	Moderate
Side-on into contact	4 (21%)	12 (13%)	0.37	0.09	Trivial
Explosiveness on contact	11 (58%)	29 (31%)	**0.03**	0.21	Small
Body position- from low body position up into contact	3 (16%)	18 (20%)	0.70	0.04	Trivial
Ball protection	17 (90%)	90 (98%)	0.08	0.17	Small
Post-contact					
Leg drive on contact	11 (58%)	48 (52%)	0.65	0.03	Trivial
Arm and shoulder usage	9 (47%)	40 (44%)	0.76	0.03	Trivial
Go to ground and present ball/offload	17 (90%)	89 (97%)	0.16	0.13	Small

Table 31. Ball carrier upper body tackle side-on proficiency results for HIA and non-HIA tackles (includes % occurrence, p values, Phi and Cramer's V and interpretations).

	HIA (n=23)	Non-HIA (n=75)	p value	Phi and Cramer's V	Interpretation
Pre-contact					
Aware of tackler (attunement)	15 (65%)	45 (60%)	0.65	0.05	Trivial
Shifting the ball away from contact	13 (56%)	35 (47%)	0.41	0.08	Trivial
Body position - upright to low	5 (22%)	13 (17%)	0.63	0.05	Small
Body position-straight back	21 (91%)	66 (88%)	0.66	0.04	Trivial
Head up and forward, eyes open	15 (65%)	61 (81%)	0.11	0.16	Small
Shuffle or evasive manoeuvre	2 (9%)	17 (23%)	0.14	0.15	Small
Contact					
Fending away from contact	2 (9%)	14 (19%)	0.26	0.11	Small
Explosiveness away from contact	9 (39%)	25 (33%)	0.61	0.05	Trivial
Ball protection	22 (96%)	67 (89%)	0.36	0.09	Trivial
Post-contact					
Leg drive on contact	8 (35%)	31 (41%)	0.57	0.06	Trivial
Go to ground and present ball/offload	21 (91%)	66 (88%)	0.66	0.04	Trivial

Table 32. Ball carrier lower body tackle front-on proficiency results for HIA and non-HIA tackles (includes % occurrence, p values, Phi and Cramer's V and interpretations).

	HIA (n=19)	Non-HIA (n=30)	p value	Phi and Cramer's V	Interpretation
Pre-contact					
Eyes focused on tackler	18 (95%)	27 (90%)	0.56	0.08	Trivial
Shifting the ball away from contact	10 (53%)	18 (60%)	0.61	0.07	Trivial
Body position - upright to low	12 (63%)	13 (43%)	0.18	0.19	Small
Body position-straight back	15 (79%)	28 (93%)	0.13	0.21	Small
Head up and forward, eyes open	17 (90%)	27 (90%)	0.95	<0.01	Trivial
Shuffle or evasive manoeuvre	7 (37%)	10 (33%)	0.80	0.04	Trivial
Contact					
Fending into contact	4 (21%)	3 (10%)	0.28	0.15	Small
Side-on into contact	5 (26%)	8 (27%)	0.98	<0.01	Trivial
Explosiveness on contact	10 (53%)	7 (23%)	**0.04**	0.30	Moderate
Body position-from low body position up into contact	2 (11%)	4 (13%)	0.77	0.04	Trivial
Ball protection	18 (95%)	29 (97%)	0.74	0.05	Trivial
Post-contact					
Leg drive on contact	7 (37%)	11 (37%)	0.99	<0.01	Trivial
Arm and shoulder usage	5 (26%)	4 (13%)	0.25	0.16	Small
Go to ground and present ball/offload	18 (95%)	28 (93%)	0.84	0.03	Trivial

Table 33. Ball carrier lower body tackle side-on proficiency results for HIA and non-HIA tackles (includes % occurrence, p values, Phi and Cramer's V and interpretations).

	HIA (n=13)	Non-HIA (n=36)	p value	Phi and Cramer's V	Interpretation
Pre-contact					
Aware of tackler (attunement)	11 (85%)	29 (81%)	0.75	0.05	Trivial
Shifting the ball away from contact	8 (62%)	25 (69%)	0.60	0.07	Trivial
Body position - upright to low	2 (15%)	4 (11%)	0.69	0.06	Trivial
Body Position- straight back	12 (92%)	35 (97%)	0.44	0.11	Small
Head up and forward, eyes open	13(100%)	33 (92%)	0.28	0.16	Small
Shuffle or evasive manoeuvre	4 (31%)	20 (56%)	0.13	0.22	Small
Contact					
Fending away from contact	1 (8%)	10 (28%)	0.14	0.21	Small
Explosiveness away from contact	7 (54%)	13 (36%)	0.27	0.16	Small
Ball protection	13(100%)	33 (92%)	0.28	0.16	Small
Post-contact					
Leg drive on contact	4 (31%)	14 (39%)	0.60	0.07	Trivial
Go to ground and present ball/offload	13(100%)	32 (89%)	0.21	0.18	Small

7.4 Discussion

7.4.1 General

Tackle characteristics that influence tackler HIA risk were identified using match video evidence. Several tackler-specific proficiency variables were identified as having a lower propensity to result in a HIA for the tackler. Examples include, “identify/track ball carrier onto shoulder”, “head up and forward/face up”, “straight back, centre of gravity forward of support base” and “head placement on correct side of ball carrier” (Figure 31). The results provide an evidence-base for elite level coaches to develop and implement HIA prevention strategies for tacklers.

The tackler’s judgement arises in a dynamic scenario in which the ball carrier can adjust his speed, configuration and direction. However, much fewer ball carrier proficiency variables that result in a tackler HIA were identified. This highlights the importance of tackler proficiency characteristics for prevention.

Figure 31. Example of a tackler not executing "identify/track ball carrier onto shoulder", "head up and forward/face up", "straight back, centre of gravity forward of support base" and "head placement on correct side of ball carrier" during a HIA case.

7.4.2 Tackler

When a tackler did not identify/track the ball carrier onto their shoulder, they generally placed their head in line with the ball carrier's trajectory. Exhibiting the characteristic "head up and forward/face up" resulted in the tackler being able to track the ball carrier's motion and be aware of their surrounding environment. Thus, the tacklers susceptibility to receiving a head impact was reduced.

When "shortening steps" was not exhibited, the tackler generally planted his feet during the pre- contact phase of the tackle (Figure 32). This is consistent with the findings of Chapter 5 which identified foot planting as risk factor for direct head impact causation. Tacklers exhibiting "shortening steps" ensured their feet remained active. This afforded them time to orientate themselves properly as well as adapt to changes in the ball carrier's motion/trajectory. "Shortening steps" reduces general injury risk for the tackler in front-on tackles [116] and increases the tackler's likelihood of success in the tackle (Chapter 6).

Figure 32. Example of tackler planting their feet and not executing "shortening steps" during a HIA case.

Post-contact tackling characteristics such as "arm usage (punch forward and wrap i.e. hit-and-stick)" and "pull ball carrier with arms to ground" exhibited differences between HIA and non-HIA cases. However, all head impacts occurred before the post-contact phase. These tackler characteristics do not lower the propensity of a head impact. However, they may be an indicator for sideline medical staff that a head impact has occurred. This is also the case for lower body tackles.

For 35% of side-on upper body tackle HIA cases and one side-on lower body tackle HIA case, it was another tackler from the same team that impacted the tackler's head. This was due to both team mates tackling the same ball carrier. This indicates the importance of environmental awareness and effective communication between tacklers when engaging in a two-tackler tackle. The same principles can be applied as with the single tackler cases e.g. "shortening steps" may have afforded the impacted player time to orientate themselves properly and avoid the head impact from their teammate.

In 95% of front-on lower body tackle HIA cases where the tackler did not exhibit "straight back, centre of gravity forward of support base," the tackler's head was facing down (i.e. not exhibiting the "head up and forward/face up" characteristic). Therefore, the tackler may have been unaware of the ball carrier's oncoming motion and their surrounding environment. In 69% of lower body tackle front-on HIA cases, placing the tackler's centre of gravity behind their support base resulted in the tackler's weight being transmitted through the heels. This resulted in foot planting and the aforementioned breakdown in tackle proficiency.

For side-on lower body tackles, an inability to "identify/track the ball carrier onto shoulder" had a higher propensity to result in a HIA for the tackler. In 15% of lower body tackle side-on HIA cases, the tackler dove in front of the oncoming ball carrier with their head facing downward. Therefore, no attempt was made to use the shoulders (Figure 33).

Figure 33. Tackler with head facing downwards and not tracking the ball carrier onto shoulder during a HIA case.

Recently, Davidow et al. [221] conducted a separate study on technique during head impact tackles. The study did not split the tackle into upper- and lower body tackles but similarly found that head impacted tacklers had lower contact proficiency for “identify/track ball carrier onto shoulder”, “straight back, centre of gravity forward of support base”, “head up and forward/face up”, “shortening steps”, “head placement on correct side of ball carrier” and “arm usage (punch forward and wrap i.e. hit-and-stick)”.

7.4.3 Ball Carrier

Fending into contact was exhibited in almost half of all upper body tackle front-on HIA cases (47%). According to Law 7 of rugby union, the ball carrier is only permitted to fend off an opponent by using the palm of the hand [222]. However, in 67% of these cases it was the fending arm (upper arm, elbow and forearm), and not the palm of the hand, that contacted the tackler’s head (Figure 34). None of these cases resulted in a foul being given. As of November 2016, World Rugby added a reckless tackle sanction to the laws of the game by stating that “a player is deemed to have made reckless contact during a tackle or attempted tackle or during other phases of the game if in making contact, the player knew or should have known that there was a risk of making contact with the head of an opponent, but did so anyway. This sanction applies even if the tackle starts below the line of the shoulders. This type of contact also applies to grabbing and rolling/ twisting around the head/ neck area even if the contact starts below the line of the shoulders [223].” The minimum and maximum sanction for a reckless tackle is a yellow and red card, respectively. The current findings agree with this addition to the law and illustrates the importance of its enforcement. With regards to HIA prevention, coaches should place focus on correct fending during tackle-based training drills. Referees should also be alert to head contact during the fend.

Davidow et al. [221] also found ball carriers to exhibit “fending into contact” more in tackler head impact cases. However, the study identified a number of ball carrier characteristics with a higher propensity to result in a tackler head impact that were not identified in this study such as, “Body position - straight back”, “Body position - upright to low” and “side-on into contact”. It is unclear why these findings differ to those in the current study. A potential reason may be due to the dataset utilised by Davidow et al. [221] consisting entirely of professional and semi-professional southern hemisphere games.

“Explosiveness on contact” had a higher propensity to result in a tackler HIA for upper and lower body front-on tackles. This is consistent with a previous study that identified energy transfer in the tackle as a HIA risk factor [206]. It is difficult to mitigate against this risk as ball carrier explosivity is a desirable trait.

Figure 34. An example of the fending arm contacting the tackler's head.

7.4.4 Limitations

The tackle is a dynamic and open phase of play and this must be appreciated when analysing tackling characteristics [32, 116]. Certain proficiency characteristics may have influenced other proficiency characteristics. For example, failure to exhibit “straight back, centre of gravity forward of support base” may have affected the tackler’s ability to exhibit “head up and forward/face up”. A definition based on a player being removed for a HIA and not returning to play was utilised for this study. Although this is a strong indication of concussion, it is not fully robust for diagnosis. Access to player medical notes would have clarified this. The HIA sample size was larger than the injury sample size utilised by Burger et al [116]. However, a larger sample size would have been beneficial. Elite club level rugby union games were analysed as non-HIA cases. Ideally, international games would be included in the control dataset also. However, the results may be applicable to both youth and amateur level rugby union. Further research is needed to clarify this. Nonetheless the findings can be utilised for a baseline of HIA prevention techniques.

7.5 Conclusion

Analysis of elite level match video evidence identified tackle proficiency characteristics that influence tackler HIA risk. In both front- and side-on upper- and lower body tackles, “head up and forward/face up” and “head placement on correct side of ball carrier” were identified as tackler characteristics that have a lower propensity to result in a tackler HIA. Additionally, “identify/track ball carrier onto shoulder” and "shortening steps" were identified for both front- and side-on upper body tackles. "Straight back, centre of gravity forward of support base" and "identify/track ball carrier onto shoulder" have a lower propensity to cause a HIA for front- and side-on lower body tackles, respectively.

The ball carrier characteristic "fending into contact" was exhibited in 47% of all upper body tackle front-on HIA cases. In 67% of these cases, the fending arm (upper arm, elbow and forearm) contacted the tacklers head. Much fewer ball carrier proficiency characteristics that result in a tackler HIA were identified. No side-on ball carrier characteristics were identified. This highlights the importance of tackler proficiency characteristics for HIA prevention. The findings provide an evidence-base for elite level coaches to develop and implement HIA prevention strategies for tacklers.

Additional contributor. Karl Denvir was the second reviewer involved in this study.

8 Can tackle height influence performance and head injury assessment risk in elite level rugby union?

Related publications. Tierney GJ, Simms CK. Can tackle height influence tackle gainline success outcomes in elite level rugby union? International Journal of Sports Science & Coaching. 2018;13(3):415-20.

Tierney GJ, Simms CK. Can tackle height influence head injury assessment risk in elite rugby union? Journal of Science and Medicine in Sport. 2018:1-5.

8.1 Introduction

The Burger et al. [116] tackle proficiency criteria listed "contact (the ball carrier) in the centre of gravity" as a desirable tackler characteristic. However, the characteristic was not found to influence tackler success or HIA risk in Chapter 6 and 7, respectively. Furthermore, Hendricks et al. [1] identified that shoulder tackles targeted at the ball carrier's mid-torso were associated with positive tackler outcomes.

Furthermore, upper body tackles were identified as the greatest cause of head impacts for the tackler in Chapter 5. The tackle height law in rugby union is currently set at the line of the ball carrier's shoulder. Any contact above this line is regarded as foul play [118]. Lowering the tackle height law has been recommended since the 1970s for neck injury prevention [224]. Scher [224] identified that players were tackled around the neck in 36% of catastrophic cervical spinal cord injuries. The evidence base for lowering the tackle height law for concussion injury prevention is currently limited. To guide prevention strategies and before laws changes can be made, it is essential to examine the effect of tackle height on concussion risk.

Accordingly, the aim of this study is to use match video evidence to examine the effect of tackle height on HIA risk for the tackler. Tackle height will be assessed based on intended primary contact location on the ball carrier. A secondary aim is to identify tackle heights that have a higher propensity to result in tackle gainline success for the tackler.

8.2 Methods

8.2.1 Definitions and data collection

All tackle, tackle gainline and HIA related definitions utilised in Chapter 6 and 7 were used for this study. Fuller et al. [118] defined the following for arm, shoulder and smother tackles; Arm Tackle - “Tackler impedes/stops ball carrier with upper limb(s)”; Shoulder tackle - “Tackler impedes/stops ball carrier with shoulder as the first point of contact followed by use of arm(s)”; Smother tackle - “Tackler uses chest and wraps both arms around ball carrier”. The HIA video data from Chapter 7 was utilised for this study. In brief, this data consists of 74 tackles that resulted in a HIA for the tackler (19 upper body and 19 lower body front-on tackles and 23 upper body and 13 lower body side-on tackles) from elite level competitions. To provide non-HIA cases and for the tackle gainline analysis, all games from one season of the abovementioned competitions were assigned a number. A random number generator (http://www.random.org/) selected five games. Every non-HIA/injury tackle (n=965) from these games was analysed.

8.2.2 Tackle analysis

Each tackle analysed was categorised based on tackle direction (front- or side-on), tackle type (arm, collision, jersey, lift, shoulder, smother or tap [118]) and tackle height (upper trunk, mid-trunk, lower trunk, upper leg or lower leg, see Figure 35). The videos were analysed using Sports Code (Version 8).

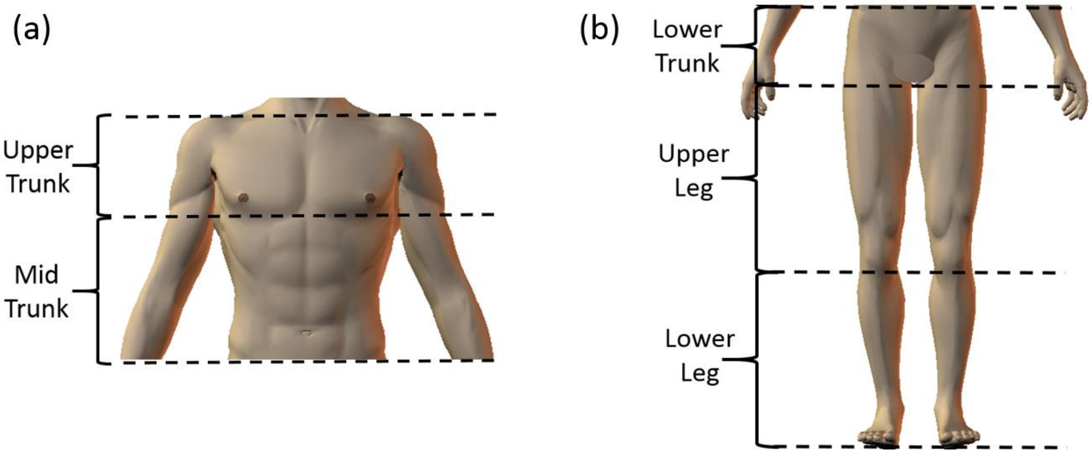

Figure 35. The ball carrier’s body split into (a) upper trunk and mid-trunk regions for upper body tackles and (b) lower trunk, upper leg and lower leg regions for lower body tackles.

8.2.3 Statistical Analysis

For upper and lower body front- and side-on tackles, only the main tackle type that resulted in a HIA for each subcategory and the tackle type matched control cases (non-HIA) were utilised for the statistical analysis. All non-HIA tackles were utilised for the tackle gainline analysis. The Relative Risk (RR), 95% Confidence Interval (CI) and probability (*p*) values were calculated for each tackle height [203], see Chapter 5. A variable was considered to have statistical significance if the 95% CI for the RR value did not include 1 and the *p*-value was <0.05.

8.2.4 Reliability

Sixty tackles (including both HIA and non-HIA cases) were selected using a random number generator (http://www.random.org/). For intra-rater reliability, the reviewer conducted the analysis on these 60 cases at least one week after the initial set. To assess inter-rater reliability, an external reviewer conducted the analysis on the same 60 cases. Intra- and inter-rater reliability were assessed using Cohen's Kappa (K). A Cohen's Kappa value greater than 0.8 indicates almost perfect agreement [213]. For intra-rater reliability, Cohen's kappa values of 0.93, 0.97 and 0.92 were achieved for tackle height, direction and type, respectively. For inter-rater reliability, Cohen's kappa values of 0.83, 0.83, and 0.82 were achieved for tackle height, direction and type, respectively.

