An Investigation of Transmission Range for an Instrumented Mouthguard Head Impact Telemetry System for Rugby Union

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Abstract

Concussions and sub concussive head impacts in contact sports have become a significant issue over the past two decades. The consensus in current literature is that large head impacts with high linear and rotational acceleration are the main cause of concussions in sport. Head impact telemetry (HIT) systems have been developed to measure and monitor the inertial loading of the head. HIT technology has now evolved so these systems can be worn by athletes in competition. There are currently very few validated HIT systems able to monitor player loads. Existing systems have been found to overestimate impacts, do not record in real-time or are not suitable to be used in non-helmet sports, such as rugby. The purpose of this study was to investigate the transmission range of the PROTECHT™ instrumented mouthguard under different conditions, to identify particular conditions that significantly affect signal quality. Head impacts were simulated using specialist software, on an instrumented mouthguard, under different conditions across two days of testing. Signal quality was evaluated under each condition. Standing and kneeling were found to have no significant effect on signal quality. However, lying prone on the ground did have a significant effect on signal quality. Under these conditions, there was a significant relationship between an increase in distance and an increase in packet loss, which was represented by a decrease in signal quality. This correlation holds when incorporating head direction and head orientation. This study highlights the importance of this investigation as the transmission range of PROTECHT™ head impact telemetry system is now known under the conditions investigated. The results reported in this study provide insight regarding conditions under which the system successfully transmits real time data and those where improvements will be required.

Declarations and Statements

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed …[redacted]………. Date 19/03/2021…………………………….

This work is the result of my own independent study/investigation, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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List of Abbreviations

Abbreviation	**Explanation**
mTBI	Mild Traumatic Brain Injury
PLA	Peak Linear Acceleration
PRA	Peak Rotational Acceleration
AF	American Football
WR	World Rugby
NFL	National Football League
iMG	Instrumented Mouthguard
HIT	Head Impact Telemetry
OL	Offensive Lineman
DL	Defensive Lineman
WRU	Welsh Rugby Union

Section 1: Introduction

1.1 The Importance of Real-Time Assessment of Head Impacts in Collision Sports

Rugby union is the most popular full-contact sport in the world and is played in over 150 countries, from professional level to grass roots (Fuller, Taylor, & Raftery, 2015). The risk of concussion and longer-term brain injury is a major concern in rugby, with a growing number of publications dedicated to this issue (Cross, Kemp, Smith, Trewartha, & Stokes, 2016; Cross, Kemp, Smith, Trewartha, & Stokes, 2016; Hume et al., 2016; King, Hume, Gissane, & Clark, 2016; King, Hume, Brughelli, & Gissane, 2014; Moore, Ranson, & Mathema, 2015; Ranson, George, Rafferty, Miles, & Moore, 2018; Salmon, Sullivan, Handcock, Rehrer, & Niven, 2018; Tierney & Simms, 2017). Rugby, however, is not the only sport with this issue. Sports such as: American Football, Aussie League Football, Rugby League, Lacrosse, Football, Ice Hockey and Cycling/BMX, all have concerns about concussive injuries and the cumulative effect of repetitive non-concussive impacts over both professional and amateur sporting careers (Patton et al., 2020). The international governing body, World Rugby (WR), has issued recommendations to ensure athlete health and safety (World Rugby, 2019). Among these, developing evidence-based methods such as using head impact telemetry systems to ensure consistent recognition of brain injuries on the field and timely removal from play are of paramount importance (Cross et al., 2016; Fuller et al., 2015). Timely identification of potentially injurious impacts is very important, combined with existing video systems such as Hawkeye, for extra objective evidence to inform medical decision making (Patton et al., 2020) As a result of these recommendations, there is now a focus in the rugby sports medicine community to develop systems, methods and metrics to detect, characterise, monitor and manage head impacts in real time (Greybe, Jones, Brown, & Williams, 2020; Patton et al., 2020).

Swansea-based company Sports and Wellbeing Analytics Ltd (SWA) (Swansea, Wales, U.K.) was founded in 2016. In collaboration with Swansea University and industrial partners, the company developed a real-time head impact telemetry system (PROTECHT™), utilising bespoke instrumented mouthguards (iMG) (Greybe, Jones, Brown & Williams, 2020). This system was designed specifically to measure head impacts in rugby, with sensor electronics embedded in the iMG plastic. Unlike existing head impact systems designed for American football (AF), the PROTECHT™ system was designed for the unique, non-helmeted collision dynamics of rugby union. A fundamental issue of the development of this real-time system is the on-field range over which data from the iMG can be successfully transmitted to a receiver on the sideline.

The primary objectives of this thesis were to ensure that the PROTECHT™ iMG system is reliably and repeatably transmitting impacts from all areas of a rugby playing field and identifying any conditions where impact transmission is compromised. This includes orientation of the transmitting iMG relative to the sideline receiver. In rugby and AF, for example, players involved in the scrum and blocking respectively are in a forward-leaning, ground-facing position during these events. It is therefore imperative that an assessment of head impact data transmission includes these conditions in addition to testing distances with the iMG orientation facing the receiver. This information would then be used to generate hypotheses for the company regarding the reasons for any compromised transmission. A comprehensive set of transmission range testing data for the PROTECHT™ iMG system was generated. Data transmission performance was assessed *in vivo* (in a human mouth) from the iMG to the sideline receiver, from every section of the pitch at different heights and orientations. This information was subsequently sent to the company and commercial partners to inform hardware and software strategies to overcome transmission problems.

1.2 Current Injury Epidemiology in Rugby Union

Since rugby union turned professional following the Rugby World Cup in 1995, the sport has grown into the hard hitting, tactical, physical sport that it is today. With the large amounts of money now invested into the teams and players, players have the best facilities and training methods available to them. Professionalisation has seen an increase in players' body mass (Sedeaud et al., 2012) which has caused players to be exposed to larger impacts and forces than ever before.

1.3 The Brain Injury Problem in Rugby Union

Rugby has one of the highest reported concussion rates out of all contact sports (Stanwell, Williams, Iverson, Gardner, & Baker, 2014). Head impacts are now a major concern in rugby. Thus, improving the research surrounding head impacts sustained in rugby can help prevent problems widely publicised in the American National Football League (NFL) (Fainaru & Fainaru-Wada, 2019a). With concussion being a major issue in rugby, World Rugby now have a return to play protocol which all players and coaches have to follow at all levels of rugby union. The return to play protocol is based on a player being diagnosed with a concussion down to visible symptoms, such as: loss of consciousness, seizures and dizziness. In elite rugby union, a player also undertakes an HIA (Head Injury Assessment); these are a series of neurocognitive tests designed to test the areas of the brain which may be affected by a traumatic brain injury (McCrory et al., 2017). A player can only return to play if they pass the HIA; any doubt by the medical professional and the player is ruled out of the game. A head impact telemetry system could have medical professionals identify players who are at an increased risk of having been exposed to forces high enough to cause a concussion.

There is a great need for a real time head impact data to inform athlete management strategies on the pitch following each head impact. Systems like this can also manage cumulative head impact load and minimise the risk of brain injury. Real time data helps to identify players who may have accumulated a series of head impacts, potentially causing brain injury. Without it being real-time, players' loads could not be observed until neurocognitive disturbances are apparent.

Researchers have been interested in developing head impact telemetry systems (HITs) for collision sports *in vivo* since the 1960s (Patton, 2016). Technological developments have made this a reality in the past decade, with commercial systems available in the forms of instrumented helmets (Mihalik, Bell, Marshall, & Guskiewicz, 2007), headbands (Patton, 2016), adhesive skin patches (King et al., 2016) and most recently, iMG (Camarillo, Shull, Mattson, Shultz, & Garza, 2013; King et al., 2014).

There is little literature regarding head impact telemetry in rugby. New technologies being developed for non-helmeted sports have now become more important as they could potentially assist in resolving this gap in the literature. Previous head impact research in rugby was conducted using X2 XPatch sensors (X2 Biosystems Ltd, Seattle, WA, USA). These were adhered to the mastoid process on the side of the players' heads. These systems have been reported to overestimate head impact inertial values due to soft tissue artefact (Kuo et al., 2018; Wu et al., 2016). These adhesive patches also do not comply with WR clothing regulations (World Rugby Laws of the Game 4.5c), so they cannot be worn in games. This has meant that there has been very little game data collected.

Bartsch et al., (2019) have collected data in AF and boxing using an iMG manufactured in a hard-plastic casing, which is not suitable for non-helmeted sports. They are not suitable as players have no protection around their mouth, this increases the likelihood of injury to both the player wearing the iMG and the tackler if they are impacted in the mouth. These iMGs in the hard-plastic have been collecting data for both games and training (Bartsch et al., 2019; Hedin, Gibson, Bartsch, & Samorezov, 2016). The Sportsguard iMG (Sportsguard Laboratories Inc, Ohio, USA) is one of few HIT systems that currently transmit data real-time. Given the low number of such systems worldwide, there is limited published or publicly available data about the transmission range, particularly when the sensor is inside the head.

1.4 Thesis Overview

The topic of head impacts in contact sports has received much attention in the media and scientific literature in the past decade. A review of literature pertaining to this issue is provided in Section 2. Section 2.1 provides an insight into the frequency of head impacts in both rugby union and American Football. Section 2.2 discusses the key concepts relating to head impact epidemiology, physical impact mechanisms and subsequent short- and long-term neurocognitive outcomes Section 2.3 provides insight into the background of rugby, the rules and how it has evolved over the years. Section 2.4 discusses which match events cause the most head impacts and concussions. Section 2.5 provides insight into the biomechanics of head impacts and how they affect the brain. In Section 2.6, the rules and regulations in rugby union are discussed, as they affect the development of head impact telemetry systems. An insight into how head impact telemetry systems work and current systems available are also discussed in Section 2.6. Sections 2.7 and 2.8 provide a critical analysis of the requirements needed for a head impact telemetry system to be successful, how signal transmission works and what affects it. Section 2.9 provides an overall summary of the literature review with the main hypotheses being investigated in this thesis stated.

An experimental overview for the methodology is described in Section 3.1, with an in-depth description into how the PROTECHT™ system works being provided in Section 3.2. Section 3.3 then states which experiments are being conducted to test which hypotheses, with the independent, dependent and extraneous variable stated for each experiment. Section 3.4 provides a range testing measurement method and the factors that influence the results. Section 3.5 describes the method for each experiment conducted. Section 4.1 provides an overview of why we have done these experiments and how they were conducted. Sections 4.2 - 4.6 describe the results for the hypotheses presented in Section 2.9.

Currently there are no normative head impact values for rugby players sustained during a match. This can only be achieved once a HIT system is reliably producing real-time valid data. Once medical staff and coaches understand the typical values a player will sustain during a match, this will allow them to use the system as a monitoring tool, to determine the load each player is sustaining. This allows the medics the data necessary to decide whether any player needs time off. For example, if a player has accumulated an abnormally large amount of head impacts during training and a game, the medical staff have the data necessary to make a decision on the player's involvement thereafter. The aim for the system is to act as a load monitoring tool, as there is currently no threshold value for concussion and these values will all be individual and dependent on different factors.

These problems can be resolved once the normative head impact values are known by validating a HIT system which can transmit data reliably over the entirety of a rugby pitch. Once this has been successfully achieved the system can be used with sports teams to find the typical number and magnitude of hits sustained during games and over a season. Once these have been established and compared to current literature, the particular kinematics and events that cause the highest magnitude impacts and the greatest number of impacts can be analysed. This analysis can be crucial to making the sport safer and prevent long-term neurological damage to the players.

Current research is suggesting that brain injuries can be caused by repetitive head impacts, in addition to single high-magnitude impacts. There is very little data from rugby players on the average number and average magnitude of the impacts sustained. Players are currently only being checked for concussion if they are seen to take an impact to the head or they have symptoms of a concussion. Since it is impossible for medics to witness every head impact, player self-reporting is crucial. However, it has been found that of the players who sustained concussions, only 45% reported their injury, with the most common reasons for not reporting their concussion being: the player not thinking it was serious enough for medical attention, not wanting to be withheld from competing, and lack of awareness of probable concussion (Davies & Bird, 2015).

The aim of this project is to investigate the transmission range for an iMG HIT system for rugby. The PROTECHT™ system needs to be capable of transmitting data reliably, with low error rates, over the entirety of a rugby pitch. Once this is achieved it can be used across a range of sports to inform stakeholders of the severity of potential brain injuries that are currently being sustained in sports.

Section 2: Literature Review

2.1 Head Impacts in Contact Sports

2.1.1 Overview

Due to their intense nature, head impacts are a well-documented occurrence in contact and collision sports. In particular, many studies have reported frequent, high magnitude impacts in sports such as rugby union (King, Hume, Brughelli, & Gissane, 2015; Roberts, Trewartha, England, Goodison, & Stokes, 2017; Tierney, Lawler, Denvir, McQuilkin, & Simms, 2016; West et al., 2020), American Football (AF) (Allison, Kang, Bolte IV, Maltese, & Arbogast, 2014; A. Bartsch, Samorezov, Benzel, Miele, & Brett, 2014; Guskiewicz et al., 2007; King et al., 2016), rugby league (King, Hume, Gissane, & Clark, 2015), ice hockey (Reed et al., 2010), lacrosse (Miyashita, Diakogeorgiou, Marrie, & Danaher, 2016) and soccer (Press & Rowson, 2017). Increasingly, scientific evidence is showing strong links between these repetitive head impacts and long-term neurodegenerative challenges, including chronic traumatic encephalopathy (CTE) (Abreu, Comartie, & Spradley, 2016; Omalu, Hamilton, Kamboh, DeKosky, & Bailes, 2010). Crucially, this evidence is not only based on impacts which result in identifiable acute concussive symptoms, but also the repetitive lower level impacts which do not (Schultz et al., 2018).

2.1.2 Frequency of Head Impacts in Rugby

A recent study used iMG data collected from amateur rugby players over a season of matches. They found that there was a cumulative total of 20,687 impacts, with a mean number of 95 ± 133 impacts to the head per player (King et al., 2014). Positions were not compared, but the mean linear acceleration measured over a season of matches was similar to the mean linear accelerations previously reported for youth, high school and collegiate AF players (King et al., 2014). There are currently no studies which have compared the number of head impacts between players in rugby.

This is where a HIT system, such as the one presented in this thesis can, help determine whether certain positions are more prone to sustaining a higher frequency of head impacts. The majority of these systems won’t have been real-time so players could have continued after sustaining a significant impact. Currently at games the match day doctor will watch live footage via Hawkeye; this gives them various camera angles and the ability to pause and rewind footage if they see any impacts which concern them. If accurate real-time sensor data worked in tandem with Hawkeye, this would allow medics to assess impacts they have missed during the game. The problem at the moment, however, is that the HIT system needs to be reliable and not drop random impacts or pick up noise such as shouting in order for it to be effective.

2.1.3 Frequency of Head Impacts in American Football

When looking at AF, it was found in one study that the typical player sustained a mean of 774 ± 502 impacts during a 15 week season (Broglio, Martini, Kasper, Eckner, & Kutcher, 2013). Another study reported that the average player, in a 14 week season, sustained 652 impacts, with the playing position affecting the number of hits sustained (Broglio et al., 2011). Both of these studies found that offensive lineman (OL) sustained the highest number of head impacts. This was also found in another study which also showed that OL develop more post-impact symptoms than other player positions, but they do not report these symptoms as a concussion (Baugh et al., 2015). These studies show that players are sustaining a high number of head impacts during a season and that, with players suffering with post-impact symptoms, there is a need for a reliable head impact telemetry system to manage the players load and magnitude of head impacts. Campolettano et al., (2019) found when they collected head impacts in AF, to quantify the factors contributing towards player head impact exposure, even after controlling for player position, team, practice participation and ability, that differences between individuals still accounted for 48% of the variance in head impact exposure in practice. Therefore, it is also important to consider head impact exposure on a subject-specific basis, rather than estimating head impact exposure from aggregate data.

When looking at the research conducted on head impacts in rugby union compared to American football, there is a substantial difference. A systematic review using head patches found that, with a threshold of 10 g, amateur rugby players sustained the most impacts per player per game (Nguyen et al., 2019). However, at thresholds of greater than 14.4 g, AF athletes sustained the most impacts, between 19 and 24.4 impacts per player per game, whilst wearing sensors embedded in the helmet (Nguyen et al., 2019).

American football studies have shown that players sustain a substantial amount of head impacts over a season. However, most published AF head impact studies in the past decade have used inertial sensors embedded in helmets, which are not directly coupled to the head (Broglio, Martini, Kasper, Eckner, & Kutcher, 2013; Crisco et al., 2011; Mihalik, Bell, Marshall, & Guskiewicz, 2007). While AF studies have shown that players sustain a substantial amount of head impacts over a season, recording methods require careful appraisal for data to be understood. For example, without video verification of each impact, helmet-derived impacts may be recorded when the helmet is not actually on the player’s head (Patton 2020). The number of impacts sustained and the magnitude of the forces sustained between positions has also been compared (King et al., 2014; King et al., 2015; Kuo et al., 2018; Nguyen et al., 2019). These values, however, may be imprecise and perpetuating the problem of misleading data which has been found to compromise the integrity of the head impact telemetry field (Patton, 2020).

Considerably less head impact data is available in rugby union, primarily due to the evolution of head impact sensors being focused on helmeted sports (Patton, 2011). The head impact telemetry field has evolved in parallel with the miniaturisation of electronic componentry, which has enabled the development of these systems for non-helmeted sports (Bartsch et al., 2014, Camarillo et al., 2012; Greybe et al., 2020; Patton et al., 2020).

2.2 Short and Long Term Outcomes of Repetitive Head Impacts

2.2.1 Short Term Effects and Concussion

A concussion is any disturbance in brain function caused by a direct or indirect force to the head (King, Brughelli, Hume, & Gissane, 2013). Concussions are a prevalent and costly mTBI which may result in insomnia and sleeping difficulties, these being the most frequently reported and greatly impairing recovery, especially during adolescence (Yamakawa et al., 2019). This is a concern as this is when the majority of players start playing contact rugby. The immediate short- term symptoms of a concussion are headache, fatigue, dizziness and taking longer to think. This can lead to frustration, forgetfulness and fatigue being the symptoms most likely to develop during the follow-up period that had not been initially present (Eisenberg, Meehan, & Mannix, 2014). Concussion symptoms typically subside within a few weeks in most people, in 15%–20% of the cases, the symptoms can continue beyond a few weeks. Problems with attention, processing speed, memory, and cognitive flexibility are some of the most common post-concussive symptoms (Hylin et al., 2013). Repeated concussions with loss or altered consciousness are common to many contact sports; the result of this can exacerbate these symptoms (Hylin et al., 2013). A higher rate of lower extremity musculoskeletal injuries has been reported in athletes who have sustained a concussion previously (50%) than in non-concussed athletes (20%) (Herman et al., 2017).

At present, there is no 100% sensitive and specific concussion screening assessment that exists (Sussman, Ho, Pendharkar, & Ghajar, 2016). Concussion is difficult to identify as athletes commonly hide symptoms, with only 10% of cases resulting in loss of consciousness and symptoms only lasting up to 15 minutes (Hedin et al., 2016). This means that even with the current findings they could be underreporting the actual number of concussions because concussions will be going unnoticed. The PROTECHT™ system will never be able to diagnose a concussion but, with it being a real-time head impact monitoring system, this would help with head impact monitoring and show the magnitude and frequency of the hits sustained. Studies in AF have reported that 5.1% of players at college have suffered at least one concussion, 14.7% then suffered another concussion the same season with 30.8% of all concussions returning to play the same day (Guskiewicz, Weaver, Padua, & Garrett, 2000). One in 20 AF athletes have been reported to suffer a concussion each year at college (Nacht, 2015). Meehan et al., (2013) found that 30.5% of athletes reported a previously undiagnosed possible concussion. A similar study was conducted in professional men's rugby union. This study found that players who returned to play in the same season after a diagnosed concussion had a 60% great risk of time-loss due to injury compared to players without concussion (Cross et al., 2016). Another study also found that players with a history of previous concussions are more likely to have future concussions than those with no history, with one in 15 players with a concussion more likely to have additional concussions in the same playing season. Alongside this, previous concussions may be associated with slower recovery of neurological function (Guskiewicz et al., 2003).

