A Comparison of Worst Case Scenario Running Demands Between U20 and Senior Elite Rugby Union Players

Georgina Saunders

Submitted to Swansea University in fulfilment of the requirements of the Degree of Masters by Research 2023

Abstract

Introduction. Previous research has analysed the Worst Case Scenario (WCS) running demands in Elite senior Rugby Union and U20 Rugby Union separately, but no study has researched the difference in WCS running demands between the two. Multiple studies have analysed the Total Distance (TD) and High-Speed Running (HSR) distance covered by positions in Rugby Union but have not analysed the WCS HSR and TD demands. Analysing these demands can aid coaches in creating training sessions to optimally prepare the players for match demands. **Methodology.** This study analysed the differences in WCS TD and HSR demands between U20 and Elite senior international Rugby Union players. Data was collected from the French, Georgian and English senior rugby teams (n=146) and from the English U20 Rugby Union players (n=43). All players wore 10Hz Catapult or StatSports GPS units. The players were split into forwards (F) and backs (B), and then further categorised into positional subgroups (FR = front row; SR = second row; BR = back row; HB = halfback; MF = midfield; B3 = back-three). The metrics measured were total distance, relative metres per minute, high-speed running, and high-speed running metres per minute. **Results.** Overall, the study demonstrated that the U20s had higher WCS running demands than the seniors. The backs consistently had higher WCS running demands across all epochs when compared to the forwards. The results demonstrated for HSR WCS demands, there was a significant difference between Elite Seniors and U20s ($p<0.001$), between Elite senior and U20 forwards and backs ($p<0.001$), and, between different positional groups ($p<0.001$). Additionally, for HSR WCS demands, there was a 15% difference between seniors and U20s at 600s epoch. When analysing HSR m/min WCS demands, there was a significant difference between seniors and U20 ($p<0.001$), forwards and backs ($p<0.001$) and positional groups ($p<0.001$). For TD WCS demands, there was a significant difference between seniors and U20 ($p<0.001$), forwards vs backs ($p<0.001$), and positional group ($p = 0.003$). The difference between forwards and backs were all less than 10%. There was also a significant difference for relative m/min between seniors and U20s ($p<0.001$), forwards vs backs ($p<0.001$), and positional groups ($p<0.001$). **Conclusion.** This study demonstrates the different WCS running demands of U20s and Elite senior international rugby players, and the different WCS running demands between forwards, backs, and other positional subgroups. This novel study into men's Rugby Union provides new insight into the elite game and will support coaches in creating training sessions in which players reach their WCS running demands, that reflect the demands of optimal match performance. This study will also support coaches in developing training sessions to transition U20 players to the increased WCS running demands in senior rugby.

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 19/01/2023

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

Signed [redacted]

Date 19/01/2023

I hereby give consent for my thesis, if accepted, to be available for electronic sharing

Signed [redacted]

Date 19/01/2023

The University's ethical procedures have been followed and, where appropriate, that ethical approval has been granted.

Signed [redacted]

Date 19/01/2023

Table of Contents

Acknowledgements

Firstly, I would like to thank Professor Liam Kilduff for guiding me throughout this postgraduate study and ensuring I stayed focused and on track to finish the project whilst encouraging me to develop my understanding and knowledge.

I would also like to thank Dan Cunningham and David Shearer for their help and support throughout the last 18 months, I really appreciate them both being at the end of zoom or email if I ever needed help (especially with statistical analysis)

Finally, I would like to thank my parents, family and friends who encouraged me to continue my studies and finish my masters project throughout the last 18 months.

List of Figures

List of Tables

List of Abbreviations

B – Backs

B3 – Back 3

BIP – Ball in Play

BR – Back Row

CV – Coefficient of Variation

dGPS – Differential Global Positioning Units

F- Forwards

FR – Front Row

GPS – Global Positioning System

HB – Half Backs

HML – High Metabolic Load

HR – Heart Rate

HSR – High Speed Running

ICC – Interclass Correlation

M – Mean

MF – Midfield

MPM – Meters Per Minute

OOP – Out of Play

RHIE – Repeated Bouts of High Intensity Exercise

RL – Rugby League

RU – Rugby Union

SD – Standard Deviation

SR – Second Row

TD – Total Distance

TMA – Time Motion Analysis

Vmax – Maximum Velocity

W:R – Work to Rest Ratio

WCS – Worst Case Scenario

Chapter 1 – Introduction

Rugby is a high intensity intermittent sport, dominated by high force impacts (Austin, Gabbett & Jenkins, 2011), consisting of recurring events in which short periods of high-intensity bursts lasting between 5 and 15 seconds, with low intensity exercise or rest of approximately 40 seconds (Docherty, Wenger & Neary, 1988). Since 1995, when Rugby Union became a professional sport, there has been an improving understanding of the demands, with the game constantly evolving, including the implementation of many rule changes. This in turn has required changes in the required fitness profile of the players, such as endurance, speed, agility, power, flexibility, and other sport-specific skills (Duthie, Pyne & Hooper, 2012).

Global Positioning Systems (GPS) have been used to quantify the workloads of players during competitive matches and training at elite level (Cahill, Lamb, Worsfold, Headey & Murray, 2013). This development allowed coaches and sport scientists to access more accurate information regarding the running demands of players in both competition and training (Hartwig, Naughton & Searl, 2011). Several studies have specifically reported the movement demands of professional rugby players; Tee et al. (2016) found that on average, Rugby Union players cover 5050 ± 1639m per game, with a sprinting distance of 10 ± 4m per minute; Cahill et al. (2013) highlighted a mean total distance per game of English Premiership Rugby players being 5850m and 6545m, forwards and backs respectively; and, Jones et al. (2014) demonstrating that forwards covered 60.4 ± 7.8 $m{\bullet}min^{-1}$ and backs covered 67.8 ± 8.2 $m{\bullet}min^{-1}$ during European Cup games. These studies illustrated the different positional demands in professional rugby, but fewer studies have researched the running demands in U20 rugby. There are differences in match demands and intensities between senior level rugby and U20 age groups. Cunningham et al. (2016) highlighted that U20 forwards, on average, covered 5.37 ± 0.83km, compared to backs who covered 6.23 ± 0.08km on average per game, which are noticeably lower than the distances Jones et al. (2015) highlighted for English Premiership rugby players. Cunningham et al. (2016) also demonstrated that forwards and backs cover, on average 61.5 ± 8.0m and 69.1 ± 7.6m of HSR distance each game respectively.

Bridgeman & Gill (2021) completed a systematic review comparing age-grade and senior level Rugby Union using GPS and accelerometer units. There was a total of 1206 participants in 34 studies, 17 for senior rugby, and 17 from age-grade rugby. After collating all the studies, the results showed that international forwards covered 6427m on average per game, compared to backs who covered 7002m per game. This systematic review completed in 2021 demonstrated that forwards and backs are now covering more distance than they used to, which is likely due to the increased speed and intensity of the game. The collated U20 studies demonstrated that both forwards and backs covered significantly less per game than senior level (F = 4846, B = 5886). This systematic review also highlighted the differences in HSR during match play between senior rugby and age grade. Pollard et al. (2018) reported that backs performed more HSR than forwards in international rugby (7.5 ± 1.9 m/min vs 3.3 ± 1.5 m/min), reflecting previous findings by Jones et al. (2015) demonstrating backs completed more HSR than forwards (509 ± 150m vs 231 ± 167m). When comparing senior to age-grade rugby union, the studies demonstrated that front row, second row and back 3 positions completed more HSR distance in age-grade than senior, whereas senior midfield positions covered more HSR distance than age-graded players.

The studies above analysed and compared the game demands of senior level and age-grade rugby, and the following studies analysed the difference in demands throughout match-play. A study completed by Jones et al. (2015) used a fixed time epoch of 10 minutes, with transient fatigue changes being reported throughout match-play, with the greatest demands covered during the first 10-minutes of each half. The results showed that the 60-70-minute epoch recorded the lowest metreage (58.2 $\pm$ 16.3m$\cdot$min^{-1}) on average, coupled with the lowest bouts of HSR and accelerations. This demonstrated that the metreage was significantly lower in the second half of the game when compared with the first half (64.7 $\pm$ 10.2m$\cdot$min^{-1} vs 67.6 $\pm$ 8.0m$\cdot$min^{-1}). This study highlights the importance of assessing WCS in Rugby Union to ensure players are prepared for the highest intensity bouts during match play. Using smaller fixed-time epochs highlights the most demanding periods of match-play, but can still underestimate the highest demands, and has been considered inferior to using rolling epochs to assess peak HSR in elite football matches (Varley et al. 2012).

To date, very few studies have looked at WCS in Rugby Union (Reardon et al., 2017; Cunningham et al., 2018; Sheppy et al., 2020), with the majority of studies assessing the average movement demands during matches, which underestimates peak demands, and thus Worst-Case Scenarios in rugby. WCS can be defined as bouts of the single longest ball-in-play time (Reardon et al., 2017) and longest periods and distance of HSR.

A study showed that the average bout of repeated high-intensity efforts (RHIE) was between 28-52 seconds (Austin et al., 2011), therefore, due to WCS situations being a higher intensity and longer duration than a normal bout of RHIE, it would suggest that this would potentially be a longer duration than 28 - 52 seconds. Varley et al., (2012) demonstrated that there was a 20-25% underestimation of peak HSR and 31% overestimation of HSR using a fixed epoch. Cunningham et al., (2018) highlighted that fixed epochs underestimated relative distance (11%) and HSR (approximately 20%) when compared to a rolling epoch. It is important to ensure that coaches are aware of this relative accuracy of using fixed and rolling epochs when assessing WCS.

Sheppy et al., (2020) demonstrated that WCS total distance and HSR demands decreased as the epoch length increased when assessed in women's international rugby. This study additionally illustrated that backs experienced greater WCS demands, with front row players having the lowest WCS values of all positions. To ensure athletes are optimally prepared for the highest demands during competition, it is crucial that the players are training at the same intensity (Gabbett, 2016). Therefore, to ensure players are optimally prepared for competition, WCS demands must be highlighted so the players can train at that intensity, to prepare for the worst demands the players could face during match play.

The aim of the study is to analyse and compare the WCS running demands in elite level Rugby Union between seniors and U20s. The directional hypothesis would state that there will be a significant difference between seniors and U20s, forwards and backs and specific positional groups for both TD and HSR. This could be due to the difference in body mass of the U20s and seniors which are likely to affect the running demands in a different way to the movement demand. These limiting metrics analysed would show this affect and allow future research to consider the effect of body in separate analysis and studies. Additionally, the difference in the WCS running demands between seniors and U20 could be due to the difference in style of play and skill level along with external factors such as the weather or the score of the game.This study is novel as no study has previously assessed rolling WCS demands for HSR and TD on international Elite senior and U20 level Rugby Union. This study can allow us to create specific targets for future running interventions in elite rugby union and gives us scope for future work following on from the results of this study. Being able to understand the difference and similarities between U20 and senior, both positionally and between these two groups, will provide useful information for coaches to understand the changes players will face in match play, and therefore adapt training accordingly.

Chapter 2 – Literature Review

2.1 – Physiological Characteristics of Rugby Union Players

2.1.1– Aerobic Endurance

Changes in physiological capacities seem to follow similar trends to the players anthropometrical characteristics (Duthie et al., 2003). A study was carried out on the Brazilian Rugby Union team assessing the physical and physiological differences between backs and forwards (Rico-González et al., 2021). The results of the Yo-Yo test highlighted that backs covered a much greater distance than the forwards (backs: 2305.9 ± 231.3m; forwards 1802.4 ± 361.2m) which is shown from GPS data during a rugby match. However, when looking into the results of the yo-yo test, we need to be aware that it is a measure of aerobic capacity and the weight of the individual during the turning is important and so doesn't necessarily imply that more distance has been covered by the backs as they are usually lighter than the forwards. This needs to be taken into account as their weight effects the results of the test. Another systematic review analysed the aerobic capacity of U20 age grade Rugby Union players (Owen et al., 2020). This study demonstrated that when the players completed the multi-stage fitness test, backs performed better than forwards for both estimated VO2 max at U19 (50.65 ± 3.76 vs 47.08 ± 4.24 $mL.kg^{-1}.min^{-1}$) and actual stages of the test completed at U20 (102 ± 12 vs 86 ± 15 stages) (Ball et al., 2018). Overall, positional differences were observed in the aerobic capacity of backs and forwards, and more specifically, props were identified to be the worst performers for aerobic endurance (Durandt et al., 2006). This study highlights the differences between positional groups and therefore reinforces the importance of a study analysing the difference in WCS demands between the forwards and backs and more specifically, different positional groups. Fitness tests of aerobic capacity aren't a direct correlation to an athletes HSR and TD during matches but it can suggest the difference between players in different positions. As Rugby Union is predominantly aerobic, with periods of anaerobic bouts including high speed running, physical collisions and explosive acceleration (Bradley et al., 2015), it highlights the importance of the players having a high level of both aerobic and anaerobic endurance.

2.1.2 – Anaerobic Capacity

There is an insufficient amount of data collected analysing the anaerobic capacities of professional Elite senior Rugby Union players, with previous research focussing on cycle ergometry or short intervals on a treadmill (Rigg & Reilly, 1988; Maud & Shultz, 1984; Bell et al., 1993). Rugby Union players are required to have a high anaerobic capacity in order to completed sustained periods of HSR and repeated high intensity efforts such as tackling, collisions, and scrummaging (Deutsch et al., 2007). Austin et al. (2013) created 3 repeated high intensity exercise tests (RHIE backs, RHIE RU forwards test and RHIE RL forwards test) which all include a variety of 10-20m sprints, decelerations, tackles, and scrummaging in the RU forwards test. The study completed by Deutsch et al. (2007) demonstrated that forwards take part in more high-intensity work than backs as they are involved in scrums, rucks and mauls, whereas backs spend 2-3 times longer performing high-intensity running. This study corroborates with the potential findings of this current study as it would suggest that the backs would have higher HSR and HSR m/min WCS statistics when compared to the forwards. This present study is only analysing the running demands of professional rugby union players, whereas Deutsch et al. (2007) analysed other demands such as collisions/scrums/rucks. Therefore, if these other demands were included in this study, then it could suggest the forwards have higher WCS demands in other areas of the game. One study demonstrated that forwards are able to produce a higher absolute peak power output across a range of 7-40 seconds, when compared with the backs, However, when these results are relative to body mass, there is no significant difference (Maud & Shultz, 1984) so this highlights the important of body mass being taken into account when analysing running demands as this study demonstrates that when bodyweight is taken into account, there is no difference. Cho et al. (2019) compared the anaerobic capacity between collegiate level and professional rugby players, which demonstrated that the backs and forwards in professional level rugby had a higher aerobic capacity than at collegiate level rugby. Due to the importance of the anaerobic systems in Rugby Union, it is perhaps surprising there is limited information about the differences between positions. The lack of reliable and replicable anaerobic tests may explain why there are limited studies in this area (Owen at al., 2020). Anaerobic capacity is generally not analysed due to the lack of common tests in the literature. Power, speed, and strength will all use the players anaerobic systems and therefore these factors are used as an estimation of the players anaerobic capacity.