8.3 Results

8.3.1 HIA analysis

Tackling at the upper trunk accounts for nearly half (47%) of all HIA tackles (Figure 36). Tackling at the upper legs accounts for 30%. Shoulder (79%; n=15) and smother tackles (65%; n=15) account for the majority of upper body front- and side-on tackler HIAs, respectively (Figure 37). Shoulder tackles also account for the majority of lower body front- and side-on tackles (95%; n=18 and 71%; n=10, respectively).

Tackling at the upper trunk has a greater propensity to result in a tackler HIA for front-on upper body shoulder tackles (RR=1.48; 95% CI=1.16-1.90; p<0.01) and side-on upper body smother tackles (RR=2.30; 95% CI=1.82-2.92; p<0.01), see Table 34. Tackling at the mid-trunk had a lower propensity to result in a tackler HIA for side-on smother tackles (RR=0.11; 95% CI=0.02-0.75; p=0.02). An example of an upper trunk and mid trunk HIA tackle case can be seen in Figure 38.

For front-on lower body shoulder tackles, tackling at the lower trunk has a lower propensity to result in a tackler HIA (RR=0.45; 95% CI=0.23-0.88; p<0.02), see Table 35. Tackling at the upper legs has a greater propensity to result in a tackler HIA for front- (RR=2.60; 95% CI=1.70-3.97; p<0.01) and side-on (RR=3.34; 95% CI=1.65-6.79; p<0.01) lower body shoulder tackles. An example of a lower trunk, upper leg and lower leg HIA tackle case can be seen in Figure 39.

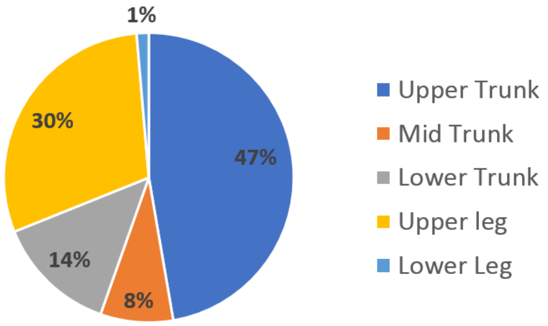

Figure 36. The tackle height distribution for all HIA tackles

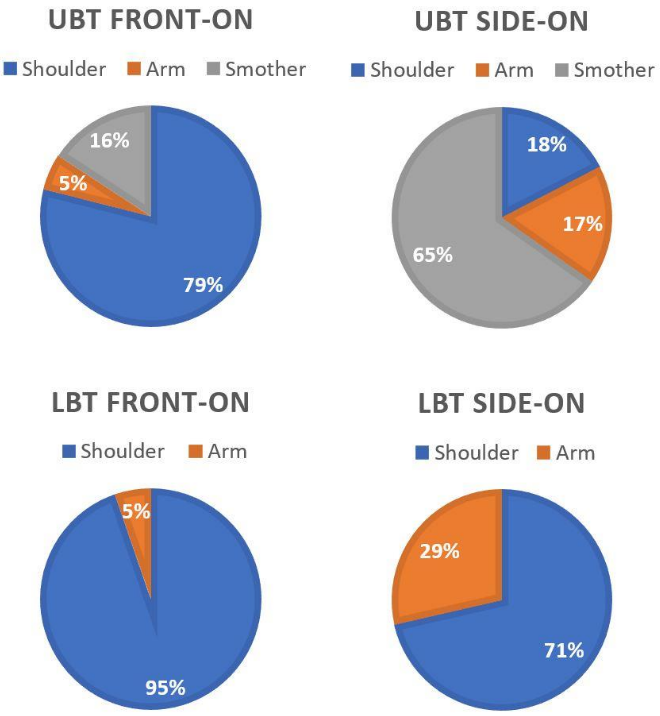

Figure 37. The tackle height distribution of HIA tackles for front- and side-on Upper Body Tackles (UBT) and Lower Body Tackles (LBT) based on tackle type.

Table 34. The Relative Risk (RR) of tackle heights on HIA aetiology with 95% Confidence Interval (CI) and p-value for front- and side-on upper body tackles.

Upper Body Tackles	HIA	Non-HIA	RR (95% CI)	p-value
Front-On (Shoulder Tackle)	(n=15)	(n=130)		
Upper Trunk	13 (87%)	76 (58%)	1.48 (1.16-1.90)	**<0.01**
Mid-Trunk	2 (13%)	54 (42%)	0.32 (0.09-1.19)	0.09
Side-On (Smother Tackle)	(n=15)	(n=148)		
Upper Trunk	14 (93%)	60 (41%)	2.30 (1.82-2.92)	**<0.01**
Mid-Trunk	1 (7%)	88 (59%)	0.11 (0.02-0.75)	**0.02**


[redacted] [redacted] [redacted]

Figure 38. Example of an (a) upper trunk and (b) mid trunk HIA tackle.

Table 35. The Relative Risk (RR) of tackle heights on HIA aetiology with 95% Confidence Interval (CI) and p-value for front- and side-on Lower Body Tackles.

Lower Body Tackles	HIA	Non-HIA	RR (95% CI)	p-value
Front-On (Shoulder Tackle)	(n=18)	(n=152)		
Lower Trunk	6 (33%)	112 (74%)	0.45 (0.23-0.88)	**0.02**
Upper Leg	12 (67%)	39 (25%)	2.60 (1.70-3.97)	**<0.01**
Lower Leg	0 (0%)	1 (1%)	2.68 (0.11-63.6)	0.54
Side-On (Shoulder Tackle)	(n=10)	(n=43)		
Lower Trunk	3 (30%)	33 (77%)	0.39 (0.15-1.02)	0.06
Upper Leg	7 (70%)	9 (21%)	3.34 (1.65-6.79)	**<0.01**
Lower Leg	0 (0%)	1 (2%)	1.33 (0.06-30.6)	0.86

Figure 39. Example of a (a) lower trunk, (b) upper leg and (c) lower leg HIA tackle case.

8.3.2 Tackle gainline analysis

8.3.2.1 Arm tackles

Tackling the upper legs has a greater propensity to result in tackler success for both front- (RR=2.23; 95% CI=1.23-4.05; p<0.01) and side-on (RR=3.23; 95% CI=1.73-6.05; p<0.01) arm tackles (Table 36). However, for side-on arm tackles, tackling the lower trunk has a lower propensity to result in tackler success (RR=0.44; 95% CI=0.22-0.86; p=0.02).

8.3.2.2 Shoulder tackles

Tackling the lower trunk has a greater propensity to result in tackler success during front-on (RR=1.39; 95% CI=1.02-1.89; p=0.04) shoulder tackles (Table 37). However, tackling the upper legs has a lower propensity (RR=0.37; 95% CI=0.20-0.69; p<0.01). For side-on shoulder tackles, tackling the mid-trunk has a greater propensity to result in tackler success (RR=1.98; 95% CI=1.12-3.51; p=0.02).

8.3.2.3 Smother Tackles

Tackling the mid trunk has a greater propensity to result in tackler success during front- (RR=2.34; 95% CI=1.53-3.56; p<0.01) and side-on (RR=1.82; 95% CI=1.39-2.39; p<0.01) smother tackles (Table 38). Tackling the upper trunk has a lower propensity for both front- (RR=0.66; 95% CI=0.52-0.86; p<0.01) and side-on (RR=0.36; 95% CI=0.21-0.60; p<0.01) smother tackles.

Table 36. The effect of tackle height on tackler and ball carrier success for arm tackles (includes % occurrence, Relative Risk (RR) with 95% Confidence Intervals (95% CI) and p values).

Arm Tackle	Tackler Success	Ball Carrier Success	RR (95% CI)	p-value
Front-On	(n=37)	(n=63)		
Upper Trunk	3 (8%)	11 (18%)	0.46 (0.14-1.56)	0.21
Mid Trunk	0 (0%)	4 (6%)	0.19 (0.01-3.38)	0.26
Lower Trunk	8 (22%)	24 (38%)	0.57 (0.28-1.13)	0.11
Upper Leg	17 (46%)	13 (21%)	2.23 (1.23-4.05)	**<0.01**
Lower Leg	9 (24%)	11 (17%)	1.39 (0.64-3.04)	0.41
Side-On	(n=29)	(n=87)		
Upper Trunk	0 (0%)	6 (7%)	0.23 (0.01-3.89)	0.31
Mid Trunk	2 (7%)	10 (11%)	0.60 (0.14-2.58)	0.49
Lower Trunk	7 (24%)	48 (55%)	0.44 (0.22-0.86)	**0.02**
Upper Leg	14 (48%)	13 (15%)	3.23 (1.73-6.05)	**<0.01**
Lower Leg	6 (21%)	10 (11%)	1.80 (0.72-4.52)	0.21

Table 37. The effect of tackle height on tackler and ball carrier success for shoulder tackles (includes % occurrence, Relative Risk (RR) with 95% Confidence Intervals (95% CI) and p values).

Shoulder Tackle	Tackler Success	Ball Carrier Success	RR (95% CI)	p-value
Front-On	(n=162)	(n=120)		
Upper Trunk	38 (23%)	38 (32%)	0.74 (0.51-1.09)	0.12
Mid Trunk	37 (23%)	17 (14%)	1.61 (0.96-2.72)	0.07
Lower Trunk	73 (45%)	39 (32%)	1.39 (1.02-1.89)	**0.04**
Upper Leg	13 (8%)	26 (22%)	0.37 (0.20-0.69)	**<0.01**
Lower Leg	1 (1%)	0 (0%)	2.23 (0.09-54.2)	0.62
Side-On	(n=71)	(n=37)		
Upper Trunk	8 (11%)	9 (24%)	0.46 (0.19-1.10)	0.08
Mid Trunk	38 (53%)	10 (27%)	1.98 (1.12-3.51)	**0.02**
Lower Trunk	21 (30%)	12 (32%)	0.91 (0.51-1.64)	0.76
Upper Leg	4 (6%)	5 (14%)	0.42 (0.12-1.46)	0.17
Lower Leg	0 (0%)	1 (3%)	0.18 (0.01-4.22)	0.28

Table 38. The effect of tackle height on tackler and ball carrier success for smother tackles (includes % occurrence, Relative Risk (RR) with 95% Confidence Intervals (95% CI) and p values).

Smother Tackle	Tackler Success	Ball Carrier Success	RR (95% CI)	p-value
Front-On	(n=56)	(n=156)		
Upper Trunk	30 (54%)	125 (80%)	0.66 (0.52-0.86)	**<0.01**
Mid Trunk	26 (46%)	31 (20%)	2.34 (1.53-3.56)	**<0.01**
Side-On	(n=65)	(n=82)		
Upper Trunk	13 (20%)	46 (56%)	0.36 (0.21-0.60)	**<0.01**
Mid Trunk	52 (80%)	36 (44%)	1.82 (1.39-2.39)	**<0.01**

8.4 Discussion

8.4.1 HIA analysis

Match video evidence was utilised to examine the effect of tackle height on tackler HIA risk. The results suggest tackling below the upper trunk for upper body tackles. Tackling at the upper trunk accounts for nearly half (47%) of all HIA tackles. Tackles to the upper trunk also had a greater propensity to result in a tackler HIA for both front- and side-on upper body tackles. For lower body tackles, the results suggest tackling at the lower trunk and avoiding the upper legs. Tackles to the lower trunk had a lower propensity to result in a tackler HIA in front-on shoulder tackles. However, tackles to the upper legs had a higher propensity for both front- and side-on shoulder tackles. These findings can be utilised by coaches to develop tackle height specific prevention strategies and training drills.

Lowering the maximum legal tackle height to below the upper trunk of the ball carrier could reduce tackler HIA risk during upper body tackles. However, lowering the maximum legal tackle height may increase the likelihood of upper leg related HIAs.

The results suggest tackling at the upper legs has a higher propensity to result in a tackler HIA than tackling at the upper trunk. Thus, simply lowering the allowable tackle height might increase the number of tackles to the upper leg region. This could have an adverse effect on HIA reduction. The findings indicate the importance of effective coaching strategies that place emphasis on tackling lower risk regions such as the mid- and lower trunk.

During certain upper trunk tackles, the ball carrier entered the tackle bent-at-the-waist (crouched position) [206]. This resulted in an upper trunk tackle being almost unavoidable, particularly for front-on tackles. Therefore, a change to the tackle height law would have to ensure this is mitigated against which is challenging. Tucker et al. [206] found that an upright tackler was 1.5 times more likely to experience a HIA than a bent at the waist tackler. Therefore, a sanction that penalises the tackler for causing direct head impacts (to either the tackler or ball carrier) due to tackling upright at the upper trunk may be a more suitable intervention than lowering the tackle height law. This would result in tacklers, even those who receive a HIA, being sanctioned for tackling upright and at the upper trunk. Additionally, tacklers would not be penalised during head impact cases if they were bent-at-the-waist when tackling at the upper trunk as this is indicative of attempting to tackle lower. This could mitigate against the issue of ball carriers entering the tackle in a bent-at-the-waist position which makes upper trunk tackles almost unavoidable. Furthermore, the sanction could encourage tackling at lower risk body regions whilst deterring upright tackling at the upper trunk. Potentially a combination of a lower tackle height law and a sanction that deters upright tackling could be a suitable intervention.

Quarrie and Hopkins [110] found that tackling high (roughly at the upper trunk) resulted in the highest general injury rate for the ball carrier (3.4 injuries per 1000 tackle events). However, Quarrie and Hopkins [110] also identified that tackling low (roughly at the upper and lower legs) resulted in the highest general injury rate for the tackler (2.2 injuries per 1000 tackle events). The current study found that tackling at the upper legs had the highest propensity to result in a tackler HIA. The upper legs of the ball carrier can move rapidly and dynamically which could make safe head placement difficult. This could increase the risk of a tackler HIA in comparison to tackling at the lower trunk, for example, which tends to follow the bulk movement of the player [202]. The results demonstrate that tackling the mid/lower trunk has a lower propensity to result in a tackler HIA. This supports the recommendation of contacting the ball carrier's centre of gravity (roughly lower trunk) proposed in previous contact technique-based studies [116, 120, 121].

8.4.2 Tackle gainline analysis

The findings show that tackle height influences tackler success outcomes. However, this is dependent on the type of tackle executed. The results highlight the importance of incorporating tackle height into training drills. Players are initially coached to aim for the ball carrier's centre of gravity as this is the best target area to assess tackle technique [1, 120-122]. However, the findings suggest that technically proficient players can advance to more challenging contact techniques. For example, contacting the mid trunk during smother tackles.

Arm tackles to the upper legs were an effective tackle strategy. By tackling the upper legs, the tackler can clasp the ball carrier's two legs together, impede the run and bring the ball carrier to ground. However, arm tackles at the lower trunk were found to be ineffective. Side-on shoulder tackles to the mid trunk were an effective tackle strategy. This supports the findings of Hendricks et al. [1] who reported that shoulder tackles at the ball carrier's mid-torso (roughly mid trunk) were associated with positive tackler outcomes.

Front- and side-on upper trunk smother tackles were ineffective for the tackler. Upper trunk smother tackles generally enabled the ball carrier to remain on their feet and continue moving forward. Shoulder tackles to the upper trunk also had no greater propensity to result in tackler success. This provides further evidence to discourage tackling at the upper trunk.

8.4.3 Limitations

The tackle is a dynamic and open phase of play by nature. This must be considered when analysing tackles [32, 116]. Similar to Chapter 7, the study utilised a definition based on a player being removed for a HIA and not returning to play. This could be considered a strong indication of concussion. However, it cannot be fully regarded as a diagnosis. Only five games, involving eight elite level teams, were selected for the non-HIA cases. This could make the data susceptible to outliers and only applicable to the elite game. Further monitoring of other teams should be pursued.

8.5 Conclusion

Analysis of match video evidence from elite level rugby union games indicates that tackle height can influence tackler HIA aetiology. To reduce tackler HIA risk, the results suggest tackling below the upper trunk for upper body tackles. The results also support tackling at the lower trunk for lower body tackles and avoiding the upper legs. The tackle gainline findings recommend tackling at the upper legs for arm tackles, mid/lower trunk for shoulder tackles and mid trunk for smother tackles. Tackles to the upper trunk did not positively influence tackler success outcomes. Both sets of findings can be utilised to develop tackle height specific coaching strategies that place emphasis on tackling at lower HIA risk body regions such as the mid and lower trunk.

9 Assessment of Model-Based Image-Matching for future reconstruction of unhelmeted sport head impact kinematics

Related publication. Tierney GJ, Joodaki H, Krosshaug T, Forman JL, Crandall JR, Simms CK. Assessment of model-based image-matching for future reconstruction of unhelmeted sport head impact kinematics. Sports Biomechanics. 2018;17(1):33-47.

9.1 Introduction

The reliable reconstruction of six degree of freedom head movement patterns during sport impacts can be challenging [169]. However, a greater understanding of the kinematics of concussive and non-concussive head impacts would be beneficial to guide prevention strategies [90].

The retrospective analysis of injuries resulting from sporting events typically involves standard video coverage. This video is not primarily intended for kinematic analysis. Model-Based Image-Matching (MBIM) is an approach that can be used to measure six degree of freedom motion from un-calibrated video data [144]. MBIM has been applied to a head injury case in skiing [145]. Though, it has currently only been validated for the hip, ankle and knee joints [144, 225]. It is hypothesised that MBIM has high potential for reconstructing 6 degree of freedom (DOF) head motion time-histories in sport impacts.

The relative velocity of a vehicle striking a pedestrian cadaver in a staged impact test is 40km/h (11 m/s). This is similar to the average closing speed (10.4 m/s) in elite level rugby union tackles [202]. Therefore, staged pedestrian cadaver impact tests can serve as a useful means for MBIM assessment. The average duration and change in head angular velocity of concussive head impacts from rugby union are broadly similar to those observed during head contact with the windscreen in a staged cadaver impact study at 40 km/h (Table 39). The head-windscreen linear velocity changes are certainly higher than the average value reported for rugby union head impacts. However, the general head impact mechanism and point of contact (temporal region) of a head-windscreen impact is similar to a direct head impact in rugby union [8, 139].

Table 39. A comparison of head kinematics in a 40km/h vehicle-cadaver impact during windscreen contact with average head kinematics in rugby union concussive head impacts.