Laboratory-based studies on neuromuscular control after a concussion have suggested that concussions may increase the risk of subsequent musculoskeletal injury (Herman et al., 2017). Herman et al., (2017) found that, when looking at NCAA athletes from 2006 to 2013, the odds of sustaining a musculoskeletal injury were 3.39 times higher in the concussed athlete ($p<0.01$), based on the number of days lost because of injury between concussed and non-concussed athletes. This supports the laboratory-based results and may have implications for medical practitioners who are under increasing pressure to diagnose concussions correctly.

2.2.2 Long Term Effects of Repetitive Head Impacts

There is mounting evidence suggesting that the pathology contributing to long term problems after repetitive mTBI may be caused by repetitive exposure to subconcussive hits to the head, even in those with no history of a clinically evident mTBI (Sundman, Doraiswamy, & Morey, 2015). General cognitive failures, depression, anxiety sleep quality, and sleepiness were found to be from the long term effects of a mTBI (Dean & Sterr, 2013). (Konrad et al., 2011) found that all the individuals who had sustained a mTBI even in well-recovered individuals over half a decade ago, continue to have long-term cognitive and emotional sequelae relevant for everyday social and professional life. This may lead to lasting damage to the brain which is not detectable by standard MRI and needs to be taken seriously (Konrad et al., 2011).

In addition to the challenges of concussive injuries, serious, long-term neurocognitive issues such as Chronic Traumatic Encephalopathy (CTE) have been identified in many former contact sport athletes (Coughlin et al., 2015). CTE is a progressive neurodegenerative disease caused by repetitive head trauma (Saulle & Greenwald, 2012). It was found that the number of years of exposure, not the number of concussions, was significantly associated with worse tau pathology in CTE (Stein, Alvarez, & Mckee, 2015). This is because CTE is characterised by fibrillar tangles of hyperphosphorylated tau (McKee et al., 2013).

Tau is a phosphoprotein which helps to regulate the transport of vesicles or organelles among the microtubules, support axonal outgrowth, and anchor enzymes (Omalu et al., 2010). This means that repetitive impacts to the head cause as much damage as concussive hits. CTE is clinically associated with symptoms of irritability, impulsivity, aggression, depression, short-term memory loss and heighted suicidality which typically begins to present around 8-10 years after retirement from sport (McKee et al., 2009). It is also reported to result in executive dysfunction, memory impairment, apathy, poor impulse control and eventually dementia (Baugh et al., 2012). Boxing and brain injuries were commonly linked with CTE first being discovered in boxers as early as 1928 (Martland, 1928) and was known as punch drunk syndrome, or dementia pugilistica (Critchley, 1957). This occurred through the boxers taking repeated sub-concussive impacts to the head and the occasional concussive impact (Iverson, 2016).

CTE is neuropathologically characterized by aggregation and accumulation of hyperphosphorylated tau protein (McKee et al., 2009). This together with the accumulation of tau inclusions in cortical layers two and three, distinguishes CTE from other pathologies like Alzheimer's disease (Falcon et al., 2019).

Post-mortem findings indicate that CTE may affect a broader population than was initially conceptualised, particularly contact sport athletes and those with a history of military combat (Baugh et al., 2012). The accumulation of these impacts led to the boxers suffering from symptoms linked to Parkinson's disease at only 30-40 years of age. It was found that CTE was more prevalent in professional boxers when compared to amateur boxers, this was concluded to be down to the shorter bouts and the use of headgear (McCrory, Zazryn, & Cameron, 2007). CTE has now been discovered in other sports, with American Football being the highest profile sport over the last decade to discover it with ex-players who played in the NFL (Abreu et al., 2016). The discovery of CTE in the NFL has led to one of the biggest cases of player mistreatment with notices of monetary awards before holdbacks totalling $746,619.267 as of 17/02/20 for ex-players in concussions suit (Otal, Layer, & Laimants, 2020). One study looking at an ex professional rugby union player confirmed CTE after a comprehensive pathological report, which adds to current understanding of CTE in contact sports (Stewart, McNamara, Lawlor, Hutchinson, & Farrell, 2016).

The main issue with CTE is the fact that it can only be diagnosed post-mortem by finding aggregations of phosphorylated tau. This means that currently, players cannot be helped if they are suffering from it but they can be helped by trying to prevent it. Non-invasive neuroimaging, however, may allow early diagnosis as well as improve our understanding of the underlying pathophysiology of repetitive brain trauma (Ng et al., 2014). The problem with this is that non-invasive techniques of diagnosing CTE are in their early stages and aren't reliable enough to help current players. This is where the need for real-time monitoring of head impacts for players is crucial as this will help us monitor players load to help prevent players sustaining enough repetitive brain impacts which would eventually lead to them getting CTE.

It has been found in small studies that men with a history of mTBI are more likely to have lower testosterone levels and to suffer from pituitary insufficiencies or erectile dysfunction (Grashow et al., 2019). This in itself is a big concern for men, for example, who have been playing American football since they were 12 years old. They will have sustained a high number of mTBI and the majority of them will have suffered at least one concussion. Grashow et al., (2019) findings suggest these men are likely to be suffering from these dysfunctions from a young age which could prevent them from having children.

2.2.3 Recognising Acute Injury

There are current methods to help diagnose concussions using screening tools and video reviews. The problems with these tests are that they will help diagnose some concussions, but a lot of the time players can sustain a concussion without losing consciousness. This was found during a study which recorded five witnessed, recorded concussive incidents and 17 unrecognised concussive incidents (King et al., 2013). When the latter happens, it is down to the player to either pull themselves out of the game to get checked or down to the doctor/physio to spot the impact and pull the player from the game for the assessment. King et al., (2013) found in their study that players would try and avoid being tested post-match. When a player has been pulled out of the game and is undergoing the screening tests, poor baseline scores may not affect the results for the side-line results. This is where a real-time head impact monitoring system is necessary (Hanlon & Bir, 2012). It would allow medics see each hit a player has sustained and the magnitude of the hit. This would prevent concussions from being missed and players continuing to play, and will help coaches monitor player loads and help prevent further concussive hits (Morrison & Daigle, 2015).

Previous research regarding HIT systems in collision sports have mainly focused on American Football (AF) and the effects of single head impacts and short-term neurocognitive responses (Baugh et al., 2015). Neurocognitive responses are the responses to tests which test neurocognitive functions. These functions are associated with specific pathways within the brain and can be used to deduce which areas of the brain are affected when problems such as a concussion are suspected (Sharafkhaneh & Grogan, 2015) More recently, researchers have proposed that the more serious, long-term neurocognitive challenges experienced by some former collision sport athletes is due to the regular, sub-concussive impacts sustained throughout the athlete’s career (Broglio et al., 2011).

2.2.4 Second Impact Syndrome

Second impact syndrome (SIS) was first described in 1973 by Richard Schneider (Wetjen, Pichelmann, & Atkinson, 2010). It is a condition in which an individual experiences a second mTBI before complete recovery from an initial head injury (Halstead & Walter, 2010). Fatalities have been reported following two or more successive head impacts in a short time frame. While fatalities are relatively uncommon, medics should be aware of SIS and should educate players of the risks of SIS who have experienced or are at risk of experiencing a head injury (May, Foris, & Donnally III, 2019).

In the only systematic review on SIS, there were only 17 cases reported, with only five of these cases involving a repeated injury all occurring within seven days of the initial injury (McCrory, Davis, & Makdissi, 2012). The problem with SIS is with the fact that it is so rare there have been very few cases where it has been diagnosed. This has led to medical professionals being cautious when diagnosing SIS and whether repeated mTBI is required to cause brain swelling or whether a single blow to the head is sufficient (McCrory et al., 2012).

2.2.5 Post-concussion Syndrome

When individuals sustain mTBI often, they report a constellation of physical, cognitive and emotional/behavioural symptoms referred to as post-concussion symptoms (Ryan & Warden, 2003). The most commonly reported post-concussion symptoms are dizziness, headache, irritability, fatigue etc (Eisenberg et al., 2014; Ryan & Warden, 2003). These symptoms will normally subside within one month, but in some individuals these symptoms can persist from months to years following the injury and there may even be permanent damage, this is called Post-concussive syndrome (Ryan & Warden, 2003).

Approximately 10% of patients with concussions develop persistent signs and symptoms known as post-concussion syndrome (Willer & Leddy, 2006). There are currently no scientifically established treatments for post-concussion syndrome, and therefore rest and cognitive rehabilitation are traditionally applied, with limited effectiveness (Willer & Leddy, 2006).

2.2.6 Cost Brain Injuries Have to Rugby and American Football

With the lack of data in rugby, we can compare these few studies with the data from American Football as there have been a lot of studies in American Football since the discovery of CTE in former players.

Since rugby became a professional sport in 1995, reported injury rates in elite rugby players have increased from 47/1000 player hours to 74/1000 player hours (Bathgate, Best, Craig, & Jamieson, 2002). This includes a greater number of concussions in the game caused by head impacts. One study found that match concussion incidence was at 8.9/1000 playing hours, with subsequent incidence of any injury for players who returned the same season following a concussion 60% higher than those who hadn't had a concussion (Cross et al., 2016). The increase in number of head impacts and concussions is a concern due to the link with CTE.

Early Retirement

Increases in players' body size, speed and strength, the intensity and number of collisions and corresponding increases in reported concussions has followed the 1995 professionalisation of rugby (Quarrie & Hopkins, 2007). In both rugby and AF, numerous reports exist of player retirements due to brain injury concerns. NFL players with a documented concussion history face a higher franchise release rate and significant salary reductions following post-concussion performance decrements (Navarro et al., 2017). Mental health conditions, including depression, have also been linked to the frequency and number of concussions (Guskiewicz et al., 2007; Hutchison, Di Battista, McCoskey, & Watling, 2018; Yrondi, Brauge, LeMen, Arbus, & Pariente, 2017) In rugby, (Hume et al., 2016) reported lower cognitive function in former rugby players compared with non-collision controls.

Retired players who reported either three or more, or under three, previous concussions were three times or 1.5 times, respectively, more likely to be diagnosed with depression compared to players with no concussions. (Guskiewicz et al., 2007). The NFL retired players' association found that the nine-year risk of depression diagnosis ranged from 3% in players with no concussions, to 26.8% in the 10+ concussions group (Korngold, Farrell, & Fozdar, 2013)

Suicides

There have been high profile suicides in ex-NFL players due to brain injuries sustained such as CTE. A case study reviewing current literature on CTE in former NFL players who committed suicide identified that the psychological and cognitive consequences of CTE were key variables associated in players committing suicide (Abreu et al., 2016). With CTE being found in ex-NFL players the link between CTE and the players' suicides has become apparent. With changes in the brain due to CTE and the high-profile nature of the suicide cases being well documented, players and coaches need to understand the damage that repeated concussions and repetitive impacts have on the brain. A head impact monitoring system can help monitor player loads and help coaches and medical professionals make informed decisions when players need time out to allow their brains to recover (Bartsch et al., 2014; Greybe et al., 2020; Patton et al., 2014). In the longer term, this may prove to be a valuable strategy to minimise brain damage, by facilitating objective monitoring of head impact exposure.

Lawsuits

Brain injury in AF has been acknowledged as a significant issue for more than two decades (Guskiewicz et al., 2003), including individual lawsuits for concussion-related injuries (Pachman & Lamba, 2017). In 2016, a successful medical negligence lawsuit was bought against the National Football League (NFL). This resulted in a compensation pay-out of $1.35billion to former AF players struggling with neurocognitive challenges and the families of players who succumbed to CTE (Harris, 2016).

With high numbers of CTE lawsuits an imminent threat, the future of AF and other collision sports may become dependent on their insurers (Fainaru & Fainaru-Wada, 2019b). The willingness of insurers to cover acute and prospective neurological injury may also depend on the inclusion of neurological disabilities in relevant workers' compensation statutes. In Rugby Union, players' welfare and insurance depend upon their member union. The most recent Welsh Rugby Union (WRU) insurance document published to the public in 2016 only covers death and permanent disablement, it does not cover neurological injury (Welsh Rugby, 2016). Scottish Rugby's must recent insurance cover only covers total loss of intellectual capacity, not general neurological injury (Scottish Rugby, 2020).

To help reduce the costs being suffered in sports because of concussions, continued improvement in both prevention and management of concussed athletes will require extensive research from different disciplines (Musumeci, Ravalli, Amorini, & Lazzarino, 2019).

The first high-profile concussion-related lawsuit in AF alleged that the injuries sustained were due to second-impact syndrome. This is where after an initial trauma, the brain is left more vulnerable and susceptible to subsequent injury (Pachman & Lamba, 2017). The university had prematurely and improperly allowed the player to play after he sustained an initial concussion in practice a month earlier. The case settled for $7.5 million, leaving open many questions regarding the standard of care (Pachman & Lamba, 2017). Rugby players are now claiming brain injuries, such as early onset dementia, are the result of repeated head impacts sustained whilst playing (Dyer, 2020).

This case and other cases both in AF and rugby union started causation for subsequent litigations. These lawsuits have led to new rules such as school medical professionals having autonomous and final authority in deciding when an athlete returns to play from a concussion or other injury (Pachman & Lamba, 2017). This allows medical personnel to make the necessary decisions objectively, without the potential conflicts of interest. These cases support why monitoring player loads using a reliable HIT system is so important.

2.3 Background, Context and Collisions in Rugby Union

2.3.1 Head Impacts in Contact Sports

Concussions and brain injuries have become a major health and safety issue in all contact sports, with researchers trying to quantify the extent of the problem. There is very little data about head impacts in rugby games due to the difficulties in developing a head impact telemetry (HIT) system suitable for rugby. Current head impact data is mainly from AF, which has used sensors embedded in helmets.

2.3.2 Physical Requirements of Rugby

Amateur to professional

Since rugby turned professional in 1995, there has been an increase in injuries to both professional and amateur players (Garraway, Lee, Hutton, Russell, & Macleod, 2000). An injury episode occurred in a professional team every 59 minutes of competitive play during a full season in 1997-1998 (Garraway et al., 2000). With rugby turning professional this in turn resulted in national unions developing high-performance training models for elite player development, where physical preparation is an important component, to ensure success in future years (Duthie, 2006). High performance models for elite player development have contributed to a difference in players' physical size (Sedeaud et al., 2012).

Difference in height and mass

There has been an increase in funding towards player development in rugby. Since turning professional there has been a rapid increase in player mass, this increase is over and above the moderate increases in body mass occurring over time (Quarrie & Hopkins, 2007). The Super 14 is an international club rugby union competition in the southern hemisphere. In just one season there was an increase in total high-intensity efforts, sprint frequency, and work to rest ratios across all playing positions during games (Austin, Gabbett, & Jenkins, 2011). With the physical demands of rugby increasing, teams' and players' training have had to reflect this.

2.3.3 Incidence of Brain Injuries in Rugby

Rugby players' size, strength, speed, power and ability increasing has resulted in the forces experienced by the players during games increasing. The size of impact forces is dependent upon two things; mass and acceleration; with players' mass increasing and the players getting faster, this results in an increase in impact forces (Sedeaud et al., 2012).

Upper body tackles and lower body tackles have been reported to account for 37% and 23% of head impact cases respectively, with the tackler as the head impacted player for 97% of cases (Tierney et al., 2016). One study found that rugby players were exposed to a high risk of sustaining a mild traumatic brain injury (mTBI) and concussion, particularly whilst tackling and being tackled head on (Kemp, Hudson, Brooks, & Fuller, 2008).

Another study found that during one season, when players self-diagnosed a concussion after they experienced symptoms following a head impact, 45% of players self-reported at least one concussion. Of these, only 46.6% were presented to medical staff (Fraas, Coughlan, Hart, & McCarthy, 2014). These high brain injury rates are mainly associated with tackle dynamics.

2.3.4 Current Rugby Safety Recommendations

In rugby there are laws written to keep players safe. If these laws are broken, the player has committed foul play and can be sanctioned (World Rugby Laws of the Game Rule 9: Foul Play). Rules protecting players include:

- Players must not physically abuse opponents
- Players cannot tackle a player early or without the ball
- Players cannot tackle an opponent whilst in the air
- Players must bind their arms in the tackle, shoulder charges are dangerous play and sanctioned

- Players must not tackle (or try to tackle) an opponent above the line of the shoulders, even if the tackle starts below the line of the shoulders
- A stiff-arm tackle is dangerous play. A player makes a stiff-arm tackle when using a stiff-arm to strike an opponent

2.4 Match Events in Rugby and their Link to Concussions

2.4.1 Overview

In rugby there are many different events which can lead to a player sustaining a head impact. The main events studied are: tackling, rucks, mauls, scrums and lineouts. These events take place all across the pitch and at different heights, so the PROTECHT™ system will need to be able to measure impacts at all these heights and distances.

2.4.2 Tackles

Tackling is an important skill for performance in rugby. Bitchell et al., (2020) reported that tackle events contributed to the highest proportion of match injuries (being tackled: 20-31%, tackling: 30-42%) in the elite men's game. West et al., (2020) also found that the tackle accounted for the highest proportion of match injuries, with 43% being as a result of a tackle event compared to running being the second most common activity with 12%. Tackling has been found to be the highest risk factor involved in sustaining a mTBI during rugby matches (Fraas et al., 2014; Roberts, Trewartha, England, Goodison, & Stokes, 2017; Tierney et al., 2016) An mTBI is defined as a head injury associated with alternation of consciousness or post-traumatic amnesia for 24 hours or less, or loss of consciousness for less than 30 minutes (Finkel, Yerry, Scher, & Choi, 2012).

A study which looked at tackle height and location found that nearly 50% of tackles involved being tackled from behind the ball carrier, with most tackles involving two or three tacklers with the contact between the mid-torso and hip-thigh region of the ball carrier (King, Hume, & Clark, 2010). Tackle success has been studied looking at different tackler characteristics. It was found that shoulder tackles targeted at the ball-carrier mid-torso region increased the likelihood of success in the tackle (Hendricks, Matthews, Roode, & Lambert, 2014).

Tackle height has been investigated to see if there is a significant difference in head inertial kinematics when comparing upper body tackles to lower body tackles. The results of the study indicated that tackle height strongly affects the head kinematics experienced by the ball carrier (Tierney, Richter, Denvir, & Simms, 2018). These results support the new proposition of lowering the current tackle height laws to below the chest. However, when a lowered tackle height rule change was introduced it failed. The study which conducted the trial found when comparing the Championship to the Championship Cup, tacklers contacted the ball carrier's head and neck 30% less often. However, this did not influence concussion incidence rates, as more concussions were sustained in the tacklers who were tackling lower (Stokes et al., 2019). This is due to the fact when players try to tackle lower, they are at a greater risk of getting impacted in the head by the ball carriers' knees. If the tacklers get their heads on the wrong side of the tackle and go across the ball carrier, they are at a higher risk of getting kneed in the head, which can lead to a concussion.

From the limited numbers of studies on head impacts in rugby union it was found that high speed going into the tackle, high impact force, collisions and contact with a player's head/neck were identified as significant ($p<0.01$) risk factors for ball carriers and tacklers (Fuller et al., 2008). Within rugby union, it was found that the tackle is the main cause of concussion with the tackler at highest risk of suffering a concussion (Tierney & Simms, 2018).

2.4.3 Rucks, Mauls, Scrums and Lineouts

Rucks, mauls, scrums and lineouts all take place at different heights from the ground. Rucks are the lowest to the floor followed by scrums, mauls and lineouts. The PROTECHT™ system will need to be able to receiver data from the iMG at each of the heights for it to be reliable. Rucks were found to be the second most common event in rugby behind tackles (Fuller, Brooks, Cancea, Hall, & Kemp, 2007). The relative risk for contact events to cause injury were rated as: lineout – very low; ruck – low; maul and tackle – average; collision and scrum – high (Fuller et al., 2007). A study looking at the risk of injury by match contact event found that there was a significantly greater risk of injury per legal tackle compared with all other contact events, but the risk was not different for the tackled or tackling player (Roberts et al., 2017).

2.5 Biomechanics of Brain Injury

2.5.1 Overview of Brain Injury Biomechanics

To be able to understand mTBI, we must first understand the brain itself and the biomechanics involved during an impact to the head and what happens to the brain during this impact. The brain may be the most critical organ to protect from trauma, because anatomical injuries to its structures are currently irreversible with the consequences of injury often being life changing (Melvin & Lighthall, 2002). There are two broad categories of forces associated with brain injuries: contact and inertial. Both forces occur during impact loading, where the head is struck or strikes a surface; however, only inertial (acceleration) loading occurs from impulsive head motions where the head isn't struck by an object (Meaney & Smith, 2011). Everyone's ability to withstand impacts to the brain is different. What this shows is further support of growing evidence in individual-specific threshold for mild traumatic brain injury that will vary based on the individual's intrinsic factors.