2.1.3 – Speed

Speed, acceleration, and deceleration are important requirements in Rugby Union as it is vital that all players can make short sharp changes of direction, can sprint to break away from defenders and can catch attackers. Rugby players typically perform sprint distances of 10-20m but sometimes must sprint over 100m (Deutsch et al., 1998). Most speed tests are completed over 10m, 20m, and 30m. Studies of sprinting distances of 30-40m show that backs are faster than forwards (Gabbett, 2000; Smart et al., 2013). Rigg & Reilly (1988) also demonstrated that professional backs were significantly faster over 40m than forwards (5.81s vs. 6.26s respectively). Another study by Darrall-Jones et al. (2016) demonstrated that backs were faster than forwards over 10m, 20m, and 40m sprints, and, that forwards had lower acceleration that backs over 5-10m and 10-20m.

These physiological characteristics mentioned above can be measured and correlated to external and internal demands which are quantified by using GPS units and HR monitors.

2.2 – Physical Demands of Rugby Union

2.2.1 – Whole Match Demands

Rugby is a high-impact collision sport which is aerobic in nature with high-intensity bouts, including movements such as high-speed running (HSR), tackling and aggressive play (Roberts et al., 2008). The most common ways of measuring physical demands of Rugby Union are using time motion analysis (TMA) or GPS. TMA however, can be time consuming and prone to error as demands and results are influenced by the observer’s knowledge (McKenzie et al., 1989). Early studies conducted demonstrate that in competitive matches 85% of the time is spent in low-intensity activities, and 15% in high-intensity activities (Deutsch et al., 2002). Roberts et al. (2008) completed a study in elite English Rugby Union to assess the physical demands during a competitive match. The study demonstrated that, on average, players cover 5852.5m per game, with 558.5m on average being high intensity running or sprinting. HSR represents only 9% of the total distance covered, lower than the 15% found by Deutsch et al. (2002) found. A study completed by Pollard et al. (2018)

highlighted that on average, Rugby Union players covered 67.6 ± 4.8 metres per minute and an average of 5.5 ± 2.8 metres per minute. The same study also analysed the maximum GPS outputs for metres per minute and HSR metres per minute during a game with the results being 189.9 ± 18.3 metres per minute and 94.6 ± 25.5 HSR metres per minute. Analysing the demands of rugby union as a whole is very limiting as the positions have very different roles during a match. It is much more beneficial to separate the forwards from the backs, and even further down into specific positional groups to ensure the training sessions are developing the areas of each players needs to perform optimally. Therefore this present study differentiates between forwards and backs and further positional groups to allow practitioners to see the difference and create appropriate training sessions.

2.2.2 – Whole Match Demands Using GPS Units

The global positioning system (GPS) emerged in the 1960-1970s and is a navigational system originally developed for the American Department of Defence for positioning, navigation, and timing in the military, but has since been used by the public for many different uses (Scott et al., 2016). GPS technology works through a GPS receiver from a minimum of three satellites in a constellation of at least twenty-four. The original GPS units lacked accuracy due to the low navigation accuracy, as well as the signal between the unit and the satellite being influenced by obstructions such as tall buildings. Modern GPS technology has overcome this issue by using differential GPS (dGPS) (McNeff, 2002) involving the use of stationary receivers placed at known locations on the ground, to compare with the satellites, allowing for a more accurate calculation of the data. GPS units enable three-dimensional movements of an individual or group, with the ability to be tracked over time in air, water or on land-based environments (Larsson, 2003). GPS allows for real-time feedback in sport and is time efficient whilst allowing for simultaneous tracking of multiple athletes, unlike video motion analysis, which can only track movements of one athlete (Aughey, 2010). The development of GPS has enabled them to be augmented to use the inertial sensors; tri-axial accelerometers, magnetometers and gyroscopes which has increased the data available to characterise the activity profiles and load of the athletes (Malone et al., 2017). The technological advances to the GPS units have allowed them to become more valid and reliable whilst being commercially available, from 1 HZ to 5 Hz to 10 Hz units (Gastin & Williams, 2010) and now with

15 Hz units more recently becoming available. In sport, GPS units are worn in a custom-made vest or match shirt, to prevent excess movement and the unit sits between the scapulae.

GPS units provide live movement patterns, distances, and velocities (Cummins et al., 2013) which can be used instead of video-based TMA which requires analysis by trained professionals. Additionally, GPS provides a better understanding of specific and positional physiological demands of team sports and can further be used to design training programmes to optimally prepare athletes for on-field performance (Cummins et al., 2013). There is a vast amount of literature highlighting activity profiles of athletes from field sports which includes markers such as total distance, and velocity bands, whilst also detecting fatigue in matches and identifying periods of most intense play (Aughey, 2010).

There are a significant number of studies which cover the movement demands and physical demands of Rugby Union through use of GPS units (Coughlan et al., 2011; Venter et al., 2011; Pollard et al., 2018; Howe et al., 2020). An early study completed by Coughlan et al. (2011) assessed the movement demands between a forward and a back at elite level Rugby Union. The results highlighted the average distance covered was 6715m and the majority of the game time was spent standing or walking, interspersed with bouts of medium or high intensity running. Additionally, the backs performed more high-intensity sprints and reached a greater maximal speed when compared with the forwards. Venter et al. (2011) illustrated that elite U19 rugby players covered on average 4469.95m ± 292.25m during a game. The outside backs spent 36 mins 12s ± 2 min 21s (60.34 ± 3.92%) of the time walking which is significantly more than the 25 mins 15s ± 5 min 59s (42.1 ± 9.99%) of the front row. These studies highlight the importance to analyse the WCS demands of professional rugby players as both the above studies show that backs cover greater distance and more high-speed running than the forwards. The GPS technology offered a valuable insight into the severity of impacts experienced by the different playing positions which was not available prior to their availability. Pollard et al. (2018) assessed the difference between GPS measurements, and ball in play measurements, in international Rugby Union. The GPS demonstrated that the average metreage covered per minute was 67.6 ± 4.8m and the average HSR per minute was 5.5 ± 2.8m. However, this study demonstrated that GPS underestimated the actual runnning demands when compared to the average ball in play data, which will be discussed in section 8 of this review. Additionally, Sheppy et al. (2020) assessed movement demands in women's rugby and highlighted the players covered, on average, 5.8km per match with whole team reductions from first half to second half (2984m vs 2797m, respectively). This study only used data from players who played at least 60 minutes of the game and during a rugby union game, players are subbed off during the second half and so the number of players whose data was used for this second half would be less than the first half and this needs to be considered when analysing this study. Understanding match requirements can assist coaches with planning specific training sessions and allow for full recovery between training and matches (Venter et al., 2011). However, it would be more beneficial to analyse the game with the differentiation of forwards and backs and more specific positional groups as there are likely to be positional differences and players would benefit from different training stimuli.

2.2.3 – Match Demands – Forwards vs Backs

More recently, Roberts et al. (2008), used TMA to analyse the movement demands in professional Rugby Union. The results illustrated that forwards spend a greater percentage of time in high-intensity activities when compared to backs (F = 11.5% vs B = 3.8%). However, backs spend more time performing high intensity running than forwards (B = 1.6%, F = 1.1%). When comparing total distance covered between positions from Deutsch et al. (1998) and Roberts et al. (2008), the players covered more distance in the 2008 study (forwards = 5581 vs 4240m; backs = 6217 vs 5640m). However, this large difference between the two studies could be due to the different skill level of the players and different metrics used. Even though there was a difference between the 1998 and 2008 study, the backs consistently covered more distance during a game, and this highlights the importance of continually assessing the running demands in rugby union to see how the game is constantly changing and to ensure training is always matching the demands of the game each year. Another study highlighted that backs have a greater total distance than forwards during a Rugby Union match (B = 7225m; F = 6658m) (Cunniffe et al., 2009). Yamamoto et al. (2020) completed a study using GPS to determine match demands in elite Japanese Rugby Union players, and demonstrated the total distance covered was higher for backs than forwards (B = 6392 ± 646.8m; F = 5731.1 ± 507.8m). Assessing the average total distance covered is beneficial to ensure that players are matching or exceeding this in training sessions, but it would be more beneficial to assess the WCS demands as this allows the coaches to push the players harder to ensure they are prepared for the toughest running demands during a game.

2.2.4 – Match Demands - Positional Groups

An early study (Docherty et al., 1988), compared the physical match demands between props and centres. The results exhibited that props spend a greater percentage of their time jogging than centres (17.3% vs 15.5%), but centres spend a much larger percentage sprinting than the props (3.1% vs 0.8%). Deutsch et al. (2007) highlighted that front row forwards spent 22.5% of the relative time jogging and outside backs spent 15.5% of the relative time jogging, these being the highest and lowest of the positional groups, respectively. However, outside backs spend the longest percentage of time sprinting and front row forwards spend the least (0.87% vs 0.11%). A subsequent study (Hartwig et al., 2011) analysed the duration spent in each locomotor category in adolescent Rugby Union players, corroborated the findings above, with the forwards spending a greater percentage of time jogging when compared with the backs (F= 14.5 ± 2.7%; B = 13.6 ± 2.5%) and the backs spending a greater time sprinting than the forwards (B = 1.3%; F = 0.9%). More specifically, Tee et al. (2016) completed a study using GPS to compare the game demands of professional Rugby Union between positions, illustrating again that tight forwards spend a greater duration of time jogging compared to the outside backs (39m/min vs 25m/min), and as previously found outside backs have a greater sprinting distance than all other positions except for the inside backs, and with tight forwards performing the lowest sprint distance (measured as a max speed during the distances which were reported relative to their playing time) (OB = 7.3 $m \cdot min^{-1}$; IB = 9.1 $m \cdot min^{-1}$; TF = 1.5 $m \cdot min^{-1}$). These above studies would suggest that the forwards could potentially have higher WCS demands for TD when compared which the backs, which opposes what is predicted in the study. However, total distance includes low intensity, medium intensity and high intensity running so the backs may cover a greater TD overall even though these studies highlight that forwards cover a greater distance jogging during the game. Cahill et al. (2012) illustrated that scrum halves cover the greatest distance during matches, and the front row the least, with a difference of nearly 2km due to the differing demands of the positional roles. The study also demonstrated that outside backs have the highest maximum speed (31.7 ± 3.2 kmph) with front row forwards having the slowest maximum speed (24.5 ± 3.6 kmph). The outside backs subsequently spent 51.9% of their total distance in the slowest speed category which was a higher proportion than any other position. The explanation for the outside backs having the highest max speed but spending the most time in the slowest speed category is due to the nature of their position, where they make longer faster runs during the attacking phase but cover the backfield when defending so are not constantly following the ball during play. Within the forwards groups, the back row covered significantly more distance and higher speeds than the front row players ($P < 0.0005$), and, covered five times more than the front row at 81-95% of Vmax. This study demonstrates the need for position specific training as each position has very specific demands and therefore to coach a front row player to reach max speeds as frequently as the outside backs wouldn't be beneficial to their position as they aren't making long fast runs during attacking play.

Quarrie et al. (2013) evaluated the positional differences in international Rugby Union. The results highlighted that fullbacks covered the greatest distance (6300m ± 300m) compared to the flankers who covered the least distance (5400m ± 710m). However, when specifically looking at the forwards, the props and hookers covered significantly greater distances at speeds of 2.0 and 4.0 m/s when compared to flankers, but flankers moved further than hookers and props at speeds of 6.0 and 8.0m/s. Jones et al. (2015) assessed the differences between positions analysing metres per minute (±SD). This study demonstrated that half backs have the greatest total metres per minute and tight forwards have the lowest (HB = 69.1 ± 7.5; TF = 60.7 ± 6.0). Additionally, Jones et al. (2015) illustrated that outside backs perform the greatest distance at high- speed running and tight forwards perform the least (OB = 6.3 ± 2.0 $m \cdot min^{-1}$: TF = 1.9 ± 1.0 $m \cdot min^{-1}$). Cunningham et al. (2016) assessed the movement demands in elite U20 Rugby Union matches. The results highlighted that the inside backs covered the greatest total distance, and the front row covered the least (IB = 6510 ± 710m; front row = 4970 ± 750m). However, the backs three performed the greatest distance of HSR (728.4 ± 150.2m) and the front row performed the least distance of HSR (211.6 ± 112.7).

When looking at all the studies, results highlight that backs cover a greater distance in games compared to forwards due to the nature of the positions. Additionally, the studies highlight that the back three players reach the highest maximum speeds during match play, with front rows having the lowest maximum speeds. Overall, the research demonstrates that positional groups and forwards/backs have significantly different locomotor demands which means that training needs to specific to the individual positions. The difference between forwards and backs, and more specific positional groups is highlighted throughout this session with results consistently showing backs cover a greater total distance and HSR demands during the game so analysing the WCS for these running demands would allow coaches to push players in training and further develop their knowledge on match demands for different positions.

2.2.5 – Positional Match Demands Using GPS

Most GPS studies analyse the different demands between the forwards and backs, with some specifically measuring positional groups, such as the front row, back row and back three. Tee et al. (2016) highlighted the differing demands in matches between tight forwards, loose forwards, scrum-halves, inside backs and outside backs. The results demonstrated that scrum halves covered the highest relative distance per minute (Scrum Halves – 99 $m.min^{-1}$; tight forwards – 81$m.min^{-1}$; Outside backs – 78 $m.min^{-1}$). Additionally, it was shown that players walk more during match play than any other movement speed which highlights the intermittent nature of Rugby Union with regular stoppages. This study shows the differences between positions are significant and therefore allows coaches to create specific training sessions to ensure players are optimally prepared for match play. This increases the benefits and use of GPS monitors during match play. Deutsch et al. (2007) quantified the movement patterns of different positions during Rugby Union match-play. The study demonstrated that outside backs perform the highest running aspects of match play whilst front row forwards performed the least, but they completed the most high-intensity non-running activities such as rucking and mauling. An early study (Roberts et al., 2008) assessed the physical demands of elite English Rugby Union, highlighting that backs covered a greater total distance than forwards (B = 6127m vs F = 5581m) and greater distances of high intensity running (B = 448m vs F = 298m). However, forwards performed more high intensity activity than the backs (F = 9.09 minutes vs B = 3.04 minutes). All players travelled a further distance in the first 10 minutes when compared to 50-60 minutes and 70-80 minutes. This would make sense as during a game, players will fatigue, and therefore they will cover less distance and less HSR as the game progresses. This is where analysing WCS is beneficial as you can see what the highest bouts of movement are and can allow coaches to ensure players are optimally prepared even during the last 30 minutes of the game. These results highlight the difference in physical demands between the forwards and backs but no deterioration in high-intensity activity during match play. Quarrie et al. (1996) completed research into the evaluation of player actions and movements during international Rugby Union. The results corroborated with the previous study mentioned, showing that forwards performed more high intensity activity, such as scrums, rucks and tackles, but backs covered a total greater distance throughout a game, with the mean distance covered ranging from 5400m to 6300m, position dependent. Additionally, Cahill et al. (2012) analysed the movement characteristics of elite English Rugby Union players during 44 competitive matches. The results revealed that the game is played predominantly at low speeds with very limited distances covered 'sprinting' by the backs (50 ± 76m) or forwards (37 ± 64m). Overall, the backs covered greater absolute and relative distances ($P < 0.05$) than the forwards and of all positions, the scrum half covered the greatest total distance during a match (7098 ± 778m), with the front row covering the least (5158 ± 200m). The study showed that the backs row covered the greatest distances at 'sprinting' speeds, especially the number 8 (77m). Again, these findings highlight the differences in running demands between elite Rugby Union playing positions and reinforce the need for specialised training programmes to suit all the players positions. As shown above, players spend most their time performing low intensity running which highlights the need for their aerobic base to be consistently worked on to ensure they can maintain this pace, with bouts of high intensity work to ensure their anaerobic capacity is large enough to reach the high intensity bouts of play.