Head Impact	Duration (ms)	Change in Linear Velocity (m/s)	Change in Angular Velocity (rad/s)
40 km/h side struck pedestrian (windscreen contact)	14	13	40
Rugby union	12 [226]	4 ± 2 m/s [139]	33 [22]

Accordingly, the goal of this study is to assess the accuracy and repeatability of the MBIM method for estimating 6 degree of freedom head displacements and velocities. The approach will be conducted on a vehicle-cadaver impact case. Reflective marker-based motion capture system head kinematic time-histories are available as an independent measure. If the MBIM approach is successful, it has the potential to aid in our understanding of head motion patterns in sport collisions.

9.2 Methods

9.2.1 Vehicle-cadaver test

The vehicle-cadaver test methodology has been previously described in detail [159, 227, 228]. Briefly, the test was conducted with a deceleration-type sled (VIA systems model 713, Michigan, USA) at the University of Virginia. The striking vehicle buck was mounted on the sled and propelled into a stationary adult male cadaver in mid-gait stance (Figure 40) at 40km/h (11 m/s). Although the impact appears planar in Figure 40, the head exhibits substantial six degree of freedom motion.

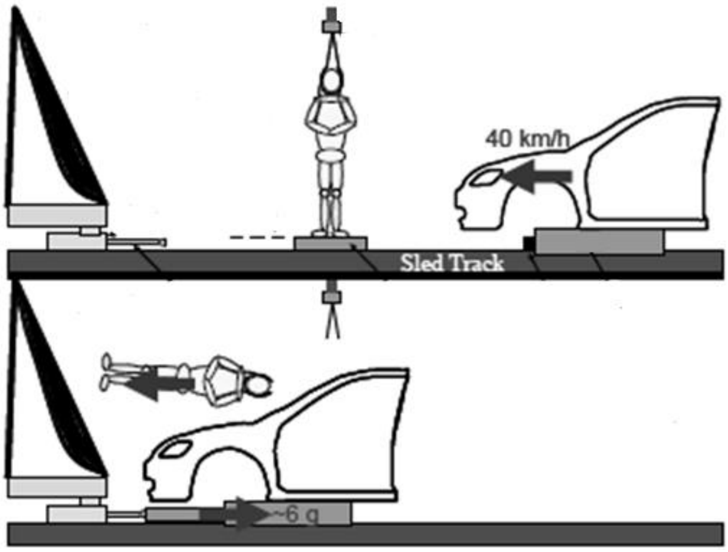

Figure 40. Schematic of the Vehicle-cadaver impact [227].

9.2.2 Reflective Marker-Based Tracking

The 3D motion data of the cadaver head in the pedestrian impact test were captured with a Vicon MX (Oxford, UK) optoelectronic motion capture system. Within a calibrated volume, the reflective marker-based system uses multiple cameras to record the motion of spherical retro-reflective markers attached to the subject. The reflective marker-based system combines this information from all the cameras and thus records the 3D motion of each individual marker [171].

A total of 25 Vicon cameras were used to record the cadaver motion at 1000 Hz. This is a typical sample rate of wearable head sensors [169]. The arrangement of the cameras around the capture volume encompassed the entire area of interaction between the cadaver and the buck. To capture head kinematics, an array of seven reflective markers was attached around the periphery of the head (Figure 41).

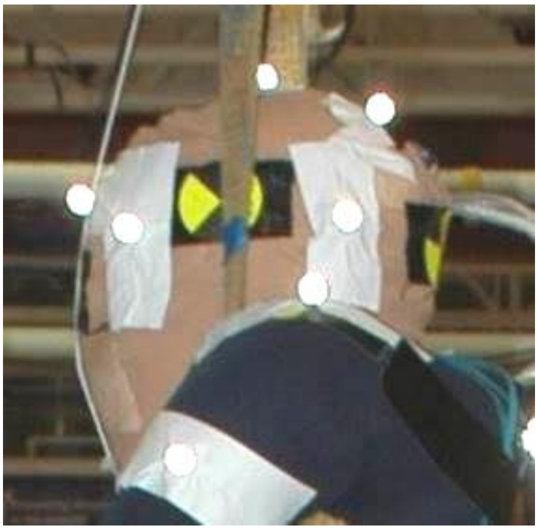

Figure 41. The Vicon marker array affixed to the external surface of the cadaver head.

Data processing was performed using Matlab. The head marker information was transformed to calculate the linear position of the head CG (midway point between the left and right zygomatic processes) and the rotation matrix for the head at each time frame. A series of successive rotations, of order yaw (ψ), pitch (θ) and roll (ϕ) (local Z, Y and X axes), were defined to record head orientation. The Matlab gradient function was used to compute the time derivatives of the yaw, pitch and roll angles. The components of the head local angular velocity (Figure 42) were then calculated (Section 2.5). A low pass Butterworth filter (Cut-off frequency = 110Hz [229, 230]) was applied to the angular velocity data.

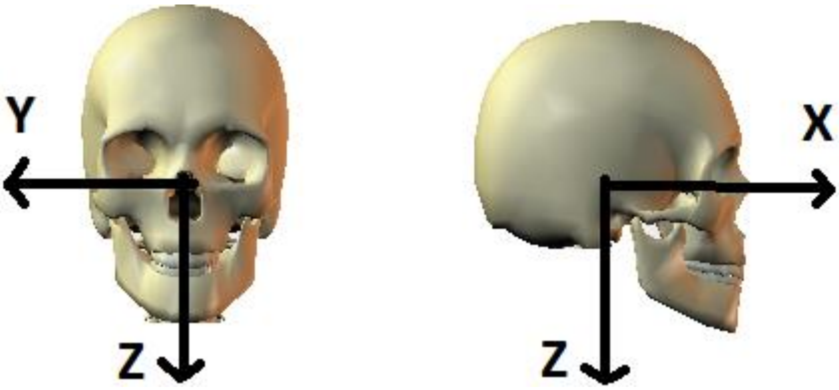

Figure 42. The local axes of the head

9.2.3 Model-Based Image-Matching (MBIM)

MBIM has been described in detail by Krosshaug and Bahr [144]. Briefly, the approach uses a multibody skeleton model to estimate human body joint angle time-histories from multiple camera views of human movement. For each video frame, the skeleton model is manipulated manually to match the target subject in the multiple camera views.

The matching was conducted on synchronised video of three camera views of the vehicle-cadaver impact. The resolution for each video was 800x600 pixels. The head represented approximately 24x28 pixels in Camera 1, 45x44 pixels in Camera 2 and 67x55 pixels in Camera 3. This could be considered analogous to a three camera view sport head impact for which one zoomed-in and two zoomed-out camera views are available. Three researchers (R1, R2 and R3) performed the MBIM technique to assess inter and intra-rater reliability (Researcher R1 performed the MBIM technique three times).

The camera locations (Figure 43) were treated as unknowns during the MBIM process since camera location will not generally be known during sport impact reconstruction. The matching was performed using 3-D animation software Poser. The surroundings were built in a virtual environment based on the dimensions of the laboratory. The video was imported into the background of the Poser workspace. The surroundings were then matched to the background video footage for each camera view. This was achieved by manually adjusting the camera positioning tool which contains three translational and three rotational degrees of freedom, as well as variable focal length. Although not necessary here, this tool facilitates application of the method to sport cases where a camera position, orientation and focal length are changing. A skeleton model was then used for cadaver matching. For this study, only the skeleton's skull was manipulated to fit the cadaver's head for each video frame (Figure 44).

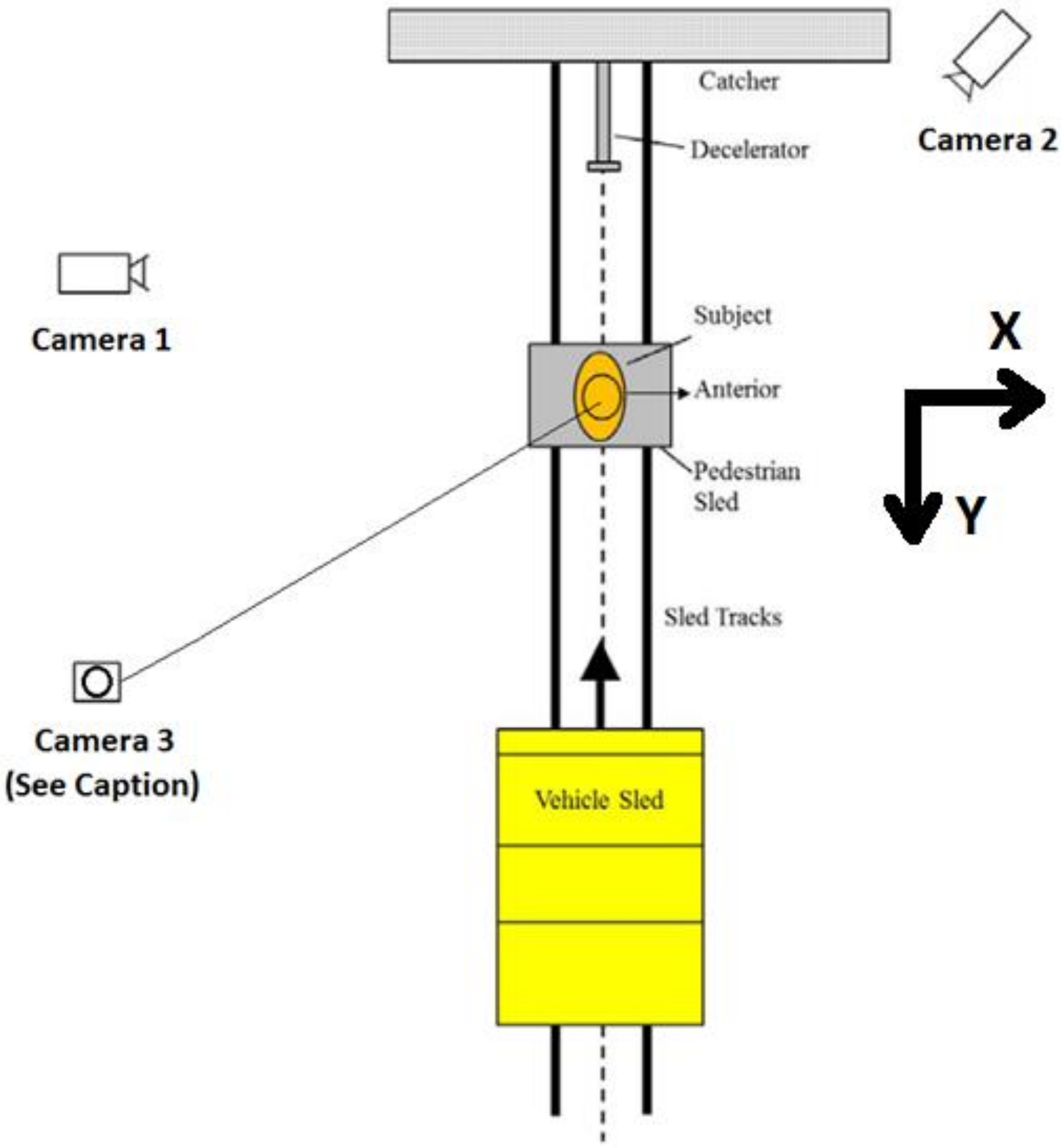

Figure 43. The location of the cameras used for the MBIM with global coordinate system indicated (Positive Z-direction going into page). Note that camera 3 was located directly above the cadaver subject.

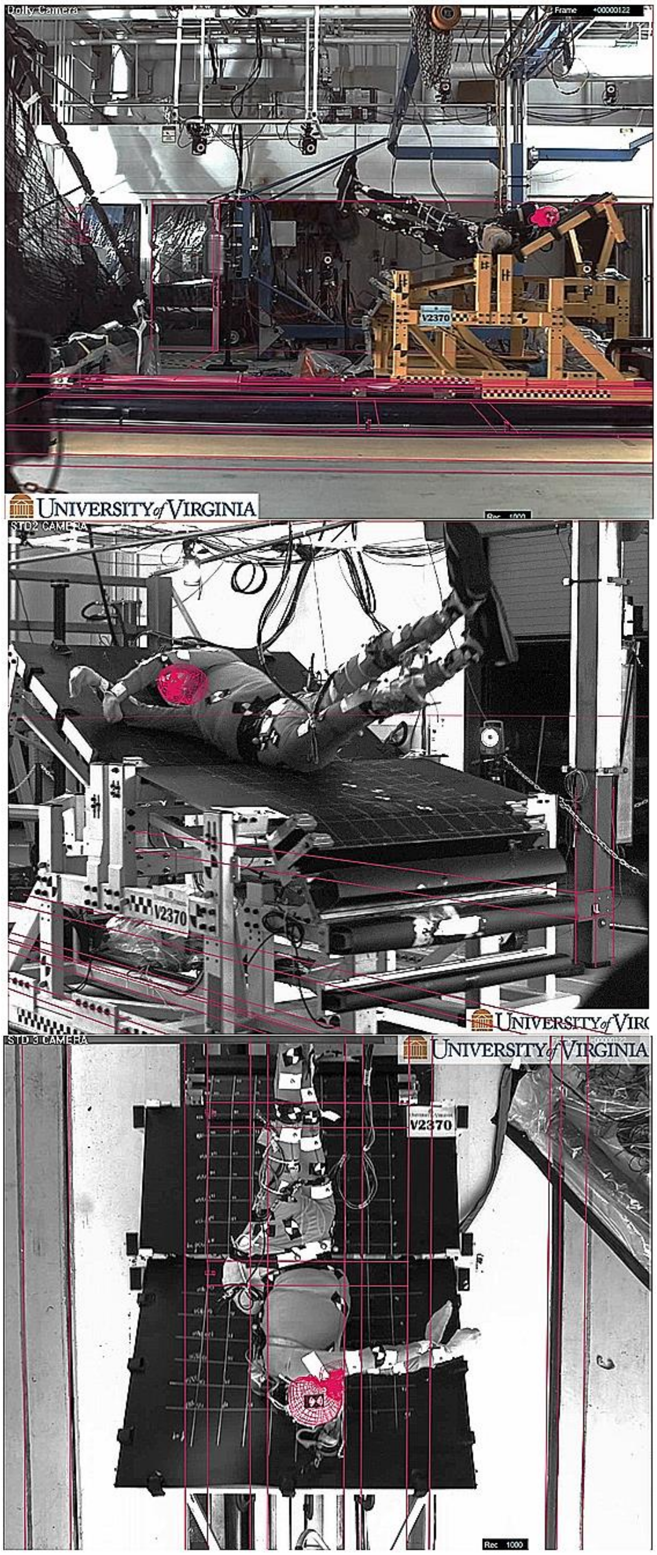

Figure 44. An example of the MBIM skeleton matching with the background video for frame 1 for (a) Camera 1, (b) Camera 2 and (c) Camera 3.

The Vicon cameras recorded at 1000 fps. The MBIM was only conducted using 100 fps video as this is typical of uncompressed broadcast video [231]. The approach yielded

MBIM based head linear/rotational position measurements every 10 ms (known as a key frame). Cubic splines were fitted to interpolate between these discrete head linear/rotational position measurements [144]. Similar to the reflective marker-based system approach, the head CG position, orientation, linear and angular velocity were calculated.

9.2.4 Statistical Analysis

Similar to Mok et al. [225], the differences between the marker-based motion capture measures and the MBIM discrete measures were quantified using Root Mean Square Error (RMSE). Intra-class Correlation Coefficients (ICC) were calculated to assess the intra- and inter-rater reliability. Due to the MBIM technique providing continuous joint angle time-histories, two-way mixed model average ICC measures were calculated [232]. ICC coefficients greater than 0.90 are indicative of excellent reliability [225]. Researcher R1 conducted the MBIM analysis three times for intra-rater reliability. Researcher R2 and R3 both conducted the analysis once. Therefore, researcher R1's first analysis was used for the inter-rater reliability calculation.

9.3 Results

9.3.1 Validity

Figure 45 shows the MBIM head CG linear displacements and velocities in the global coordinate system (Figure 43) compared to the marker-based results. Figure 46 shows the corresponding successive rotation angles and body local angular velocities compared to the marker-based system results. The head impact with the windscreen lasted for 14 ms (between 8 and 22 ms). The RMS error was under 20 mm for all head linear displacements and 0.01-0.03 rad for head successive rotations (yaw, pitch and roll), see Table 40. The MBIM method yielded RMS errors of 0.44-1.80 m/s for head linear velocities and 4.39-5.61 rad/s for head angular velocities (Table 40). Particular challenges for the head local Z axis angular velocity component (ω_Z) can be seen in Figure 46c.

9.3.2 Inter-rater reliability and intra-rater reliability

For both inter-and intra-rater reliability, ICC coefficients greater than or equal to 0.95 were demonstrated for all parameters (Table 41).

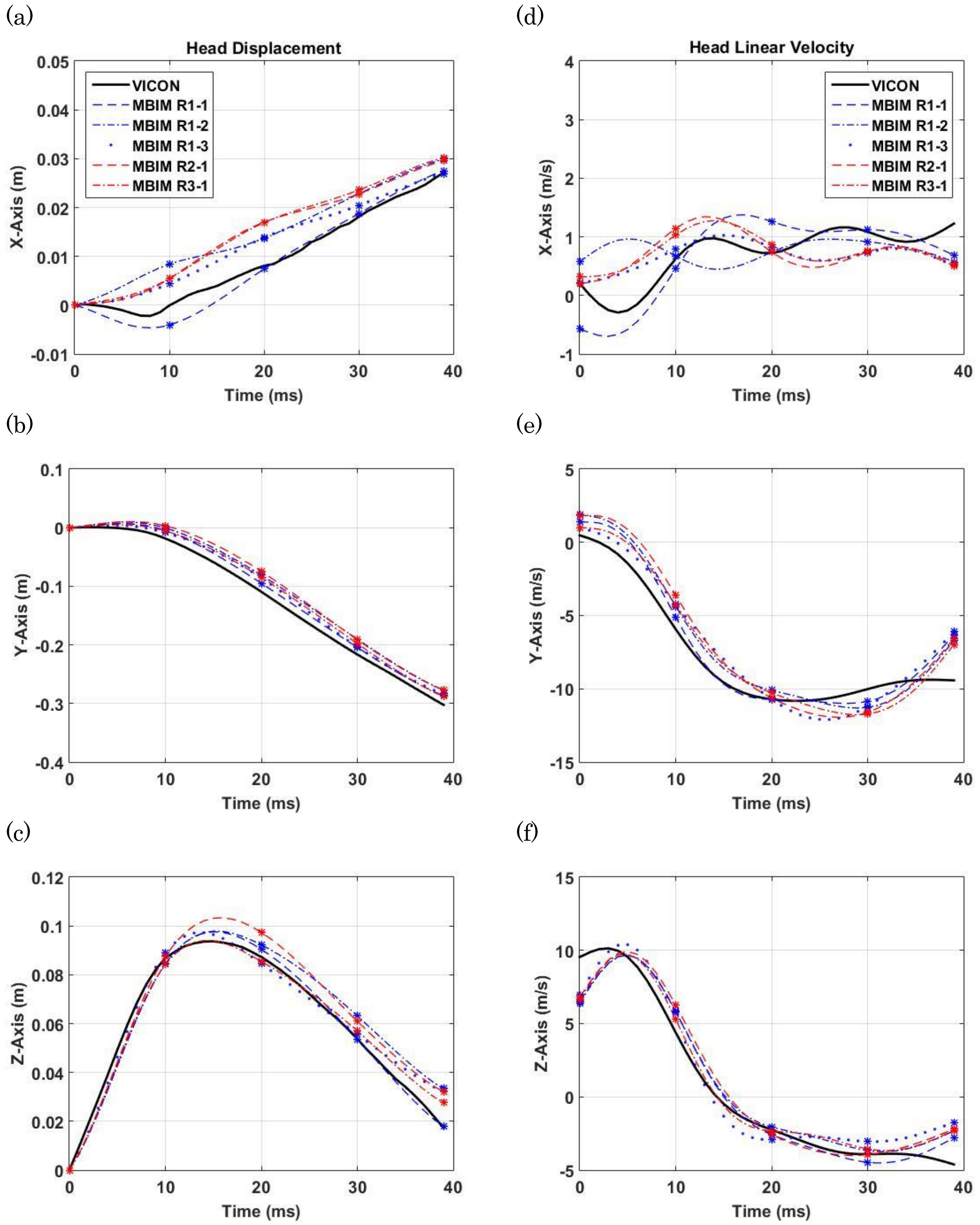

Figure 45. Head CG displacement (a-c) and linear velocity (d-f) in the global coordinate system (Figure 43) calculated with the reflective marker-based motion analysis (Black line) and the MBIM technique for Researcher 1 (R1) (Blue lines) and Researcher 2 (R2) and 3 (R3) (Red lines). The MBIM discrete measures are indicated with markers.