2.5.2 Finite Element Modelling

Finite Element Modelling is when software is used to recreate the properties of the head and brain. It can simulate impacts to the head and is fairly simple to change loads, materials, and geometry and recompute stresses (Brauer, 1995) experienced by the head. This is preferential as it wouldn't be ethical to recreate head impacts using humans as they could be left with serious brain damage. A study using Finite Element Modelling found that when they reconstructed previous cases of head impacts in American football that they had inconsistent sensor arrays which caused changes in the calculated rotational head motion. After the corrections were made it was found that there was an increased median peak angular velocity for the concussion cases from 35.6 to 41.4 rad/s. Simulations also demonstrated that impact lengths less than 40 ms did not capture the entire brain strain response and under-predicted strain (Sanchez et al., 2019). This is important to understand when creating a head impact telemetry system because the system needs to be able to record the impact for longer than 40 ms as otherwise the entire brain stress response will be under-predicted. Another study which used finite element modelling examined the effect on brain deformation associated with changing initial slope, maximum acceleration and impact energy. What the study found was that there was a strong direct relationship between maximum acceleration and brain deformation; in addition to this, a strong direct relationship was found between impact energy and brain deformation (Saboori & Walker, 2019).

2.6 Head Impact Telemetry in Contact Sport

2.6.1 Overview

Head impact telemetry systems have been used in sport for over a decade, with the most focus on AF. There are numerous types of HIT systems: head patch sensors, helmet sensors and iMG sensors.

The accuracy of these data, however, are significantly affected by soft tissue artefact and poor sensor-skull coupling (Joodaki et al., 2019; Patton et al., 2020; Wu et al., 2016). Patton et al., (2020) also found that 64% of head impact studies are likely to be inaccurate due to the lack of video verification. In addition, many studies do not report on sensor time series waveform data, potentially including false positive impacts. The ability to record and view real-time head impact data reliably, with video verification also allows for instant waveform verification.

2.6.2 Rules and Regulations in Rugby Affecting HIT Systems

Buckle Rule

In rugby there is a rule preventing current HIT systems such as X2 XPatch sensors (X2 Biosystems Ltd, Seattle, WA, USA) being used in games. This is because the X2 patch falls into rule 4.5c which states any items containing buckles, clips, rings, hinges, zippers, screws, bolts or rigid material or projection are not otherwise permitted under this law (World Rugby Laws of the Game 4.5c). There is a demand for a real-time HIT system which can be worn in games for rugby, as there is currently no valid data on the load of head impacts the players in men’s rugby union are currently experiencing in games.

Protective Head Gear

Some players in rugby wear scrum caps. These are headgear designed to protect the head from head injuries. Scrumcaps help to prevent superficial head injuries and protect the ears (Menger, Menger, & Nanda, 2016). Nearly 40% of rugby players surveyed believed headgear helped to prevent concussions despite no scientific evidence that it does (Menger et al., 2016). A HIT system such as the mouthguard, could help determine whether scrum caps help to reduce the forces exerted on the player’s brains, which will in turn help reduce the load on the player during a season (Bartsch et al., 2019; Bartsch et al., 2014; Camarillo et al., 2013; Greybe et al., 2020; Patton et al., 2020). This is important as scrum caps have been found to increase a player’s risk of injury due to the fact that they are more likely to play aggressively with the false sense of protection

(Menger et al., 2016). The study found players wearing scrum caps are four times more likely to play with increased aggression compared to players not wearing them (Menger et al., 2016).

2.6.3 Why are we Measuring Acceleration?

The PROTECHT™ system measures linear acceleration and rotational velocity (used to calculate rotational acceleration). This is because both linear and rotational acceleration are key factors involved in head impacts leading to brain injury (Post, Hoshizaki, Gilchrist, & Cusimano, 2017).

There is a clear link between head acceleration and the duration of the impact, on the resulting strain on the brain (Post et al., 2017). It has been demonstrated that as the duration of the impact increases, the magnitude of the impact needed to achieve mTBI decreases, with rotational acceleration becoming the dominant contributor (Post et al., 2017). Peak rotational acceleration has been considered the cause of brain injury in helmeted sports (King, Yang, Zhang, & Hardy, 2003). This is because wearing a helmet does not change head angular acceleration significantly but has been reported to reduce linear acceleration significantly (King et al., 2003). Existing studies suggest that linear acceleration of the head during impacts below 30g are considered relatively low in severity and anything above 40 g is considered severe (Rowson, Brolinson, Goforth, Dietter, & Duma, 2009). This is dependent upon which measurement method is used, as 30 g recorded using a helmet sensor may be significantly greater than the acceleration of the skull (Wu et al., 2016). For rotational acceleration any head impact above 3000 rad/s^2 is considered to be a significant impact (Rowson et al., 2009). It was found that a head impact with a rotational acceleration of 7483 rad/s^2 had a 90% probability of injury (Rowson et al., 2012). O’Connor et al., (2017) conducted a systematic review looking at these studies, they found that HIT systems have limited clinical utility due to low specificity in predicting concussive injury, error rates and their designs. What this shows is that these thresholds for PLA and PRA haven’t been established yet.

2.6.4 How do we Measure Acceleration?

The PROTECHT™ iMG comprises 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer. The accelerometer outputs linear acceleration in three vector components and the gyroscope outputs angular rate, in three vector components. The three-component data is transmitted via a serial interface to the computer at a rate of 952 HZ. The edge device then calculates the resultant linear and angular acceleration data (Mostafa & Hutton, 2001).

2.6.5 Head Patch Sensors

An example of a HIT system which has been used in rugby and other non-helmeted sports is the X2 XPatch (X2 Biosystems, Seattle, WA, USA). The XPatch system comprises of an instrumented plastic patch, adhered to the mastoid process on the player's head. These patches have been used to collect data in a number of non-helmeted sports such as Australian football, rugby league and rugby union games in New Zealand and Australia (Morrison & Daigle, 2015; O'Connor et al., 2017). After an assessment of the sensors was conducted in Australian football, and was compared to previous research, it was found that PLA was 17% greater than the reference PLA and PRA was 28% less than the reference PRA (McIntosh et al., 2019). These patches have now also been found to overestimate impacts due to the skin elasticity causing the patches to move more than the skull, then caused by the actual impact itself (Wu et al., 2016).

A systematic review of the X2 XPatch when compared to Standford's HIT system found that there was a low correlation between the HIT system and the XPatch when measuring rotational acceleration (Wu et al., 2016). These authors also found that there was poor agreement in impact location between the recorded impact location of the HIT system and the XPatch, and the actual impact location verified by video analysis (Wu et al., 2016). Another limitation of the XPatch system is the lack of real-time recording capability. This means that players cannot be monitored on the field, so officials cannot quantify the risk of sustaining multiple high magnitude impacts within a short time period. With the data from the XPatch not being real time, this means that a player can play a full game and sustain additional impacts after a high impact, which will cause significant damage. The data needs to be downloaded off each individual XPatch and each of the impacts for the patches will be timestamped. The only way to correlate an impact to a specific event with the XPatches is to go through game footage to the timestamp and investigate what caused the impact.

2.6.6 Helmet Sensors

HITS system specific for AF have used sensors which have been embedded into AF helmets (Greenwald, Chu, Crisco, & Finkelstein, 2003). These work by the HIT system measuring location and magnitude of head impacts with an encoder, which is an array of six spring-mounted single-axis accelerometers orientated perpendicular to the surface of the head, a telemetry unit, a data storage device, and a battery pack (Kelley et al., 2017). Non-coupled, helmet-embedded sensors reported to overestimate impact magnitude values by between 37% less to 71% more in rotation and 2-5 times high in linear acceleration (Joodaki et al., 2019). This is due to the helmet moving more than the head itself (Joodaki et al., 2019). This was proven when a study which compared head acceleration measured by a helmet-based accelerometer system for ice hockey to an anthropometric test device found that errors in peak acceleration varied from 18% to 31% and from 35% to 64% for linear and rotational acceleration (Allison et al., 2014). The HIT systems data was compared to the data from a Hybrid III model. A Hybrid III model is a crash test dummy which sensors embedded inside the head which measure both linear and rotational acceleration. The results showed that 55% of the impacts had an absolute error greater than 15% while the root mean square error was 59.1% for peak linear acceleration (Jadischke, Viano, Dau, King, & McCarthy, 2013).

2.6.7 iMG Sensors

Sportsguard Labs (Kent, Ohio, USA) have made an iMG to measure head impacts in collaboration with Prevent Biometrics (Prevent Biometrics, Minnesota, USA). They have used $ADXL_{375}$ accelerometers instead of 3-axis gyroscopes because they use a constantly oscillating mass. This results in higher power consumption than is achievable with accelerometers (Hedin et al., 2016). This has led to bigger batteries being used in the iMG making them bulkier. Using multiple linear accelerometers to calculate rotational acceleration is a proven method for high accuracy (Hedin et al., 2016). This was built with a flexible circuit allowing it to wrap around the teeth for high accuracy. The intelligent iMG meets the NFL I validity specification (Hedin et al., 2016; Siegmund, Guskiewicz, Marshall, DeMarco, & Bonin, 2016). A review of the iMG, however, found that it underestimated the linear and rotational accelerations by 3% and 17%, respectively, and that testing was only conducted whilst wearing headgear such as AF helmet and boxing headgear (Patton, 2016).

A literature review of studies that have used different HIT systems found that proper interpretation of previously reported head impacts may inform future research, but current systems have limited clinical utility due to error rates, designs, and low specificity in predicting concussive injury (O'Connor, Rowson, Duma, & Broglio, 2017). When all of these systems were compared with an iMG, it was found that the linear and rotational acceleration magnitudes were over predicted by both the skin patch and the skull cap (Wu et al., 2016). Bartsch et al., (2014) created an intelligent iMG found that it was the most reliable way of recording head impacts. The problem, however, with these iMG is that the guards themselves are made from hard plastics (Bartsch et al., 2019). These are not suitable to be used in rugby because it could cause injury to the player wearing it. This is due to the fact the players' faces are not covered and players are therefore more likely to get impacted in the face, causing injury by a hard-plastic iMG. What is needed is an iMG that works similarly to this guard but is similar to conventional mouthguards, so is made from softer plastic. This is to prevent injury and because an iMG which is coupled to the skull has been found to be the most reliable way to measure head impacts (Bartsch et al., 2014). As a result, this has led to the creation of the PROTECHT™ system, which is suitable for rugby and other non-helmet sports as the iMG is made from softer plastic, with the aim of this thesis to investigate the transmission range of PROTECHT™ system.

2.7 What the requirements are for a Head Impact Telemetry System

2.7.1 Main Requirements

The main requirements for a HIT system are: that it can produce and transmit valid and reliable data to the side-line during a game, that it is safe to wear, and that it is as comfortable for the player wearing it as possible. Without meeting these requirements, the system will not work. If the system cannot transmit the data reliably then teams won't use the system as it won't help protect the players. If the system isn't safe, then teams won't risk their players using it as it could hinder their performance. If the system isn't comfortable for the players, then no research will be able to be undertaken.

Validity

In a recent study conducted by Joodaki et al. (2019), where the relative motion between the helmet and the head in football impacts was tested. These authors reported that the helmets translated 12-41 mm and rotated up to 37 degrees with respect to the head. This led to the peak resultant linear acceleration of the helmet producing results two to five times higher than the head and the peak resultant angular velocity of the helmet ranging from 37% less to 71% more than the head. The results from this study show that the kinematics of the head and the helmet differ considerably. Therefore, using helmets with sensors inside is not a valid way of measuring head impacts and doesn't meet the requirements for a HIT system. They concluded that head motion must be measured independently of the helmet. This is why investigating the range of an iMG which is coupled to the skull, such as the PROTECHT™ system, is so important.

For a HIT system to be successful it needs to be reliable. Reliability refers to the reproducibility of the measurement when repeated at random in the same subject (Lachin, 2004)., so if a hit of 15 g is impacted against the iMG 10 times, the receiver is able to measure the impact of 15 g each time. If the receiver doesn't measure the impact at 15 g each time, the system is not reliable enough to be used. This is because the reliability of a measurement determines its maximal correlation in regression models, its sensitivity and specificity when used for predictions, and the power of a statistical test employing the measurement (Lachin, 2004). As the reliability of the measure declines, this results in its sensitivity and specificity declining, resulting in the statistical tests power being compromised.

2.8 Signal Transmission and Receiving

2.8.1 How is Data Transmitted

In the PROTECHT™ system data is transmitted via Radio Frequency Identification (RFID). RFID was first conceived in 1948 and it has taken many years for the technology to become sufficiently affordable (Roberts, 2006). RFID is a generic term for technology that uses radio waves to automatically identify objects or people (Roberts, 2006). There are several methods of identification, the most common of which is to associate the RFID tag unique identifier with an object or person. A typical RFID system will comprise of: an RFID device, an RFID device reader with an antenna and transceiver, and a host system (Roberts, 2006). Frequency allocations are managed through legislation and regulation by individual governments. Internationally, there are differences in the frequencies used by each country, although standardisation is assisting in compatibility, with Europe now using 868 MHz for ultra-high frequencies (UHF) and the US using 915 MHz (Roberts, 2006). The principal advantages of RFID system are that the tags can be read through a variety of visually and environmentally challenging conditions such as snow, ice, fog and rain, ideal for a HIT system which has to be able to work reliably outside in different conditions. With a response time of less than 100 ms, an RFID reader can read many RFID devices virtually instantaneously. Devices coupled with sensors can provide important information on a variety of different situations, such as a player's position on a rugby pitch (Roberts, 2006).

2.8.2 Protocols

There are a number of different wireless protocols that could have been used for the PROTECHT^{TM} system; Bluetooth, ultra-wideband (UWB) ZigBee and Wi-Fi; these are the main four protocol standards for short-range wireless communications with low power consumption (Lee, Su, & Shen, 2007). In a study which compared the four protocol standards they found that Bluetooth and ZigBee were suitable for low data rate applications with limited battery power, due to their low power consumption leading to a long lifetime, while UWB and Wi-Fi are better solutions for high data rate implementations because of their low normalized energy consumption (Lee et al., 2007).

2.8.3 Antennae

An antenna is a device that transmits and receives electromagnetic waves, most of which are resonant devices which operate efficiently over a relatively narrow band frequency (Bhavsar, Blas, Nguyen, & Balandin, 2000). The radio system must be tuned to the same frequency as the antenna connected to it, otherwise reception and transmission will be impaired (Bhavsar et al., 2000). Correct antenna placement is critical to the performance of an antenna as placement can affect the strength of the signal (Bhavsar et al., 2000).

2.8.4 Packets

Packets are how the data from the iMG is transferred to the receiver. For the PROTECHT™ system to be reliable enough to use to monitor head impact load for players, it needs to be able to receive the packets from across the entire pitch at different heights off the ground, orientations and with interference from other iMG and obstacles blocking the radio waves.

2.8.5 Sample Rate

There is a real need for the signal for the PROTECHT™ system to be real-time. This is to avoid complications from sustaining multiple impacts close together. When we look at current HIT systems there are common set requirements for data acquisition to be triggered. The data is transferred from the encoder to the side-line base unit via radio wave transmission, this is only triggered by impacts greater than 10 g, and a total of 40 ms of data with 8 ms of pre-trigger data are recorded at 1000 Hz (Kelley et al., 2017).

2.8.6 Factors Affecting Packet Loss

It is crucial to the project and for the success of the system that the data the iMG transmit is reliably received. There are many factors which can cause a wireless network to drop packets. Dropped packets are explained further in the methods. The main few factors are; attenuation, interference and reflections.

Attenuation

Attenuation is the reduction of the strength of a signal once transmitted (Chan & Donaldson, 1986). The two primary sources of attenuation in wireless networks are range and obstructions (Wilson & Patwari, 2010; Xie & Kumar, 2006). In the PROTECHT™ system, range and transmitting through the head and other bodies will cause attenuation. This means, when testing, it is important to recreate various possible scenarios, such as the iMG transmitting through the head to get to the receiver.

Wireless transmissions in a given system typically occur within a small range of a certain central frequency. Two simultaneous transmissions on the same frequency will interfere with each other. Interference is anything that modifies a signal in a disruptive manner. If the signals interfere with each other to the extent where each signal can no longer be discerned from the other, the receiver will not be able to interpret them, and the data will be lost. Two iMGs transmitting simultaneously will cause interference and therefore packet loss. This should not happen as the iMG check for a clear channel before sending. This is when the guards check to see if there is any interference between the iMG and the receiver on the channel the signal is to be sent down. However, interference from other sources is possible. Other sources include; mobile phones, emergency services radio, two-way radio, TV cameras etc. If another source is transmitting on a same or similar frequency to the guards of 868 MHz, then the guards signal can be disrupted, and packets lost. Any head impact system developed would need to avoid these transmission frequencies, otherwise their signal will be disrupted. Table 1 shows the transmission frequencies of technology that could affect the transmission of the PROTECHT^{TM} system.

Table 1: Transmission Frequencies for Different Technology

Technology	**Transmission Frequency (MHz)**	**Reference**
Mobile Phone-TACS	872-888	(Mann & Great Britain. National Radiological Protection Board., 2000)
Mobile Phone-GSM900	890-915	(Mann & Great Britain. National Radiological Protection Board., 2000)

Mobile Phone-GSM1800	1710-1785	(Mann & Great Britain. National Radiological Protection Board., 2000)
Mobile Phone-UMTS	1900-2200	(Mann & Great Britain. National Radiological Protection Board., 2000)
Emergency Services Radio	1173.9875-174.0	https://www.ofcom.org.uk/__data/assets/pdf_file/0021/103296/fat-emergency-services.pdf
Two-way Radio-Licensed	400-470 136-174	https://www.twoway-radio.co.uk/frequency-faq/#PMR
Two-way Radio-Unlicensed	446.00625 446.01875 446.03125 446.04375 446.05625 446.06875 446.08125 446.09375	https://www.twoway-radio.co.uk/frequency-faq/#PMR
TV Cameras	470-860	(Ellington, Addinall, & Hately, 1980)

Range

As the distance increases from the transmitter, the strength of the transmitted signal decreases, according to the inverse square law. The inverse square law states that any point source which spreads its influence equally in all directions without a limit to its range, so the energy twice as far from the source is spread over four times the area, hence one-fourth the intensity (Nave, 2016). Obstacles dampen an electromagnetic signal and therefore reduce its signal strength. The definition of an obstacle depends upon the transmission frequency the system uses. Typically, the higher the frequency, the greater the signal is attenuated by a given material (Burrows, 1967; Janek & Evans, 2010).

Reflections

Reflections of signals from objects can have both a positive and a negative effect on packet loss in a system. Reflections can act as a means for a signal to reach a receiver on a path that would have been previously inaccessible to the transmitter. Equally, reflections can cause interference with signals still being transmitted. Many real-life impacts take place with the head next to or on the ground. Depending on how the ground reflects the signal this may help or hinder the signal reaching the receiver (Burrows, 1967; Janek & Evans, 2010)

2.8.7 Effect that Proximity to the Ground has on Range

Antenna proximity to the ground plays a significant role in limiting the radio frequency range (Janek & Evans, 2010). The results obtained from the field experiments indicated that as the height of an omnidirectional monopole antenna approached a ground plane, its radiation pattern changed, by its horizontal propagation shortening (Janek & Evans, 2010). This results in the vertical radiation pattern being compressed, suggesting the existence of areas of limited to no horizontal radiation close to the ground (Janek & Evans, 2010).

2.9 Summary

2.9.1 Summary of Sections

With the high-profile nature of concussions within rugby, the need for a HIT system such as the PROTECHT^{TM} system is more important than ever before. With the sport continuing to grow and players continuing to get bigger the frequency and severity of impacts sustained by the players also continues to increase. The increase in both the magnitude and frequency of head impacts sustained by the players will need to be managed properly otherwise there will be an increase in the number of CTE cases and other brain injuries which would negatively affect the sport. The PROTECHT^{TM} system can help bridge the gap in the literature by allowing medics to monitor player loads, but this can only be achieved by validating the system. With the PROTECHT^{TM} system currently being the only HIT system suitable for rugby due to the buckle rule, this puts great emphasis on the need for the work undertaken in this thesis.