2.2.6 – Work to Rest Ratios and RHIE

A game demand which is explored more in depth in studies is work-to-rest ratios and repeated high intensity efforts (RHIE). A RHIE is defined as 'three or more sprints, tackles or a combination of both, with less than 21 second recovery between the high intensity effort' (Austin et al., 2011). Duthie et al. (2003) analysed the work to rest ratios in Rugby Union. The results demonstrated that 63% of the W:R ratios had work periods less than the rest period. Another study found that the W:R ratio for U19s was 1:1.4 and 1:2.7 for forwards and backs respectively (Deutsch et al., 1998). Additionally, McLean (1991) established the mean duration of the work periods was 19s and the most frequent W:R ratios were in the range of 1:1 and 1:1.9 with the average ball in play time of 29 minutes during an 80-minute game. A more recent study, (Eaton & George, 2005) demonstrated that the rest period was far greater than the work period for all positions. The players with the least recovery time are the back rows (1:7.48) as they are the most versatile players on a pitch and known as the ‘workhorses;’ of the team, and the players with the greatest recovery time are the outside backs (1:14.63). This study demonstrated that the average work time was much greater for the forwards compared to the backs (F = 2.42s; B = 1.72s). The mean rest periods were also greater for the backs than the forwards (B = 21.17s; F = 20.25s). Austin et al. (2011) noted a similar trend, with W:R ratios of 1:4, 1:4, 1:5 and 1:6 found for front row, back row, inside backs and outside backs respectively. However, Eaton & George (2005) highlighted different specific results compared to Austin et al. (2011) which could be due to slightly different rules between the English Premiership and Super 14 as well as different methods used to assess the movement activities. The RHIE and W:R provide us with data that is useful to assess WCS in matches and highlights the differences in needs between forwards and backs, and positional groups. For coaches and practitioners to know the W:R ratio and number of RHIE during a match is beneficial as it shows the players spend a lot more time resting than working and so it can allow coaches to create training sessions to replicate this. These findings can be used alongside WCS GPS running demand findings to ensure players are reaching these demands and having a similar amount of rest between these bouts of work that they would in matches. This allows them to ensure both their aerobic and anaerobic energy systems are able to cope with the demands and recover in time before their next bout of work during matches.

2.3 – U20 Match Demands

2.3.1 – U20 Match Demands – Forwards vs Backs

The demands of match play vary between professional and amateur rugby, and additionally between elite senior and elite U20 rugby. Cunningham et al. (2016) compared the movement demands of elite international U20 and senior international rugby union players during the season. The linear mixed models used for analysis revealed significant differences between U20 and senior rugby for both forwards and backs. There were differences in key metrics between international senior forwards and backs and U20 forwards and backs. The data shows that the senior backs m•min-1, HML distance (m) and HML efforts are significantly higher than the U20s backs counterparts. Additionally, the data highlights that the senior forwards HML distance and decelerations >4m/s are significantly higher than the U20 counterpart. However, the U20 forwards had significantly higher data for HSR m•min-1 compared to the senior forwards. This study highlights the importance of U20 international rugby for preparing players adequately across all movement characteristics before senior international rugby. The results however show that some positional groups require more time to match senior movement demands than others, such as the midfield positions. This study suggests that the seniors would cover more distance than the U20s and this could be due to the intensity of the game and potentially higher BIP time as this would mean they would be covering more meters per minute during the game. However, this study shows that the U20s cover more HSR meters per minute. This could be due to the nature of the U20s game but also depending on the threshold for HSR meters on the GPS unit, the U20s are lighter and so therefore more likely to reach the threshold for their running to count as HSR which could be why they cover greater HSR distance and less total m/min.

Match demands vary between senior level rugby and U20/age grade Rugby Union. Very few studies have analysed the match demands of international U20 Rugby Union matches, but there are more studies at university level which can be reviewed. Firstly, Cunningham et al. (2016) completed a study to quantify the movement demands of elite international U20 Rugby Union players during 15 matches in 2014/15 and 2015/16 international tournaments. Data files were only used for players who played over 60 minutes and were grouped into forwards and backs then split further into positional groups. The results highlighted that on average backs covered more distance per game than forwards (B = 6.23 ± 0.8km, F = 5.37 ± 0.83km), with backs also covering more distance of HSR (B = 656.9 ±182.7, F = 284.2 ±134.9). The study also analysed the differences between positional groups, which is shown in the table below (table 1). These findings corroborate with the findings in studies mentioned previously in this literature review highlighting the need to distinguish between forwards and backs when analysing the running demands during a rugby union match.

Another study was completed by Carling et al. (2017) which investigated performance levels in two international U20 Rugby Union teams during an intensified tournament (2015 World Cup). The teams played 5 matches in 19 games and StatSports GPS units were used to collect data during the games. The average total distance over the 5 games differed between the backs and the forwards (B = 68.22 m/min and F = 60.24 m/min). There were also differences between the forwards and backs HSR metres. On average, the forwards completed 1.04 $m \cdot min^{-1}$ whereas backs completed 4.36 $m \cdot min^{-1}$. This study however has its limitations as the five matches were concentrated into 19 days, whereas normally the players would only play 1 game each week, therefore the team might be more fatigued coming to the end of the tournament and so therefore affect the results. If the players had played these games across a 5-week period, the game demands and metrics may have been different, which is more comparable to the senior level rugby where one game is played per week.

Read et al. (2018) completed a study which assessed the physical characteristics of match-play in schoolboy and academy Rugby Union players. The study compared the difference between schoolboy and academy level matches, with the results highlighting that academy forwards and backs covered greater total distance and total jogging distance than schoolboy forwards and backs, suggesting that academies prepare individuals better for senior competition than schoolboy level. This will aid coaches when preparing U20 players for senior competition knowing that if they've come from a rugby academy, they will be closer to the senior level game compared to if they've come from schoolboy rugby.

2.3.2 – U20 Match Demands – Positional Groups

Read et al. (2017) completed a study to quantify the physical demands of U18 and U20 age grade Rugby Union. GPS units were used to collect the data and the players were classed into the 6 positional groups. The results highlighted that the backs had a greater relative distance and greater HSR distance per minute when compared to the forwards, with the difference between the forwards and backs being greater in the U20 age group. If this trend continued, we would think that when playing senior level rugby, the physical match demands would be higher again for both total relative distance and HSR distance per minute, therefore it would mean that players need to become more physically prepared in training sessions. However, a limitation with this study was that the individuals and teams used, were county level, not elite, so therefore the players were of a lower standard, which could affect the performance and hence data collected.

As mentioned above (section 2.3.1), Cunningham et al. (2016) analysed the difference in TD and HSR between positional groups. The table below shows the differences between the positional groups, highlighting the back 3 have the greatest HSR distance and the half backs cover the greatest TD. The front row and second row cover the least distance for both TD and HSR but as mentioned previously, they are involved in more collisions and plays such as rucks/malls/scrums and their role involve less running but more contact time and this shows the need to create training sessions so the forwards are prepared for the contact and the backs are more prepared for the high volume of running.

Table 1: TD and HSR differences at U20 level between positional groups (Cunningham et al., 2016)

	Front Row	Second Row	Back Row	Halfbacks	Midfield	Back 3
TD (km)	4.97 ± 0.75	5.41 ± 0.48	5.67 ± 0.96	5.84 ± 0.89	6.51 ± 0.71	6.18 ± 0.77
HSR (m)	211.6 ± 112.7	265.3 ± 94.2	359.7 ± 142.7	476.1 ± 204.1	661.7 ± 145.1	728.4 ± 150.2

2.4 – Global Positioning Systems

2.4.1 – 10 Hz GPS Devices

Prior to 2016, there was little literature reporting the validity of 10 Hz GPS units due to their recent development and limited commercial availability. Rampinini et al. (2014) demonstrated that during intermittent shuttle running over moderate distances (70m), the total distance and HSR distance had good accuracy from 10 Hz GPS units (CV = 1.9% and CV = 4.7% respectively). More recently, Nikolaidis et al. (2018) found that the mean difference between the GPS recorded distance and reference distance was less than 1%. Beato et al. (2018) had finding which corroborated the previous study. This study highlighted that in 400m trial, 128.5m trial and 20m trial, the distance bias was 1.99 ±1.81%, 2.7 ± 1.2% and 1.26 ± 1.04% respectively. These were only small errors (<5%) which support the validity of using 10 Hz GPS units to measure distance. Finally, Huggins et al. (2020) illustrated that when measuring total distance, validity measures were < 5% during all 40m trials except for one, and all 100m linear trials. These studies validate the data utilised in this thesis study, as they demonstrate the reliability and validity of the GPS units used in the data collection. These studies demonstrate GPS units can be used to measure total distance and HSR accurately with the knowledge that there will be very little to no differences between actual distance and GPS distance when using the 10 Hz units.

10 Hz GPS units were found to have good to moderate validity for measuring instantaneous velocities during a constant speed involving accelerations, regardless of the initial velocity (Varley et al., 2012), however, these 10 Hz GPS units have poor validity when decelerations are occurring. In conjunction with this, Akenhead et al. (2014) found that velocity measures were valid for runs with accelerations occurring between 0-4m/s but during accelerations greater than 4m/s, the validity has seen to be compromised. This does not affect the use of the GPS units for this current study as only TD and HSR are being analysed. However, if there is poor validity when analysing decelerations, it could mean the HSR distance is shorter than what the data says if the units aren't picking up the decelerations accurately. Contrary to this, Roe et al. (2017) demonstrated that 10 Hz GPS units provide a valid velocity measure over 40m when compared with a radar gun, with the typical errors only trivial or small. If there is a small/trivial difference between radar guns/actual distance and GPS data, it doesn't necessarily affect the data which will be collected in this study as we aren't comparing the distance between real distance and GPS units. The differences analysed are between seniors and U20s so if there is good inter unit reliability, this will ensure that the results collected are valid.

Castellano et al. (2011) highlighted that 10 Hz GPS units have high intra-unit reliability (CV < 5%) when used during linear 15 and 30m sprints. However, this same study showed that the measurements over 30m were more stable than 15m measurements. The 10 Hz GPS monitors were found to have high levels of inter-unit reliability over the 15 and 30m sprints (CV = 1.3%; CV = 0.7%, respectively). Scott et al. (2016) reviewed literature and concluded that 10 Hz GPS units were able to track fast movements accurately across short distances with a high intra-unit reliability and players should wear the same unit to prevent any variability. More recently, Nikolaidis et al. (2018) illustrated a good intra-unit reliability when comparing distances over 200m (ICC = 0.833) and inter-unit CV ranges from 1.31% to 2.20% between the different tests. Moreover, another study demonstrated that over 40m and 100m, the 10 Hz GPS monitors had reliability measures all < 5% error, with the exception of the sprint over 40m. Finally, Giersch et al. (2018) also highlighted that 10 Hz GPS units accurately measure total distance over 40m and 100m and there was a good intra-unit reliability and consistency between the units (CV = 0.96%). All the above studies highlight the validity of using GPS units for running demands but also the intra-unit reliability, showing you can compare data from different units knowing that the results you get are reliable.

Multiple studies demonstrate the inter-unit reliability of the 10 Hz GPS units during sprinting and team sports movements (Varley et al., 2012; Johnstone et al., 2012; Akenhead et al., 2014). Varley et al. (2012) highlighted that the units have moderate inter-unit reliability during instantaneous velocity involving accelerations (CV = 1.9-4.3%), constant velocity (CV = 2.0-5.3%) or during running involving decelerations (CV = 6.0%), with reliable measures being taken despite initial velocity. Johnstone et al. (2012) demonstrated that 10 Hz GPS units had high inter-unit reliability when measuring peak speeds during a team sport simulated circuit (ICC = 0.97). Additionally, Akenhead et al. (2014) stated that the 10 Hz units have good inter-unit reliability when measuring instantaneous velocity over 10m regardless of the magnitude of the mean acceleration (CV = 0.7-9.1%). However, the reliability decreased as the magnitude of the acceleration increased. As mentioned above, the fact different units still provide reliable data when compared to each other highlights the benefits of the GPS units and allows coaches and practitioners to trust the data even if the results are coming from different units.

To conclude, the 10 Hz GPS devices have been reported to be superior to the 5 Hz units for all metrics analysed; total distance (2.8% vs 1.9%), high speed running (7.5% vs 4.7%), very high-speed running (23.5% vs 10.5%) and mean metabolic power (9.0% vs 4.5%) (Rampinini et al., 2015). These findings are extremely important, particularly the total distance and high-speed running as these are most used when analysis GPS and worst-case scenario data. Varley et al. (2012) also demonstrated that 10 Hz GPS units produce greater levels of validity and reliability when assessing accelerations and decelerations and Roe et al. (2017) reported the 10 Hz units are six-fold more reliable than 5 Hz units for use in Rugby Union. These findings support the use of GPS units in this thesis study and increase the reliability of assessing WCS for total distance and HSR, as the above study highlights the reliability of using 10Hz GPS devices.