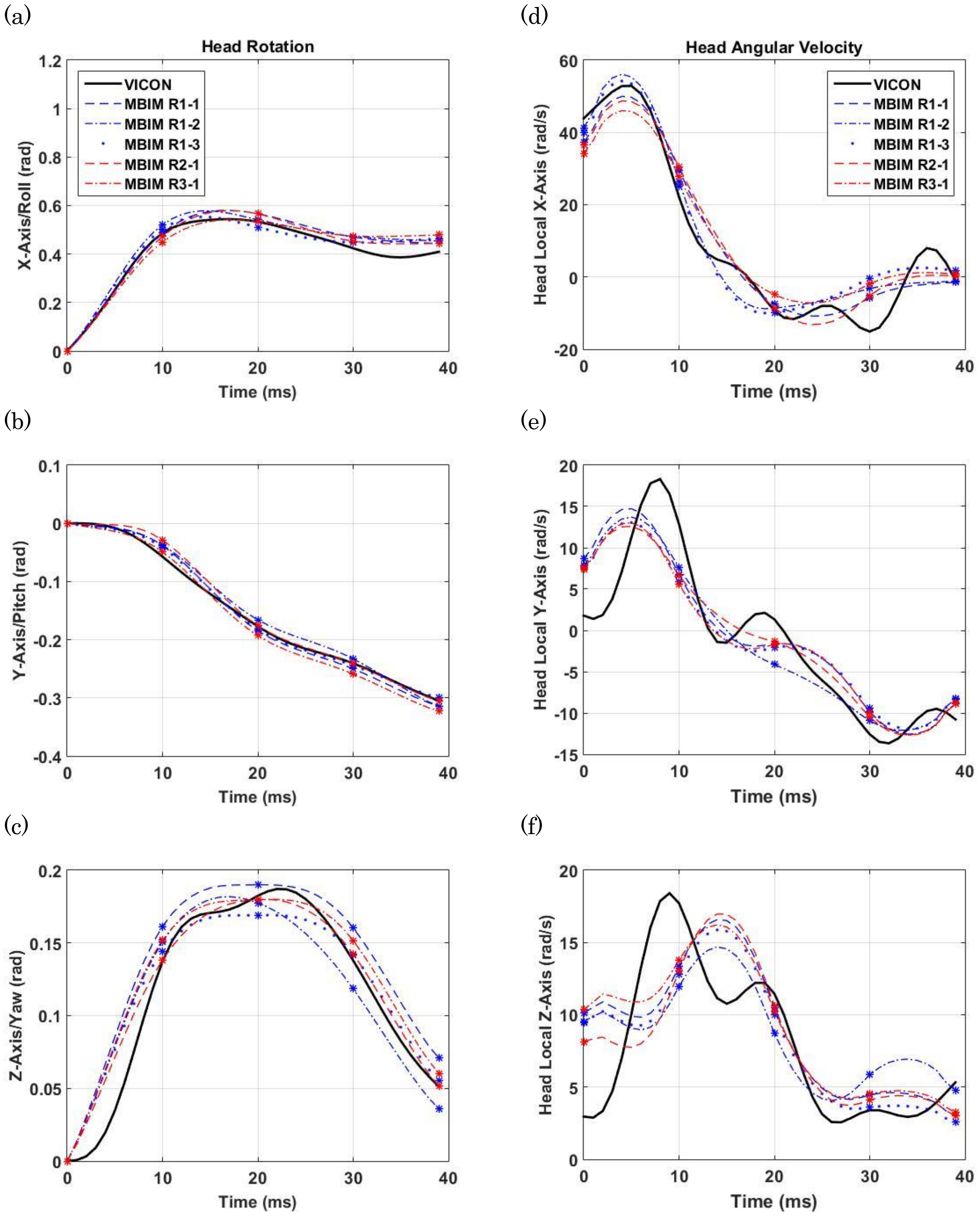

Figure 46. Head CG rotation for Roll (X), Pitch (Y) and Yaw (Z) angles (a-c) and the head angular velocity resolved in the local head axes (d-f), see Figure 42, calculated with the reflective marker-based motion analysis (Black line) and the MBIM technique for Researcher 1 (R1) (Blue lines) and Researcher 2 (R2) and 3 (R3) (Red lines). The MBIM discrete measures are indicated with markers.

Table 40. The Root Mean Square Error (RMSE) and Standard Deviation of the RMSE values for the MBIM measures compared to reflective marker-based system along with the range of reflective marker-based motion and kinematics values.

		Linear Displacement (m)	**Linear Velocity (m/s)**	**Rotation (rad)**	**Angular velocity (rad/s)**
X					
	RMSE	<0.01	0.44	0.03	5.61
	SD of RMSE	<0.01	0.05	<0.01	0.84
	Vicon Range	0 to 0.03	-0.29 to 1.23	0 to 0.55	-12.3 to 51.6
Y					
	RMSE	<0.02	1.69	0.01	5.09
	SD of RMSE	<0.01	0.15	<0.01	0.16
	Vicon Range	0 to -0.30	-10.82 to 0.48	0 to -0.31	-13.4 to 13.9
Z					
	RMSE	<0.01	1.80	0.01	4.39
	SD of RMSE	<0.01	0.08	<0.01	0.22
	Vicon Range	0 to 0.09	-4.61 to 10.13	0 to 0.19	0.37 to 15.5

Table 41. Intra-class correlation results for inter-rater reliability and intra-rater reliability.

		Inter-rater repeatability	Intra-rater repeatability
Displacement			
	X	0.96	0.95
	Y	0.99	0.99
	Z	0.99	0.99
Rotation			
	X	0.99	0.99
	Y	0.99	0.99
	Z	0.99	0.98

9.4 Discussion

9.4.1 General

The aim of this study was to establish whether MBIM is suitable for estimating 6 DOF head displacements and velocities. The results indicate that the 6 degree of freedom head displacement time histories are tracked with RMS errors between 10-20 mm for linear displacement and 0.01-0.03 rad for rotational displacement. The analysis was repeatable by both a single researcher and multiple researchers for six degree of freedom head motion data.

The assessment of the linear and rotational velocity predictions from the MBIM show larger errors, particularly for angular velocity (RMS errors up to 5.61 rad/s). The predictive capacity of the MBIM for angular velocity in this case is not very strong. The approach does provide an estimate of angular velocity in contrast to previous video analysis approaches [131, 139-141]. Though, it remains difficult to measure this parameter accurately.

The Vicon cameras recorded at 1000 fps whereas the MBIM was conducted on 100 fps video. The results show significant discrepancies in the Y and Z axis angular velocity results (Figure 46 & Table 40) even though the RMS errors for the successive rotation angles are 0.03 rad or less. High frequency head motion associated with direct head impacts is an important consideration for this [233]. Certain movements of the head were untracked by the MBIM method. For example, Figure 46c shows significant Yaw angle changes between the key frames at 0 ms and 10 ms. The resulting MBIM Z component of angular velocity is therefore poor at this stage. Unfortunately, a separate analysis using 200 fps video for the MBIM technique yielded poor results. The absolute rotation of the head between key frames was too small and resulted in operator error. Therefore, availability of higher frame rate video may not serve to improve angular velocity estimates for direct head impacts. The method may be suitable for inertial head kinematic measurement in sport as this head motion is typically of lower frequency.

The RMS error 6 DOF displacement results are similar to that achieved by Mok et al [225], who validated the MBIM technique for assessing ankle joint angles. Therefore, it is proposed that MBIM is beneficial to directly and reliably measure six degree of freedom head displacement data from video of direct head impacts in sport. The MBIM data could be combined with six degree of freedom velocity and acceleration data gained from wearable head sensors in the future [169]. This could provide accurate initial conditions and further evaluate the outputs of multibody simulations of direct head impacts in sport.

9.4.2 Limitations

The MBIM method was applied to a single head impact since only one case with suitable video was available. The cameras were positioned closer to the impact subject than in a sport collision. However, zoomed in replays offering close-up views of head impacts are often available in sport. The resolution for each video was 800x600 pixels, which is less than standard HD video quality (1280x720) [234]. Certain recognisable facial features on the cadaver such as the eyes and ears could not be seen (Figure 41). This made the matching difficult as rotational tracking was only possible based on the identification of the cadaver nose and mouth. The Vicon markers compensated for this.

There were a number of references in the background video which were suitable for constructing the MBIM virtual environment. In rugby union, there are a large number of field lines, markings, goal posts and advertising boards which can be used to build the virtual environment. The cameras were stationary in this study which is untypical of broadcast sports video. The MBIM technique can be conducted on non-stationary cameras by readjusting the camera positioning tool for each key frame. In sporting applications, the number of camera views available will vary. An initial analysis using only two camera views yielded poor results when compared to the marker-based data. The accuracy of 3 camera views for the MBIM method in this case may be partly due to Camera 1 and Camera 3 being almost perpendicular (Figure 43) to each other and thus reducing out of plane errors. It is recommended that perpendicular views are selected for the MBIM method whenever possible. The MBIM method is currently a time-consuming process that requires manual frame-by-frame matching (approximately 40 hours per case). Further work should look at automating the technique.

9.5 Conclusion

The comparison of the MBIM approach to the marker-based system shows good ability to record head linear and rotational displacement data in a head impact event. However, velocity data was less accurate, particularly for angular velocity. Higher frame rate video did not improve this. The method may be suitable for inertial head kinematic measurement in sport, as this head motion is typically of a lower frequency. The MBIM technique was repeatable by both a single researcher and multiple researchers for six degree of freedom head displacement data. The remaining study chapters of this thesis will focus on inertial head loading.

10 Ball carrier inertial head kinematics from a legal upper trunk tackle

Related publication. Tierney GJ, Gildea, K, Krosshaug T, Simms CK. Analysis of ball carrier head motion during a rugby union tackle without direct head contact: a case study. In-Review.

10.1 Introduction

Rugby union players can be involved in over 30 tackles per game [33]. The mechanics of acute concussion arising from direct head impacts in rugby union have been studied [8, 150]. However, little is known about the magnitude and influencing factors for inertial head kinematics during the tackle. High head kinematics are linked to brain injury [8-12]. There is also an emerging concept of neuronal vulnerability to injury due to repeated sub-concussive loading [13-15]. Therefore, repetitive inertial head loading may be a concern in rugby union.

For an amateur rugby union team over one season, King et al. [28] recorded 181 impacts (0.9% of total impacts) over 95g (linear acceleration concussion injury threshold utilised for comparison by King et al. [28]) and 4452 impacts (21.5% of total impacts) over 5500 rad/s^2 (rotational acceleration concussion injury threshold utilised for comparison by King et al. [28]). No concussive head impacts were included in the dataset. King et al. [28] suggested that inertial head loading accounted for a high proportion of these large head kinematic values recorded. However, no protocol was followed to examine this. By initiating a tackle, the tackler is expecting a collision. However, the ball carrier can be visually unaware of the approaching tackler [135]. Failing to brace for impact may result in a higher susceptibility to injury [135] and could lead to higher inertial head kinematics.

The direct measurement of head kinematics during tackling with on-field measurement devices remains challenging [28, 169]. An alternative approach is to use Model-Based Image-Matching (MBIM). Accordingly, the goal of this study is to use MBIM to measure the head kinematics of a visually unaware ball carrier during a real game active shoulder tackle to the upper trunk. The results will be compared to average kinematics values reported in the literature for concussive direct head impacts.

10.2 Methods

10.2.1 Data collection

A video review was conducted using freely available online video clips similar to Montgomery et al. [235]. The three criteria utilised for the review were 1) Tackle had to be to the upper trunk of the ball carrier; 2) The ball carrier had to be visually unaware of the tackle (based on the tackler approaching from outside of the ball carriers peripheral vision [116]); 3) There had to be a minimum of three synchronisable camera views available of the tackle for the MBIM reconstruction to be conducted. This will be discussed further below. In Chapter 6, it was found that the ball carrier was visually unaware during roughly one-third of side-on tackles. However, only one tackle event satisfied all three of the abovementioned criteria (due to criterion #3). In this single tackle event, the ball carrier had just passed the ball and was impacted roughly around the left scapula by the tackler. The player received on-field medical attention. The player was not immediately removed from play and the subsequent medical history is unknown. The tackle was reviewed by the on-field referee and video referees. The incident was deemed legal as the tackler had committed to the tackle before the ball had been passed.

10.2.2 Model-Based Image-Matching (MBIM)

In Chapter 9, the MBIM method demonstrated low root mean square errors for reconstructing 6 degree of freedom head motion in a vehicle cadaver head-windscreen impact. However, the MBIM method was deemed unsuitable for measuring componential angular velocity during direct head impact events (RMS errors up to 5.61 rad/s). High frequency head motion associated with the direct head impact was unmeasured by the MBIM technique, even when higher frame rate video was utilised. The MBIM method may be suitable for measuring componential angular velocity during indirect head impacts (i.e. inertial head kinematics from an impact to the body) as lower frequency head motion is typically associated with these impacts. The matching was conducted on three camera view synchronised video footage of the tackle event. Each video had a resolution of 720p and frame rate of 25 fps. The matching was performed using 3D animation software Poser. Firstly, the videos were imported into the background of the Poser workspace. A virtual environment based on the dimensions of the rugby field was then built and matched to the background video footage for every camera view. Camera locations were unknown and achieved by manually adjusting the camera positioning tool. Environment matching was conducted for each individual video frame as the cameras were moving. The skeleton model was then used for player matching. For head kinematic measurement, only the skeleton's skull was manipulated to fit the player's head in each video frame (Figure 47). Linear closing speed estimates were also calculated by tracking the players' pelvises using the MBIM protocol utilised by Krosshaug and Bahr [144]. The approach yielded MBIM based head successive rotation angles (of order yaw-pitch-roll) and linear position measurements every 40ms. The time derivatives of the yaw, pitch and roll angles were calculated using the Matlab gradient function. Hence, the components of the body local head angular velocity (Figure 48 and Section 2.5) every 40ms could be calculated. The Matlab gradient function was also utilised to calculate the componential head and pelvis linear velocity about the global coordinate system (Figure 49).

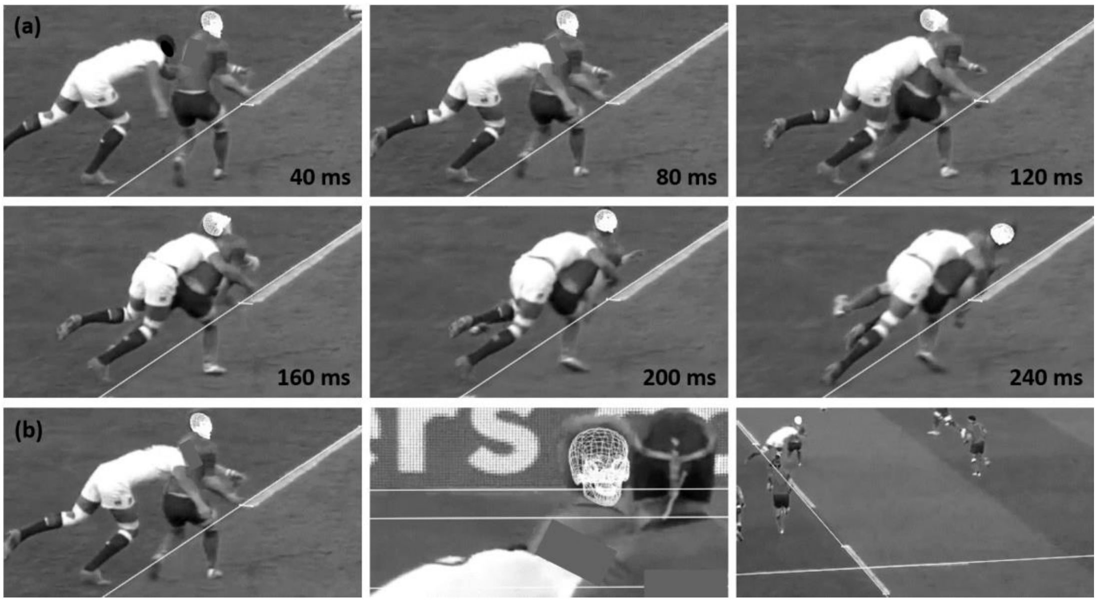

Figure 47. (a) A time lapse of the upper trunk active shoulder tackle with the MBIM matching for one camera view and (b) the MBIM matching for three camera views at time t=80ms.