2.9.2 Important Issues to Tackle

With players sustaining hundreds of hits over a season, CTE continuing to be found in ex contact sport players and with lawsuits on the rise in sports, there is a growing need for a HIT system such as the PROTECHT^{TM} to help manage player load in rugby. For that to be possible, the system needs to be thoroughly tested before it can begin to help players. Once the system is reliable it can only then be used to help players. This is where the research in this thesis will help validate the PROTECHT^{TM} system so it can then begin to help players and make rugby a safer sport.

There is a lot of data on the effects of concussions and the risk of returning to play before a player has recovered fully from a concussion. However, it is currently unknown how much damage repeated non-concussive head impacts are causing to players' brains. A HIT system can help medical professionals understand the force needed to cause a concussion and the number of impacts a player sustains in a game. In the long-term a HIT system such as this will help researchers and medical professionals understand the effects of repeated non-concussive impacts. This could eventually help reduce the number or even eliminate the number of players with life-changing brain damage, such as CTE, and make the sport safer.

2.9.3 Contributions of This Thesis

Earlier literature reveals how important it is that the PROTECHT™ system can provide reliable head acceleration data which doesn't overestimate head impacts like other systems. However, it is also important that this data can be sent reliably over a range big enough to be able to cover a rugby pitch. What is being proposed in this thesis is that the system is tested so that it is known what a reliable range is for the system. From this we can find out whether it is reliable over the entirety of a rugby pitch or whether changes need to be made. Changes such as: different antenna, more antenna, orientation of the antenna or position of the antenna on the pitch can be made to improve the signal quality and strength, if it is found to be necessary.

2.9.4 Objectives and Hypothesis

Hypothesis 1: There is a negative correlation between linear distance and signal quality

Hypothesis 2: There is a negative correlation between horizontal distance and signal quality

Hypothesis 3: There is a negative correlation between the combination of linear distance and horizontal distance, on signal quality

Hypothesis 4: Signal quality is better standing compared to kneeling or lying down

Hypothesis 5: Head orientation affects signal quality

Hypothesis 6: Signal quality is dependent upon distance from the receiver, head and body orientation from the receiver.

Section 3: Methodology

3.1 Experimental Overview

3.1.1 Purpose

With the overall objectives and goals of the thesis decided upon, data could then be collected. Once these data have been collected, the objective was to evaluate under what circumstances in terms of game dynamics, the sensor transmission may be compromised. The first step in this range evaluation of the PROTECHT™ system was to investigate the normative transmission values at different distances. From this, other factors such as height and orientation were introduced to test their influence on the transmission range of the system.

In all experiments, the percentage of packets lost was studied under a range of experimental conditions. Packet loss is when part, or all of the data sent from the iMG is lost. The iMG and software used were controlled in all experiments. They were controlled by using the same iMG and software throughout the testing.

3.1.2 Experimental Outline

One of the challenges of investigating transmission range is consistently repeating similar impacts at each location for each experiment. To make this possible, specialist software was designed and installed onto the iMG. This software allowed the iMG to send impacts repeatedly every five seconds which would have been impossible to achieve by just impacting the iMG. Testing was conducted over two days due to time constraints, with the weather being reported.

3.2 The PROTECHT® Head Impact Monitoring System

3.2.1 Overview of the System

The PROTECHT™ iMG is a novel, bespoke head impact telemetry system, developed by Swansea University in conjunction with external partners (PROTECHT™ iMG, Sport Wellbeing Analytics Ltd, Swansea, U.K.). PROTECHT™ iMG is a real-time system specifically designed for the non-helmeted impact dynamics of rugby union and other non-helmeted collision sports. The system's bespoke iMG has rigid sensor-skull coupling, limiting soft tissue artefact to decrease measurement uncertainty. Each iMG contains inertial sensors which measure both linear and rotational velocity of the player's head resulting from impact events. These measurements are sent in data packets via radio transmission to a receiver unit connected to the laptop near the sideline shown in Figure

3**Error! Reference source not found.**. The PROTECHT™ software then translates this data and displays the data during a session, which is saved for subsequent analysis. The system can provide overall head impact exposure during training and matches to give a measure of the cumulative number and magnitude of impacts that a player experiences. Since the project began, there has been significant evolution of the PROTECHT™ system. This has led to objectives being modified where appropriate.

Overall, this means the system can be utilised to monitor head impact loading with the same principles as current GPS systems monitor training load. GPS systems have been used because appropriate load monitoring can aid in minimizing the risk of injury (Halson, 2014). This is important because repetitive 'sub-concussive' head impact loading has been linked to later-life cerebral pathogenesis (Broglio et al., 2011). The PROTECHT ™ system gained World Rugby (WR) approval in October 2018 for use in competitive matches in the Pro14 competition on a trial basis.

The PROTECHT™ iMG comprises a 9-axis inertial measurement unit (IMU), 40mAh lithium battery, antennae and an induction-charging coil embedded into bespoke iMG (Figure 1, Figure 2). An IMU is a device that measures a body's force and angular rate using a combination of accelerometers and gyroscopes. The accelerometer is used to measure linear acceleration and the gyroscope is used to measure rotational velocity which is then used to calculate rotational acceleration. A40mAh battery provides sufficient recording time to measure a full match and means it is small enough to fit into the iMG.

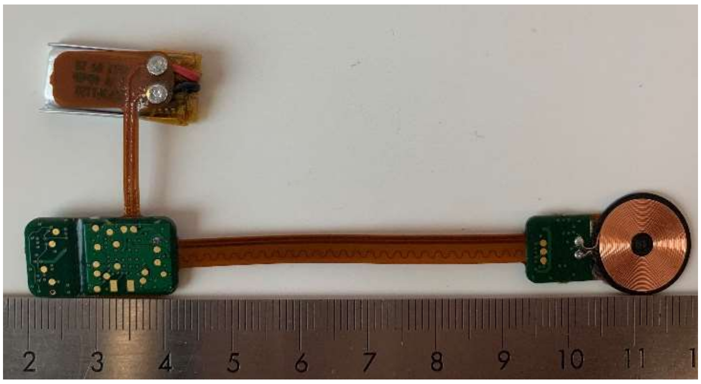

Figure 1: Electronics for PROTECHT(TM) mouthguard: rev4 version. 9-axis IMU, battery, charging coil and antenna

Figure 2: Electronics embedded in PROTECHT® mouthguard

Figure 3: (A) The receiver for the PROTECHT(TM) system. (B) The edge device used for the PROTECHT(TM) system

Table 2: Sensor specifications

Factor	**Specification of PROTECHT iMG**
IMU Sensors	3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer
Accelerometer Sampling Freq. (Hz)	1000
Gyroscope Sampling Freq. (Hz)	952
Range and Resolution of Accelerometer (g)	±200 g range at 16-bit resolution

Range and Resolution of Gyroscope (dps)	±2000 dps 16-bit resolution
Recording time (ms)	104
Battery life (hr)	4 hours (one hour to charge)
On-chip storage (No. of Impacts)	2
Transmission range (m)	150
Transmission time (s)	1 – 3.5

The IMU sensors calculate the resultant acceleration forces by using the vector sum of the vectors x, y and z. The recording time was set to 104 ms based on pilot data collected using an instrumented patch, to ensure recording of an entire head impact waveform. The theoretical transmission range is large enough so that it can cover a full rugby pitch and beyond it as the receiver can't always be right on the sideline. The transmission time is between one and three seconds, to provide information to team officials in the event of a potentially severe impact. It has been found that a minimum of bandwidth for both accelerometer and gyroscope of 500 Hz is required to study most injury criteria in non-helmeted sports (Wu et al., 2016). These values were set initially based on previous rugby research (King et al., 2014). The resultant peak linear acceleration (PLA) and peak rotational acceleration (PRA) were both defined as the one sample with the highest numerical value during the sampling period of the acceleration-time history.

Given the iMG size restrictions for rugby union, it was preferable to have fewer components included to keep the mouthguard as small as possible. In comparison to instrumented mouthguards developed for helmeted sports like AF (Bartsch et al., 2014), the PROTECHT™ iMGs are significantly smaller. This is fine in helmeted sports as the guard protrudes out of the mouth (Camarillo et al., 2013), but in rugby union this is against the rules as it creates a hazard to the player.

3.3 Experimental Design

The following hypothesis were generated, based on existing literature reviewed in Section 2 and pilot data collected with the PROTECHT™ system during the development process. The corresponding experiments were designed to test each hypothesis. The distances were defined in Equation 1:

Equation 1

$$\mathit{Linear\ distance} = y\ (x = 0), \mathit{Horizontal\ distance} = x\ (y = 0). \mathit{Overall\ distance} = \sqrt{x^2 + y^2}$$

Hypothesis 1: There is a negative correlation between linear distance and signal quality

- Experiment 1.1: A heat map was produced to show the effect of increasing linear distance from the receiver on signal quality, whilst facing the receiver in a standing position with the head in a neutral position

Table 3: Variables for Experiment 1.1

Extraneous Variables	Independent Variables	Dependent Variables
Horizontal Distance	Linear Distance	Signal Quality
Body Height		
Head Orientation		

Hypothesis 2: There is a negative correlation between horizontal distance and signal quality

- Experiment 2.1 A heat map was produced to show the effect of increasing horizontal distance from the receiver on signal quality, whilst facing the receiver in a standing position with the head in a neutral position.

Table 4: Variables for Experiment 2.1

Extraneous Variables	Independent Variables	Dependent Variables
Linear Distance	Horizontal Distance	Signal Quality
Body Height		
Head Orientation		

Hypothesis 3: Signal quality differs in relation to position on the pitch

- Experiment 3.1: A heat map was produced to show the effect of different linear and horizontal distances from the receiver on signal quality, whilst facing the receiver in a standing position with the head in a neutral position

Table 5: Variables for Experiment 3.1

Extraneous Variables	**Independent Variables**	**Dependent Variables**
Body Height	Linear Distance	Signal Quality
Head Orientation	Horizontal Distance	

- Experiment 3.2: A Pearson's correlation was performed to assess the effect of different linear and horizontal distances from the receiver on signal quality, whilst lying prone, facing the receiver with the head in a neutral position

Table 6: Variables for Experiment 3.2

Extraneous Variables	**Independent Variables**	**Dependent Variables**
Body Height	Linear Distance	Signal Quality
Head Orientation	Horizontal Distance	

Hypothesis 4: Signal quality is better standing compared to kneeling or lying down

- Experiment 4.1: A One-Way Repeated Measures ANOVA was performed to assess the effect of body height on signal quality

Table 7: Variables for Experiment 4.1

Extraneous Variables	**Independent Variables**	**Dependent Variables**
Linear Distance	Body Height	Signal Quality
Horizontal Distance		
Head Orientation		

- Experiment 4.2: A heat map was produced to show the effect of body height and linear distance on signal quality

Table 8: Variables for Experiment 4.2

Extraneous Variables	Independent Variables	Dependent Variables
Horizontal Distance	Body Height	Signal Quality
Head Orientation	Linear Distance	

- Experiment 4.3: A heat map was produced to show the effect of body height and horizontal distance on signal quality

Table 9: Variables for Experiment 4.3

Extraneous Variables	Independent Variables	Dependent Variables
Linear Distance	Body Height	Signal Quality
Head Orientation	Horizontal Distance	

- Experiment 4.4: A Pearson's correlation was performed to assess the effect of different linear and horizontal distances from the receiver on signal quality, whilst lying prone, facing the receiver with the head in a neutral position

Table 10: Variables for Experiment 4.4

Extraneous Variables	Independent Variables	Dependent Variables
Head Orientation	Body Height	Signal Quality
	Linear Distance	
	Horizontal Distance	

Hypothesis 5: Signal quality is better with head orientation being horizontal compared to face down or at 45 degrees

- Experiment 5.1: *A One-Way Repeated Measures ANOVA* was performed to assess the effect of head orientation on signal quality

Table 11: Variables for Experiment 5.1

Extraneous Variables	Independent Variables	Dependent Variables
Linear Distance	Head Orientation	Signal Quality
Horizontal Distance		

Body Height

- Experiment 5.2: A heat map was produced to show the effect of head orientation and linear distance on signal quality

Table 12: Variables for Experiment 5.2

Extraneous Variables	**Independent Variables**	**Dependent Variables**
Horizontal Distance	Head Orientation	Signal Quality
Body Height	Linear Distance	

- Experiment 5.3: A heat map was produced to show assess the effect of head orientation and horizontal distance on signal quality

Table 13: Variables for Experiment 5.3

Extraneous Variables	**Independent Variables**	**Dependent Variables**
Linear Distance	Head Orientation	Signal Quality
Body Height	Horizontal Distance	

- Experiment 5.4: A Pearson's correlation was performed to assess the effect of different linear and horizontal distances from the receiver on signal quality, whilst lying prone, facing the receiver with the head at different orientations

Table 14: Variables for Experiment 5.4

Extraneous Variables	**Independent Variables**	**Dependent Variables**
Body Height	Head Orientation	Signal Quality
	Linear Distance	
	Horizontal Distance	

Hypothesis 6: Signal quality is dependent upon distance from the receiver, head and body orientation from the receiver

- Experiment 6.1: A Pearson's correlation was performed to assess the effect of different linear and horizontal distances from the receiver on the combination of head orientation, head direction and body height on signal quality

Table 15: Variables for Experiment 6.1

Extraneous Variables	**Independent Variables**	**Dependent Variables**
Weather	Head Orientation	Signal Quality
	Linear Distance	
	Horizontal Distance	
	Body Height	

3.4 Range Testing Measurement Methods and Influencing Factors

3.4.1 Orientation of the antenna, position of the antenna on the pitch, what type of antenna are we using

When setting up the system the receiver was at the halfway line of the pitch. This was so the receiver was an equal distance away from each end of the pitch. The PROTECHT™ system uses a horizontal gain antenna meaning that it must be at the same horizontal level as the players. A horizontal gain antenna was used so that the whole pitch could be covered. The strength of the signal must be strong enough to reach all areas of the pitch otherwise this would result in a reduction of signal quality. A horizontal gain antenna is a dual-band omnidirectional antenna. They work by having a dual-band driven element and a second antenna element simultaneously producing a directional radiation pattern at an upper frequency and an omni-directional radiation pattern at a lower frequency. When an electrical current is applied to an upper and a lower frequency, the antenna system radiates in a directional pattern at the upper frequency and in an omnidirectional pattern at the lower frequency (Tallman, Santner, & Miller, 2006). This means that receiver placement is crucial otherwise signal quality will be affected.

3.4.2 Packet Loss

When the guards detect an impact, they record both linear and rotational velocity for 104 ms. Instead of the data being sent in one continuous stream, it is sent in packets. For each impact 13 packets contain linear acceleration data and 13 packets contain rotational velocity data. Packet loss is when the receiver doesn't receive all of the impact and just records the dropped packet as zero. It has been observed that the greatest amount of packet loss is when the impact is far away from the receiver. If an impact is not received after five seconds, the system has missed an entire impact. When this happens, this is marked as complete packet loss.

There are many factors that can cause packet loss, the main three factors are; Attenuation, Interference and Reflections.

Attenuation is the reduction of the strength of a signal once transmitted, the two most common causes of attenuation are range and obstructions. The strength of the transmitted signal decreases as distance increases, whereas obstacles dampen an electromagnetic signal and therefore reduce its signal strength. As the iMGs are within the head this means the signal will be transmitted through the head and other bodies, this will cause attenuation. This is why when testing the range of the system, impacts are recorded when the body is at different orientations to try to account for this.

Interference is when two simultaneous transmissions on the same frequency interfere with each other to some extent. If they interfere with each other to the point where the receiver cannot interpret which one is which, the data is lost. This can happen when two guards transmit simultaneously, but this has been taken to account for because the guards check for a clear channel before transmitting their signal. Interference from other sources is also possible, if another source is transmitting on the same or very similar frequency as the guards then the guard's signal can be disrupted causing packets to be lost. To account for this the iMGs transmit on an empty radio frequency with clear channels either side of it to limit external interference.

Reflections off objects can have a negative but also a positive effect on packet loss in the system. Reflections can cause signals to reach the receiver on different paths which previously weren't accessible to it. However, reflections can also cause interference with signals which can result in the signal being delayed or lost. Much of the testing of the system so far has taken place within a lab-based setting where reflections will have occurred. Now with the current field-testing taking place in a less controlled environment, outside in an open field with no buildings nearby, there will be fewer reflections effecting the results.

3.4.3 Weather

To make sure the weather wasn't a factor, testing was attempted to be undertaken in conditions which were similar. This is because pilot testing has shown that packet loss has been reduced during wet conditions. Weather details were recorded due to testing not always being able to be repeated in the same conditions and in case any patterns were seen which would indicate weather being an extraneous variable

3.4.4 Impacts not being picked up

When an impact is not received this means that the impact has been missed. Every impact that was missed was recorded as a maxima, meaning complete packet loss has occurred.

3.4.5 Study Participants

The study population consisted of 1 male participant throughout all the experiments for continuity (Table 16). This helped keep the heights for standing, kneeling and lying the same. These heights are shown in Table 17.

Table 16: Study Population

Gender	N	Age (years)	Weight (kg)	Height (cm)
Male	1	23	106.5	198

Table 17: Height off the floor in the different positions

Body Position	Head Position	Height off the floor (cm)
Lying down	Face down	1.4
Lying down	Head at 45°	7.8
Lying down	Head up	11
Kneeling	Face down	91
Kneeling	Head at 45°	96
Kneeling	Head up	103.5
Standing	Face down	163
Standing	Head at 45°	172.5
Standing	Head up	178

3.5 General Experimental Procedures

A preliminary investigation was conducted to find the appropriate range to test the mouthguard and the appropriate intervals between the distances measured. Pilot testing was conducted at 10 metre intervals with the participant standing, facing towards, left, away and right from the receiver, shown in Figure 5. The testing was conducted up to a distance of 90 metres due to space limitations and took place on a pavement close to buildings. The results are shown below in Table 18

Pilot testing determined that 10 metre intervals were appropriate as five metre intervals would give too much data to analyse effectively. Intervals of 20 metres were too large so it wouldn't give a clear picture as to when packet loss started within the 20 metre range. With the pilot testing being conducted on a pavement close to buildings possibly improving results, it was concluded that all future testing would take place on a field, preferably a rugby pitch, away from buildings.

After these preliminary investigations, tests were completed to investigate the effects of linear distance and horizontal distance from the receiver, head orientation, head direction and body height on signal quality. The same human participant and iMG were used for all tests to ensure consistency. The testing was conducted on different days, with the weather being recorded for each day of testing. Ten automatically generated impacts were recorded at every location and variable and an average was taken for each. Heat maps and scatter plots were produced to show the effects of each individual and combination of variables.

For all results relating to this section, the participant stood at different locations on the pitch, at different orientations to the receiver. The iMG loaded with firmware developed specifically for the range testing, was used for all tests. This firmware was designed to automatically generate a signal every five seconds. By using this method, it was possible to verify when no signal was received by the PROTECHT™ app based on the certainty that one was generated.

Table 18: Results from pilot testing conducted on the 18th December 2018

Distance (m)	**Subject**	**Orientation and Packet Loss**											
		Front			**Left**			**Back**			**Right**		
		Test 1	**Test 2**	**Test 3**	**Test 1**	**Test 2**	**Test 3**	**Test 1**	**Test 2**	**Test 3**	**Test 1**	**Test 2**	**Test 3**
10	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0
20	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0
30	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0
40	1	0	0	0	0	0	0	1	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	1
50	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0
60	1	0	0	0	0	0	0	0	0	0	0	1	2
	2	0	0	0	0	0	0	0	0	0	0	0	0
70	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	1	1	0	0	0	0	0	0	0
80	1	0	1	0	1	0	1	0	1	1	0	0	0
	2	0	0	0	1	0	0	1	0	0	0	0	0
90	1	0	0	0	0	0	0	0	1	1	0	0	1
	2	0	0	0	1	0	0	0	0	0	1	1	0

Packet Loss	
0=	No
1=	Yes

All testing was carried out on a grass rugby pitch with no buildings within 200 metres of the pitch. The weather conditions at the time of testing were recorded in Table 19 to control for any extraneous variables potentially affecting the sensor signal. Rainfall was taken into account due to bodies of water attenuating or absorbing signals (Gorman & Siegert, 1999) The distance was measured using a pacing strategy where one pace was roughly equal to one metre.

Table 19: Weather conditions for each day of testing, not including pilot testing.