2.5 – Worst Case Scenario

2.5.1 – Worst Case Scenario for Running Demands in Rugby Union

Worst Case Scenario (WCS) has only recently become researched in sport and has allowed for developments to be made in both training sessions and matches. As mentioned in the above sections, many studies have analysed the movement and running demands of Rugby Union players (Aughey, 2010; McNeff, 2002; Cummins et al., 2013 and Scott et al., 2016) but very few studies have investigated WCS in sport, specifically Rugby Union. WCS is defined as the highest values of movement demand metrics over a certain period and is determined by analysing entire bouts of continuous ball in play (BIP) times and the longest periods of high-speed running (HSR), as well as an individual's fastest speed (Haakma, 2021). WCS is usually analysed using either rolling-average method (Delaney et al., 2017; Read et al., 2019) or fixed-time method (Carling & Dupont, 2011; Jones, West, Crewther, Cook, & Kilduff, 2015). There are different methods to assess WCS, including analysing periods of RHIE (Johnstone et al., 2014), the longest periods of ball-in-play (Cunningham et al., 2018), analysing shorter periods of fixed durations (Cunningham et al., 2018) or using moving average analysis technique across many time periods (Cunningham et al., 2018; Delaney, Duthie et al., 2016). Novak et al. (2021) completed a study in football (soccer) to assess worst case scenario using rolling-averages to quantify the match demands. The results highlighted that when using rolling averages, WCS total distance was larger with earlier occurrence in the game, whereas WCS for high-speed running was higher when associated with fewer minutes played during the match.

Reardon et al., (2017) completed the first study reporting locomotor demands of entire bouts of continuous BIP time and the difference in the demands at different levels of competition. They established WCS to be the 'single longest bout of uninterrupted gameplay' and used this to analyse different metrics during a match. The results of this study highlighted the WCS HSR for positional groups (FR and SR = 4.9 $m.min^{-1}$; BR = 6.0 $m.min^{-1}$; HB and MF = 8.1 $m.min^{-1}$; B3 = 14.1$m.min^{-1}$. Additionally, the study demonstrated that the FR and SR performed more high-speed running during the lower-level competition games (8.87m.min -1) when compared to the higher-level games (3.18m.min-1). The results also showed that WCS periods follow a similar pattern to game demands but are played at a higher pace than previously reported average game demands. Additionally, as shown in Table 2, the backs covered a greater total distance than the forwards (318m vs 289m) and carried out more high-speed running (11.1 $m \cdot min^{-1}$ vs 5.5 $m \cdot min^{-1}$) and the back three achieved the highest max velocity (6.84 m/s). The findings have shown that the general intensity of WCS periods is greater (average MPM = 117 m/min) than previously reported when analysing average game demands (average MPM = 68 m/min). The study completed by Readon et al. (2016) also observed that during WCS periods, forwards have greater low speed running and more collisions when compared to the backs. The inside and outside backs were characterised by higher max velocity than the tight five forwards during WCS periods and this is consistent within research on demands of Rugby Union globally (Quarrie et al., 2013). This study completed by Reardon et al. (2017) shows a lack of statistically significant differences between different levels of competition, but the data shows inter-competition variance between positions which provides practical significance.

Table 2: locomotor and collision demand of each positional group in Rugby Union (Reardon et al., 2017)

	Tight 5	Back Row	Inside Backs	Outside Backs
Average duration (s)	161	152	154	155
TD (m)	289 (272-305)	290 (270-309)	318 (299-336)	319 (2967-341)
Meters per min (m/min)	109 (104-114)	111 (105-117)	123 (117-129)	124 (117-131)
Max Vel (m/s)	4.9 (4.7-5.12)	5.72 (5.48-5.97)	6.02 (5.79-6.25)	6.84 (6.57-7.12)
Walk Distance (m/min)	45 (42-49)	40 (36-44)	43 (39-46)	47.71 (43-52)
LSR (m/min)	97 (89-104)	65 (56-73)	72 (64-80)	62 (52-71)
HSR (m/min)	4.9 (3-6.9)	6 (3.8-8.3)	8.1 (6-10.2)	14.1 (11.6-16.7)
Sprint Efforts	0.02 (0.04-0.07)	0.02 (0.04-0.08)	0.06 (0.00-0.11)	0.11 (0.04-0.16)
Collisions per min	0.73 (0.62-0.84)	0.89 (0.75-1.01)	0.28 (0.17-0.4)	0.41 (0.27-0.56)

Cunningham et al. (2018) completed a study assessing WCS in movement demands from GPS systems. This study compared rolling epochs to fixed-time epochs to quantify the peak movement demands of international Rugby Union whilst analysing positional differences. Professional rugby players, from three difference international teams were monitored using 10 Hz GPS units across 2014-2017 seasons.

The players were grouped into forwards and backs and then further into front row, second row, back row, halfbacks, midfields and back three. Peak values of HSR and relative distance were measured over 60-300s using rolling and fixed epochs. The results highlighted that as the epoch length increased, the intensity values of running actions decreased. Additionally, the fixed effects indicated a significant between-method differences across all epochs for relative distance covered and HSR. The fixed-length method significantly underestimated the running demands when compared to the rolling method. For all HSR time epochs (except one) all backs groups increased more from fixed to rolling than the forwards ($p < 0.001$). Linear mixed modelling of rolling averages data showed that for relative distance covered, all positions were greater than the front row ($p < 0.05$). The fixed method underestimated relative distance and HSR (11% and 20%, respectively) when compared to the rolling method. This supports the use of rolling method epochs rather than fixed, to achieve more reliable data. Rolling epochs are more reliable because they don't miss out a time block. For example, using fixed time epochs runs from 0-59s, 60-119s, 120-179s etc whereas rolling averages work from 0-59s, 1-60s, 2-61s and so on. This means that if the highest WCS bout happens between 30-90s, it won't be missed by the rolling averages, but it would be missed out of the data using the fixed method.

Table 3 - relative distance and HSR covered by the forwards, backs and team and % differences between rolling and fixed-time methods. (Cunningham et al., 2018)

HSR (m/min)	**Team**			**Forwards**			**Backs**		
Time epoch	ROLL Method	FIXED method	% Difference	ROLL Method	FIXED method	% Difference	ROLL Method	FIXED method	% Difference
	54.3 ± 25.1	49 ± 22.4	-10.9	42.5 ± 20.6	38.2 ± 17.5	-11.2	69.9 ± 21.8	63.2 ± 20.2	-10.6
120s	32.6 ± 17.6	28.5 ± 15.5	-14.4	24.9 ± 15	22 ± 13.3	-12.9	42.6 ± 15.7	36.9 ± 14.0	-15.4
180s	25.0 ± 15.6	21.1 ± 12.9	-18.6	18.9 ± 14	16.1 ± 11.3	-17.3	32.7 ± 14	27.4 ± 17.0	-19.5
240s	20.9 ± 13.5	17.5 ± 11.1	-19.8	15.5 ± 12.1	13.2 ± 10	-17.6	27.6 ± 12.2	22.8 ± 10.1	-21.3
300s	17.9 ± 11.8	14.9 ± 9.1	-20.4	13.1 ± 10.2	10.9 ± 7.3	-21.1	24.0 ± 10.8	20 ± 8.5	-19.9
Distance (m/min)									
60s	165.6 ± 22.3	148.1 ± 22.1	-11.8	156.5 ± 19	139 ± 38.2	-12.6	177.4 ± 20.6	160.1 ± 21.1	-10.8

120s	130.9 ± 17.8	117.9 ± 18.2	-11	123.7 ±15.4	111.1 ± 22	-11.4	140.1 ± 16.3	126.9 ± 16.7	-10.4
180s	115.3 ± 16.5	102.8 ± 15.8	-12.2	109.2 ± 14.6	96.9 ± 16.1	-12.7	123.4 ± 15.4	110.6 ± 15	-11.6
240s	106.7 ± 15.0	95.5 ± 14	-11.8	101 ± 12.9	90.6 ± 13.2	-11.5	114.2 ± 14.4	102.0 ± 13.4	-12
300s	100.6 ± 14.0	90.4 ± 13.9	-11.4	95.4 ± 12.2	85.7 ± 10.9	-11.4	107.5 ± 13.3	96.5 ± 13.6	-11.3

Haakma (2021) explored WCS in professional Rugby Union and assessed the best ways to prepare the players for competition. Data was collected and analysed from 51 professional Rugby Union players in 2019-2020 and Apex GPS units were used. Video analysis was also used, and the GPS data was collated with this to put the data in ball-in-play (BIP) drills. The matches were separated into 8 equal segments and the segments where the maximum BIP periods occurred, were identified. The results showed that there is no specific part of the game in which the highest WCS periods occur and so therefore the players need to be conditioned for peak demands to occur at any point during the 80 minutes. Additionally, Whitehead et al. (2018) completed a systematic review in football, looking at the use of GPS to quantify peak match demands. The study highlighted that 'the most intense periods of play occur at critical periods of match-play' which proves that it is important to prepare players for peak periods of the game, which could occur at any time during the match.

2.5.2 – Methodologies for Measuring Worst Case Scenario

As mentioned above (Cunningham et al., 2016), both fixed-time and rolling averages are used to measure WCS. When using a fixed-time methodology, the game is split into fixed periods from the start to the end of the game, for example, periods of 1-minute (0-59s, 60-119s, 120-179s etc) (Oliva-Lozano et al., 2021). Jones et al. (2015) looked at the positional and temporal movements in professional Rugby Union, using a fixed-time method. The game was split into 10-minute fixed periods and any extra time in each half was excluded from the data. The study highlighted the differing demands based on positions with an overall decline in performance from the first halves of each 40-minute block. However, a fixed-time method was used, and extra time was excluded from results therefore, important data might have been missed.

Carling and Dupont (2010) used fixed-time periods to analyse the reduction in physical and skill performance during a professional football match. Fixed-time periods of 5-minutes were used, and any extra time was excluded from the results to 'facilitate comparison, as the duration of respective match halves were never identical'. The results highlighted those players covered a greater distance during the first versus second halves of games (5694 ± 287m vs. 5432 ± 252m, $P < 0.001$), but the individual ball possession didn't differ between halves. Additionally, the study showed that the ball was in play for a significantly longer time during the first 5-minutes of play compared to the last 5-minutes of play.

Due to rugby being a high intensity intermittent sport, with high force impacts (Austin, Gabbett & Jenkins, 2011), HSR and total distance per fixed-time period will never be of the same duration. When using fixed-time periods, BIP and out of play (OOP) times are analysed and using BIP or OOP can significantly change the results. For example, the backs have a greater repositioning time than forwards during OOP and so therefore this would dramatically increase the backs total distance as well as other metrics (Pollard et al., 2018). This means that when using a fixed-time method to assess WCS, if OOP time isn't included, it could affect the data and therefore could be worth including it to see the real metrics, as backs cover larger distances than forwards during OOP time.

WCS can be measured using a rolling epoch method which produces average metrics over time. Rolling-averages are different to fixed-time periods and the sample length is calculated so that there are no missed samples. If the epoch length is 120s, rolling-averages overlap in time, for example, 1-9s, 2-10s, 3-11s and so on. Owen (2019) completed a study analysing peak periods of play using rolling epochs to assess movement demands. The results highlighted that the forwards moved at a significantly lower intensity and slower relative distance than the backs during peak periods of match play. Additionally, both the forwards and backs covered greater distance during the first couple of minutes when compared to the last. Read et al. (2019) completed a study using English academy Rugby Union players to assess HSR during match play. The results demonstrated that the backs, on average, had greater running intensity than the forwards and as the game progressed, the running speed decreased. This correlated with Delaney et al. (2017) and Whitehead et al. (2018).

2.5.3 – Fixed-time vs Rolling Averages to Assess WCS

Multiple studies which assess WCS in team sports compare the results between fixed-time and rolling-averages methodologies to assess the reliability and validity of each. Cunningham et al. (2018) assessed WCS movement demands in Rugby Union matches and compared fixed length to rolling averages epochs. The players were monitored for peak HSR (>5 m. s -1) and TD ((m.min-1) values over 60-300 seconds. The results highlighted that overall, fixed-time method underestimates both HSR and TD and when comparing positions, HSR demands were higher for the backs when compared to the front row when using rolling-averages, compared to fixed-time methods. Additionally, Cunningham et al. (2018) demonstrated that backs travelled a larger distance HSR and TD when compared to forwards in fixed-time and rolling-averages. Table 3 shows the relative distance and HSR covered by the forwards, backs and teams and highlights the differences between rolling-averages and fixed-time epochs.

Sheppy et al. (2020) completed a study using the women's Welsh Rugby Union team to compare rolling-average and fixed-time epoch methods to assess the WCS locomotor demands. TD, HSR and relative distance were analysed, and epochs of 60s were used to give both fixed-time and rolling-average periods. The epoch lengths ranged from 60s-600s, and the data was recorded for both the full game and then each half. The results highlighted that fixed-time methodologies underestimate TD WCS by approximately 8.25% and HSR WCS by approximately 10-26%, depending on the epoch length and playing position. In contrast to Cunningham et al. (2018), the study highlighted that forwards and backs covered similar TD throughout the entire match, with reductions in distance covered in the second half when compared to the first half.

Both these studies mentioned corroborate with Reardon et al. (2017) as they all have shown that using fixed-time methodology or rolling-averages, when the epoch length is increased, the distance or HSR decreased for both the forwards and backs. Additionally, the findings from these studies provide coaches and players with an insight to HSR and TD WCS which can allow coaches to develop training sessions to ensure maximum benefit for players.

2.6 – Common Limitations of WCS

As WCS is a relatively new area of research, there are limited studies analysing it in rugby and so therefore there are a few limitations in the research which has been carried out so far. Cunningham et al. (2018), Owen (2019) and Sheppy et al. (2020) all included OOP time in their analysis, which could be classed as a limitation of the studies because rugby doesn't follow strict OOP times and sequences, so therefore in each game there is never the same amount of BIP and OOP time. In general, greater individual efforts are performed during BIP time, so including OOP time in the analysis could impact the data as it could potentially state that players are covering different TD and HSR metres, which could impact training sessions.

Furthermore, another limitation is that in multiple studies, the data was only used if the players played more than 60 minutes of the game. This is a limitation because important metrics from substitute players will have been missed which would reduce the validity of the WCS data. Lancome et al. (2016) found that substitution players, both forwards and backs, covered greater distance and more high-speed running over their match participation time, compared to the players who started the match. This study also found that all players performed a greater running distance and speed during the first 10 minutes of play, including substitute players coming on during the match. This additionally highlights the need to include substitute players in the analysis. Cunningham et al. (2018) and Sheppy et al. (2020) both used players who played > 60 minutes but as Lancome (2016) highlights, substitute players and players who compete in < 60 minutes should still be included as their peak demands (HSR and TD) might influence the WCS data.