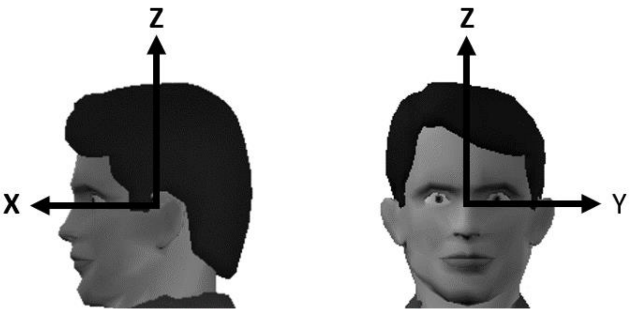

Figure 48. The local axes of the head.

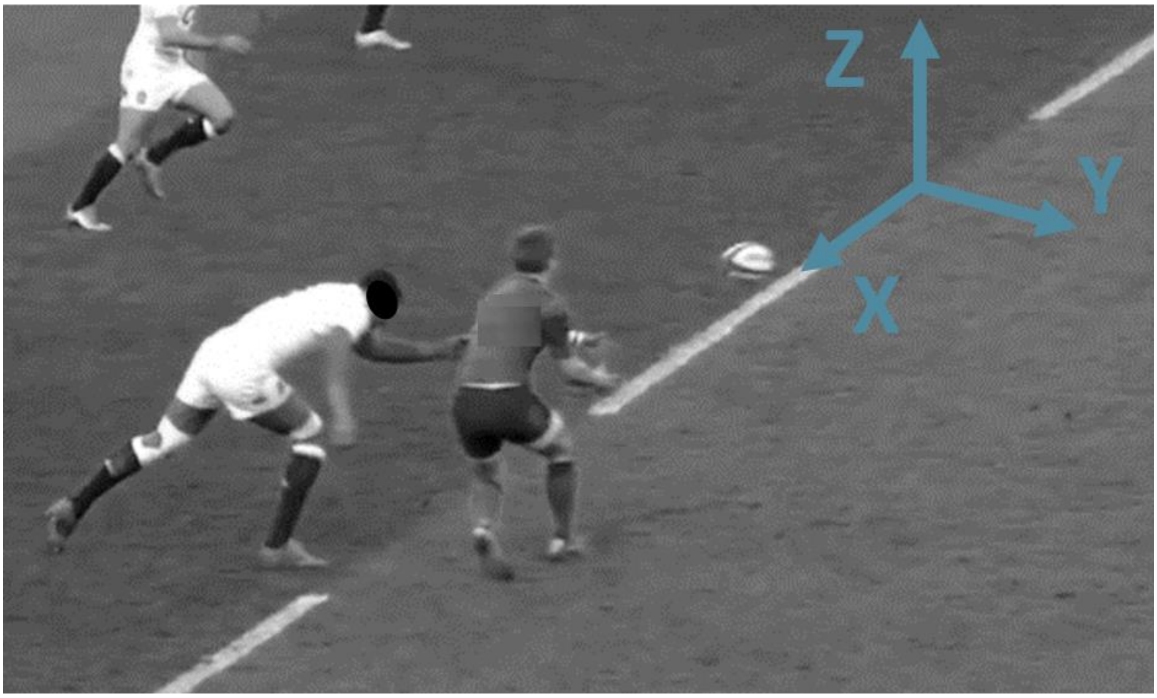

Figure 49. The global coordinate system utilised for the MBIM method.

10.2.3 Kinematic analysis

The maximum change in componential head angular velocities were compared to the average concussion values reported in the literature for unhelmeted sports [8]. This was not conducted for the maximum change in head linear velocity, as componential data was not available for unhelmeted sports [139].

10.3 Results

Figure 50 shows the componential maximum change in head linear velocity results for the ball carrier. Figure 51 demonstrates that the componential head angular velocities measured are similar to the average values reported for concussive direct head impacts in unhelmeted sports [8]. For the X and Y components, the maximum change in head angular velocity is greater than the average concussion values. Table 42 illustrates the ball carrier componential head linear and angular velocity values for each time frame. The resultant tackler linear closing speed was 5.5 m/s (-2.5 m/s, 4.9 m/s and -0.6 m/s in the global X, Y and Z direction, respectively). The resultant ball carrier linear closing speed was 3.1 m/s (-0.6 m/s, -3.0 m/s and -0.3 m/s in the global X, Y and Z direction, respectively).

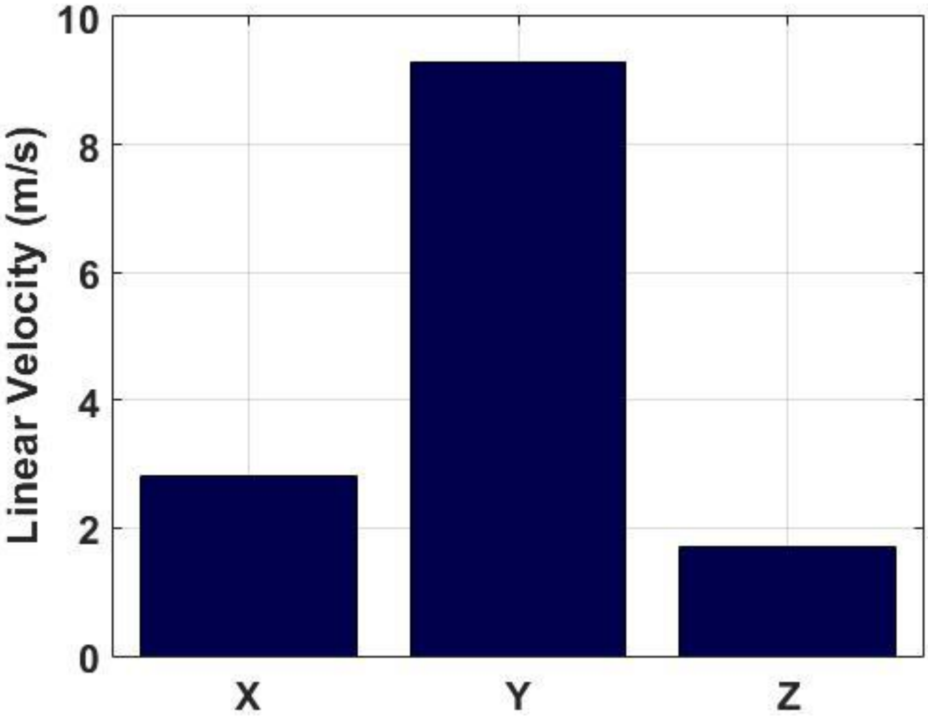

Figure 50. The componential maximum change in head linear velocity results about the global coordinate system (Figure 49).

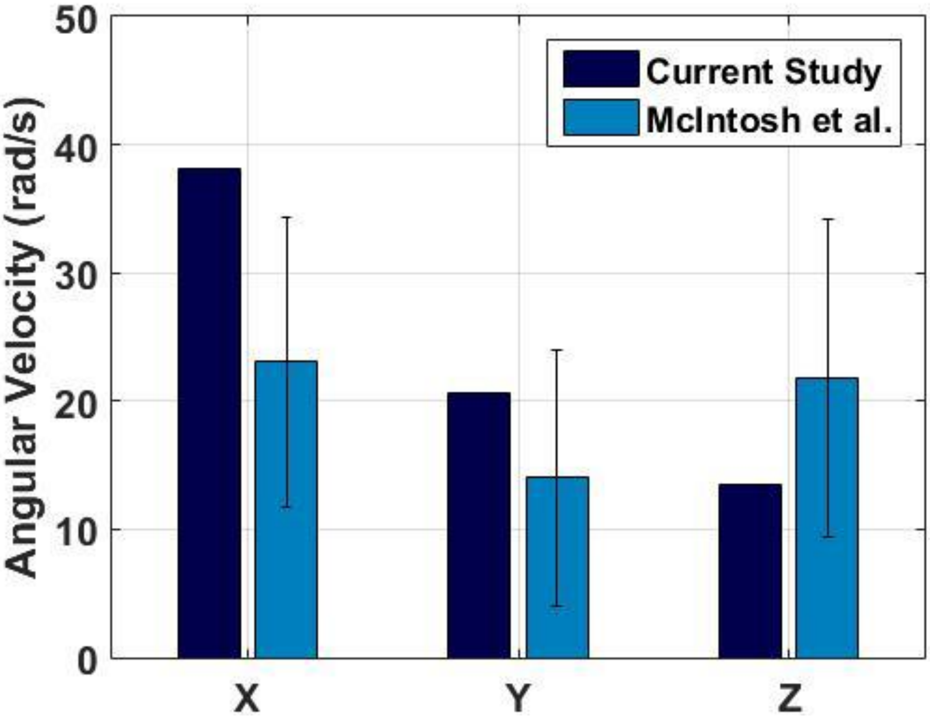

Figure 51. The componential maximum change in head local angular velocity results from inertial head loading in this study compared to the corresponding average concussion values from direct head impacts reported in the literature [8].

Table 42. The ball carrier head linear and angular velocity values for each time frame.

Time (ms)	Linear velocity (m/s)			Angular velocity (rad/s)		
	X	Y	Z	X	Y	Z
0	-0.9	-3.7	0.1	0.2	0.1	-0.4
40	-0.9	-3.5	0.1	0.3	0.2	-1.1
80	-0.9	-0.5	0.3	-13.3	-8.5	3.9
120	-0.8	3.4	0.2	-10.0	-9.7	-9.6
160	-0.1	2.9	-0.9	14.2	4.7	2.7
200	-1.2	3.4	-1.4	24.7	10.9	-7.6
240	-2.9	5.6	-1.4	16.0	5.1	-5.1

10.4 Discussion

10.4.1 General

This study aimed to use the MBIM method to measure head kinematics of a visually unaware ball carrier during a rugby union active shoulder tackle to the upper trunk. The componential head angular velocities measured are similar to the average values reported for concussive direct head impacts in unhelmeted sports [8]. The long term medical outcome of this case is unknown. However, the results indicate that legal active shoulder tackles to the upper trunk where the ball carrier is visually unaware are a concern for inertial head loading. A conclusion regarding injury risk associated with these tackles requires correlation with injury data. This should be a focus of future work.

The current maximum legal tackle height in rugby union is set at the line of the ball carrier's shoulders [118]. Lowering the tackle height has been under discussion for many years [206, 224]. The previous chapters have shown that upper body tackles (Chapter 5), especially when primary contact is with the ball carrier's upper trunk (Chapter 8), are the main cause of direct head impacts for the tackler. The current findings indicate that tackling at the upper trunk can lead to high inertial head kinematics for the ball carrier, similar to average concussion values. Lower tackle heights may reduce inertial head kinematics for the ball carrier. However, this is currently unknown. Though MBIM analysis of an unaware ball carrier tackled at a similar closing speed but lower down would be beneficial for comparison, such video that satisfies the aforementioned selection criteria is currently unavailable.

The ball carrier was impacted by the tackler just after passing the ball. The tackle was subsequently reviewed by the on-field referee/video referees and regarded as legal play. This was due to the tackler committing to the tackle before the ball had been passed. It could be considered difficult for a ball carrier to protect themselves/brace when impacted from behind and without the ball in their hands. Further work should look at these types of tackles. Examination of their incidence and propensity for injury and high head kinematics is needed.

10.4.2 Limitations

The validation study for MBIM (Chapter 9) was conducted in a controlled laboratory setting with stationary cameras positioned close to the test subject. The cameras were also positioned relatively perpendicular to each other. This was considered ideal for 3D head motion tracking. The abovementioned parameters have not been assessed for their effect on MBIM validity and could potentially result in larger errors than those reported. Root mean square errors up to 5.61 rad/s and 1.80m/s were measured for componential angular and linear velocity reconstruction in the validation study, respectively. This should be considered when interpreting the current results. Linear and angular acceleration were not measured using the MBIM method as the sampling frequency (video frame rate) was too low. Head acceleration measures typically require 1000 Hz sampling frequency [28]. The frame rate used in the current study was 25 fps and could be considered low. It is possible that higher frequency head motion occurred. The time duration associated with the head kinematics measured in this study (Table 42) are much longer than those typically associated with concussive direct head impacts (peak values usually measured within 54 ms [150]).

The MBIM approach is currently time-consuming. This case took approximately 60 hours to complete. Further work should look at automating/semi-automating the MBIM technique. The sample size for this study was only one due to the selection criteria utilised. Access to multiple camera view synchronised video footage directly from the sports broadcaster could allow more cases to be analysed.

The concussion values reported by McIntosh et al. [8] used a multibody modelling approach. McIntosh et al. [8] refined and validated the contact properties of the model's head using published data from cadaver impact tests/finite element simulations. Nonetheless, the modelling approach used by McIntosh et al. [8] was not fully validated for sport head impact reconstruction.

10.5 Conclusion

This study used MBIM to track the head kinematics of a visually unaware ball carrier during a shoulder tackle to the upper trunk. The componential head angular velocities measured were similar to average values previously reported for concussive direct head impacts in unhelmeted sports. The combination of a high legal tackle height configuration and a visually unaware ball carrier can lead to high inertial head kinematics. This is potentially a concern. The effect of a lower tackle height on ball carrier inertial head kinematics is needed.

11 Could lowering the tackle height in rugby union reduce ball carrier inertial head kinematics?

Related publications. Tierney GJ, Simms CK. The effects of tackle height on inertial loading of the head and neck in Rugby Union: A multibody model analysis. Brain Injury. 2017;31(13-14):1925-31.

Tierney GJ, Richter C, Denvir K, Simms CK. Could lowering the tackle height in rugby union reduce ball carrier inertial head kinematics? Journal of Biomechanics. 2018:1-8.

Tierney GJ, Simms CK. Predictive capacity of the MADYMO multibody human body model applied to head kinematics during rugby union tackles. In-Review.

11.1 Introduction

High ball carrier inertial head kinematics can occur during an upper trunk tackle (Chapter 10). The componential head angular velocities were similar to average values previously reported for concussive direct head impacts in unhelmeted sports [8]. It was postulated that tackling lower may have reduced the ball carrier's inertial head kinematics. The tackle height law in rugby union is currently set at the line of the ball carrier's shoulders. Any contact above this line is deemed foul play [118]. It has been an area of concern with respect to injury for many years [224]. Furthermore, future law changes must ensure that the ball carrier is better protected [118]. Before laws can be changed, it is essential to examine the effect of tackle height on ball carrier inertial head kinematics.

Staged tackles in a marker-based 3D motion capture laboratory and multibody modelling simulations allow tackles to be reconstructed in a controlled environment, as well as simulate more severe collisions in a modelling environment, respectively. Accordingly, the goal of this study is to use multibody model tackle simulations together with human volunteer tackles in a marker-based 3D motion analysis laboratory to examine the effect of tackle height on ball carrier inertial head kinematics. The study will examine the effect of lowering the tackle height to below the upper trunk, in front-on shoulder tackle events [118] where no direct contact is made with the head. Ethical approval for the staged tackles was given by the Trinity College Dublin Faculty of Health Sciences Ethics Committee.

The models have not yet been fully validated for sport collisions. The whole-body motion data gained from the staged tackles would enable a multibody model assessment for inertial head kinematic reconstruction during rugby tackles for the first time. Therefore, a secondary goal of this study is to assess the predictive capacity of the model for inertial head kinematic reconstruction during staged rugby union tackles.

11.2 Methods

11.2.1 Multibody modelling

11.2.1.1 Multibody model

The 50th percentile MADYMO pedestrian model was used as a basis for simulating player-to-player contact forces during the tackles. This model consists of 52 rigid bodies connected by kinematic joints. Ellipsoids are utilised for surface representation and contact evaluation. Although originally developed for vehicle pedestrian impact modelling, the model has been validated for various blunt impact locations (pelvis, abdomen, thorax and shoulder) [151-154]. Furthermore, the model has been validated for head translations, rotations and velocity [158]. A similar MADYMO human body model has been used as a tool for investigating head kinematics during direct head impacts in unhelmeted sports [8, 9, 150]. Although further evaluation for application to rugby union is clearly needed, the MADYMO pedestrian model is suitable for preliminary impact analysis. Focus will be placed more on trends than on absolute values of kinematic predictions.

11.2.1.2 Initial Video Analysis

To provide estimates of player-to-player contact configurations, video analysis was conducted on the 40 control tackles utilised in Chapter 5. No direct impact to the head or injury occurred during these tackles. The ball carrier and tackler orientation were then estimated two-dimensionally by creating multibody representations of the players at the time of impact (Figure 52). Ball carrier and tackler trunk angles with respect to the horizontal and the players' overall orientations were yielded. Results showed that, at the instant of contact, tackler trunk angles ranged from 0-90 degrees.

Ball carrier trunk angles independently ranged from 40-90 degrees. These trunk angle ranges were utilised to develop the multibody model player-to-player configurations for this study.

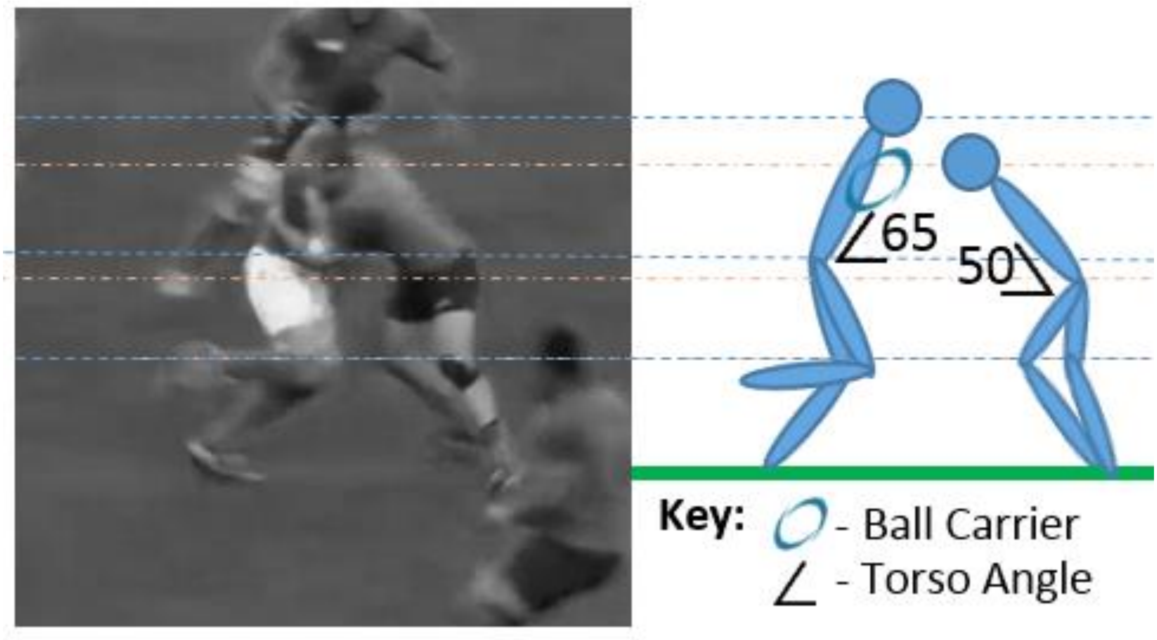

Figure 52. Two-dimensional tackle configuration with player trunk angle with respect to the horizontal for an Upper Body Tackle.