Date	Temperature (°C)	Humidity (%)	Rainfall (mm)
17th December 2019	4	76	0.5
18th December 2019	7	92	14.7

3.5.1 Experiment 1.1

To test the linear range of the system directly in front of the receiver, the receiver was set up level with the half way line, 10 metres back from the boundary line (Figure 4). The volunteer then stood facing the receiver with their head in a neutral position 10 metres away from the receiver, and this was the set interval. Using specialist software which sends an impact to the guard every five seconds the volunteer would wait 60 seconds to make sure 10 impacts came through before changing position.

The volunteer then repeated this at 10 metre increments up to a distance of 110 metres. The maximum distance of 110 metres was considered to be appropriate as the maximum distance from the receiver to the far sides of the pitch were within 94-108 metres (Figure 4).

For each impact recorded, both the linear acceleration (LA) and rotational acceleration (RA) time curves were analysed to see whether there was any packet loss. LA was defined as how fast the velocity of the mass of the head changes and was measured in g. RA was defined as the time rate of change of the angular velocity of the mass of the head. Angular velocity was then converted to angular acceleration also known as rotational acceleration and was measured in rad/s². The number of packets lost were calculated and recorded.

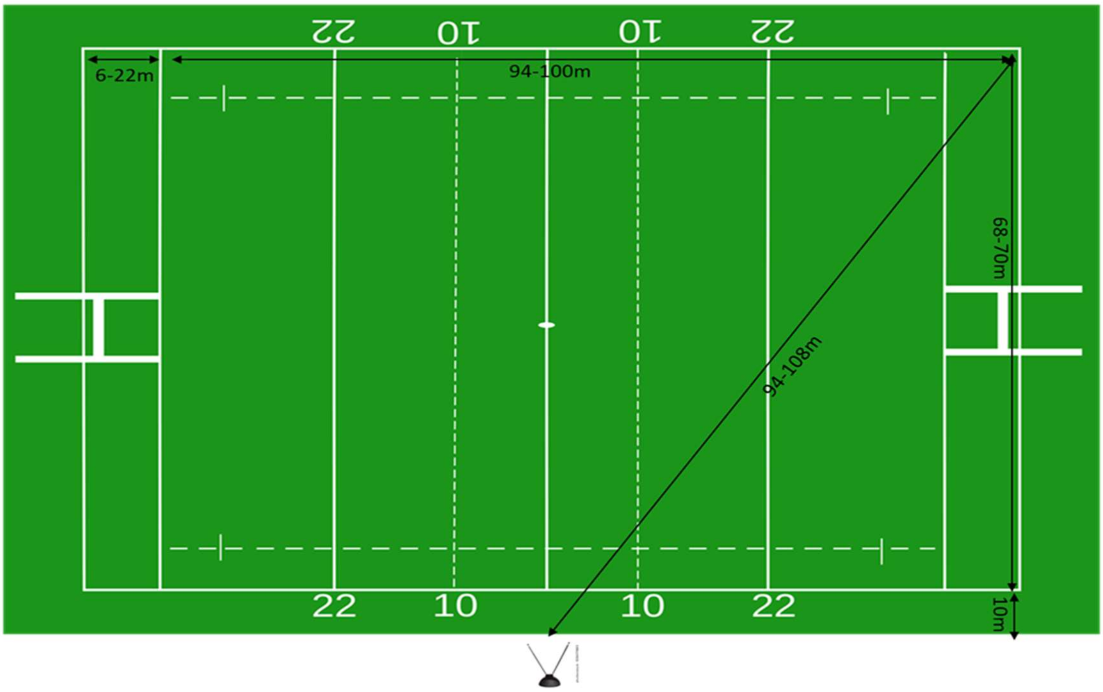

Figure 4: Rugby Pitch Dimensions

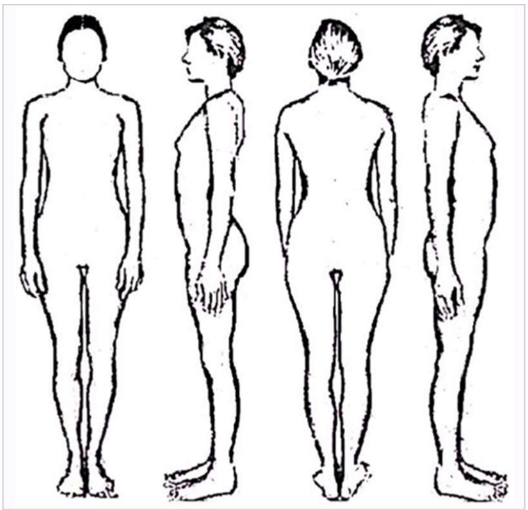

Figure 5: Different orientations of participant; Front On, Left Side, Facing Away, Right Side

All of the results were put into a table with the means and standard deviations calculated to compare the packet loss at each distance. The results were tested for normality using a Shapiro Wilk test. The results were then presented in heat maps showing packet loss at each location.

3.5.2 Experiment 2.1

To test the horizontal range the receiver was first set up level with the goal line, 10 metres back from the boundary line (Figure 6). The volunteer stood 10 metres away, directly in front of the receiver as shown in Figure 6. Only half the pitch was used because with the receiver being in the middle of the pitch the range should be equal to both sides of the pitch. The same process for testing the linear range was used to test the horizontal range, but up to a distance of 80 metres. The maximum distance of 80 metres was considered to be appropriate due to the maximum distance from the receiver to the far side of the pitch being between 63-72 metres. This was then repeated using the same methods as for the linear range testing.

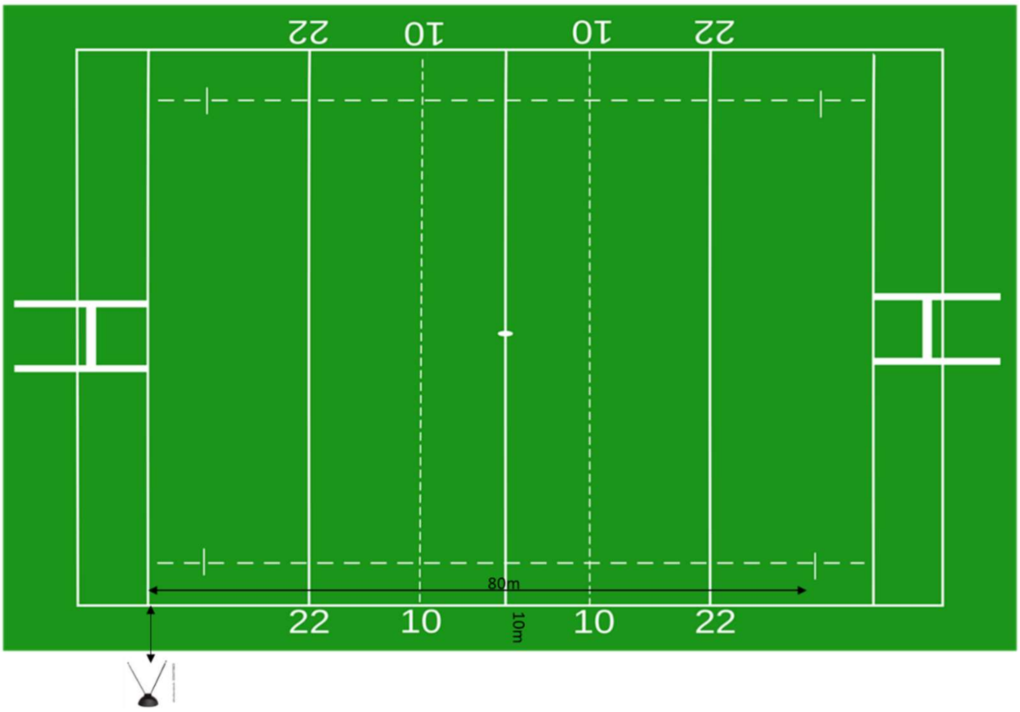

Figure 6: Horizontal Pitch Dimensions

The same statistical analysis was conducted as for the linear range testing.

3.5.3 Experiment 3.1

Preliminary investigations found that a 20 metre by 20 metre quadrant was too large an area to test the range of the mouthguard because of the sudden increase in packet loss between quadrants. From this the ideal locations to be tested were calculated and are shown in Figure 7. To test the overall range across the entirety of a pitch, the receiver was set up level with the halfway line, 10 metres back from the boundary line. The volunteer then carried out the same testing as previously for the linear and horizontal testing using the software. The volunteer then tested at each green zone marked on

Figure 7: Each position to be range tested

, until each zone was covered.

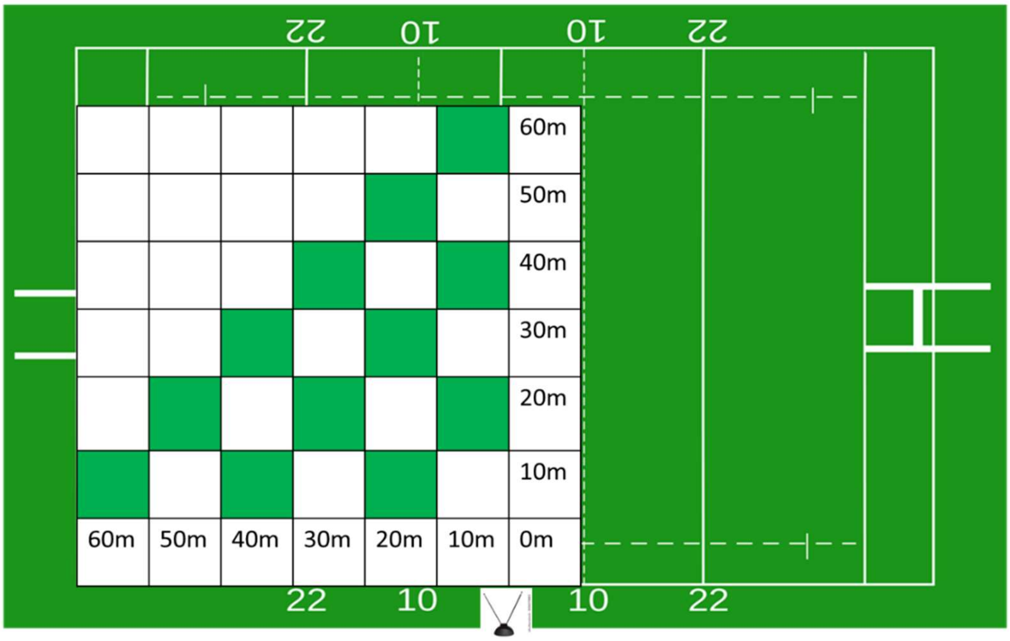

Figure 7: Each position to be range tested

The same statistical analysis used for the previous two experiments was used. A heat map was created to show packet loss across each position.

3.5.4 Experiment 3.2

The same testing procedures were carried out as previously in experiment 3.1. However, the participant was now lying prone on the floor, with their head facing towards the receiver in a neutral position.

The same statistical analysis used for the previous experiments was used. A scatter graph was created to compare packet loss over increasing distance. A Pearson's correlation was also conducted to find out whether there is a correlation between increasing distance and packet loss.

3.5.5 Experiment 4.1

The same testing procedures were carried out as previously in experiment 3.1. However, the participant now repeated the experiment whilst kneeling and lying prone on the floor, with their head facing towards the receiver in a neutral position.

The same statistical analysis used experiment 3.1 was used. A heat map was created to show packet loss across each position. A one-way repeated measures ANOVA was conducted to test for overall significance for body height. Post hoc tests were conducted to test for significance between groups.

3.5.6 Experiment 4.2

The same testing procedures were carried out as previously in experiment 4.1.

The same statistical analysis used for experiment 3.1 was used. A heat map was created to show packet loss across each position.

3.5.7 Experiment 4.3

The same testing procedures were carried out as previously in experiment 4.1.

The same statistical analysis used for experiment 3.1 was used. A heat map was created to show packet loss across each position.

3.5.8 Experiment 4.4

The same testing procedures were carried out as previously in experiment 4.1.

The same statistical analysis used for the experiment 3.1 was used. A scatter graph was created to compare body height and packet loss over increasing distance. A Pearson's correlation was also conducted to find out whether there is a correlation between body height and increasing distance and packet loss.

3.5.9 Experiment 5.1

The same testing procedures were carried out as previously in experiment 4.1. However, the participant now repeated the experiment with their head in a neutral position, at 45 degrees and facing down at the floor.

The same statistical analysis used experiment 4.1 was used. A heat map was created to show packet loss across each position. A one-way repeated measures ANOVA was conducted to test for overall significance for head orientation. Post hoc tests were conducted to test for significance between groups.

3.5.10 Experiment 5.2

The same testing procedures were carried out as previously in experiment 5.1.

The same statistical analysis used for experiment 3.1 was used. A heat map was created to show packet loss across each position.

3.5.11 Experiment 5.3

The same testing procedures were carried out as previously in experiment 5.1.

The same statistical analysis used for experiment 3.1 was used. A heat map was created to show packet loss across each position.

3.5.12 Experiment 5.4

The same testing procedures were carried out as previously in experiment 5.1.

The same statistical analysis used for the experiment 3.1 was used. A scatter graph was created to compare head orientation and packet loss over increasing distance. A Pearson's correlation was also conducted to find out whether there is a correlation between head orientation and increasing distance and packet loss.

3.5.13 Experiment 6.1

The same testing procedures were carried out as previously in experiments 3.1, 4.1 and 5.1. the participant now repeated the experiment facing towards and facing away from the receiver.

The same statistical analysis used experiment 5.1 was used. A heat map was created to show packet loss across each position. A two-way repeated measures ANOVA was conducted to test for overall significance between head direction and orientation. Post hoc tests were conducted to test for significance between groups. A scatter graph was created to compare how the combination of head orientation, head direction and body height compared over increasing distance. A Pearson's correlation was also conducted to see if there is a correlation between the variables and increasing distance and packet loss.

Section 4: Results

4.1 Overview

The primary objectives of this thesis were to determine under what conditions the PROTECHT™ iMG system was able to successfully transmit real-time data and where this was compromised. This information would then be used to generate hypotheses for the company regarding the reasons for this. A comprehensive set of transmission range testing data for the PROTECHT™ iMG system was generated. Data transmission performance was assessed in vivo (in a human mouth) from the iMG to the sideline receiver, from every section of the pitch at different heights and orientations. This information was subsequently used by the company and commercial partners to develop hardware and software strategies to overcome transmission problems. This was necessary because of the need to find out whether there is attenuation of signal quality at different heights and orientations.

This section contains results from iMG range testing

4.2 Linear & Horizontal Distance vs Signal Quality (Hypotheses 1 & 2)

For the linear distance tests, the participant stood directly in front of the receiver and then moved back in 10 metre increments linearly until 110 metres was reached. For the horizontal distance tests, the participant stood 10 metres in front of the receiver and maintained this linear distance throughout these tests and then moved in 10 metre increments horizontally, until 80 metres was reached.

A heat map showing the results for signal quality at the different linear and horizontal distances tested in Experiments 1.1 and 1.2 is shown in Figure 8. This addressed both hypotheses one and two, which proposed there to be a negative correlation between signal quality (measured as packet loss) and increasing linear and horizontal distance respectively between the iMG and receiver. For both experiments, the participant wearing the mouthguard was facing forwards towards the receiver in a standing position. This was done to control for potential effects of height and orientation of the iMG relative to the receiver.

Given the zero values for both experiments, it was impossible to apply any statistical analyses to these data. It can be concluded from these results that under these conditions (standing, facing the receiver with the head in a neutral position), increases in linear and horizontal distance, individually, have no effect on signal quality. From this we can reject both hypothesis one and two.

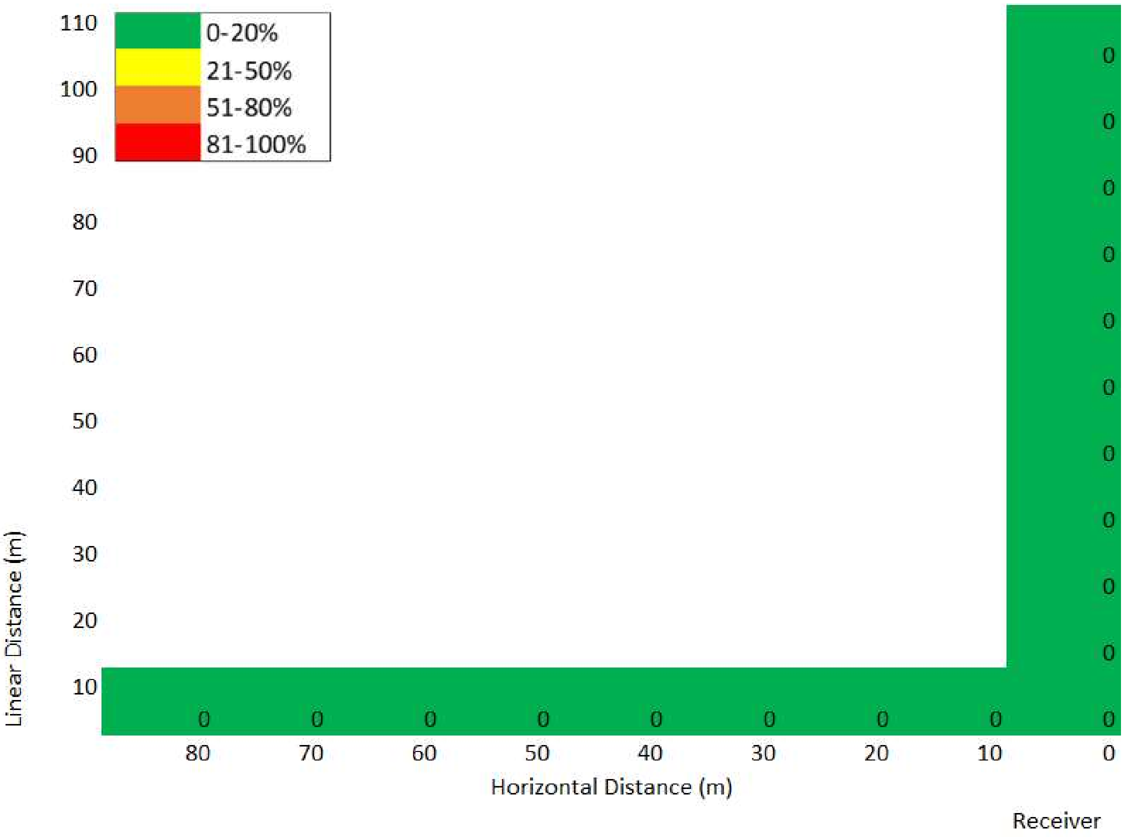

Figure 8: A heat map showing packet loss over an increase in linear and horizontal distance whilst standing and facing the receiver with the head in a neutral position

4.3 Signal Quality vs Linear x Horizontal Distance (Hypothesis 3)

While linear and horizontal distance, individually, did not have an effect on signal quality, the combination of the two was tested to find out whether the signal quality of the iMG was the same over the entire pitch. Experiment 3.1 was undertaken to determine whether spatial location on the pitch affected signal quality. A heat map showing the average values for signal quality for this experiment is given in Figure 9. The participant (therefore the iMG) remained standing with a neutral head position, facing the receiver for the whole experiment.

As there were no non-zero values in this dataset, no statistical method was applied to analyse these data. It can be concluded from these data that under these conditions (Standing with a neutral head position, facing the receiver), that spatial location on the pitch did not affect signal quality. From this, we can reject the hypothesis under these conditions.