Novak et al. (2021) highlighted some risks and limitations of using WCS to assess match demands. Firstly, this study highlighted that there is a high variability and WCS occurs at different times of the matches which shows that real demands vary on when specific scenarios occur. Additionally, even if WCS is a reliable metric, it only reflects external loads for locomotor variables. This does not reflect the true WCS demands as they are much more complex than this. For example, during a 3-minute period, a player might run 450m and 50m of sprinting after 80 minutes of match play and high loads. Univariate WCS targets would still underprepare players for multivariate scenarios. From this, WCS is highly individualised so therefore cannot be generalised to the whole squad as the individual has an internal response to certain scenarios and multiple individuals would not respond in the same way. To ensure WCS is accurate for individuals, internal responses need to be monitored too. Additionally, as previously mentioned, WCS is multivariate and so to replicate this and to prepare players optimally, so multivariate demands need to be met. For example, high volume sprinting couple with multiple accelerations, decelerations, collisions, and skill involvements as preparing players for one demand would not provide adequate preparation for match play. Novak et al. (2021) created a framework to define WCS as a construct with various combinations. This framework demonstrates that there are measurable variables which may be associated with WCS and WCS leads to different internal responses. Novak et al. (2021) highlighted there are 3 potential groupings for the variables: physical, technical and contextual. The figure shows examples of these different variables which all impact whether a WCS situation will come about from it. The figure then highlights the internal response and when there is a WCS situation which are dependent on the variable which the individual experiences. This study can be linked to studies and WCS in rugby union. It can enable us to predict outcomes of WCS by using the measurable variables. For example, if the play in the game is very open, there is more space to cover more distance and to potentially run faster, leading to increased HSR meters. This could lead to a WCS situation for both total distance and HSR which would therefore increase the players heart rate and RPE amongst other factors. Whereas, if you have a substitute come on at 70 minutes against another player who has played the full game, the player who has just come on is going to be less fatigued and so therefore is more likely to reach a WCS situation when compared to the player who has already played 70 minutes. These factors can be assessed before and after a game to explain certain WCS situation and how they could have impacted the play.

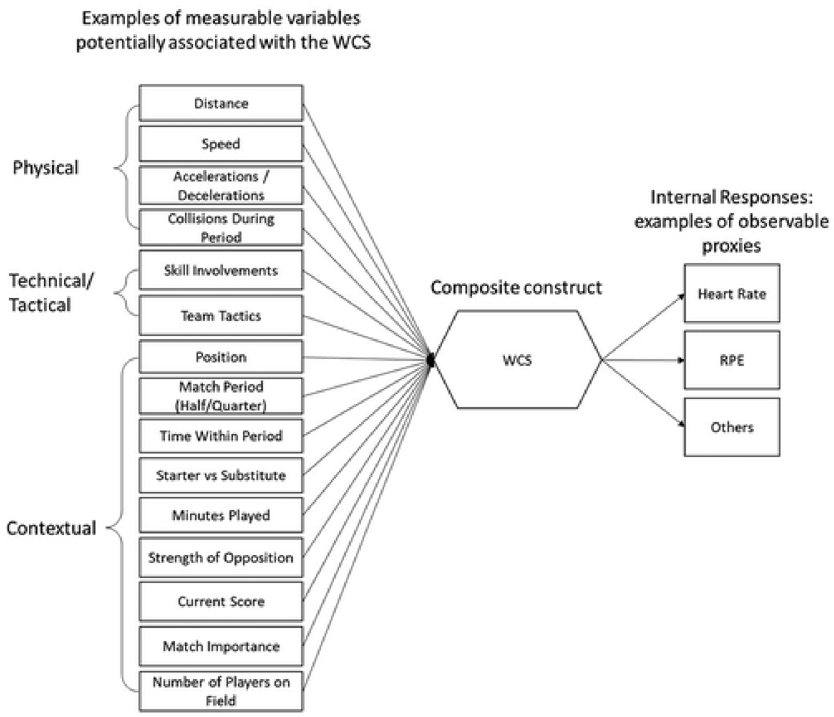

Figure 1: A framework to define and investigate WCS as a construct with various combinations of factors and external loads and measures of internal response.

Chapter 3 – Methodology

3.1 – Participants

Data was collected from the French, Georgian and English Elite senior Rugby Union players (n=146), along with the English U20 players (n=43) from a series of games dating between 2014-2019. A total of 189 participants were used across the four international teams. All participants provided written consent to participate in the study which was approved by the Rugby Union boards and ethics committees. The team physiotherapist ensured that all the players were physically fit, and the players had to be healthy and free from injury at the start of the study.

The U20 players provided files from 15 games from two Six Nations tournaments and the 2015 Junior World Cup. The seniors provided data from 44 games from the international tournament games played from 2014-2017.

Players were grouped into positions; front row forwards (FR), second row (SR) and back row (BR); these were in a broader group called the forwards (F). The halfbacks (HB), midfield (MF) and back three (B3) were in a broader group called the backs (B), (Jones et al., 2015). GPS files were collected from competitive matches; Georgia (11), England (5), France (4), England U20s (19). The external demands of match play were quantified by using GPS monitors. The senior forwards were aged 24 ± 4 years, 188.5cm ± 6.7 and their body mass was 111.3 ± 9.3kg. The backs were ages 23 ± 4 years, 181.8cm ± 6.3 and their body mass was 90.0kg ± 8.1. The high-speed running threshold for all players was set at >5m/s.

Table 4: U20 Anthropometric Characteristics

Positional Group	**Age (years) M ± SD**	**Height (cm) M ± SD**	**Mass (kg) M ± SD**
front row	19.5 ± 0.7	184.4 ± 3.0	111.8 ± 5.6
second row	19.7 ± 0.5	199.7 ± 2.3	115.2 ± 4.1
back row	19.9 ± 0.3	187.7 ± 2.7	101.6 ± 3.9
halfbacks	19.6 ± 0.4	176.0 ± 2.1	84.2 ± 4.1

midfield	19.5 ± 0.6	183.0 ± 4.9	96.1 ± 6.6
back 3	19.6 ± 0.5	183.7 ± 4.3	89.6 ± 4.9

Table 5: senior Anthropometric Characteristics

Positional Group	**Age (years) M ± SD**	**Height (cm) M ± SD**	**Mass (kg) M ± SD**
front row	26.1 ± 2.3	185.7 ± 4.2	119.1 ± 5.0
second row	26.4 ± 3.3	199.2 ± 1.6	116.8 ± 4.8
back row	26.0 ± 3.3	190.0 ± 2.6	117.7 ± 10.4
halfbacks	24.2 ± 2.5	179.5 ± 6.0	88.7 ± 4.6
midfield	25.7 ± 1.3	190.2 ± 4.1	102.3 ± 6.9
back 3	24.6 ± 3.4	1832.6 ± 4.1	91.7 ± 2.1

3.2 – Experimental Procedures

GPS Units

Every player wore a StatSports or Catapult GPS unit was placed in a GPS pocket in the back of the playing jersey sitting on the upper thoracic spine between the scapulae. Waldron et al. (2021) completed a study, using soccer players, which demonstrated that there were no differences for peak velocity and distance > 5.5 m/s when using three different GPS units and PlayerMaker units. As some of the data collected in the study used Catapult devices and some used StatSports units, it’s essential that there are no significant differences between the devices to ensure the results are valid. The GPS units all have a sampling frequency of 10Hz and have been made commercially available, proven to be valid and reliable in team sports (Scott, Scott & Kelly, 2016) and suitable for the use in Rugby Union (Roe et al., 2017). Rampinini et al. (2015) demonstrated that the 10Hz GPS units quantify movement patterns with a greater reliability than 1Hz and 5Hz units for the metrics used in this study. Johnston et al. (2014) illustrated that 10Hz units were a valid and reliable measure of total distance and speed when compared with 15Hz GPS, which exhibited a lower validity for both metrics. Varley et al. (2012) reported 10Hz GPS units are three times more valid and six times more reliable than 5Hz units. GPS units have been used in multiple studies in Rugby Union (Coughlan et al., 2011; Venter, Opperman & Opperman., 2011). Beato, Devereux & Stiff (2018) highlighted that StatSports units were reliable when measuring peak speed and distance when compared to radar guns. Additionally, Johnston et al. (2014) demonstrated that 10Hz Catapult GPS units were a valid ($p > 0.05$) and reliable (%TEM = 1.3%) measure of total distance when testing athlete running demands. This study also highlighted that the 10Hz Catapult GPS units measured running demands with a greater validity and interunit reliability than 15Hz units.

The standard operating procedure for using the GPS units and collecting the data is as follows. The units were turned on 20-30 minutes before training sessions and matches to engage the satellites which orbit the earth. The sport scientists/coaches will ensure all the units have connected to the satellites before the start of the session or match to ensure their data is being collected live and accurately. Once the units were set up, the coaches placed the GPS units into the jerseys of the players to ensure they were being worn correctly and placed in the right way. If a player was subbed off during a game or training session, the unit would be placed onto the ’bench’ on the online software to ensure the coaches are aware that they were not playing at that time and so their data for this period was not included into any analysis or results. To prevent inter-unit variation, all participants were assigned a unit which they kept for the entirety of the season and each unit contained the individual’s metrics, such as height, weight and age. Additionally, the individuals 10m and 30m sprint times were calculated and put into the StatSports system and Catapult software to ensure HSR was relative rather than absolute.

There are factors which might affect the GPS data which is collected. The strength of the signals can be affected by the environment, such as urban surroundings/build up areas/tall buildings/stadiums or heavy tree coverage. For example, if one match was played outside in open space, the connection to the GPS satellites is realistically going to be strong compared to a match in a big stadium in the middle of a city with lots of tall buildings. This could reduce the number of connections to satellites and therefore effect the transmission of signals between the satellites and GPS units, resulting in ‘losses’ of data.

3.3 – Worst Case Scenario

The StatSports and Catapult systems produced both fixed and rolling epochs, but in the study, only rolling epochs were used due to the nature of the data and previous studies showing rolling average epochs produce more valid results

(Cunningham et al., 2018). Epoch length were 60s-600s in increments of 60s. The actual length of the samples was calculated using sampling rate which allows for the missed samples. The sampling rate used was 10Hz, so for example, for a 60s epoch length, the epoch length in samples was 600. When using rolling averages, values were calculated using the current and 599 preceding samples.

3.4 – Statistical Analysis

The data collected consisted of repeated measurements of the same individuals across a variety of matches and competitions. To account for fixed and random effects in the data, with no independence, a mixed level linear model was used. These models examine the differences in dependent variables and random intercepts for both participants and game were used to account for the nature of the data within both the players and the games. Previous studies (Cunningham et al., 2018) attempted to model random slopes for the same variables which resulted in over specified models and therefore they were abandoned, so were not used in this study. All analysis was performed on Jamovi with an alpha level set at 0.05, the confidence intervals were set at 95% and were calculated using the following equation.

95% Confidence Intervals = $\overline{\bar{X} \pm 1.96 * (\frac{\sigma}{\sqrt{n}})}$

The statistical analysis highlighted the significant main effects for all groups being analysed; age group, forwards vs backs epoch length, positional groups for HSR, total distance, relative m/min and HSR m/min This split the data into the difference distances covered for each epoch to assess whether there was difference between the positional groups and forwards vs backs. A p value was determined using the statistical analysis method which allows practitioners to assess whether there was a significant difference between the age groups and different positions. This can allow practitioners to easily see the differences for age groups and across the epochs for different positional groups which provides them with data which they can create training sessions off to ensure their players are optimally prepared for matches. Additionally, the analysis provided us with the average HSR distance, average TD, average HSR m/min and average relative m/min for the forwards and backs at both U20s and Seniors at each epoch which will be presented in a graph in the results section. The epochs in results are measured in seconds (60-600) with each epoch showing the average for

HSR, HSR m/min, TD and relative m/min for the U20s and seniors. The metrics used for TD and HSR were done in meters rather than kilometers because the data collected would be better represented as meters due to the number e.g., 70m and 82m.

Chapter 4 – Results

4.1 – HSR Distance –Forwards vs Backs

Linear mixed models for HSR distance indicated significant main effects for age group ($p < 0.01$), forwards vs. backs ($p < 0.00$) and epoch length ($p < 0.001$). There was a significant interaction for age group * forwards vs. backs ($p < 0.031$), indicating that the difference between age group was dependent on whether the players were either forwards or backs. Simple effects analysis for the forwards indicated significant difference in HSR distances at epochs 360-600 seconds. The results demonstrated that the difference between U20 and Elite Seniors were greater for longer epochs. Simple effects analysis for the backs indicated significant difference in HSR distances at 180-600 seconds which indicated that differences between U20 and Elite Seniors were greater for longer epochs.

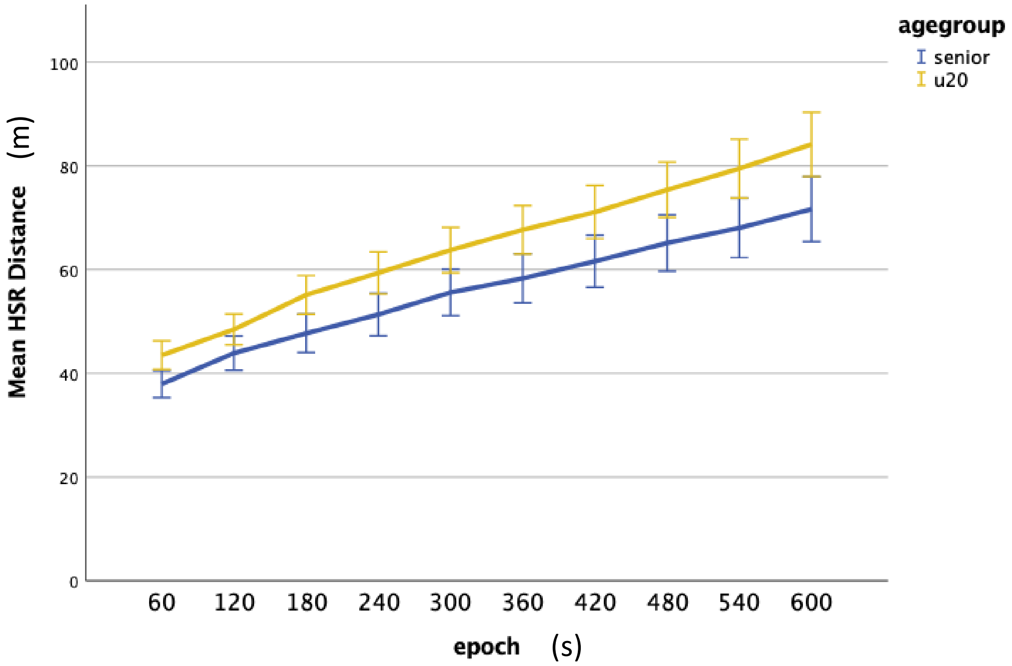

Figure 2 – graph showing HSR distance differences between forwards at senior and U20, comparing the mean HSR Distance (m) at different epoch lengths (s)