11.2.1.3 Tackle reconstructions

A shoulder tackle is when the "tackler impedes/stops the ball carrier with his/her shoulder as the first point of contact followed by use of the arm(s)" [118]. Using applicable tackling and ball carrying techniques (e.g. head placed to the side of and not in the trajectory of the ball carrier, see Chapter 5), multibody front-on shoulder tackles where no direct impact to the head/neck occurred were developed. Using a customised Matlab script together with the MADYSCALE function, the model mass, moments of inertia and height were scaled based on average elite player height and mass (1.86 m and 101 kg, respectively) [99]. Player-to-player and player-to-ground contact evaluations using the built-in MADYMO contact stiffness functions were applied. An integration timestep of 1e-5 s was used. The coefficient of friction for player-to-player contact was set at 0.34 [150].

The ball carrier and tackler trunk angles were the only parameters varied to examine the effect of tackle height on ball carrier inertial head kinematics (Figure 53). For each given ball carrier trunk angle, simulations were run by increasing the tackler trunk angle from zero up to the ball carrier's trunk angle in increments of 10 degrees. For example, for a ball carrier trunk angle of 60 degrees, 7 simulations were run for the tackler's trunk angle ranging from 0-60 degrees, see Table 43. Figure 53 shows an example of three of these configurations. The greater the tackler trunk angle, the greater the tackle height. Although the player-to-player configurations were deliberately simplified, they were broadly representative of the actual front-on shoulder tackles identified from the video analysis. This approach resulted in 45 multibody simulations.

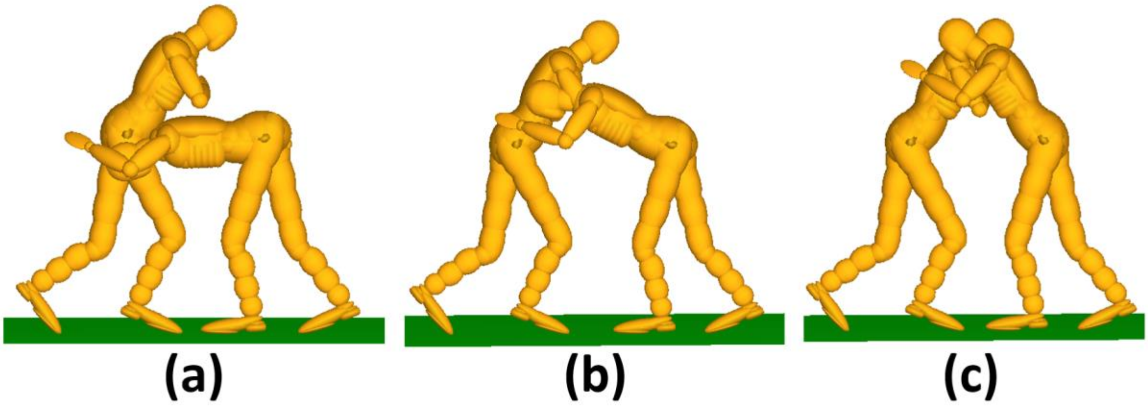

Figure 53. The player to player configuration for the multibody simulations for the conditions of the ball carrier incoming trunk angle of 60 degrees and tackler incoming trunk angle of a) 0 degrees, b) 30 degrees and c) 60 degrees.

Table 43. Design matrix of the 45 simulations based on ball carrier (BC) and tackler trunk angle with corresponding impact location on the ball carrier (Figure 54).

Tackler Angle BC Angle	0	10	20	30	40	50	60	70	80	90
40	7	3	2	1	1	-	-	-	-	-
50	7	5	3	2	1	1	-	-	-	-
60	7	5	4	3	2	1	1	-	-	-
70	7	5	4	3	2	2	1	1	-	-
80	7	6	5	4	3	2	2	1	1	-
90	7	6	5	4	3	3	2	2	1	1

Initial velocities were based on the average elite tackler and ball carrier speeds recorded 0.1s prior to impact (5.6 m/s and 4.8 m/s, respectively) [202]. Modelling muscle activation with a passive multibody model is challenging [8, 9, 150]. Therefore, all simulations were run using an unlocked joint condition. An unlocked joint condition results in the joints of the body being free to articulate within the physiological range of motion without active muscle resistance i.e. similar to that exhibited by a cadaver. This muscle activation condition can be regarded as a low awareness state. The simulations were run for 35 ms to include the upper bound of duration for a rugby union contact event in which the head experiences >10g of resultant linear acceleration [28]. For each tackle simulation, the ball carrier peak resutlant head linear acceleration, angular acceleration and change in angular velocity values were extracted. These global parameters correlate with concussion injury likelihood [8].

11.2.1.4 Tackle height analysis

To assess tackle heights, the ball carrier model was split into 7 regions (Figure 54). Each tackle simulation was categorised, based on impact location, from 1-7 (Table 43). The average head kinematics were compared between groups. To assess the general effect of lowering the tackle height law to below the chest, the 7 impact location categories were merged into two main impact locations. The upper trunk category (regions 1-3 in Figure 54) was defined as at or above the chest. The mid/lower trunk category (regions 4-7 in Figure 54) was defined as below the chest. Mean time histories (±1 SD) were plotted for each head kinematic output for upper and mid/lower trunk tackles. The ratio of peak resultant head linear acceleration, angular acceleration and change in angular velocity values between upper and mid/lower trunk tackles, based on the mean time histories, were also calculated.

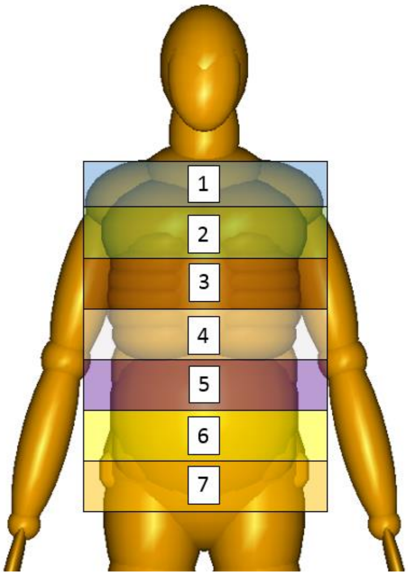

Figure 54. The ball carrier multibody model split into seven regions to assess impact location.

11.2.2 Staged rugby tackles

11.2.2.1 Laboratory trials

Two pairs of professional rugby players performed twenty tackles (10 tackles per pair; each player conducted 5 tackles as the ball carrier and 5 tackles as the tackler) in a marker-based 3D motion laboratory. The players were positioned 2.5 metres apart and initiated the tackles from a standing start. The players were instructed to vary the tackle height on the ball carrier such that a number of upper trunk tackles and mid/lower trunk tackles were executed i.e. tackles above and below the chest of the ball carrier respectively (Figure 55). The tackles were made competitive by instructing both players to attempt to achieve tackle gainline success (Chapter 6).

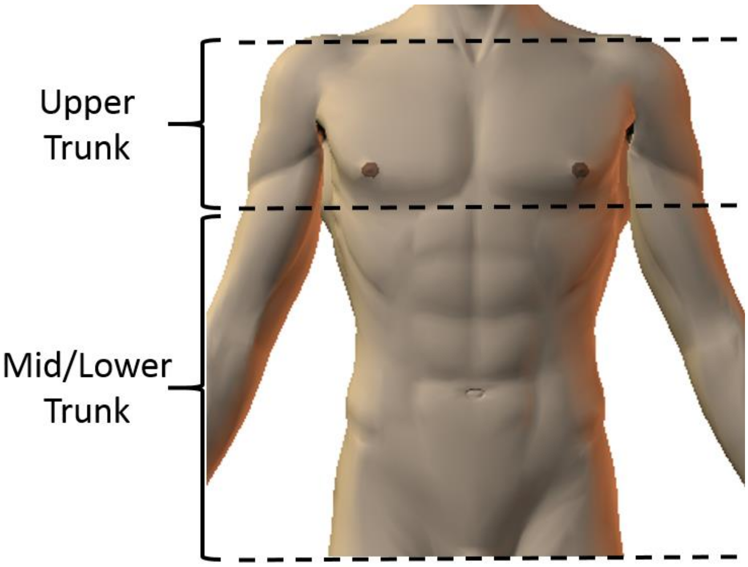

Figure 55. Upper trunk and mid/lower trunk tackles based on the impact location on the ball carrier.

11.2.2.2 Marker-based motion analysis.

A front, side and oblique view of each tackle was recorded with video cameras (Bonita 720C, Vicon, UK) recording at 66.6 Hz. These cameras were synchronised with a 10 camera infra-red motion analysis system (Bonita-B10, Vicon, UK) recording at 200 Hz.

Subjects wore reflective markers secured to the shoe or to the skin using tape, at bony landmarks (lower limbs, pelvis, trunk, arms and head). Markers were attached according to the plug-in-gait model protocol. Additional markers (C5, left and right ribcage and sacrum) were placed to allow an accurate reconstruction of the markers needed to apply the plug-in-gait model. The model utilised 43 reflective markers (10 mm radius) attached to each subject. This marker configuration enabled a three-dimensional description of the head, trunk, upper arm, forearm, pelvis, upper leg, shank and foot (Figure 56).

Figure 56. An image sequence of a staged mid/lower trunk tackle with the plug-in-gait model overlay.

11.2.3 Multibody modelling assessment

The MADYMO human body ellipsoid model was utilised for simulating the staged rugby tackle laboratory trials (Figure 57) using the aforementioned multibody modelling simulation protocol. The model was scaled based on the players' height and mass. A customised Matlab script enabled the three-dimensional description of the head, trunk, upper arm, forearm, pelvis, upper leg, shank and foot gained from the staged rugby tackle laboratory trials to be utilised for positioning and orienting the model at the time of impact. The script then enabled the angular velocities for each body region and the pelvis linear velocity to be calculated and used as initial conditions for the simulations. The simulations were run for 100 ms.

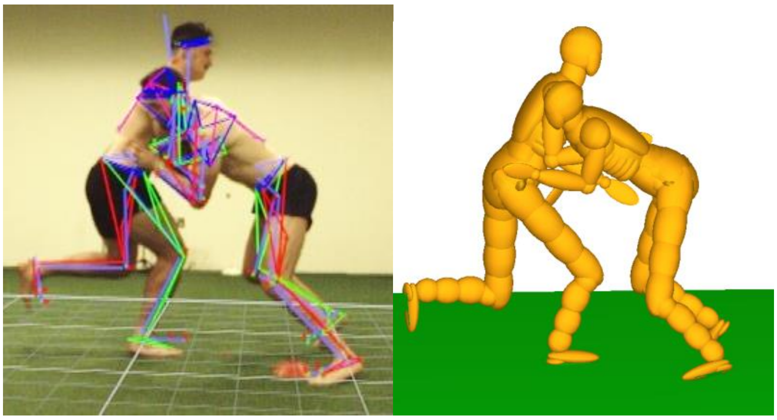

Figure 57. A staged tackle in the motion analysis laboratory (left) reconstructed in the multibody modelling environment (right).

11.2.4 Kinematic and statistical analysis

11.2.4.1 Multibody modelling and staged tackle reconstructions

The plug-in-gait model was used to calculate the ball carriers successive head rotation angles about the global coordinate system and allowed head position to be determined. Angular and linear head kinematics were then computed (Section 2.5). The location of the ball carrier and tackler's body centre of gravity was exported from the plug-in-gait model. This enabled the calculation of both ball carrier and tackler impact speeds [202]. A zero lag four-way filter with a 15 Hz cut of frequency was applied to the plug-in-gait model data.

All statistics were calculated using SPSS (IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp.). The resultant ball carrier peak linear acceleration, angular acceleration and change in head angular velocity were compared between upper trunk and mid/lower trunk tackles. A Mann-Whitney U test was utilised as the data was non-parametric (based on a Shapiro-Wilk test). Effect Sizes (ES) were assessed using the SPSS Z-statistic and calculating the r-score [236]. r values of <0.1, 0.1 - <0.3, 0.3 - <0.5 and ≥0.5 are considered indicative of a trivial, small, moderate and large effect sizes respectively [236]. The resultant ball carrier and tackler impact speeds were compared for upper trunk and mid/lower trunk tackles using a student t-test as this data was normally distributed. Cohen's d was calculated to assess effect sizes [116]. Cohen's d effect sizes of <0.2, 0.2 - <0.6, 0.6 - <1.2, and 1.2 - ≤2 were considered trivial, small, moderate, and large, respectively [116].

11.2.4.2 Multibody modelling assessment

The absolute and percentage differences in resultant head linear and angular velocity for the ball carrier were calculated for each trial. A Mann-Whitney U-test was conducted to assess whether the multibody simulations identified the same kinematic trend for tackles to the upper and mid/lower trunk as the staged tackles. Effect sizes were assessed using the abovementioned SPSS Z-statistic and r-score method.

11.3 Results

11.3.1 Multibody Modelling

Figure 58 indicates that tackle height affects ball carrier inertial head kinematics. Linear acceleration increases as tackle height increases. A sharp increase can be seen for peak angular acceleration and change in angular velocity as tackle height increases from region 7 to region 4. It then appears to level off.

Figure 59 illustrates that the multibody simulations predict a difference between upper and mid/lower trunk tackles. Upper trunk tackles appear to cause much greater inertial head kinematics for the ball carrier. Average ball carrier peak resultant head linear acceleration, angular acceleration and change in angular velocity values for upper trunk tackles were greater than for mid/lower trunk tackles by a factor of 1.5, 2.5 and 1.7, respectively.

11.3.2 Staged Rugby Tackles

The median peak resultant head linear acceleration ($p=0.10$; $ES=0.36$), angular acceleration ($p=0.03$; $ES=0.50$) and change in head angular velocity ($p<0.01$; $ES=0.64$) values for upper trunk tackles are greater than mid/lower trunk tackles (Figure 60). Median ball carrier peak resultant head linear acceleration, angular acceleration and change in angular velocity values for upper trunk tackles were greater than for mid/lower trunk tackles by a factor of 1.8, 2.2 and 2.3, respectively. The mean impact speeds for the tackler and ball carrier were slightly higher for upper trunk tackles (Table 44). However, the difference was statistically insignificant.

11.3.3 Multibody modelling assessment

Nineteen tackles were reconstructed for the multibody modelling assessment. Twenty cases could not be reconstructed as body markers fell off a participant during a tackle. Therefore, 8 mid/lower trunk tackles and 11 upper trunk tackles were executed.

Table 45 shows the change in ball carrier head linear and angular velocity results for each tackle trial. In some cases, very high percentage errors (up to 366%) were recorded. Table 46 illustrates that the MADYMO simulations identified that tackles to the upper trunk caused greater changes in head linear and angular velocity for the ball carrier than mid/lower trunk tackles.

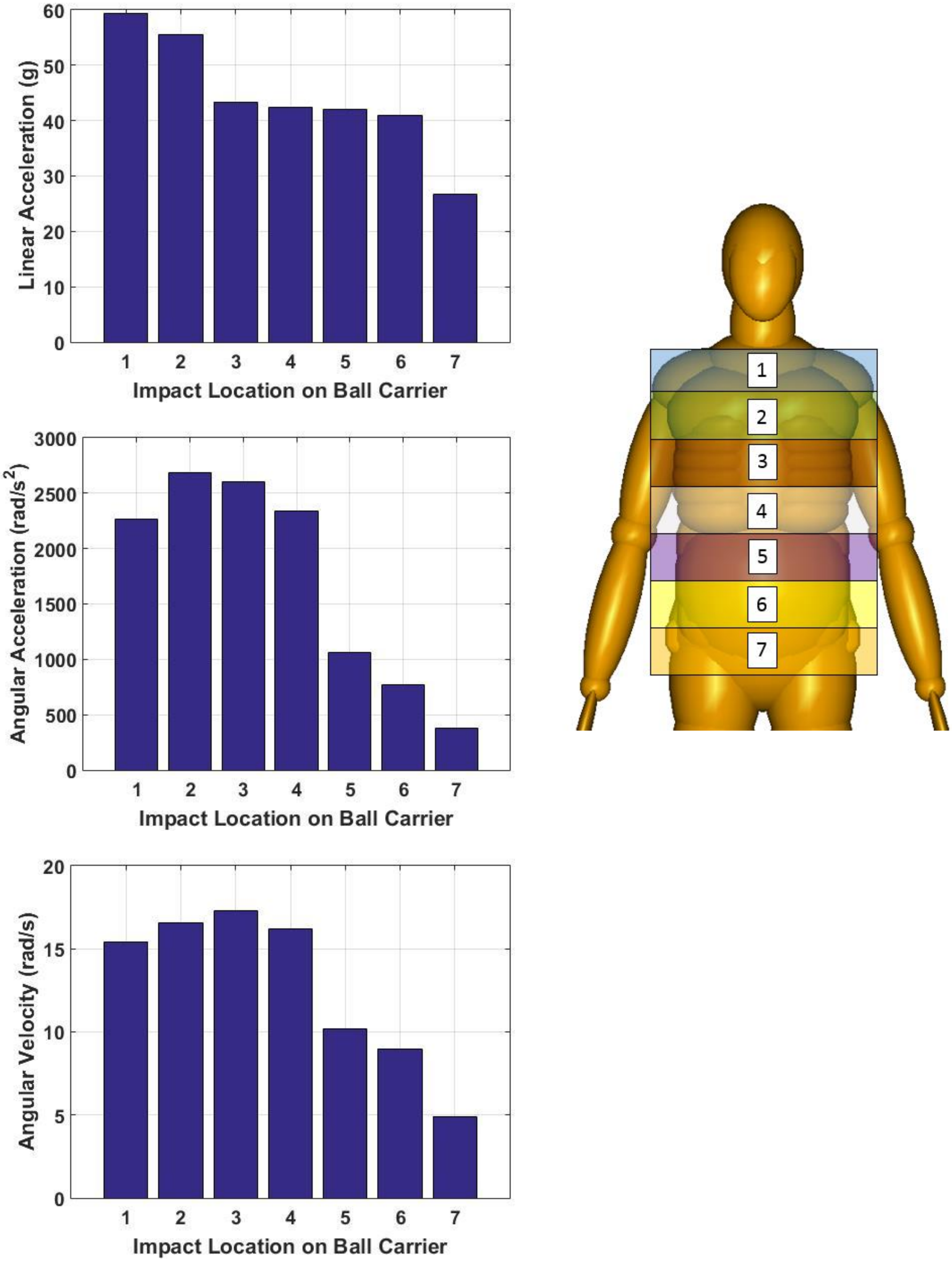

Figure 58. The predicted effect of tackle height on ball carrier peak resultant head linear acceleration, angular acceleration and change in head angular velocity from the multibody simulations.