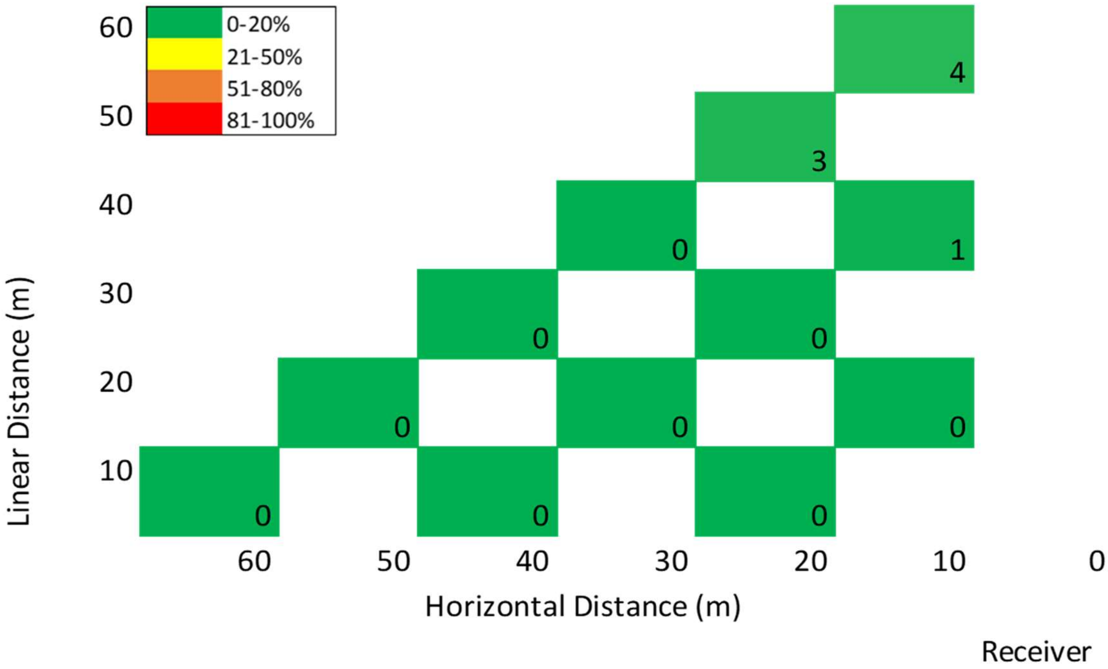

Figure 9: A heat map showing packet loss at different linear and horizontal distances whilst standing facing the receiver with a neutral head position

Experiment 3.2 was undertaken to determine whether spatial location on the pitch affected signal quality while the participant was lying in a prone position on the ground, with the head orientated upwards towards the receiver. Average values are given in the heat map in Figure 10 showing the overall signal quality for these conditions.

It is clear in Figure 10 that there is a relationship between signal quality and distance when lying in a prone position, facing the receiver with the head orientated upwards.

To assess this further, the overall distance from the receiver to each of the positions shown in Figure 10 was calculated by the trigonometric Equation 2. Here, d = overall distance, l = linear distance and h= horizontal distance from the receiver. The resulting values for overall distance were plotted against those for signal quality (% packet loss) are given inFigure 11. A Pearson correlation was performed to determine the relationship between overall distance from the receiver and signal quality, while lying in a prone position with the head orientated towards the receiver.

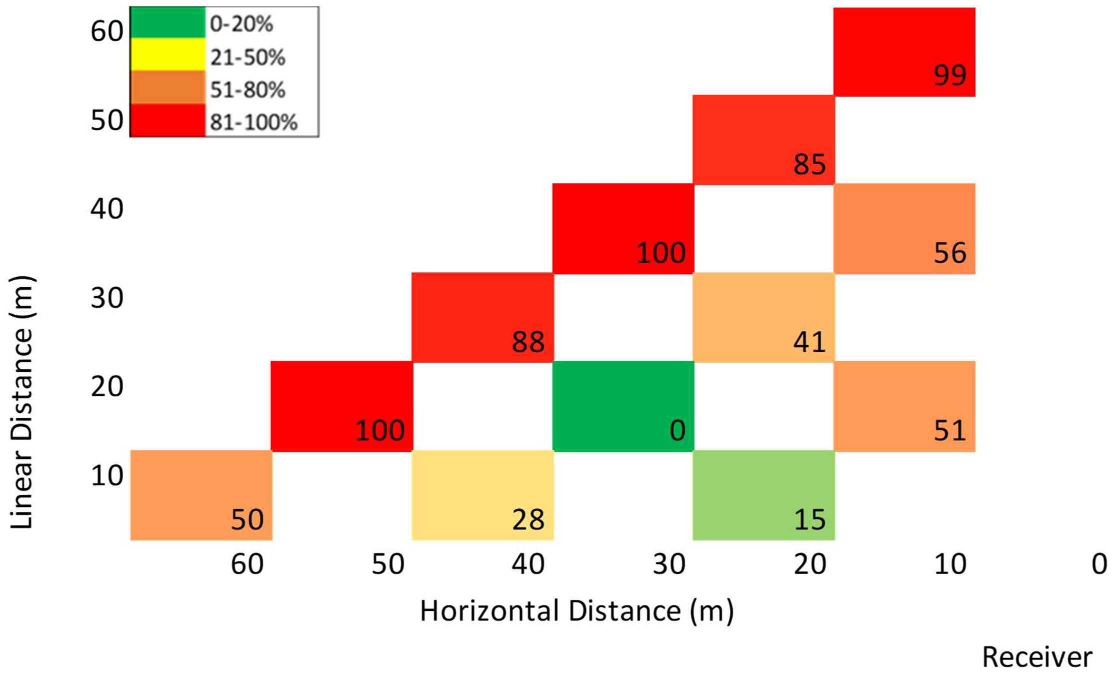

Figure 10: A heat map showing packet loss at different linear and horizontal distances whilst lying in a prone position on the ground, facing the receiver, with the head orientated upwards towards the receiver

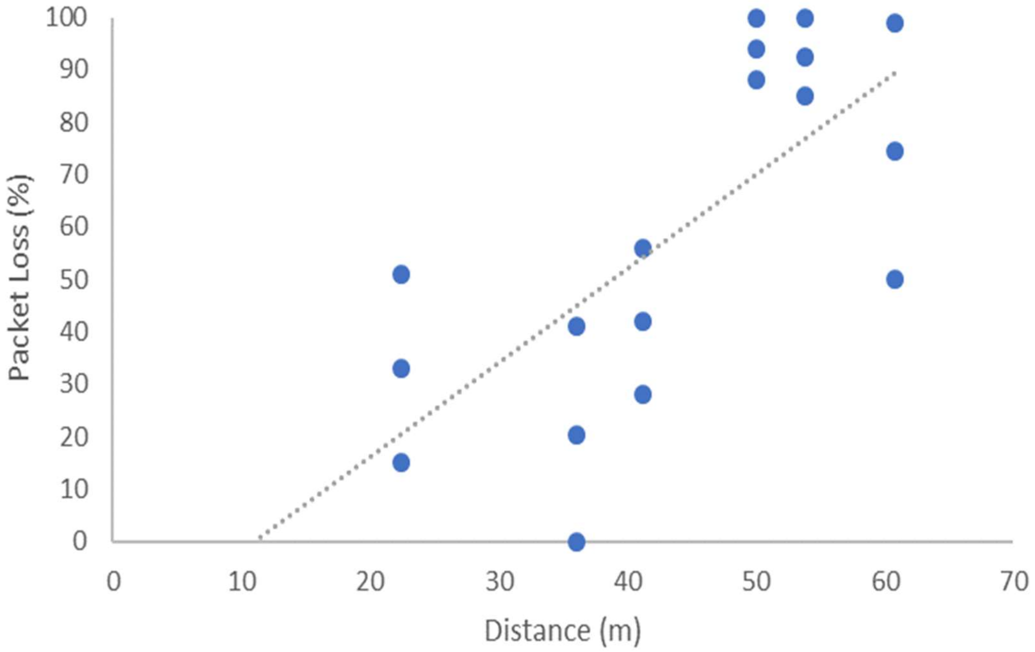

Figure 11: A scatter graph showing the effect of increasing distance on packet loss whilst lying down in a prone position, facing at the receiver with the head orientated upwards

Equation 2

$$d^2 = l^2 + h^2$$

A significant positive correlation was found between the overall distance from the receiver and signal quality, when lying in a prone position, when facing the receiver with the head orientated upwards towards the receiver (Pearson correlation =.70, *p* = .012). R-squared also showed that a proportion of the variability was of the response data around its mean was due to overall distance from the receiver under these conditions (R^2=0.61). From this, we can accept the hypothesis.

4.4 Signal Quality vs Body Height and Distance from Receiver when Facing Receiver (Hypothesis 4)

To test the effect of body height (height of the iMG from the ground), the same procedures were followed as previously with the participant standing with their head in a neutral position facing towards the receiver. This was then repeated at each position with the participant kneeling and then again lying down.

Experiment 4.1 was performed to assess the effect of body height, or the height of the iMG from the ground, on signal quality. Experiment 4.2 was performed to assess the effects of the combination of body height and linear distance on signal quality. Experiment 4.3 was performed to assess the effect that the combination of body height and horizontal distance have on signal quality. Heat maps showing signal quality at different locations on the pitch while facing the receiver when standing, kneeling and lying in a prone position are given in Figure 9, Figure 12 and Figure 10, respectively.

A one-way repeated measures ANOVA was conducted to determine whether differences in signal quality exist between three different body heights. This was due to the iMG being at different absolute distances from the ground and because distance from the ground may cause attenuation of signal quality. Mauchly's test indicated that the assumption of sphericity had been violated, $x^2(2) = 95.02$, $p < .01$. For the corrected Greenhouse-Geisser estimates of sphericity, the results showed a significant difference between body heights, $F(1, 11) = 6.84$, $p = .024$. Post hoc tests using a Wilcoxon Signed-Ranks test indicated that signal quality whilst standing was significantly different to signal quality whilst lying prone on the ground, $Z = -2.09$, $p = .035$. Signal quality whilst kneeling was also significantly different to signal quality whilst lying down, $Z = -2.10$, $p = .035$. Signal quality whilst standing was not significantly different to signal quality whilst kneeling, $Z = -.45$, $p = .655$). This hypothesis can therefore be accepted; lying down has a significant effect on signal quality compared to kneeling and standing, while facing the receiver with the head orientated towards the receiver.

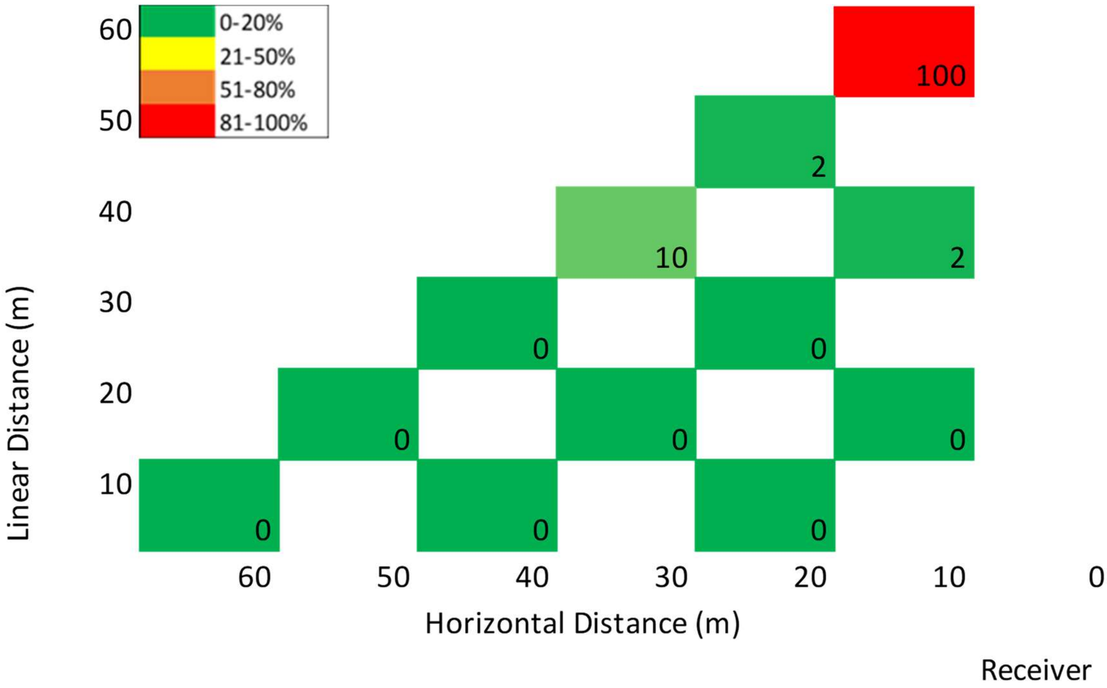

Figure 12: A heat map showing packet loss at different linear and horizontal distances whilst kneeling facing the receiver with the head in a neutral position

Experiment 4.4 was conducted to ascertain the effect of the combination of body height and linear and horizontal distance from the receiver on signal quality. A scatter plot showing signal quality, measured by the percentage of packet loss, relative to increasing overall distance from the receiver is given in Figure 13. Overall distance was calculated using the same method given in Equation 2.

A significant positive correlation was found between the combination of body heights, overall distance from the receiver and signal quality, when facing the receiver (Pearson correlation =.36, p = .030. R-squared also showed that a large percentage of the variability was of the response data around its mean was due to overall distance from the receiver under these conditions (R^2=0.78). This hypothesis can therefore be accepted; the combination of distance and body height has a strong relationship on signal quality whilst facing the receiver with a neutral head position.

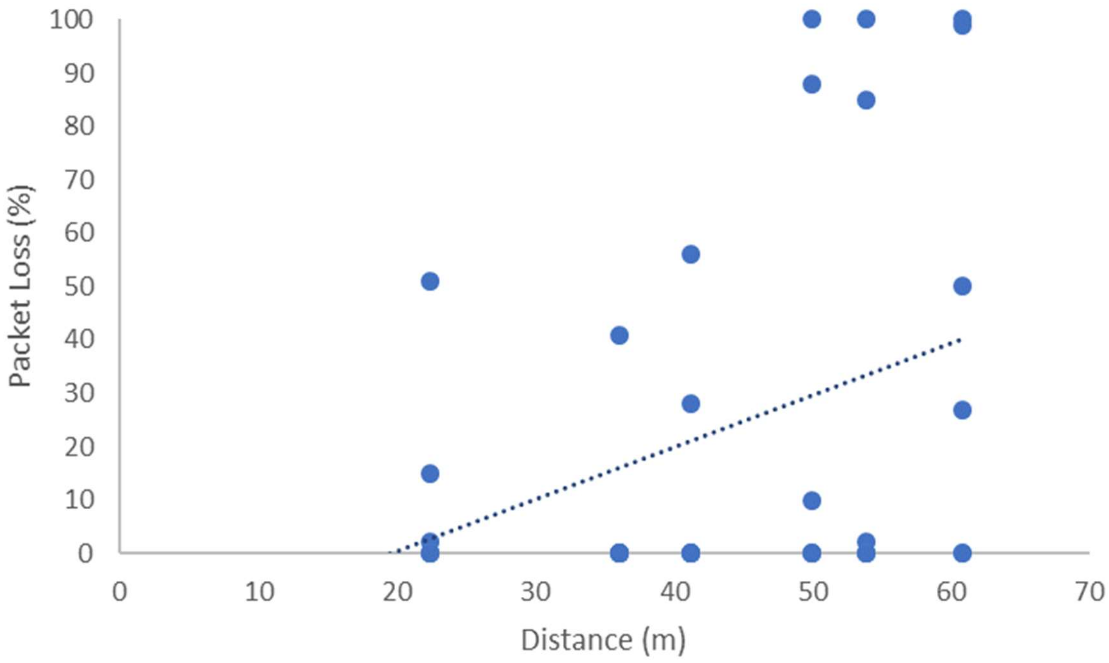

Figure 13: A scatter graph showing the effect of increasing distance on signal quality when the different body heights are combined whilst the participant's head is in a neutral position facing towards the receiver

Significant relationships were found between the overall distance from the receiver and signal quality, when lying in a prone position, when facing the receiver with the head orientated upwards towards the receiver. Based on these findings, combined with the results from experiments one to four, it was decided that all subsequent analyses would focus on the influence on signal quality whilst the participant was lying in a prone position on the ground.

4.5 Signal quality vs Head orientation and Distance from Receiver when Facing Receiver lying prone on the ground (Hypothesis 5)

To test the effect of head orientation (angle of the iMG from the ground), the same procedures were followed as previously but with the participant lying down, with their head in a neutral position, facing towards the receiver. This was then repeated at each position with the participants head at 45 degrees and then again with their head facing down towards the ground.

Experiment 5.1 was performed to assess the effect of head orientation, or the angle between the iMG and the ground, on signal quality. Experiment 5.2 was performed to assess the effects of the combination of head orientation and linear distance on signal quality. Experiment 5.3 was performed to assess the effects of head orientation and horizontal distance on signal quality. Heat maps showing signal quality at different locations on the pitch while lying prone on the ground facing the receiver are given as follows:

- Head in a neutral position (Figure 10)
- Head at 45 degrees (Figure 14)
- Head facing down towards the ground (Figure 15)

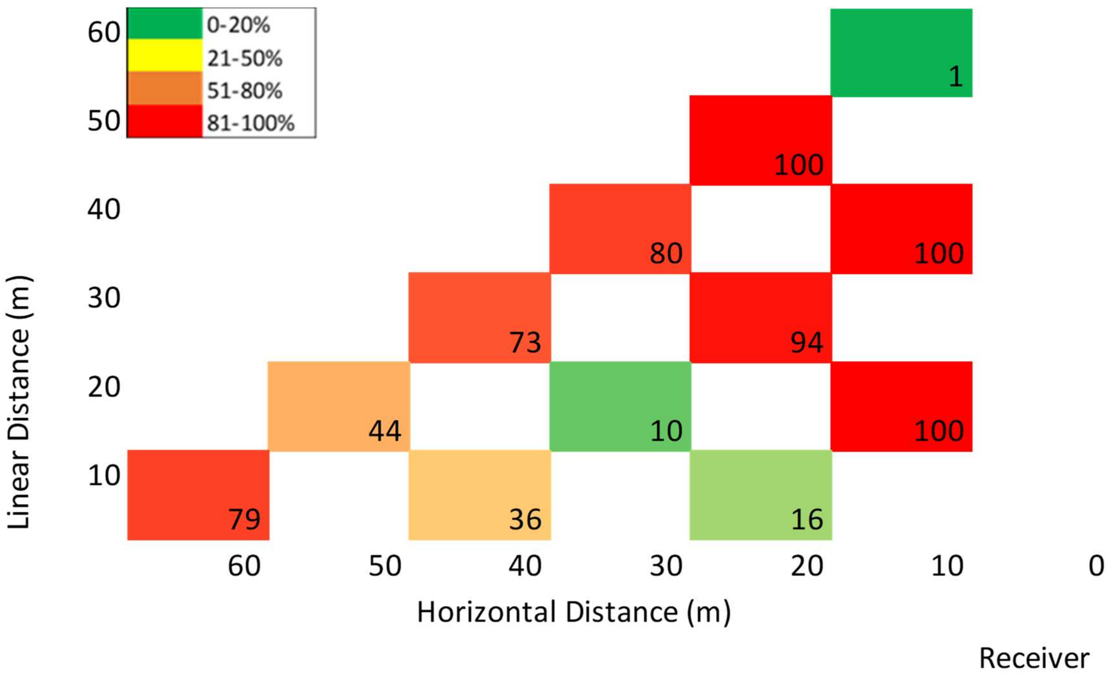

Figure 14: A heat map showing packet loss at different linear and horizontal distances whilst lying in a prone position on the ground, facing the receiver, with the head orientated 45 degrees to the receiver

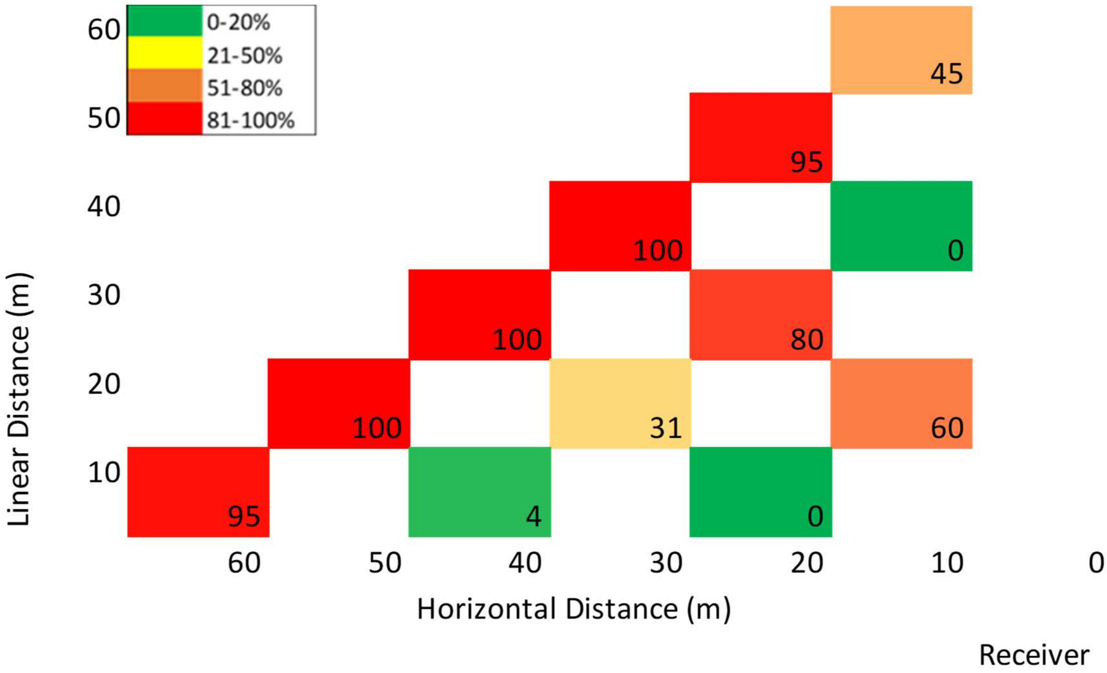

Figure 15: A heat map showing packet loss at different linear and horizontal distances whilst lying in a prone position on the ground, facing the receiver, with the head orientated downwards towards the receiver

A one-way repeated measures ANOVA was conducted to determine whether differences in signal quality exist at three different head orientations. Mauchly's test indicated that the assumption of sphericity had not been violated, $x^2(2) = 1.29$, $p = .525$. The results showed that signal quality wasn't significantly affected by head orientation when lying in a prone position on the ground, facing the receiver, $F(2,22) = 13.03$, $p = .984$. This was unexpected due to how signal quality is affected by attenuation of the signal at the different head orientations.