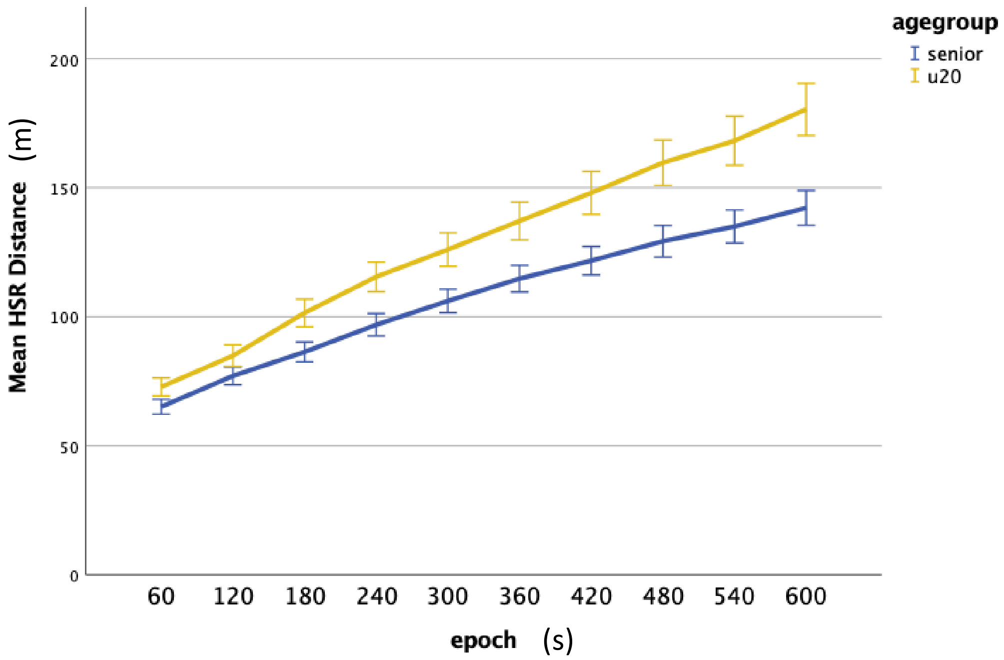

Figure 3 – graph showing HSR distance differences between backs at senior and U20 comparing the mean HSR Distance (m) at different epoch lengths (s)

4.2 – HSR Distance – Positional Groups

Linear mixed models for HSR distance indicated significant main effects for age group (F (1, 184) = 22.62, $p < 0.001$), positional group ($p < 0.001$) and epoch ($p < 0.001$). There was significant interaction for age group * positional group ($p < 0.001$) indicating the difference between age groups was dependent on the positional groups of the players. Additionally, for age group * positional group * epoch, $p = 0.030$, indicating there was a significant interaction, highlighting that there was a difference when the epochs were included into the analysis. Simple effects analysis for the front row players indicated a significant difference in HSR distance at all epochs, second row (300-600 seconds), half backs (180-600 seconds), midfield players (180-600 seconds). The differences between age groups and these positional groups were greater as the epochs got longer. There were no significant differences in HSR distance at any epochs for back row and back three positions.

Table 6 – positional groups p values at each epoch interval for HSR distance

Front Row		Second Row		Back Row		Halfbacks		Midfield		Back 3	
Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value
60	0.008	60	0.119	60	0.732	60	0.185	60	0.204	60	0.464
120	0.006	120	0.172	120	0.601	120	0.121	120	0.21	120	0.423
180	0.007	180	0.052	180	0.909	180	0.002	180	0.045	180	0.715
240	0.005	240	0.055	240	0.997	240	<.001	240	0.019	240	0.774
300	0.01	300	0.046	300	0.978	300	<.001	300	0.023	300	0.931
360	0.009	360	0.017	360	0.815	360	<.001	360	0.017	360	0.577
420	0.029	420	0.011	420	0.999	420	<.001	420	0.005	420	0.679
480	0.023	480	0.006	480	0.879	480	<.001	480	0.003	480	0.576
540	0.022	540	0.008	540	0.525	540	<.001	540	<.001	540	0.661
600	0.033	600	0.01	600	0.423	600	<.001	600	<.001	600	0.343

4.3 – Total Distance – Forwards vs Backs

Linear mixed models for total distance indicated significant main effects for senior vs U20, $p < 0.001$, forwards vs. backs, $p < 0.001$, epochs, $p < 0.001$, Elite senior vs. U20 * FB, $p = 0.287$, Elite senior vs. U20 * epoch, $p < 0.001$ and epoch * FB, $p < 0.001$. Simple effects analysis indicated a significant difference in total distance at 180-600 second for the forwards and 360-600 seconds for the backs. This indicated that differences at U20 and senior, for both forwards and backs, were greater as epochs got longer.

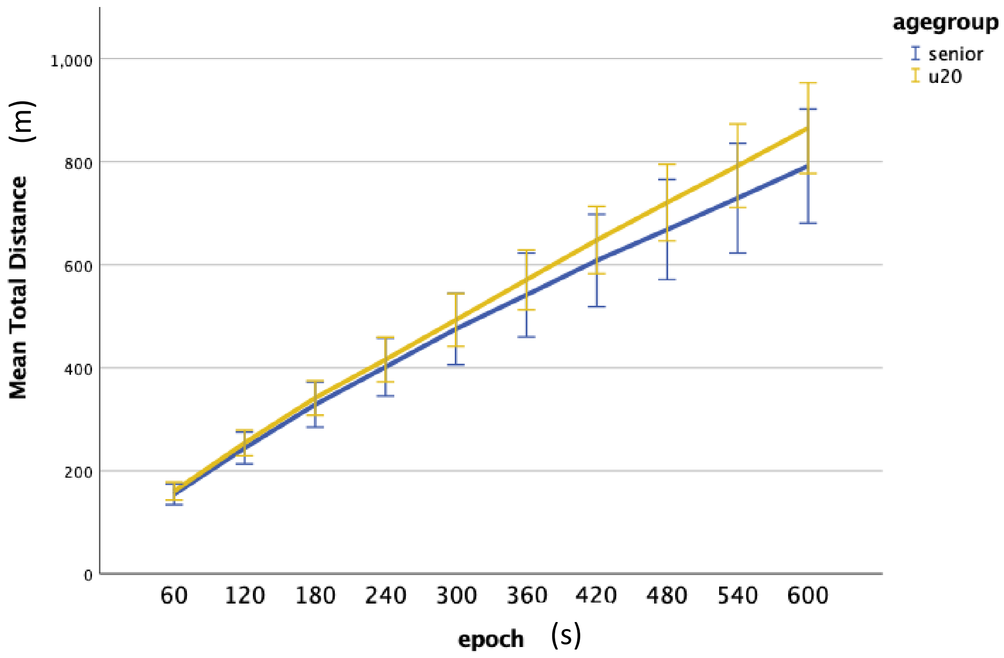

Figure 4 – Graph showing total distance differences between forwards at senior and U20 comparing the mean HSR TD (m) at different epoch lengths (s)

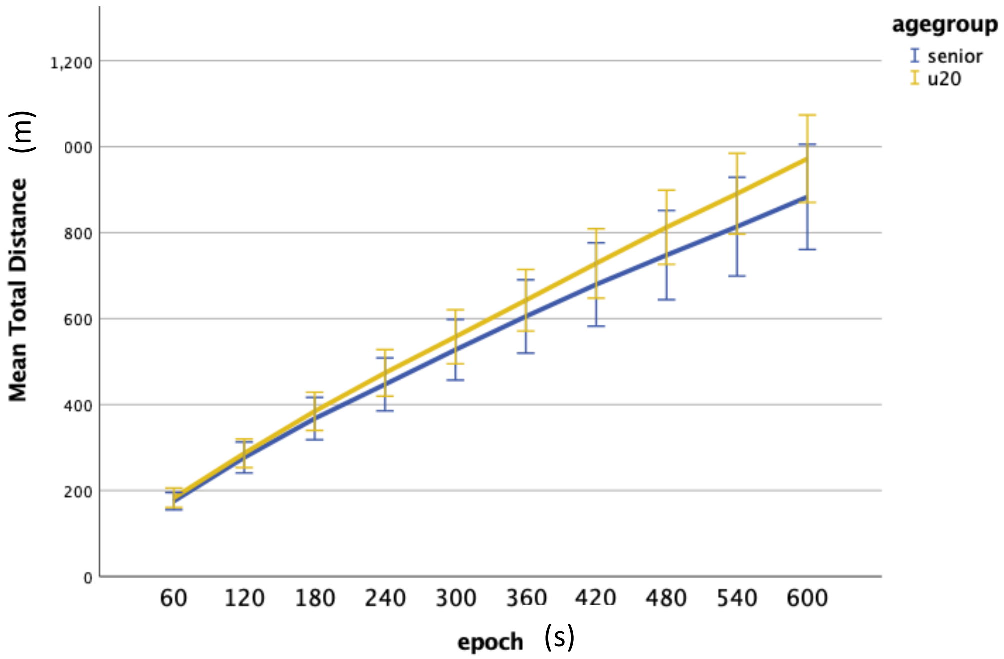

Figure 5 – Graph showing total distance differences between backs at senior and U20 comparing the mean HSR TD (m) at different epoch lengths (s)

4.4 – Total Distance – Positional Groups

Linear mixed models for total distance indicated a significant main effect for Elite senior vs. U20 ($p < 0.001$)**,** for positional group ($p < 0.001$) and for epoch, (p

<0.001). There were significant interactions between age group*epoch (p < 0.001), age group*positional group (p = 0.003) and epoch*positional group (p < 0.001). Simple effects analysis for front row players indicated a significant difference in total distance at all epochs, 360-600 seconds for second row, 480-600 seconds for back row, 360-600 seconds for halfbacks, 360-600 seconds for midfield players, and 600 seconds only for the back 3. There were differences between Elite Seniors and U20 in all positions for total distance. For all positions, except front row players, as the epochs lengthened, the differences between Elite Seniors and U20 became greater.

Table 7 – positional groups p values at each epoch interval for total distance

Front Row		**Second Row**		**Back Row**		**Halfbacks**		**Midfield**		**Back 3**	
Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value
60	0.025	60	0.753	60	0.896	60	0.697	60	0.683	60	0.571
120	0.01	120	0.455	120	0.875	120	0.766	120	0.522	120	0.683
180	0.002	180	0.235	180	0.888	180	0.728	180	0.543	180	0.838
240	0.002	240	0.166	240	0.795	240	0.278	240	0.172	240	0.453
300	0.001	300	0.118	300	0.992	300	0.108	300	0.154	300	0.437
360	<.001	360	0.03	360	0.64	360	0.023	360	0.041	360	0.384
420	<.001	420	0.008	420	0.224	420	0.004	420	0.002	420	0.221
480	<.001	480	0.002	480	0.042	480	<.001	480	<.001	480	0.046
540	<.001	540	<.001	540	0.009	540	<.001	540	<.001	540	0.051
600	<.001	600	<.001	600	0.004	600	<.001	600	<.001	600	0.017

4.5 – Relative m/min – Forwards vs. Backs

Linear mixed models for relative m/min indicated significant main effects for age group (p < 0.001), forwards vs. backs (p < 0.001) and for epochs (p < 0.001). There were significant interactions for only epoch*forwards vs. backs (p<0.001). Simple effects analysis for forwards indicated a significant difference in relative m/min for all time periods, but for backs, there was only a significant difference in relative m/min at 480-600 seconds. This indicated there were differences between forwards and backs at U20 and Elite Seniors and the differences were greater as epochs lengthened.

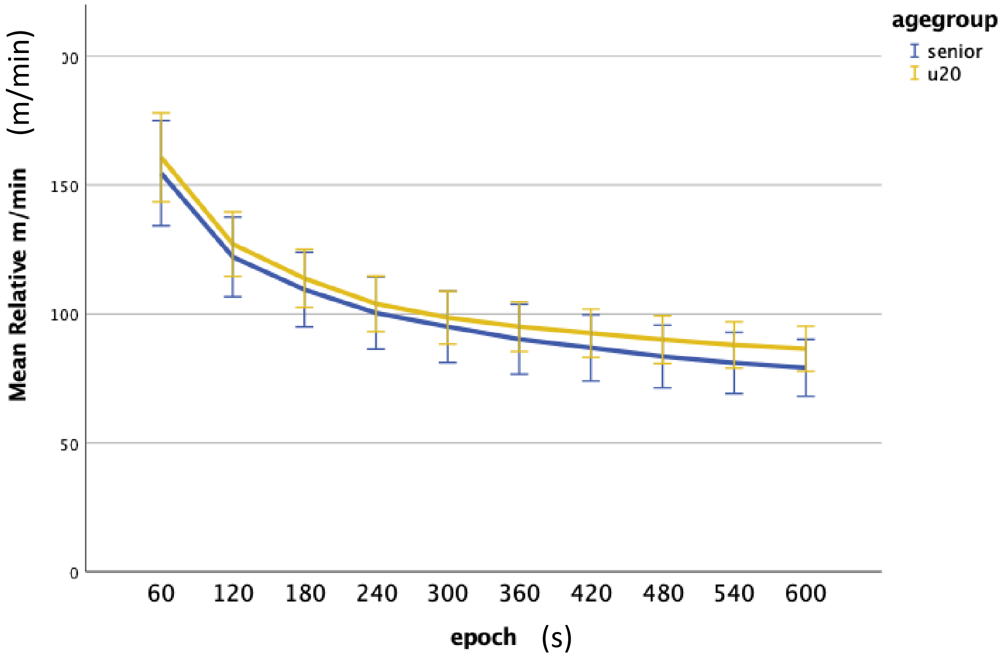

Figure 6 – Graph showing relative m/min differences between forwards at senior and U20 levels, comparing the mean relative m/min (m/min) at different epoch lengths (s)

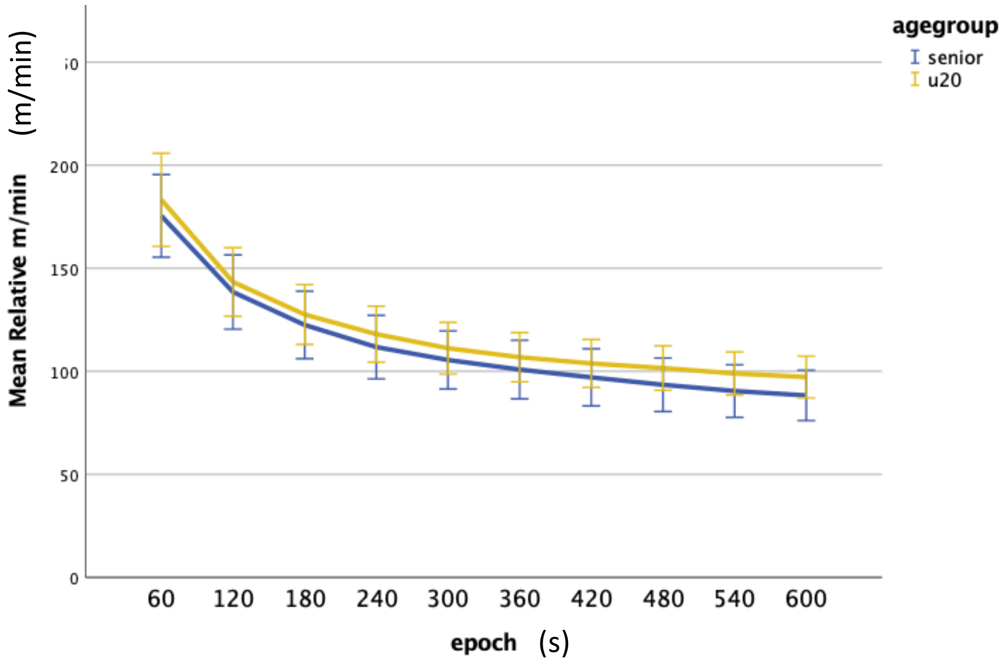

Figure 7 – Graph showing relative m/min differences between backs at senior and U20 level, comparing the mean relative m/min (m/min) at different epoch lengths (s)

4.6 – Relative m/min – Positional Groups

Linear mixed models for relative m/min indicated significant main effects for age group (p < 0.001), epoch (p < 0.001) and positional group (p < 0.001). There were significant interactions for age group*positional group (p < 0.001) and epoch*positional group (p < 0.001). Simple effects analysis indicated a significant difference in relative m/min for front row (60-600 seconds), second row (60-180 and 540-600 second) halfbacks (60 and 480-600 seconds), and midfield players (60 and 420-600 seconds) This indicated there were differences between the positions at Elite senior and U20 level, which were greater in the first and last few epochs.