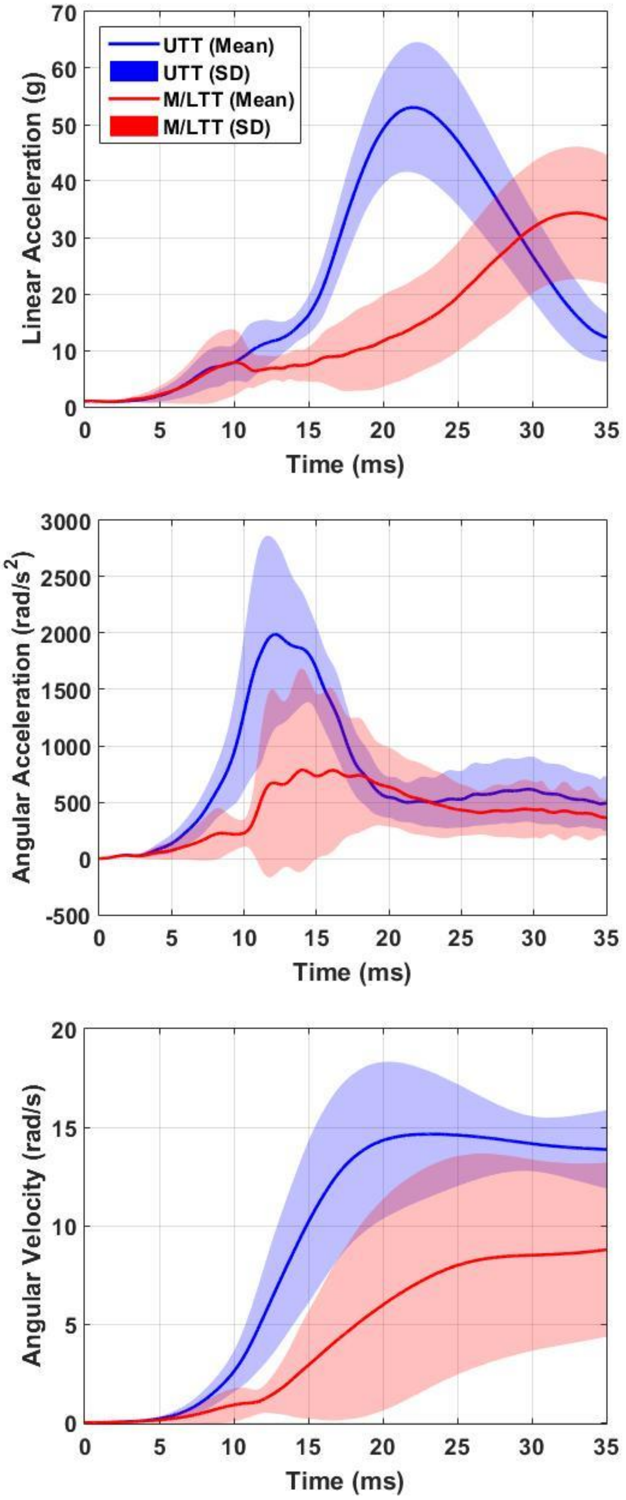

Figure 59. The mean (±1 SD) ball carrier resultant head linear acceleration, angular acceleration and change in head angular velocity time histories from the multibody simulations for Upper Trunk Tackles (UTT; Blue) and Mid/Lower Trunk Tackles (M/LTT; Red).

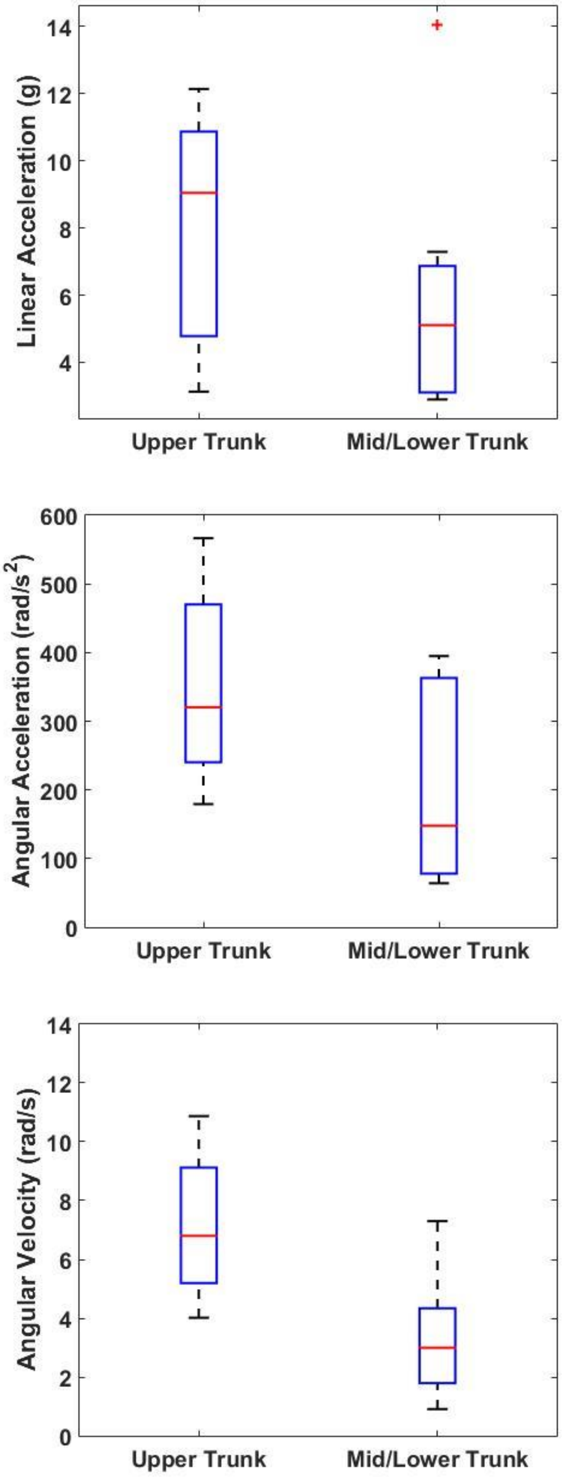

Figure 60. The median ball carrier peak resultant head linear acceleration, angular acceleration and change in head angular velocity values (red line) with upper and lower quartiles (blue box) and outliers (red cross) from the staged tackles for upper trunk and mid/lower trunk tackles.

Table 44. The mean (±1 SD) ball carrier and tackler impact speeds for upper trunk and mid/lower trunk tackles with p-values and effect size for the staged tackles.

Impact Speed	Upper Trunk	Mid/Lower Trunk	p-value	Effect Size	Interpretation
Ball Carrier	1.7 (±0.5)	1.4 (±0.6)	0.18	0.63	Moderate
Tackler	2.5 (±0.6)	2.1 (±0.5)	0.13	0.72	Moderate

Table 45. The multibody model predictions (MADYMO) for ball carrier change in head linear and angular velocity compared with the 3D motion laboratory measures (Vicon).

Ball Carrier		Change in resultant head linear velocity (m/s)				Change in resultant head angular velocity (rad/s)			
Tackle ID	**Closing Speed (m/s)**	**Vicon**	**MADYMO**	**Difference (MADYMO - Vicon)**	**Error (% of Vicon)**	**Vicon**	**MADYMO**	**Difference (MADYMO - Vicon)**	**Error (% of Vicon)**
Mid/Lower 2	4.04	1.03	0.59	-0.44	-43	2.52	3.92	1.40	56
Mid/Lower 3	3.06	0.88	0.35	-0.53	-60	3.00	4.92	1.92	64
Mid/Lower 4	3.70	1.06	0.70	-0.35	-33	1.73	4.09	2.36	136
Mid/Lower 5	2.89	0.90	0.47	-0.43	-48	3.59	4.79	1.20	33
Mid/Lower 6	4.20	1.45	0.50	-0.95	-65	3.42	5.28	1.86	54
Mid/Lower 7	3.78	0.84	0.60	-0.24	-28	1.81	3.78	1.97	109
Mid/Lower 8	3.85	0.92	1.22	0.30	33	7.30	10.91	3.61	49
Mid/Lower 9	4.22	1.18	0.17	-1.01	-86	0.91	4.22	3.31	366
Upper 1	3.87	0.90	0.94	0.04	5	4.07	4.21	0.14	4
Upper 2	3.95	1.49	1.38	-0.11	-7	5.00	7.85	2.85	57
Upper 3	4.26	0.45	1.94	1.50	336	5.79	4.48	-1.31	-23
Upper 4	4.05	1.17	1.12	-0.05	-4	6.81	5.73	-1.09	-16
Upper 5	4.38	1.33	1.27	-0.06	-4	6.80	8.51	1.71	25
Upper 6	4.53	2.23	2.45	0.22	10	6.11	7.43	1.32	22
Upper 7	4.88	2.52	1.02	-1.50	-59	10.20	8.52	-1.67	-16
Upper 8	4.54	1.43	1.57	0.14	10	4.02	6.30	2.28	57
Upper 9	5.18	2.21	1.52	-0.69	-31	7.64	8.63	0.99	13
Upper 10	4.57	2.53	1.42	-1.11	-44	9.62	6.76	-2.86	-30
Upper 11	4.00	2.68	1.44	-1.23	-46	10.87	5.79	-5.08	-47

Table 46. The median (with 25th and 75th percentiles) MADYMO and Vicon ball carrier change in head linear and angular velocity values for upper and mid/lower trunk tackles.

	Upper Trunk Tackle (n=11)	Mid/Lower Trunk Tackle (n=8)	p-value	Effect Size	Interpretation
Linear Velocity (m/s)					
MADYMO	1.42 (1.12-1.57)	0.55 (0.38-0.68)	<0.01	0.77	Large
Vicon	1.49 (1.17-2.52)	0.98 (0.89-1.15)	0.03	0.50	Large
Angular Velocity (rad/s)					
MADYMO	6.76 (5.73-8.51)	4.51 (3.96-5.19)	0.03	0.50	Large
Vicon	6.80 (5.00-9.62)	2.76 (1.75-3.55)	<0.01	0.70	Large

11.4 Discussion

11.4.1 General

Tackle height has a considerable effect on ball carrier inertial head kinematics. The findings suggest that the ball carrier inertial head kinematics measured in Chapter 10 would have been reduced had the tackle occurred lower down on the body. However, further real-world data is needed to support this finding [169]. The laws of mechanics explain that the energy transmitted during an impact is attenuated along a damped/deformable linkage system through viscous dissipation [237]. Thus, the head kinematics resulting from an impact to the body are inversely related to the distance of the impact from the head. In a front-on shoulder tackle, most ball carrier rotation occurs in the sagittal plane. The overall ball carrier angular momentum about the point of contact is conserved in the tackle. This results in lower rotational inertia above the point of contact when the tackle height is greater and hence greater head rotations.

Head kinematics have been linked to brain injury [8-12] and there is a concept of neuronal vulnerability to injury due to repetitive sub-concussive loading [13-15]. Given that players can be involved in over 30 tackles per game [33], repetitive inertial head loading from upper trunk tackles in comparison to mid/lower trunk tackles may be a concern in rugby union. However, this cannot be concluded from the current study. Further prospective longitudinal studies considering both concussion history and overall head impact exposure are needed to conclude this [16].

The whole-body staged rugby tackle data was utilised to assess the predictive capacity of the MADYMO ellipsoid human body model for head kinematic reconstruction. The results demonstrate that the predictive capacity is limited on an individual case basis. Errors ranged up to 336% and 366% for change in resultant head linear and angular velocity, respectively. However, the simulations also identified that tackles to the upper trunk cause greater changes in head linear and angular velocity for the ball carrier than mid/lower trunk tackles.

11.4.2 Multibody Modelling

By lowering the tackle height law to below the chest, based on the peak ratios of upper trunk tackles to mid/lower trunk tackles, average ball carrier peak head linear acceleration, angular acceleration and change in angular velocity values could be reduced by 35%, 61% and 40%, respectively. The kinematic values reported in this study are within the range of reported head kinematic values reported for general rugby union play [28]. However, the accuracy of the numerical values predicted must be considered given the modelling assessment results.

11.4.3 Staged Rugby Tackles

The results of the staged tackles support the principal findings of the multibody modelling tackles. The head kinematics values from the staged rugby tackles are lower than that reported for general play [28]. The tackle intensity was also significantly lower. The impact speeds of the ball carrier and tackler (Table 44) were around 2-3 times lower than average impact speeds in the elite game environment [202]. Thus, substantially higher ball carrier inertial head kinematics are expected to occur during competitive play tackles. The ball carriers in this study had high awareness levels of the tackle, enabling them to fully brace for the impact. This could reduce inertial head kinematics as neck muscle are more likely to be highly activated. Further research is required to support these two abovementioned points. The outlier in Figure 60 suggests that high relative inertial head kinematics can be experienced during a mid/lower trunk tackle. Though, overall, the inertial head kinematics for mid/lower trunk tackles are significantly less than for upper trunk tackles.

11.4.4 Multibody modelling assessment

The intensity of the staged tackles resulted in relatively low changes in ball carrier head linear and angular velocity. This resulted in high percentage errors for the model predictions even though the absolute errors could be considered small. The model was validated based on vehicle-cadaver collisions (usually at 40 km/h [159]) and thus may be better suited for reconstructing inertial head kinematics in higher velocity impacts.

This may explain why the model has previously shown lower errors for inertial head kinematic predictions during vehicle-cadaver collisions (maximum of 36% for head linear velocity predictions at the point of head-windscreen contact [158]).

Future work could utilise the 3D motion laboratory data to optimise the numerous input parameters of the model. The accuracy for sport impact reconstruction could then be re-evaluated. This should include optimising contact friction properties, contact stiffness, joint stiffness and model shape. In recent years, the development of active human body models has become a promising prospect [238]. These allow active muscle behaviour to be exhibited by the model during an impact. However, active models require muscle activation parameters as initial conditions which are not yet fully known [239]. Examples of active human body models are the MADYMO active human body model [238] and the OpenSim rugby model [239]. Active models can be assessed for sport impact reconstruction using the 3D motion laboratory data gained in the current study.

11.4.5 Limitations

Only a small sample size was utilised in the staged rugby tackles (4 players). The sampling frequency used in the staged rugby tackles may be too low for capturing accurate head acceleration data [233]. However, the frequency of inertial head acceleration is likely to be lower than that of direct head impacts. The unlocked joint condition is more representative of a cadaver than a trained rugby player bracing for contact. The results of this study provide biomechanical support for the proposition of lowering the tackle height law in rugby union. Nonetheless, the changing of laws in sport is a complex process and will require further research, collaborations and discussions between players, coaches, referees, sports scientists and biomechanists.

For the multibody modelling assessment, the plug-in gait model configuration is not identical to the MADYMO model. The plug-in-gait model treats the trunk of the player as one rigid body whereas the multibody model treats it as two. The plug-in-gait model also treats the neck/head as one rigid body whereas the multibody model treats it as two. Both models can be considered insufficient given the articulation in the human spine. This led to some differences in initial linear velocities when matching initial angular velocities in the joints. The average difference at time zero between the linear velocity of the head for the multibody model and the 3D motion laboratory results was 0.2 m/s and 0.5 m/s for the ball carrier and tackler, respectively. The multibody model has only two degrees of freedom for the shoulder joint. This potentially led to errors in the positioning of the players' arms in the simulations. The study only presented a comparison of resultant head kinematics for the multibody modelling assessment. Componential head kinematics were compared between the two methods. However, large differences were also measured and no clear trends were illustrated. High velocity sports impact validation data is currently unavailable. Clearly, a direct head impact could not be executed in the motion analysis laboratory. Approaches such as MBIM could enable whole body kinematic data to be extracted from direct head impacts in real games. The development of MBIM and instrumented mouthguards [169] could make direct head impact validation data available in the future.

11.5 Conclusion

Tackle height strongly affects the inertial head kinematics experienced by the ball carrier in legal front-on shoulder tackles. Higher ball carrier inertial head kinematics were identified for upper trunk tackles when compared to mid/lower trunk tackles in both the multibody simulations and staged rugby tackles. In the multibody simulations, average ball carrier peak resultant head linear acceleration, angular acceleration and change in angular velocity values for upper trunk tackles were greater than for mid/lower trunk tackles by a factor of 1.5, 2.5 and 1.7, respectively. Model validation is a limitation of this aspect of the study, however the trends are supported by the staged tackles. In the staged tackles, median ball carrier peak resultant head linear acceleration, angular acceleration and change in angular velocity values for upper trunk tackles were greater than for mid/lower trunk tackles by a factor of 1.8 ($p=0.10$), 2.2 ($p=0.03$) and 2.3 ($p<0.01$), respectively. The findings support the proposition of lowering the current tackle height law to below the upper trunk. The predictive capacity of the MADYMO human body ellipsoid model was assessed using the whole-body staged rugby tackle data. The model is currently unsuitable for detailed reconstruction of head kinematics on an individual case basis. However, the model identified the kinematic trend that upper trunk tackles cause greater ball carrier inertial head kinematics than mid/lower trunk tackles, even with significant variation in initial player-to-player configurations and speeds.

Additional contributor. Chris Richter assisted with the staged rugby tackle trials and applied the plug-in-gait model to the marker-based data.

12 Discussion

The aim of this thesis was to biomechanically assess direct and inertial head loading in rugby union to identify concussion injury prevention strategies. The rationale was based on the high concussion incidence rate in rugby union [2]. Furthermore, insufficient research was conducted on the regular head loading environment associated with rugby union [16]. In particular, little was known about the magnitude and influencing factors for head kinematics during regular play without any direct head contact.

From the initial video analysis (Chapter 5), the tackle phase of play was identified as a major cause of direct head impacts with the tackler at most risk. The tackle accounted for 60% of direct head impacts, of which 61% and 39% were upper- and lower body tackles, respectively. The remaining direct head impacts occurred from rucks (19%), diving for a loose ball/scoring a try (13%) and ground contact (8%). The tackler received 97% of tackle related direct head impacts. The findings agree with previous literature that identified tackles as the main cause of concussion in rugby union [103, 106]. Most tackle related direct head impacts occurred in the second half of the game (81%). The majority (63%) of upper body tackle related direct head impacts occurred in the last quarter. It was postulated that player time-in-game influenced tackle technique [1, 115, 116] and/or that players placed themselves in high risk scenarios towards the end of a game. Player-to-player configurations and characteristics associated with direct- and non-direct head impact events during the tackle were established. Direct head impact tackles generally had at least one player entering at high speed. For upper- and lower body tackles, incorrect tackler head placement was the most important factor for direct head impact causation. Tackler foot planting potentially influenced this during upper body tackles.