Experiment 5.4 was conducted to ascertain the effect of the combination of head orientation and linear and horizontal distance from the receiver on signal quality. A scatter plot showing signal quality, measured by the percentage of packet loss, relative to increasing overall distance from the receiver is given in Figure 16. Overall distance was calculated using the same method given in Equation 2.

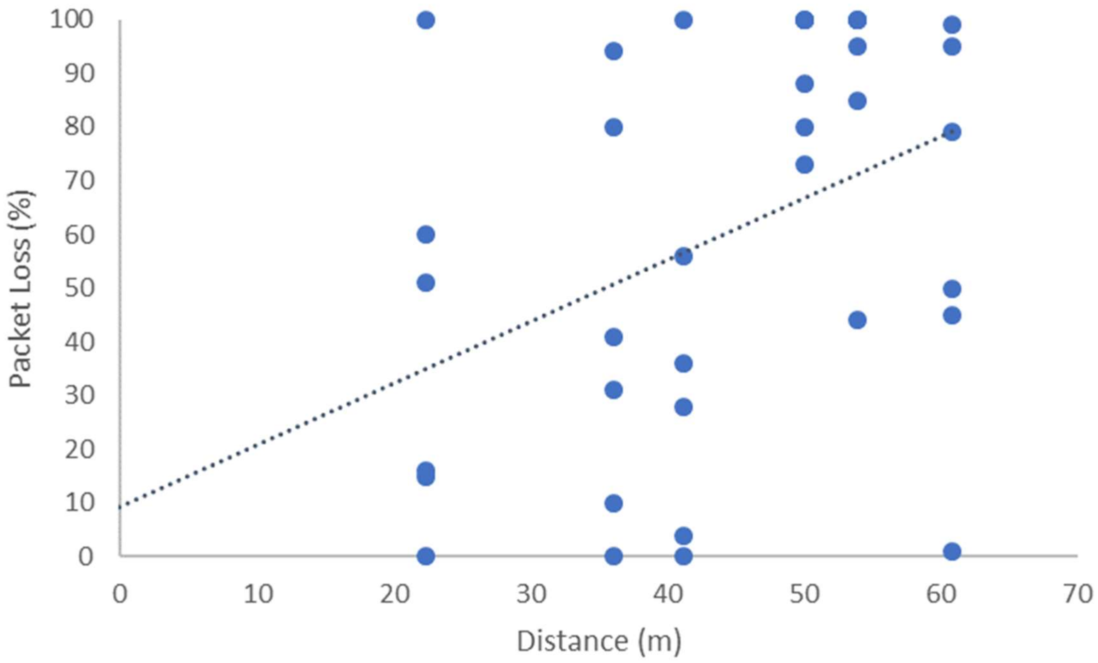

Figure 16: A scatter graph showing the effect of increasing distance on packet loss at different orientations whilst lying down in a prone position, facing the receiver

A significant positive correlation was found between the combination of head orientation, overall distance from the receiver and signal quality, when lying in a prone position, when facing the receiver (Pearson correlation =.391, *p* = .018. R-squared showed that a proportion of the variability was of the response data around its mean was due to overall distance from the receiver under these conditions (R^2=0.44). This hypothesis can therefore be accepted; the combination of distance and head orientation has a strong relationship on signal quality whilst lying prone on the ground, facing the receiver.

4.6 Signal quality vs Distance, Head Orientation and Head Direction from the receiver whilst lying prone on the ground (Hypothesis 6)

To test the effect of head orientation (angle of the iMG from the ground), and head direction (which way the iMG was facing), the same procedures were followed as previously with the participant lying prone on the ground, with their head in a neutral position facing towards the receiver. This was then repeated at each position with the participant as follows:

- Facing towards the receiver with their head at 45 degrees to the ground
- Facing towards the receiver with their head facing down towards the ground
- Facing away from the receiver with their head in a neutral position

- Facing away from the receiver with their head at 45 degrees to the ground
- Facing away from the receiver with their head facing down towards to the ground

Experiment 6.1 was conducted to assess the effect of the combination of linear distance, horizontal distance, head orientation, head direction and body height from the receiver on signal quality. A heat map showing signal quality at different locations on the pitch with a combined average for head orientation, head direction and body height from the receiver is shown in Figure 17.

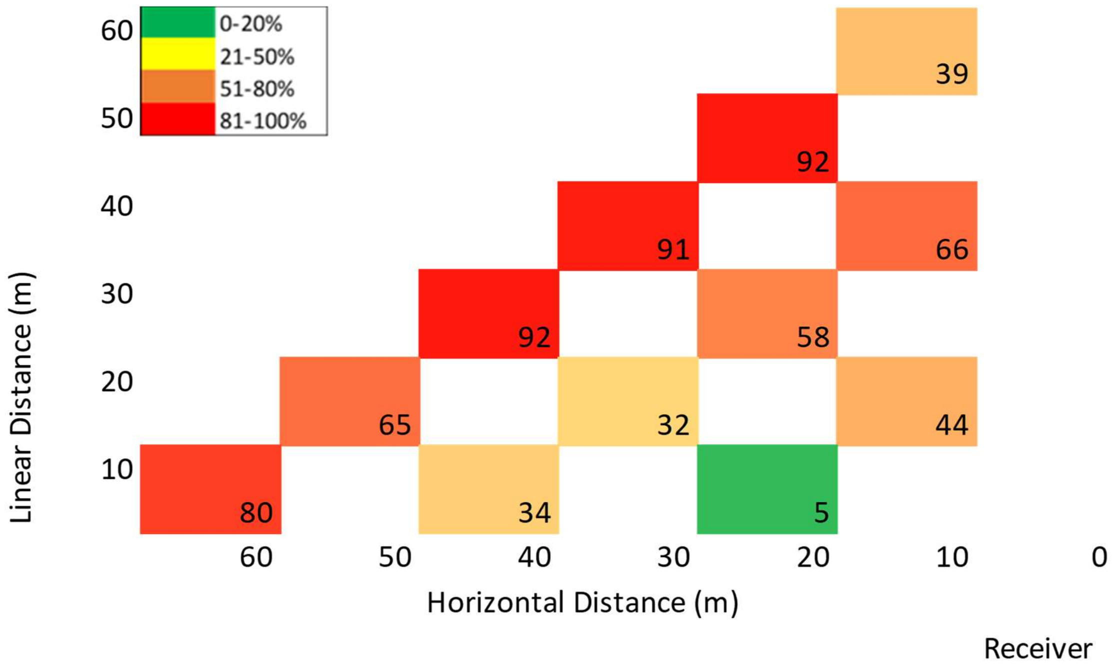

Figure 17: A heat map showing packet loss at different linear and horizontal distances with a combined average for head orientation, head direction and body height from the receiver

A two-way repeated measures ANOVA was conducted to compare the effect of head direction and orientation on signal quality. Mauchly's test indicated that the assumption of sphericity had been met for the main effects of direction as there were only two levels, and orientation, $x^2(2) = 3.81$, $p = .149$.

All effects are reported as not significant at $p < .05$. This was unexpected as both variables were expected to have an effect due to predicted attenuation of signal quality.

A scatter plot showing an increase in distance and signal quality, when all of the results for the different head orientations and directions are combined are shown in Figure 18. Overall distance was calculated using the same method given in Equation 2.

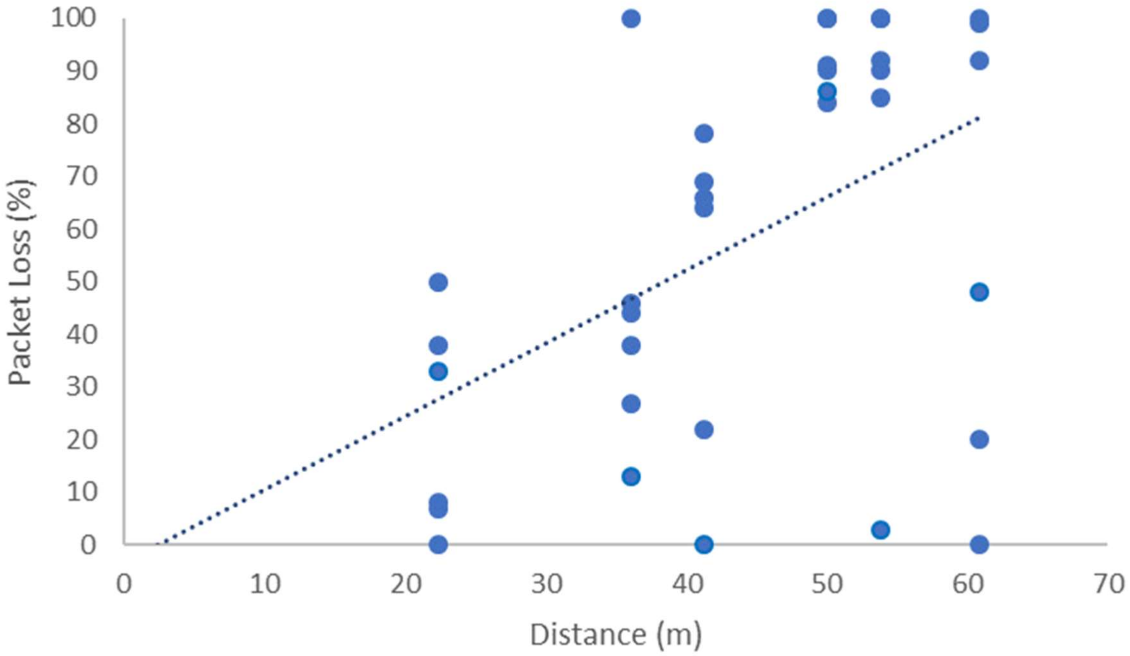

Figure 18: A scatter graph showing packet loss at increasing overall distance with a combined average for head orientation and head direction from the receiver

When lying in a prone position, a significant positive relationship was found between increasing overall distance and signal quality, when combining all results for the different head orientations and directions, (Pearson correlation =.48, p = .006). R-squared also showed that a large proportion of the variability was of the response data around its mean was due to overall distance from the receiver under these conditions (R^2=0.60). This hypothesis can therefore be accepted; the combination of distance, head orientation and head direction had a strong relationship on signal quality whilst lying prone on the ground.

The main findings from the experiments show:

- When standing, facing the receiver with the head in a neutral position, increases in linear and horizontal distance separately have no effect on signal quality.
- When standing, facing the receiver with the head in a neutral position, increases in linear and horizontal distance combined have no effect on signal quality.
- When lying down prone, there is a significant correlation between distance and signal quality, and this correlation holds when incorporating head direction/orientation.
- A significant difference between lying down prone and both standing and kneeling.

- A significant positive correlation was found between the combination of body heights, overall distance from the receiver and signal quality, when facing the receiver.
- No significant difference between head orientations.
- A significant positive correlation was found between the combination of head orientation, overall distance from the receiver and signal quality, when lying in a prone position, when facing the receiver.
- All effects reported where not significant when conducting a two-way repeated measures ANOVA between head orientation and direction.
- A significant positive relationship was found between increasing linear distance and signal quality, when combining all results for the different head orientations and directions, whilst lying prone on the ground.

The main findings help show the need of this study, with signal quality only being affected when the iMG is near the ground, and not being affected by direction or orientation. This is important when applying these results to rugby itself, with hits occurring across a range of different heights, with the majority of them occurring close to the floor. With lying down significantly affecting signal quality this needs to be taken into consideration when looking at data from rugby games.

Section 5: Discussion

5.1 General Findings

The PROTECHT™ system, with the capabilities of measuring and transmitting head impact timeseries data in real time has applications in all contact and collision sports. In addition to rugby union, this system could also be of benefit to other collision sports and combat activities. These include American football (AF), rugby union, Australian Rules football, lacrosse, ice hockey, Gaelic football, roller derby, boxing, soccer, martial arts and military applications. The majority of existing head impact research is focused on AF, rugby union and rugby league.

In collision sports such as rugby union and rugby league, a majority of head impacts are reported to happen during the tackle event, to the tackler (Fuller et al., 2008; Roberts et al., 2017; Roberts, Trewartha, England, & Stokes, 2015; Stokes et al., 2019; Tierney et al., 2016; West et al., 2020). The safest head position of the tackler is head up with contact at the players thigh (Tierney et al., 2016), with incorrect head position leading to a significant increase in head injuries (Sobue et al., 2018). In AF, players on the offensive lineman (OL) and defensive lineman (DL) will stand in either a two-point or three-point stance before the ball is snapped. With both stances, the players' heads are lower to the ground than when standing, with a three-point stance being lower than when kneeling. This means that when players begin to block, they are facing the ground, with the initial impact being sustained low to the ground. For successful transmission of head impact sensor data, the PROTECHT™ system must reliably transmit when the player's head is in these positions. In other contact sports, the size of the pitches, rinks etc., will influence the PROTECHT™ system's ability to transmit data successfully. Optimising the applicability of the system for a wider range of contact sports is therefore necessary. The system needs to accommodate the typical head impact kinematics and ensure reliable transmission, in situations where head impacts are more likely to be sustained. This will enable head impact dynamics to be studied and better understood in sports with limited existing data. This is particularly important for female athletes in contact sports.

Recent pending medical negligence lawsuits in rugby union (Dyer, 2020) and considerable previous AF cases (Azad, Li, Pendharkar, Veeravagu, & Grant, 2016; Guskiewicz et al., 2007; McKee et al., 2009) highlight the urgency required for the development of reliable, quantitative methods of measuring head impact exposure. These medical negligence lawsuits also have implications for insurance policies (Dyer, 2020). The most recent publicly available WRU insurance coverage did not cover any neurological injury and states it doesn’t cover degenerative conditions (Welsh Rugby, 2016). Scottish Rugby’s most recent insurance is similar as the cover for neurological injuries only covers the player if they are completely unable to function after the injury (Scottish Rugby, 2020) This highlights the risk players are taking with regards to their safety.

With insurers not willing to cover neurological injury, this highlights the importance of getting head impact exposure data accurate and in real time, to help protect players. If these problems continue in rugby union then lawsuits involving clinical negligence similar to the $1.6 billion pay-out from the NFL to former AF players is likely to happen (Legg, 2015). There is currently only one insurer who will cover the NFL and national collegiate athletics association (NCAA) AF (Fainaru & Fainaru-Wada, 2019b).

Once the data from these systems is understood, this enables researchers to comprehend what impact and duration values have on the individual and more generally. This then enables the introduction of minimum standards for recording and reporting of head impact data across sports. This may also be a necessary requirement if head impact telemetry data is to be accepted as scientific evidence in legal settings (Christensen, Crowder, Ousley, & Houck, 2014; Edmond, 2004). For data from HIT systems such as PROTECH™ to be admissible for court, it must demonstrate reliability, repeatability and validity, for the data to be used (Christensen et al., 2014; Edmond, 2004). Currently, there are no accepted thresholds for head impact severity, partly due to the variability in methods used globally to record head impacts in sports (Patton 2014). Greater understanding of impact severity has implications of considerable gravity for contact sport organisations. It is likely that insurance companies will increasingly refer to head impact telemetry data in underwriting policies regarding brain injury, both acute and long term. It is important that these decisions be based on optimised systems which can provide reliable data from anywhere on the pitch, particularly in player positions and orientations susceptible to possible brain injury. Without insurance, no sports can operate.

It is apparent from the results that the two main problems are distance from the receiver and when the player is lying prone on the ground. These two variables can’t be changed as in rugby a lot of the game is spent on the floor with tackling and rucks being the two most common match events (Fuller et al., 2007). During a three year study, tackles were found to be the cause of 76% of head injury assessments (HIA), with the tackler experiencing significantly greater propensity for an HIA than the ball carrier (Tucker et al., 2017). With studies conducting video analysis of games, they will miss head impacts which occur during rucks as they will not be visable on video. This is another reason why the PROTECHT™ system is important as it can measure impacts from players which aren't visable on video. However, with the signal quality being affected for the impacts close to the ground, this reduces the ability of medics to able to monitor their players' loads. This means that changes to the PROTECHT™ system will be needed to make sure signal quality is not affected by these variables; otherwise data will be compromised for the two most common match events. The positive from the testing is that neither head orientation or head direction have a significant effect on signal quality.

5.2 Body Height

5.2.1 Effect of Head Height on Signal Transmission

The results show us that there is a significant difference in signal quality when impacts are transmitted at different body heights. The only significant differences were between standing and lying, and kneeling and lying. No significant difference was found between standing and kneeling, however, so there is only a problem in signal quality when lying down. This was expected, as previous research found that antenna proximity to the ground significantly limits radio frequency range (Janek & Evans, 2010). The results from this study indicated that as the height of the antenna approached a ground plane, its radiation pattern changed such that the, horizontal propagation shortened (Janek & Evans, 2010). This results in the vertical radiation pattern being compressed, producing areas of limited to no horizontal radiation close to the ground (Janek & Evans, 2010). This means that, with the type of antenna being used in the PROTECHT™ system, the closer the player and antenna are to the ground, the more it starts to affect the radiation pattern of the radio waves. This affects the overall range of the system, because with areas of the pitch having no horizontal radiation when close to the ground, the antenna range is narrowed. This affects the horizontal range of the system, making it almost completely directional, so that it only records impacts directly in front of the receiver. With the vertical radiation pattern also being compressed, this affects the linear range of the system by shortening the range. This in turn affects the overall range of the system and the signal quality of the results being collected.

5.2.2 Implications for Rugby and Other Contact Sports

The PROTECHT™ system not being able to reproduce the results across each body height creates a problem. For the system to be reliable it needs to be able reproduce results across any height. As these results showed a significant difference between lying down and the other heights, the system reliability cannot be confirmed with the version used in this study. This has implications for rugby, as impacts occurring close to the ground will, based on these data, be missed. This is due to the majority of match head impact events being tackles and rucks, which typically occur when a player is low to the ground (Fuller et al., 2007). With 76% of HIAs occurring during tackles (Tucker et al., 2017), a large proportion of these HIAs will be missed. However, head to head contact has been found to account for the most tackler HIAs (Tucker et al., 2017). These are likely to be recorded, because they are sustained when a tackler goes into a tackle too high. The system should be able to record these impacts, since kneeling and standing did not have a significant effect on signal quality.

With high tackles causing the majority of head impacts leading to concussions, it was proposed that the legal tackle height was lowered (Tierney et al., 2018). This study, reported that the players who aimed to tackle lower actually suffered more concussions than the control group (Stokes et al., 2019). Even with the tackler impacting the ball carrier's head and neck 30% less, tacklers' concussion incidence increased. When tackling lower, tackle technique is crucial to player safety. If the tackler gets their head on the wrong side of the tackle, they are highly likely get kneed or kicked in the head, as their head is going across the ball carrier. This shows that the tackle height being as it is, the ball carrier is at a higher risk of sustaining a head impact than if the lowered tackle height was introduced. With the previously proposed lowered tackle height rule, the risk of sustaining a head impact for the ball carrier decreases, but for the tackler increases.

Currently, the PROTECHT™ system will likely record high tackles with head to head contact, however, head impacts which occur when tackling lower to the ground may be missed. With the proposed lowered tackle height, more head impacts would likely be missed, as head impacts would be lower down to the ground. This would have the greatest effect on backs, who are significantly more likely to be injured during a tackle than forwards (Fuller et al., 2007).