Table 8 – positional groups p values at each epoch interval for relative m/min

Front Row		**Second Row**		**Back Row**		**Halfbacks**		**Midfield**		**Back 3**	
Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value
60	<.001	60	0.006	60	0.375	60	0.008	60	0.002	60	0.219
120	<.001	120	0.013	120	0.608	120	0.399	120	0.085	120	0.531
180	<.001	180	0.023	180	0.916	180	0.199	180	0.327	180	0.862
240	<.001	240	0.061	240	0.919	240	0.139	240	0.101	240	0.728
300	<.001	300	0.11	300	0.818	300	0.156	300	0.196	300	0.863
360	<.001	360	0.073	360	0.52	360	0.135	360	0.12	360	0.919
420	<.001	420	0.066	420	0.255	420	0.121	420	0.04	420	0.793
480	<.001	480	0.06	480	0.118	480	0.037	480	0.033	480	0.499
540	<.001	540	0.039	540	0.082	540	0.021	540	0.013	540	0.649
600	<.001	600	0.037	600	0.078	600	0.012	600	0.013	600	0.594

4.7 – HSR m/min – Forwards vs Backs

Linear mixed models for HSR m/min indicated significant main effects for age group (p < 0.001), epoch (p < 0.001) and forwards vs. backs (p < 0.001). There were significant interactions for age group*epoch (p < 0.001) and epoch*forwards vs. backs (p < 0.001). Simple effects analysis indicated a significant difference in HSR m/min for forwards at 60-180 seconds and for backs at all time periods which indicated, the shorter the epoch, the greater the differences were between Elite Seniors and U20 for both forwards and backs.

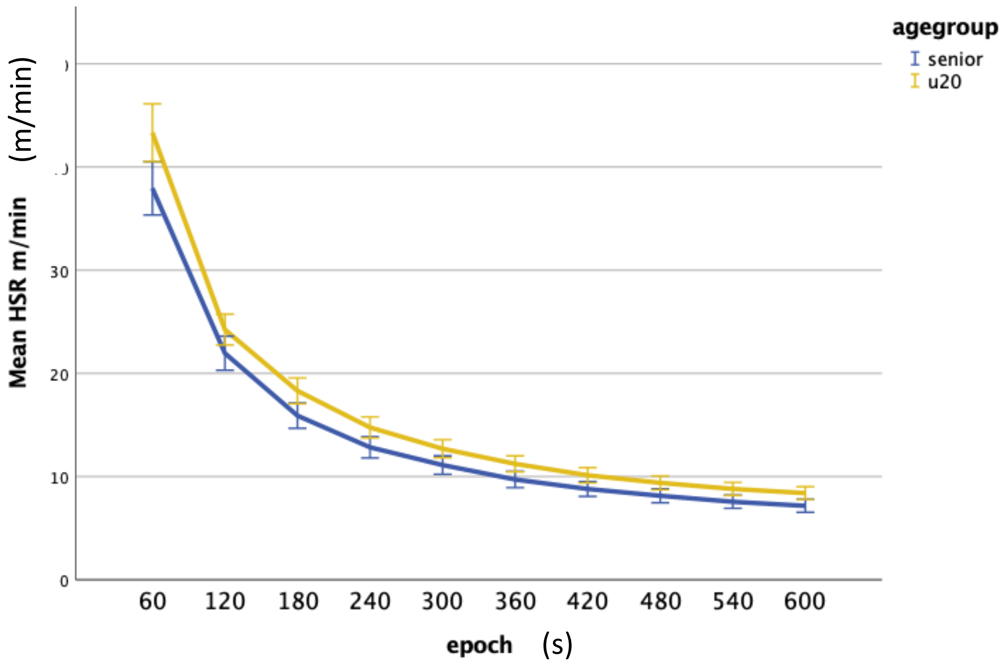

Figure 8 – Graph showing HSR m/min differences between forwards at senior and U20 level, comparing the mean HSR m/min) at different epoch lengths (s)

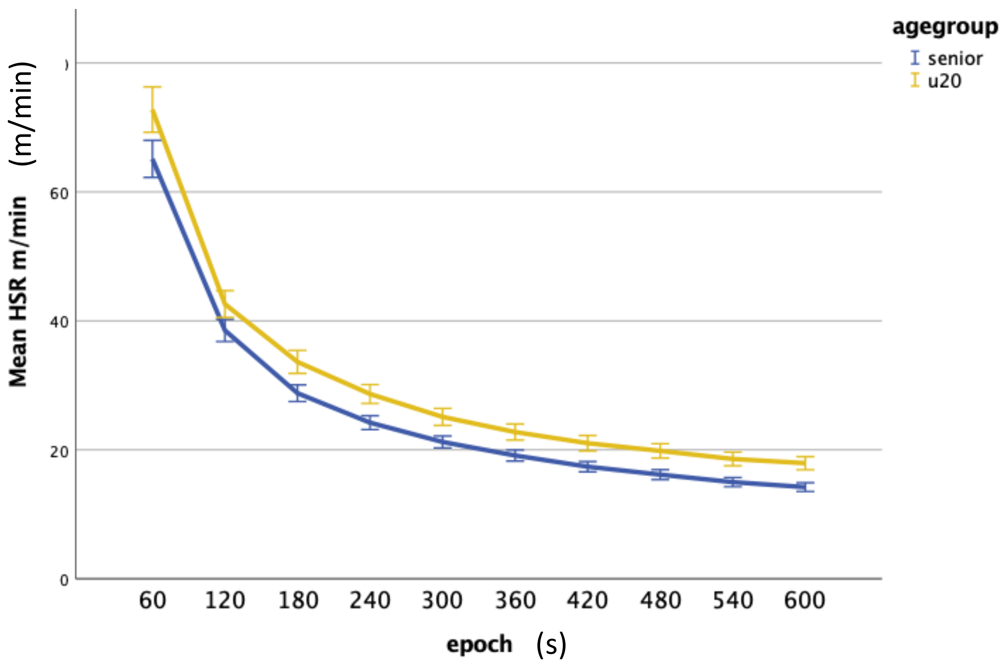

Figure 9 – Graph showing HSR m/min differences between backs at senior and U20 level, comparing the mean HSR m/min) at different epoch lengths (s)

4.8 – HSR m/min – Positional Groups

Linear mixed models for HSR m/min indicated significant main effects for age group ($p < 0.001$), epoch ($p < 0.001$) and positional group ($p < 0.001$). There were significant interactions for age group*epoch ($p < 0.001$), age group*positional group ($p < 0.001$) and epoch*positional group ($p < 0.001$). Simple effects analysis indicated a significant difference in HSR m/min for front row players (6-240 seconds), second row (6-180 seconds), halfbacks (60-600 seconds) and midfield players (60-240 seconds). This demonstrated that the shorter the epoch, the greater the differences were between Elite Seniors and U20 for the different positional groups.

Table 9 – positional groups p values at each epoch interval for HSR m/min

Front Row		**Second Row**		**Back Row**		**Halfbacks**		**Midfield**		**Back 3**	
Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value	Epoch (s)	p value
60	0.021	60	<.001	60	0.335	60	<.001	60	<.001	60	0.106
120	0.026	120	0.026	120	0.679	120	<.001	120	0.004	120	0.213
180	0.033	180	0.032	180	0.877	180	<.001	180	0.005	180	0.616
240	0.032	240	0.127	240	0.766	240	0.002	240	0.02	240	0.93
300	0.052	300	0.215	300	0.636	300	0.004	300	0.065	300	0.891
360	0.054	360	0.203	360	0.497	360	0.012	360	0.101	360	0.93
420	0.09	420	0.246	420	0.547	420	0.012	420	0.097	420	0.961
480	0.074	480	0.283	480	0.561	480	0.013	480	0.115	480	0.912
540	0.073	540	0.378	540	0.659	540	0.02	540	0.087	540	0.799
600	0.082	600	0.449	600	0.66	600	0.026	600	0.069	600	0.905

Chapter 5 – Discussion

The aim of this study was to compare the Worst-Case Scenario (WCS) running demands of Elite senior international and elite U20 level Rugby Union matches. Additionally, the study aimed to investigate the WCS differences between forwards and backs, and more specifically, positional groups between Elite senior and U20 level. This is the first study to analyse the differences in WCS demands between Elite senior international and U20 international competitions, with positional differences included.

The key findings of the study highlighted that U20 elite rugby players, most of the time, had greater WCS demands for all metrics when compared with Elite senior Rugby Union players (Figures 2-9 and tables 7-10) which is what was expected after reading other papers and analysing the work of others. The results have increased knowledge and understanding of WCS demands on the pathway from U20 level to senior level Rugby Union match-play and may have implications for coaches and practitioners to implement and adapt training sessions to prepare players for the transitions from U20 to senior level rugby.

When comparing TD, TD m/min, HSR, HSR m/min for WCS running demands, it differed between U20 and Elite Seniors, for forwards and backs and positional groups across the different categories. For total distance, high-speed running, and relative m/min, for both forwards and backs, as the epochs got longer, the differences between Elite Seniors and U20 increased, with U20s always having run more metres (Figures 2-9). However, for HSR m/min, for forwards, as the epochs lengthened, the difference between U20 and Elite senior level players decreased. These results are what we expected due to the increase running demands of backs and the fact that forwards are involved in more contacts and collisions and lower running demands. This study can enable practitioners to adapt training sessions to ensure all players are ready to compete at optimal performance and make changes to specific positional training if needed. There are many factors which play a part in these results, including the thresholds for HSR, the skill levels and experience of the players, the contact element and the weight and size of the players.

HSR Distance/HSR m/min

The study highlighted that there was a significant difference between WCS HSR distance between forwards at Elite senior and U20 level, with the difference becoming greater as the epoch lengthened. The difference between the average HSR distance forwards at 120s epoch was 9%, with the U20 covering a greater distance. At 600s epoch, this difference increased to 15% between U20s and Elite Seniors. There was a percentage difference of above 20% for both second rows and halfbacks, with the U20s covering a greater HSR distance than the Elite Seniors. Additionally, the total m/min for the shorter epochs, was much higher than the longer epochs. There was a difference of at least 9% between the Elite Seniors and U20s for both the forwards and backs, with the U20 consistently covering more HSR m/min. There was also a significant difference for WCS HSR m/min between Elite senior and U20 positional groups. However, as mentioned in the results, there was no difference in the back 3 group. The greatest differences were seen in the midfield and halfback positions, with the percentage difference being above 10% for all epochs, and for epochs 8, 9 and 10, there was at least a 30% difference between the halfbacks at U20 and Elite senior level rugby. Roberts et al. (2008) highlighted that in Rugby Union, backs spent more time performing high intensity running when compared to forwards, which supports the findings of the present study. This might be due to the positional demands which do not change from U20 to Elite senior level rugby. Forwards aim to play in tighter channels, in which they will only gain a few metres compared to the backs, who run in wider channels with more space for HSR. Therefore, the backs, generally, cover more HSR metres than forwards. In general, Jones et al. (2015) illustrated that Outside backs perform the greatest distance at high- speed running and tight forwards perform the least (6.3 ± 2.0 m·min^{-1} vs 1.9 ± 1.0 m·min^{-1}). This supports other findings and research as it shows backs cover greater HSR distance than forwards. There is no age-grade difference in this study, but it highlights the key finding that backs, overall, cover greater HSR metres than forwards. In conjunction with this, Reardon et al. (2017) analysed WCS demands between positions during a match. The results demonstrated that FR and SR performed more HSR metres during lower-level competitions, which could be an additional factor as to why U20s cover greater HSR metres than Elite senior international players.

Cunningham et al. (2016) reported that senior professional players in each positional group, covered less HSR distance than the Elite U20 players. This might reflect the game demands as Elite senior players have a higher level of skill compared to younger age groups, including U20s which impacts the demands of match-play in team sports (Read et al., 2017). However, one factor that cannot explain the difference is the use of different GPS units. Varley et al. (2012) demonstrated there is an inter-unit reliability during instantaneous velocity involving accelerations (CV = 1.9-4.3%), constant velocity (CV = 2.0-5.3%) or during running involving decelerations (CV = 6.0%), and Johnstone et al. (2012) highlighted that 10Hz GPS units have a high inter-unit reliability when measuring peak speeds and HSR. These studies highlight that StatSports, and Catapult units can be used interchangeably when measuring demands of match play. The U20s, especially the back row positions, were a lot lighter than their senior counterparts (Tables 4 and 5) which influences their running demands. Knechtle et al. (2011) demonstrated that marathon runners ran faster when they were lighter, and the lighter individuals were faster than the heavier individuals. This can be carried across to the present study and the players involved. The U20 players in the data were, on average, lighter than their senior counterparts, so they are realistically more likely to be faster than the seniors. Bridgeman & Gill (2021) highlighted this in a systematic review that there are many differences at senior and U20 levels and when analysing the GPS results, they shouldn't be taken in isolation and instead the characteristics such as mass, should be considered as this impacts the running capabilities of the players. When analysing the HSR demands, the thresholds were absolute, rather than relative, therefore if the U20s are lighter and so faster, they are more likely to spend more time in the HSR threshold zone and could be the reason as to why they are consistently performing more HSR m/min when analysing the WCS demands. Additionally, an U20 rugby union game is much more open than a senior level game. The players have much more space to make line breaks and therefore more likely to reach the absolute HSR threshold, whereas the seniors are less likely if they are heavier and not as quick. Additionally, the senior game has many more collisions and contact situations which means there are more breakdown situations and therefore the players aren't running for long periods of time. When analysing HSR, the players must be moving for enough time for their running to be considered HSR meters. If the seniors are at breakdown situations more frequently, they might not be running enough for their GPS unit to register their movements at a HSR pace. This could have impacted the data and could be another reason as to why the U20s are consistently covering more HSR meters and HSR m/min than the senior players.