Several studies have been published recently that support the findings of Chapter 5. This includes studies assessing the effect of tackle speed [207] and head placement [208] on concussion risk. Furthermore, Tucker et al. [205, 206] identified that tackles were the main cause of Head Injury Assessments (HIAs) with the tackler at most risk. Tucker et al. [206] also identified that an upright tackler (indicative of an upper body tackle) and high-speed tackles were HIA risk factors.

From Chapter 5, the tackle was understood to be a key area to focus on. More in-depth video analysis was conducted on tackle characteristics associated with tackler HIAs. Tackle height appeared to play a role in head impact aetiology and required further investigation. Additionally, tackle characteristics and height were assessed in terms of tackle success outcomes. This ensured that the concussion prevention strategies put forth were beneficial for performance also. Lastly, it appeared qualitatively that certain legal tackles to the upper body were causing significant ball carrier inertial head loading. By utilising a combination of Model-Based Image-Matching (MBIM), multibody modelling and staged tackles in a motion analysis laboratory, the influence of tackle height on ball carrier inertial head kinematics was examined. Based on the aforementioned approaches, a range of prevention strategies have been put forth.

12.1 Tackle characteristics

Chapter 6 utilised tackle based technical criteria [116] and match video evidence to identify changes in ball carrier and tackler proficiency characteristics as player time-in-game increased. Separately, a tackle count was conducted to identify differences in the number of tackles occurring between the quarters of a game. The study found that player time-in-game does not affect tackler or ball carrier tackle proficiency at the elite level. The findings support the theory that elite players do not reach the upper limit for repeatedly engaging in high energy impact tackles [93] during the eighty minutes of a game. The findings suggest that the high level of tackle-based training, fitness and physical conditioning experienced by elite level players reduces their susceptibility to tackle technique deterioration. Significantly more tackles occur in the final quarter than the first and second. This provided an alternative explanation for more head impacts occurring in the later stages of a game.

Several tackle characteristics that had a higher propensity towards tackle gainline success for the ball carrier and tackler were identified. For the ball carrier and tackler, characteristics indicative of strong and powerful tackle technique such as “explosiveness on contact” and “leg drive on contact” were effective. “Explosiveness on contact” has previously been shown to help prevent the ball carrier from getting injured in front-on tackles [116]. Therefore, “explosiveness on contact” carries the twin benefit of protecting the ball carrier and dominating the tackle.

The tackle criteria from Chapter 6 were utilised to identify characteristics that have a lower propensity to result in a HIA for the tackler in upper- and lower body tackles (Chapter 7). Several tackler specific proficiency variables were identified. Examples include, “identify/track ball carrier onto shoulder”, “head up and forward/face up”, “straight back, centre of gravity forward of support base” and “head placement on correct side of ball carrier”. For the ball carrier, a lot less proficiency variables that result in a tackler HIA were identified. No side-on ball carrier characteristics were identified. This highlights the importance of effective and safe tackler proficiency characteristics. Therefore, focus should be placed more on tackler characteristics for HIA prevention. Nonetheless, the ball carrier characteristic, “fending into contact” was identified as a concern. Fending was exhibited in 47% of front-on upper body tackle related HIA cases. In 67% of these cases, it was the fending arm (upper arm, elbow and forearm), and not the palm of the hand, that contacted the tacklers’ head. With regards to prevention, coaches should place focus on correct fending during training drills. Referees should also be alert to head contact during the fend. Fending could potentially be made illegal. It is not an essential skill or aspect of the game but clearly an issue for head impact causation. Previous studies have shown that fending has a positive effect on ball carrier tackle outcomes such as offloading [1] and compromising tackler positioning [216]. “Explosiveness on contact” had a higher propensity to result in a tackler HIA for upper and lower body front-on tackles. This is consistent with previous findings that identified high energy transfer in the tackle as a HIA risk factor [206]. Risk mitigation is difficult as ball carrier explosivity is a desirable trait.

Similar findings were recently published by Davidow et al. [221] who found that head impacted tacklers had lower contact proficiency for “identify/track ball carrier onto shoulder”, “straight back, centre of gravity forward of support base”, “head up and forward/face up”, “shortening steps”, “head placement on correct side of ball carrier” and “arm usage (punch forward and wrap i.e. hit-and-stick)”. Davidow et al. [221] also found ball carriers to exhibit “fending into contact” more in tackler head impact cases. However, ball carriers also appeared to exhibit “body position - straight back”, “body position - upright to low” and “side-on into contact” more in tackler head impact cases. It is unclear why these findings differ to those in Chapter 7. A potential reason may be due to the dataset utilised by Davidow et al. [221] consisting entirely of professional and semi-professional southern hemisphere games.

The tackle technique findings provide an evidence base for coaches to develop and implement technical based concussion prevention strategies that are safe and effective. Table 47 illustrates tackler characteristics that had both a positive influence on performance and head impact mitigation. No side-on tackle characteristics overlapped.

Table 47. Tackler characteristics, for front on tackles, that had a higher propensity to result in tackler gainline success and a lower propensity to result in a direct head impact.

Tackler characteristics
Straight back, centre of gravity forward of support base
Shortening steps
Arm usage (punch forward and wrap i.e. hit-and-stick)

12.2 Tackle height

12.2.1 Direct head impact

Lowering the tackle height law in rugby union has been suggested [224] but the evidence base was limited. Further analysis of match video evidence illustrated that tackle height influences tackler HIA aetiology (Chapter 8). Tackling at the upper trunk accounts for nearly half (47%) of all tackler HIAs. For upper body front-on shoulder tackles and side-on smother tackles, tackling at the upper trunk had a greater propensity to result in a tackler HIA. For side-on upper body smother tackles, tackling at the mid-trunk had a lower propensity. Front- and side-on upper trunk smother tackles were an ineffective strategy for tackler success (tackle gainline). Furthermore, shoulder tackles to the upper trunk had no greater propensity to result in tackler success. This provides more evidence to discourage tackling at the upper trunk. Quarrie and Hopkins [110] found that tackling high (roughly at the upper trunk) resulted in the highest general injury rate for the ball carrier (3.4 injuries per 1000 tackle events). However, Quarrie and Hopkins [110] identified that tackling low (roughly at the upper and lower legs) resulted in the highest general injury rate for the tackler (2.2 injuries per 1000 tackle events).

Lowering the maximum legal tackle height to below the upper trunk of the ball carrier could reduce tackler HIA risk during upper body tackles. However, lowering the tackle height law with no additional guidance may increase the likelihood of upper leg related HIAs. Tackling at the upper legs had a higher propensity to result in a tackler HIA than tackling at the upper trunk. Thus, simply lowering the allowable tackle height might increase the number of tackles to the upper leg region. This could have an adverse effect on HIA reduction. This illustrates the importance of coaching strategies that place emphasis on tackling lower risk regions such as the mid- and lower trunk. The overall risk of given tackle heights is summarised schematically in Figure 61. Tucker et al. [206] suggested lowering the tackle height law but did not specify a new limit. Subsequent monitoring would be required if a new tackle height law is introduced to ensure concussion and other injury rates do not increase. In particular, changes in upper leg related HIAs would need to be assessed. A sanction that penalises the tackler for head impacts (to either the tackler or ball carrier) due to tackling upright at the upper trunk may be a more suitable intervention than lowering the tackle height law as discussed in Chapter 8. This could mitigate the issue of ball carriers entering the tackle in a bent-at-the-waist position [206] which makes upper trunk tackles almost unavoidable. Furthermore, the sanction would encourage tackling at lower risk body regions whilst deterring upright tackling at the upper trunk. Potentially a combination of a lower tackle height law and a sanction that deters upright tackling could be a suitable intervention.

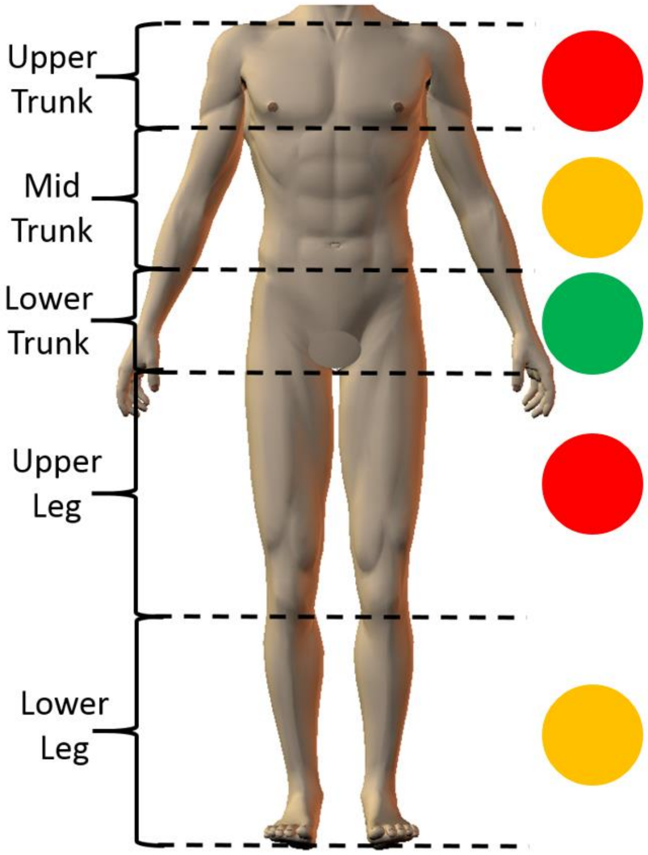

Figure 61. The risk of given tackle heights in rugby union for HIA aetiology. Red indicates a greater propensity to result in a HIA than that anticipated by chance; Orange indicates neither greater nor lower propensity to result in a HIA than that anticipated by chance; Green indicates a lower propensity to result in a HIA than that anticipated by chance.

12.2.2 Inertial head loading

An assessment was conducted on the accuracy of the MBIM method for estimating 6 degree of freedom head motion (Chapter 9). A vehicle-cadaver head-windscreen impact case was utilised. The method exhibited Root Mean Square Errors (RMSE) between 10-20 mm for linear displacement and 0.01-0.03 rad for rotational displacement for reconstructing 6 degree of freedom head motion. The rotational displacement RMSE results are similar to that achieved by Mok et al [225], who validated the MBIM technique for assessing ankle joint angles. However, the MBIM method was deemed unsuitable for measuring componential angular velocity during direct head impacts (RMSE up to 5.61 rad/s). This was due to the high frequency head motion associated with direct head impacts going unmeasured by the MBIM technique. Higher frame rate video did not improve this as it resulted in operator error. However, the MBIM method was considered suitable for measuring componential angular velocity during indirect head impacts for which lower frequency head motion is typically associated with.

The MBIM technique was subsequently utilised to measure the head kinematics of a visually unaware ball carrier during an active shoulder tackle to the upper trunk (Chapter 10). High inertial head kinematics were measured though no contact with the head or neck was made. The componential head angular velocities were similar to the average values previously reported for concussive direct head impacts in unhelmeted sports [8]. This is potentially a concern. The long term medical outcome of this case is unknown. The ball carrier was examined on the field but was not immediately removed from play. The results indicate that legal active shoulder tackles to the upper trunk of a visually unaware ball carrier can cause high inertial head kinematics. Given that there is an emerging concept of neuronal vulnerability to injury due to repetitive sub-concussive loading [13-15], repeatedly engaging in this type of tackle may be detrimental to long term player brain health. However, further prospective longitudinal studies considering both concussion history and overall head impact exposure are needed to conclude this. It was postulated that lower tackle heights may reduce inertial head kinematics for the ball carrier.

To address this, MADYMO multibody simulations and staged tackles in a motion analysis laboratory were conducted (Chapter 11). The findings illustrated that tackle height strongly affects the head kinematics experienced by the ball carrier, even without direct contact to the head or neck. Higher ball carrier head kinematics were identified during upper trunk tackles compared to mid/lower trunk tackles. By lowering the tackle height law to below the upper trunk, the multibody simulations suggest that average ball carrier peak head linear acceleration, angular acceleration and change in angular velocity values could be reduced in the tackle by 35%, 61% and 40%, respectively. Based on the staged tackles, median ball carrier peak head linear acceleration, angular acceleration and change in angular velocity values could be reduced in the tackle by 44%, 55% and 57%, respectively.

The MADYMO human body ellipsoid model was assessed for reconstructing head kinematics during the abovementioned staged tackles. The findings indicated that the model is currently unsuitable for detailed reconstruction of head kinematics on an individual case basis. However, the model identified the kinematic trend that upper trunk tackles cause greater ball carrier inertial head kinematics than mid/lower trunk tackles, even with significant variation in initial player-to-player configurations and speeds. The unlocked joint condition utilised is more representative of a cadaver than a trained rugby player bracing for contact. This may explain why the model has previously shown lower errors for head kinematic predictions during vehicle-cadaver collisions [158].

13 Conclusion

The tackle phase of play is a major cause of direct head impacts in rugby union with the tackler at most risk. Tackler characteristics that have a positive influence on tackle success and a lower propensity to result in a tackler HIA were identified, such as “identify/track ball carrier onto shoulder”, “head up and forward/face up”, “straight back, centre of gravity forward of support base” and “head placement on correct side of ball carrier”. For the ball carrier, much fewer tackle characteristics were identified. This highlights the importance of effective and safe tackler proficiency characteristics. However, “fending into contact” was identified as a concern. The characteristic was exhibited in 47% of front-on upper body tackle HIA cases. In two-thirds of these cases, it was the fending arm (upper arm, elbow and forearm), and not the palm of the hand, that contacted the tackler’s head.

A large majority (81%) of tackle related direct head impacts were found to occur in the second half of games. A disproportionate number of direct head impacts from upper body tackles (63%) occurred in the final quarter. However, tackling proficiency remained relatively constant throughout the game. Instead, more tackles occur in the final quarter of a game.

Tackling at the upper trunk has a greater propensity to result in a tackler HIA and accounts for nearly half (47%) of all cases. Upper trunk tackles also have no greater propensity to result in tackler success. Lowering the maximum legal tackle height to below the upper trunk of the ball carrier could reduce tackler HIA risk during upper body tackles. However, it may increase the likelihood of upper leg related HIAs as tackling at the upper legs has a higher propensity to result in a tackler HIA than tackling at the upper trunk.

An assessment was conducted on the accuracy of the Model-Based Image-Matching (MBIM) method for estimating 6 degree of freedom head motion. The method exhibited Root Mean Square Errors (RMSE) between 10-20 mm for linear displacement and 0.01-0.03 rad for rotational displacement for reconstructing 6 degree of freedom head motion. However, the MBIM method was deemed unsuitable for measuring componential angular velocity during direct head impacts (RMSE up to 5.61 rad/s). This was due to the high frequency head motion associated with direct head impacts going unmeasured by the MBIM technique. Higher frame rate video did not improve this as it resulted in operator error. However, the MBIM method was considered suitable for measuring componential angular velocity during indirect head impacts for which lower frequency head motion is typically associated with.

For inertial head loading, MBIM was utilised to measure the head kinematics of a visually unaware ball carrier during an active shoulder tackle to the upper trunk. The componential head angular velocities were similar to the average values previously reported for concussive direct head impacts in unhelmeted sports. This is potentially a concern. It was postulated that lower tackle heights may reduce inertial head kinematics for the ball carrier.

Staged tackles in a motion analysis laboratory and multibody simulations indicated that higher tackle heights cause greater ball carrier inertial head kinematics. By lowering the tackle height law to below the upper trunk, the multibody simulations suggest that average ball carrier peak head linear acceleration, angular acceleration and change in angular velocity values could be reduced in the tackle by 35%, 61% and 40%, respectively. Based on the staged tackles, median ball carrier peak head linear acceleration, angular acceleration and change in angular velocity values could be reduced in the tackle by 44%, 55% and 57%, respectively. The MADYMO ellipsoid human body model was assessed for reconstructing head kinematics during the abovementioned staged rugby union tackles. The results indicated that the model is currently unsuitable for detailed reconstruction of head kinematics on an individual case basis. However, the model identified the kinematic trend that upper trunk tackles cause greater ball carrier inertial head kinematics than mid/lower trunk tackles, even with significant variations in initial player-to-player configurations and speeds.

The findings from this thesis provide an evidence base, at the elite level, for coaches to develop and implement technical based concussion prevention strategies for players. Upper trunk tackles were identified as a risk factor for direct head impacts for tacklers and high inertial head kinematics for ball carriers. Tackling at the upper trunk of the ball carrier should be discouraged. A lower tackle height law may help combat against this, however it may not be enough to rely solely on an intervention. Tackling is an open, dynamic and highly technical skill. Therefore, a strong emphasis must be placed on safe tackle technique in training to ensure that it is replicated in a competitive scenario.

14 Further work

The approaches utilised throughout the thesis can be used for other levels of rugby union and similar contact sports such as Gaelic football, Australian rules football and American football. Representative older rugby union games could be analysed to identify changes in player characteristics with time e.g. identify if players tackled lower before the professional era of rugby union. The tackle technique analysis focused on tackler HIAs. The tackler accounted for nearly all (97%) tackle-related head impacts (Chapter 5). However, recent studies report that the tackler accounts for 70-72% [206, 207]. Further work should conduct analysis on ball carrier HIA risk. Unfortunately, the data collection approach undertaken resulted in an insufficient ball carrier sample size (n<10) for HIA analysis. The variation in the return to play protocols at different levels of the game indicates scope for further research (Section 2.7).

The development of active human body models has become a promising prospect. The active models should be assessed for sport impact reconstruction using the motion analysis laboratory data (Chapter 11). The future combination of Model-Based Image-Matching and instrumented mouthguards can provide direct validation data for sport impacts. The MBIM technique has shown significant promise. However, the method is currently time-consuming. Further work should explore automating the technique. An automated MBIM technique could be used on higher frame rate video. Hence, head kinematic predictions could be improved.

The effect of tackle height on inertial head kinematics could be further examined. An instrumented mouthguard-based study could be conducted on a rugby union team during games and training. The study could encompass clinical approaches for analysing concussion such as advanced medical imaging and concussion injury blood biomarkers. Synchronising the mouthguards with match video footage would enable inertial head kinematics to be cross referenced to specific impact events. Overall player head kinematic exposure could then be correlated with the clinical data.

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