With rucks being the second most common match event in rugby after tackles (Fuller et al., 2007), this is another key part of the game which needs to be monitored for head impacts. The majority of studies looking at head impacts have not used video analysis when researching injuries in sports matches (Gunnar Brolinson et al., 2006; Press & Rowson, 2017; Roberts et al., 2017; Stokes et al., 2019; Tierney et al., 2016). However, this is a problem when looking at rugby specifically, head impacts can occur in rucks and not be seen on video due to players being in the way. This can result in player loads being underestimated by medical professionals. This is where reliable head impact telemetry systems are important, as they can record head impacts missed on film, allowing medical professionals to objectively monitor their players loads. The observed limitation with the PROTECHT™ system, however, is the significant effect that being low to the ground has on signal quality. This will result in most head impacts sustained during rucks, not being recorded. Impacts are already being missed with video analysis, which has an effect on the players sustaining them, as they are at an increased risk of sustaining multiple damaging impacts and continuing to play. This has a greater consequence for forwards than backs when relating to the number of impacts sustained by player position in rugby, as they are more involved in rucks and mauls. As a result, forwards are more likely to be injured in rucks and mauls than backs (Fuller et al., 2007). All of these injuries would have occurred low to the ground and would most likely have been missed by the PROTECHT™ system when looking at the results.

Body height having a significant effect on the ability of the PROTECHT™ system to successfully transmit data is also a problem in other contact sports. In AF, the positions with the most frequent impacts are OL and DL (Crisco et al., 2011).. With the system not consistently transmitting data below kneeling height, recorded head impact data from these AF positions may not reflect the true number, frequency and magnitude.

Overall, these results show the system to work reliably whilst standing and kneeling with one iMG. For optimal benefit for sports teams and researchers, tests including multiple iMGs must be undertaken to assess the effects on transmission and signal quality.

5.3 Distance

5.3.1 Comparing Current Literature to the Results

The results presented here show that increasing distance between the iMG and receiver does not have an effect on signal quality, when standing facing the receiver with the head in a neutral position. When the conditions change and the participant is lying down prone, there is a direct correlation between the effect of overall distance and signal quality. This was expected, since the strength of the transmitted signal decreases sa the distance increases from the transmitter according to the inverse square law (Burrows, 1967). The inverse square law is a physical quantity that is inversely proportional to the square of the distance from the course of that physical quantity (Burrows, 1967). The cause for this is the geometric dilution corresponding to point-source radiation into three-dimensional space (Burrows, 1967). What this means is that the further you are from the receiver the more spread out the radio waves are because of geometric dilution, so the signal gets weaker the further you are from the receiver, meaning signal quality gets worse in the system. However, the signal was not expected to decrease to the extent shown in the results.

The greater the distance between the iMG and the receiver, the more chance there also is of obstacles interfering with the signal. Obstacles dampen an electromagnetic signal and therefore reduce its signal strength (Burrows, 1967). There were no obstacles in this study, but when the system is applied in games and training there will be many obstacles affecting it, other iMGs and players' bodies, other obstacles which the PROTECHT™ system will have to be able to deal with. The definition of an obstacle depends upon the transmission frequency the system uses (Burrows, 1967). Obstacles such as other electronics which transmit a radio frequency have been taken into account by the PROTECHT™ system transmitting on a frequency with no other frequencies which can interfere with it. With this being found in literature, finding a distance where the PROTECHT™ system is reliable enough is useful to know as then if needed, more antennas can be used to make up for this drop off at distances further away or different antennas can be used (Burrows, 1967). There are different options as to how to solve the issue with increasing distance. Both antenna placement and the type of antenna being used can be changed. All of these are different ways in which the PROTECHT™ system can be optimised. By using several antennas, it is possible that at least one antenna is in line-of-sight with the iMG, improving the distance of the system (Lazaro, Girbau, & Villarino, 2009). With antenna having different radiation patterns it is important to place them in the position where they will be most effective. With radiation patterns being compressed when lower to the ground, this means that the receiver needs be moved to wherever gets the best signal quality for lying prone on the ground. Signal quality is not affected whilst standing so antenna placement can be moved for prioritising improved signal quality when lying prone on the ground.

5.3.2 Implications for Rugby and Other Contact Sports

When the conditions are changed, so that the player is lying down, this is when the problems occur. When lying down, average packet loss per impact is already above 25% at just 30 metres away from the receiver, while at 60 metres, average packet loss per impact is around 90%. This means that close to the receiver, 25% of each impacts packets will be missing, and at only 60 metres, nearly every impact has complete packet loss. This is not reliable enough to be able to determine the type of impacts that cause particular magnitude impacts. This is because in rugby contact events can occur anywhere on the field, which is 100 metres in length and 70 metres in width, plus, a maximum of 22 metres of in-goal area. Thus, if a receiver is positioned ten metres back from the half-way line, it will be 106 metres to the opposite corners of the pitch. This means that a large proportion of impacts sustained are likely to be missed with the current system settings.

Whilst standing and kneeling, facing the receiver with their head in a neutral position, the findings will have a positive effect on rugby. Since distance didn't influence signal quality under these conditions, that data will be collected from even the furthest sides of the pitch. Data from standing tackles, mauls, scrums and lineouts will all likely be collected, under the conditions tested in this research. This is important as tackles are the most common match event in rugby (Fuller et al., 2007), with head to head tackles causing the highest number of HIAs (Tucker et al., 2017). These impacts should be measured by the PROTECHT™ system over the entirety of the pitch. Other match events were rated by the risk of injury as follows: lineout- very low; maul and tackle- average; scrum- high (Fuller et al., 2007). Being able to monitor each of these match events regardless of their risk of injury is important and the PROTECHT™ system has shown it can do this. This will allow teams to compare the number of impacts players are experiencing and monitor their loads.

The data given to the rugby teams when lying down won't be as informative as desired, but this is something development of the system will improve. With this study showing almost all impacts will have complete packet loss after just 60 metres, this means that teams won't be able to measure all of the impact's players are experiencing, but the data they do get can be used. This affects match events such as: tackles, rucks, and when mauls and scrums collapse. With research finding that when players actively tried tackling lower, it actually caused more concussions for the tackler (Stokes et al., 2019), the PROTECHT™ system will need to be able to measure these impacts. With the results showing that the data starts to be lost after just 30 metres from the receiver, it means there will be limited data from these tackles, dependent upon what height the tackle occurs.

Another issue with the short range of the PROTECHT™ system, under these conditions, is when scrums and mauls collapse. Scrums were found to carry a 60% greater risk of sustaining any type of injury, when compared to a tackle (Fuller et al., 2007). Research has found that seven percent of scrum injuries and 57% of maul injuries were sustained when they collapsed (Fuller et al., 2007). With a proportion of these injuries being head injuries, the PROTECHT™ system will only be able to measure these impacts if they occur relatively close to the receiver. This limits what comparisons can be conducted between the different matches. When looking at where these impacts happen on the pitch itself, the majority of match events happen in centre-field, in the middle of the pitch (Fuller et al., 2007). When comparing the results to these findings it shows that when the iMG is close to the ground, the majority of the data will be recorded. The problem is that any of the data passed mid-field or on the far side of the field from the receiver will not be measured, due to poor signal quality. Under these conditions, teams' data will be limited with the PROTECHT™ system. However, with all of the data being collected whilst standing and kneeling, teams will still have data to be able to monitor player loads.

This has an even greater effect on AF results. This is because the ball can only be placed between the hashes on the pitch. The closest distance for the ball to the receiver, if the receiver is ten metres away from the sideline in line with the halfway line, is 28.25 metres. The furthest the ball can be placed is 60.82 metres away from the receiver, if the receiver is in the same place. Packet loss is already above 25% at 30 metres from the receiver and 90% at 60 metres Implications of this include the system potentially missing many impacts sustained by OL and DL positions, to whom the highest frequency of head impacts in AF are reported to occur (Crisco et al., 2011).

The PROTECHT™ system's reduced ability to be able to receive data when distance increases is not just a problem for rugby union. Sports such as rugby league, AF, soccer, lacrosse and field hockey have a similar rectangular area of play. To successfully transmit data across the entire pitch, the systems transmission settings would need to be improved before it can be used across a variety of sports.

5.4 Head Orientation

5.4.1 Comparing Current Literature to the Results

After conducting an experiment to test the effect of head orientation whilst lying prone on the ground, it was found that there was no significant difference between the results. This was unexpected due to the way that signal quality is affected different head orientations (Burrows, 1967; Janek & Evans, 2010). These authors reported that reflections off different objects can cause signal attenuation, so the fact that changing head orientation didn't have a significant effect on signal quality reflects the systems reliability. There is currently no HIT system which has reported the effect of head orientation on signal quality. Previous research looking at RFID tags on shipping containers investigated at the effect of changes of orientation of RFID tags. They found that tags facing outwards, towards the receiver, had the highest likelihood of being read successfully (Clarke, Twede, Tazelaar, & Boyer, 2006). These authors also reported that the presence of objects between the tag and the receiver compromised the read rate (Clarke et al., 2006). This is something future testing should consider, as bodies between the iMG and receiver could be affecting signal quality. These results do not reflect this literature, however, as orientation cannot be controlled during a game, the orientation not being a significant factor on signal quality is a positive.

There was a significant positive correlation between head orientation and overall distance, such that signal quality diminished when the iMG distance increased. This was expected, since there was also a significant correlation between an increase in distance and an increase in packet loss when lying prone on the ground. In this study, packet loss represents a decrease in signal quality (Burrows, 1967).

5.4.2 Implications for Rugby and Other Contact Sports

Given that head orientation does not significantly affect signal quality, the PROTECHT™ system will be capable of receiving impacts at any orientation, under the conditions used in these experiments. Head orientation cannot be controlled during a game, so this would have been a significant problem to overcome. If the conditions change and distance also becomes a factor, signal quality gets worse. When the signal quality gets worse this affects the reliability of the results being produced by the PROTECHT™ system

These results have shown that under the limited conditions tested in this study, head orientation was not observed to affect signal quality. In tackles, the tackler's head is supposed to stay upright going into the tackle so that they can track the ball carrier's hips and make a safe tackle. Therefore, the iMG will stay at a neutral angle to the receiver. When the tackler is looking down, however, this was shown to have statistical significance for causing tackle related significant head impacts (Tierney et al., 2016). This is similar for ball carriers, as research has shown that ball carriers tend to go into contact with a straight back and their head down (Tierney, Denvir, Farrell, & Simms, 2018). Lineouts differ, as at the start of a lineout the players' heads remain at a neutral angle as they are facing towards the hooker. This changes when the players jump for the ball, as players will be looking up towards the sky when lifting the player into the air. Another example of the orientation changing is during scrums and mauls, their heads are facing directly down towards the ground. What the research presents is that head orientation changes all the time throughout games and training exercises, and this should be recorded by the system.

5.5 Head Direction

5.5.1 Comparing Current Literature to the Results

Head direction was tested whilst lying prone on the ground. When the effect of head direction and head orientation where compared, no significant effects were found. This means that no combination of head direction and head orientation was significantly worse than the other combinations. Further testing needs to be conducted due to the limited number of testing undertaken. However, this was unexpected as both variables were expected to have an effect due to predicted attenuation of signal quality (Burrows, 1967; Janek & Evans, 2010). When RFID tags were facing towards the receiver, it was found that they had the highest chance of successfully being read (Clarke et al., 2006). When there was water between the tag and the receiver, only 25% of the tags could be read (Clarke et al., 2006). They also found that in general, when there were objects between the tag and the receiver, the read rate was worse (Clarke et al., 2006). The study concluded that the direction that the tags are facing does make a difference, especially when coupled with an obstruction between the tag and the receiver (Clarke et al., 2006). The fact that direction was not a significant factor for signal quality contracts current literature. However, since direction cannot be controlled during a game, this is an important result for the PROTECHT™ system.

5.5.2 Implications for Rugby

Head direction, or the direction that the iMG is facing relative to the receiver, did not have a significant effect on signal quality. This is a positive for the system, as head direction cannot be controlled during training or games. For scrums, the player will always be facing side-on to the receiver, as scrums go in the direction of play. However, scrums can rotate and collapse, which changes the players' head directions. Research has found that over three seasons only five percent of scrums collapsed, but the likelihood of sustaining any type of injury was four times higher and the severity of injury was six times higher (Roberts, Trewartha, England, & Stokes, 2015). This shows the importance of being able to receive data at all different head directions, as this cannot be controlled and head impacts which are sustained when scrums collapse would be missed. Mauls are similar to scrums, as they also face the same direction the play is going in, and the only time this changes is when they either rotate or collapse. The risk of injury when this happens is lower compared to the risk during a scrum (Fuller et al., 2007). Lineouts only occur on the side-line, which means that players will either be facing towards or away from the receiver. Again, this can change if a jumper is dropped, but this rarely happens. Lineouts were found to have the lowest risk of injury when compared to all other match events (Fuller et al., 2007), but it is still important to be able to measure them, as there is still a risk. During the tackle is when head direction changes the most, as it is an open skill where both tackler and ball carrier are moving (Seminati, Cazzola, Preatoni, & Trewartha, 2017). Research looking into the different types of tackles found that tackles can be characterised into two categories: front-on tackles and side-on tackles (Tierney et al., 2018). When looking at three random European Rugby Champions Cup games, there were 122 front-on tackles and 111 side-on (Tierney et al., 2018), which means that players' heads frequently face different directions to the receiver in tackles. Since head direction was not found to affect signal quality, provided the player isn't on the ground, health professionals can use the data knowing that it reflects the true load the player has experienced during the game or training. This allows them to make an informed decision on the players involvement in future training sessions and games. Signal quality not being affected also shows that the system is reliable enough to consistently produce the same result.

As packet loss increases with increasing distance, this creates a problem for the system, as it needs to be able to record impacts across the entire field. If the system is not able to do this, it will result in impacts being missed. When not directly facing the receiver, the system experienced packet loss at just 20 metres, resulting in impacts being missed. When these distances are compared to where the majority of match events take place in rugby matches, it is expected that data will be affected as well. With a large proportion of the match being played in mid-field and centre-field (Fuller et al., 2007), this means that data some data will be collected from these areas, and whichever flank the receiver is set up on. The left flank was found to have a higher percentage of match events than the right flank (Fuller et al., 2007), so this is something to consider when setting up the receiver. However, when match events happen on the far side-line or in either 22, data will be affected either partially or completely, when the player is lying on the ground. This means that the system is not reliably reproducing results over the entirety of the field, and that the results it is producing are missing data. This is significant as it effects the use of the system. Without being able to collect data over an entire pitch, sports teams will not be able to monitor the true load of players without further system optimisation.

5.6 The Importance of Head Impact Telemetry

5.6.1 Overview

Head impact telemetry has evolved considerably over the last five years, in parallel with miniaturisation of electronic componentry. In the case of the PROTECHT™ system, electronics have been successfully integrated into bespoke mouthguards, tightly coupled to the upper dentition. Amid the current global concerns about brain injuries in contact sports, there is an increasing demand for reliable, objective and impartial head impact data to inform player safety. A 2020 review of the head impact telemetry field reported an alarming 68% of published studies in this domain lacked video verification and, thus, likely include false positive impacts (Patton et al., 2020). Other reports have found poorly coupled sensors such as helmets, headbands and skin patches to grossly overestimate head impact magnitude (Camarillo et al., 2013; Joodaki et al., 2019; Kuo et al., 2018; Wu et al., 2016). This highlights the importance of real-time data combined with video verification. This provides objective and impartial data to assist medical professionals in their decision-making process for the player return-to-play protocol.

A reliable head impact telemetry system could also be employed to provide objectivity for a highly contentious issue in rugby union: whether scrum caps prevent concussion. While many players and parents believe that wearing scrum caps in rugby will keep them safe, credible studies have reported no benefits for concussive injury prevention (Menger et al., 2016). This is because wearing scrum caps leads to increased risk taking behaviour (Menger et al., 2016). The benefits of wearing a scrum cap need to be researched properly to establish if there are any benefits in wearing a scrum cap. A HIT system such as a mouthguard which is coupled to the skull and doesn't overestimate impacts, would be beneficial long term for rugby union and other contact sports. The PROTECHT™ system addresses the coupling issue and if combined with video and waveform verification, can provide reliable head impact data. The distances over which these impacts can be transmitted, however, must be optimised before systems such as this could be depended upon in cases involving the legal system. The real-time capability is important in this context, as some current rugby union medical negligence lawsuits involve players being sent back on the field despite suffering brain injuries undetected at the time (Cisneros, 2019).

5.6.2 Player Safety and Comfort

Player safety is the main priority when it comes to a HIT system. If a player is not safe wearing it then it will not be worn at all. Player comfort is equally as important when designing a HIT system. The difficulty when designing a HIT system is finding the balance between safety and comfort. One of the problems faced when designing the PROTECHT^{TM} system was players finding the guards uncomfortable with them being too tight and the tops of the iMG being too high. To make them more comfortable the guards could be looser, and the tops shaved down, but with the guards being looser it could affect the data due to the extra movement. The tops of the guards being lower means that less of the teeth are protected so are not as safe. Finding the balance between safety and comfort is crucial to the success of a PROTECHT™ system as without one or the other the system will not be successful.

5.7 Limitations

5.7.1 Reliability

For the PROTECHT™ system to become reliable, it needs to be able to reproduce results under a variety of different conditions. Systems such as the PROTECHT™ iMG will soon play a crucial role in head injury lawsuits and help establish new insurance policies for contact sports. Therefore, it is paramount that sensor systems can demonstrate reliability in recording data and reporting with clearly established limitations. This is to prevent end users such as insurance companies being misled by the data. The limitations of this study are that not all conditions were tested due to time constraints, equipment and the number of participants involved. Due to time restraints and practicality, range testing was not conducted over the entire pitch. Predetermined distance was calculated beforehand, and the range was tested. As the pitch was not covered entirely, a true reflection of the reliability of the PROTECHT™ system is not known. At the start of the investigation there were two iMGs with the software necessary for the investigation. However, during the investigation one of the iMGs stopped working, leaving only one iMG. This meant it was not possible to investigate the effect of multiple iMGs. Even though this could not be investigated, the PROTECHT™ system makes sure that when multiple iMGs send data to the receiver at the same time, each iMG waits for a clear channel before sending their data to avoid data loss.

5.7.2 Weather

Weather became an extraneous variable during the testing, as time constraints did not allow all the testing to be conducted over the course of one day. Changes in rain, air moisture and temperature could have influenced the results (Breton et al., 2017). Pilot testing confirmed that weather conditions do affect the results, so it was important to keep conditions as similar as possible. Testing was therefore conducted on days which were as similar as possible, but it is impossible to exactly replicate the conditions from the previous day's testing. This is an important variable to monitor and a variable which should be tested in the future, because weather conditions during training and games cannot be controlled.

5.8 Conclusions and Future Directions

This study represents an initial step in the process of investigating the transmission range of the PROTECHT™ system. Some issues surrounding transmission range in HIT systems were identified. This resulted in the following variables being investigated: distance, body height, head orientation and head direction. Overall, when standing and kneeling, it was found that there was no difference in signal quality and there was virtually no packet loss. However, when lying prone on the ground, it was found that there was a significant difference in signal quality from both standing and kneeling. It was also found that when lying down, increasing distance had a significant effect on signal quality. When looking for a relationship between overall distance and each variable, they were all found to have a positive correlation. So, an increase in overall distance increased packet loss, which was represented by signal quality getting worse. What these results show is that lying down affects signal quality and, when lying down, distance also becomes a factor.

The other variables individually don’t affect signal quality, but when under the specific conditions of players lying down prone with increasing distance, then there is a relationship between these variables and signal quality getting worse. How this affects rugby specifically is that some of the impacts will either have reduced signal quality or will be missed completely. The signal quality of impacts will not be affected when standing or when at a reasonable distance from the ground but will start to be affected when low to the ground. When positioned low to the ground, signal quality for these impacts will get progressively worse with an increased distance from the receiver. When lying down, there is a significant correlation between distance and signal quality (packet loss) and this correlation holds when incorporating head direction and orientation.

Future investigations using the PROTECHT™ system should investigate ways to improve signal quality when low to the ground. Until this is achieved, data produced from the system needs to be clearly presented with the reliability shown, to prevent users being misled. The effect of multiple iMGs on the data transmission can then be looked at once this has been resolved. With rainfall and ground moisture levels influencing signal quality, investigating water sports such as water polo and the expected limitations with the signal would be of interest to the future of the PROTECHT™ system. Once these minor limitations have been resolved, the PROTECHT™ system has the potential to be used in many different sports providing a new insight on head impact data.

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