Total Distance/Relative m/min

This study demonstrated that there were significant differences in total distance between U20 and Elite senior level rugby, with the difference being greater for both forwards and backs, as the epoch lengthened. When analysing the data, the percentage difference between forwards and backs for TD was much smaller than the HSR distances, with all the percentages between under 10%. Additionally, there was a significant difference between positional groups at both Elite Seniors and U20 level for total distance, with a greater difference for each position as the epoch lengthened. When analysing the m/min, the differences between forwards and backs were all under 10%. Following this, the U20s covered more relative m/min at all epochs compared to the Elite Seniors. There was a significant difference at all epochs in the front row group with the difference being 4% at 60s and 10% at 600s which would be expected, as the greatest difference was in the front row for TD too. Cunningham et al. (2016) completed a study analysing the movement demands of elite U20 Rugby Union players. These results corroborated with the finding in this study, highlighting that the backs cover more TD and HSR distance than forwards during matches. Additionally, backs covered, on average, 6.23km with forwards covering 5.37km per game. These distances covered by the U20s were reported to be higher than Super Rugby in the 2008-2009 season (Austin et al., 2011). However, the U20s TD metres were lower than the distances covered in the English Premiership, but this could be due to differences in data collection, such as subjective views on what is BIP and OOP and the style of play in the team. These results have similar findings to studies which analysed the movement demands in European (Jones et al., 2014) and Pro 12 rugby (Reardon et al., 2013). Additionally, this study showed that the relative TD m/min covered by the U20 was much greater than any other study completed in the northern hemisphere, which supports the findings of this current study, as the U20s consistently had greater relative m/min than the Elite senior players. The difference here could be due to the skill levels of the players. The U20s are less experienced than the senior players and therefore, the senior players know when they need to make certain moves/crucial runs during the game and when they don't need to run. Whereas the U20s, who are less experienced, are more likely to run more during the game as they aren't as experienced as the seniors who know when to make the definitive moves. Additionally, as mentioned in the HSR section, the style of play at U20s is much more open and there are fewer collisions which means there is more space on the field and more opportunities for the players to run. This again, could be a reason as to why the U20s cover more TD than the seniors. As the U20 players develop and train/play more at senior level, the coaches should ensure that with the U20s, they are focusing on the collisions and impact play of the game as this study shows that U20s are capable of reaching and exceeding running demands of the game.

One potential limitation which may influence the data collection, would be the choice of unit. Both Catapult Sports units and Apex StatSports units were used for different teams. However, Crang et al. (2021) recently completed a study comparing the inter-device reliability between Catapult and StatSports GPS units. The results highlighted there was a high level of reliability for both distance and peak velocity (coefficient of variation = 0.1-3.9%), with only a small variation across sessions. Additionally, Thornton et al. (2018) demonstrated that the reliability for distance, speed and max speed produced a high inter-unit reliability between Catapult and StatSports units which allows practitioners to have confidence when making comparisons between different systems. These studies above (Crang et al., 2021 & Thornton et al., 2018) emphasize the fact that the differences in HSR and TD between U20s and Elite Seniors are not due to the differences in units used, as the level of reliability is high enough to use the metrics interchangeably between the Catapult and StatSports units. Therefore, from these previous studies, the use of different GPS units cannot be used as a limitation due to the high levels of interunit reliability.

A potential component which impacts the HSR, and TD is the outcome and standard of the games. Sullivan & Coutts (2013) demonstrated in Australian football that in games when the team were winning, there were more HSR metres and therefore, if teams are winning, there is likely to be higher HSR metres, compared to if they are losing, the team will be taking part is more collisions and therefore, less movement and lower HSR metres. However, Fox et al. (2021) analysed whether winning or losing impacted the intensities during a basketball match. The results highlighted there were no significant differences in match intensity dependent upon match outcome. This can be transferred to HSR demands, if match intensity doesn't change significantly depending on the game, it would suggest that the HSR distance would not vary. Nevertheless, the standard of the match can impact the match demands. McCarra (2020) analysed the physical demands of Rugby Union and the difference between U16, U18, U20 and Seniors. The results demonstrated that as the player moved from age-grade to senior level, there was a decrease in relative distance and HSR, but an increase in contact situations. McCarra (2020) found that this was due to the skill level being lower and the defensive structures being less developed, allowing for more space on the pitch, so players have more opportunities to make line breaks in the Age Groups verses Elite senior, leading to an increase in HSR distance. This provides us with a rationale as to why the U20s are covering more HSR and TD when analysing WCS situations in match play. Additionally, the external factors such as the game plan, the individual's role within the match, the level of competition, how the opposition play, the environmental factors e.g., weather and the outcome of the game (winning or losing) effect the game and the running demands of the players. When analysing large data sets, such as the ones in this study, there was no information as to the environmental factors, the results, the game plan on the day or the oppositions game plan. This means that we couldn't understand the bigger picture to the game and so prevents us from fully interpreting the data and explaining potential causes of the results found. In a future study, the outcome and the environmental factors of these matches can be assessed and investigated to see whether this highlights any of the results more clearly and provide us with more of an explanation as to why the results showed what they did.

It's key to notice that there is a difference in the HSR and TD between seniors and U20s as this can allow coachers to adapt training to ensure players are optimally prepared for competition. It's clear that the U20s can match the running demands, however, if there are more collisions and contact situations in senior rugby, there is where the coaching for U20s would need to be focused to ensure they can perform at this level. Additionally, the U20s cover more distance and HSR, but if there are more contact demands, this would challenge the individual's fitness levels and so coaches would still need to ensure the U20s are completing conditioning drill to increase their aerobic and anaerobic endurance levels.

A final potential limitation of the above study was the positional groups used. Cunningham et al. (2016) used these positional groups (FR, SR, BR, HB, MF, B3) so therefore these are the groups which were used in the present study. Multiple studies (Duthie et al. 2005; Eaton et al. 2006; Deutsch et al. 2007) have grouped hookers with backs. However, Quarrie et al. (2013) decided that hookers are better suited to being grouped with second rows, and scrum halves should be a separate position to the fly-halves due to the scrum halves having such a unique role. This could affect the data as it may create inaccuracies in the distances covered by props if the hookers play more like the back row and second row. Additionally, many of the studies only used data if the individual played more than 60 minutes of the game. Scrum halves and props are usually replaced before 60 minutes, making their data group much smaller than others. This could have impacted the results and therefore the WCS data could have some inaccuracies. In future, collisions could be included in the metrics analysed as this could explain the TD and HSR WCS results as well as seeing more differences between Elite Seniors and U20s for different positions. This will enable coaches to further prepare players moving from U20 to senior level rugby by including the collision demands as well as running demands. Additionally, the forwards as a generic group are not an appropriate measurement and is too generalized to use, as the front rows and seconds rows are significantly different to other positions due to them being in the breakdown more often in set pieces and so therefore, if the back rows are training with this group, they would come to match day significantly underprepared.

This is the first study to compare the WCS match demands between Elite Seniors and U20 players in Rugby Union. Understanding WCS match demands ensures that suitable intensities are reached in training and specific training programmes are designed appropriately for the sport. Overall, U20 consistently cover more HSR and TD than Elite senior players, and within this, backs (HB, MF and B3) cover more HSR and TD than the forwards (FR, SR, and BR). The knowledge gained from analysing WCS differences between Seniors and U20 Rugby Union players allows practitioners and coaches to create training programmes and pathways to ensure players are prepared optimally for the step up to senior rugby. Additionally, it allows coaches to design training sessions and small sided games to match WCS demands in matches, by using the metrics from different epoch lengths, to allow players to experience the highest TD and HSR demands they might have to reach during match play. For example, coaches need to implement more HSR metres and TD metres for scrum halves and backs 3, lower HSR and TD metres for front row and second row players, and a hybrid of HSR and TD metres for backs rowers and midfield players. In the future, it would be useful to assess the different running demands (accelerations/decelerations, sprint distance, max velocities) and contact demands (tackles, scrums, collisions etc.) to compare these between the U20s and senior players for both forwards and backs and specific positional groups to see whether this effects the running demands between the positions and age groups. This can enable coaches to make more specific training programmes for the players and it allows the coaches to see what the U20s need to focus on in training and what is most important for them to develop when coming up from U20 training into the senior rugby environment to ensure they perform optimally. Sport scientists should also monitor players individual loads during each training session and matches to ensure they are training adequately but also to see if they are over training or doing more than they need to be. Using these GPS units in both training and matches allows the coaches and practitioners to continually make changes and adaptions in training throughout the season and create individualized plans when needed.

Conclusion

This study compared the WCS running demands between U20s and Elite senior international men’s Rugby Union players using rolling-averages epochs from 60-600s. The U20s consistently covered more distance in all categories when compared to the Elite seniors, with backs covering more distance than the forwards. Although further research is required to fully understand the difference in WCS demands between senior and U20 international rugby players, this study is novel and provides a greater insight to the difference in running demands, specifically WCS, between Elite senior and U20s, forwards and backs, and further positional subgroups. The knowledge gained from this study enables coaches to construct training sessions to optimally prepare athletes for competition, and suitably prepare them for the transition from U20 to senior level rugby.

Chapter 6 – List of References

Akenhead, R., French, D., Thompson, K. G., & Hayes, P. R. (2014). The acceleration dependent validity and reliability of 10 Hz GPS. *Journal of Science and Medicine in Sport*, *17*(5), 562-566.

Aughey, R. J. (2010). Australian football player work rate: evidence of fatigue and pacing?. *International journal of sports physiology and performance*, *5*(3), 394-405.

Austin, D., Gabbett, T., & Jenkins, D. (2011). The physical demands of Super 14 Rugby Union. *Journal of Science and Medicine in Sport*, *14,* 259–263. doi:10.1016/j.jsams.2011.01.003

Austin, D., Gabbett, T., Jenkins, D. (2011) Repeated high-intensity exercise in professional Rugby Union. *Journal of Sports Sciences.* 29(10), 1105-1112

Barnes, S. (1997). *Rugby's new-age travellers*. Mainstream Pub..

Beato, M., Devereux, G., & Stiff, A. (2018). Validity and reliability of global positioning system units (StatSports Viper) for measuring distance and peak speed in sports. *The Journal of Strength & Conditioning Research*, *32*(10), 2831-2837.

Bogdány, T., Boros, S., Szemerszky, R., & Köteles, F. (2016). Validation of the Firstbeat TeamBelt and BodyGuard2 systems. *Magyar Sporttudományi Szemle*, *17*(3), 5-12.

Bradley, W. J., Cavanagh, B. P., Douglas, W., Donovan, T. F., Morton, J. P., & Close, G. L. (2015). Quantification of training load, energy intake, and physiological adaptations during a rugby preseason: a case study from an elite European Rugby Union squad. *The Journal of Strength & Conditioning Research*, *29*(2), 534-544.

Cahill, N., Lamb, K., Worsfold, P., Headey, R., & Murray, S. (2013). The movement characteristics of English Premiership Rugby Union players. *Journal of Sports Sciences*, *31*(3), 229-237.

Carling, C. J., Lacome, M., Flanagan, E., O'Doherty, P., & Piscione, J. (2017). Exposure time, running and skill-related performance in international u20 Rugby Union players during an intensified tournament. *PLoS One*, *12*(11), e0186874.

Carling, C., & Dupont, G. (2011). Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play?. *Journal of sports sciences*, *29*(1), 63-71.

Castellano, J., Casamichana, D., Calleja-González, J., San Román, J., & Ostojic, S. M. (2011). Reliability and accuracy of 10 Hz GPS devices for short-distance exercise. *Journal of sports science & medicine*, *10*(1), 233.

Coughlan, G. F., Green, B. S., Pook, P. T., Toolan, E., & O'Connor, S. P. (2011). Physical game demands in elite Rugby Union: a global positioning system analysis and possible implications for rehabilitation. *Journal of orthopaedic & sports physical therapy*, *41*(8), 600-605.

Crang, Z. L., Duthie, G., Cole, M. W., Weakley, J., Hewitt, A., & Johnston, R. D. (2021). The inter-device reliability of global navigation satellite systems during team sport movement across multiple days. *Journal of Science and Medicine in Sport*.

Cummins, C., Orr, R., O'Connor, W., West, C. (2013) Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. *Sports Medicine.* 43(10), 1025-1042

Cunniffe, B., Proctor, W., Baker, J. S., & Davies, B. (2009). An evaluation of the physiological demands of elite Rugby Union using global positioning system tracking software. *The Journal of Strength & Conditioning Research*, *23*(4), 1195-1203.

Cunningham, D. J., Shearer, D. A., Carter, N., Drawer, S., Pollard, B., Bennett, M., ... & Kilduff, L. P. (2018). Assessing worst case scenarios in movement demands derived from global positioning systems during international Rugby Union matches: Rolling averages versus fixed length epochs. *PloS one*, *13*(4), e0195197.

Cunningham, D. J., Shearer, D. A., Drawer, S., Pollard, B., Eager, R., Taylor, N., ... & Kilduff, L. P. (2016). Movement demands of elite under-20s and senior international Rugby Union players. *PloS one*, *11*(11), e0164990.

Cunningham, D., Shearer, D. A., Drawer, S., Eager, R., Taylor, N., Cook, C., & Kilduff, L. P. (2016). Movement demands of elite U20 international Rugby Union players. *PLoS One*, *11*(4), e0153275.

Darrall-Jones, J. D., Jones, B., & Till, K. (2016). Anthropometric, sprint, and high-intensity running profiles of English academy Rugby Union players by position. *The Journal of Strength & Conditioning Research*, *30*(5), 1348-1358.

Delaney, J. A., Thornton, W. R., Pryor, J. F., Stewart, A. M., Dascombe, B. J., & Duthie, G. M. (2017). Peak running intensity of international rugby: implications for training prescription. *International journal of sports physiology and performance*, *12*(8), 1039-1045.

Deutsch, M. U., Kearney, G. A., & Rehrer, N. J. (2002). A comparison of com-petition work rates in elite club and 'Super 12'rugby. In *Science and Foot-ball IV: Proceedings of the Fourth World Congress of Science and Football* (pp. 161-166). London: Routledge.

Deutsch, M. U., Kearney, G. A., & Rehrer, N. J. (2007). Time–motion analysis of professional Rugby Union players during match-play. *Journal of sports sciences*, *25*(4), 461-472.

Deutsch, M. U., Maw, G. J., Jenkins, D., & Reaburn, P. (1998). Heart rate, blood lactate and kinematic data of elite colts (under-19) Rugby Union players during competition. *Journal of sports sciences*, *16*(6), 561-570.

Docherty, D., Wenger, W. A., & Neary, P. (1988). Time-motion analysis related to the physiological demands of rugby. *Journal of human movement studies*, *14*(6), 269-277.

Durandt, J., Du Toit, S., Borresen, J., Hew-Butler, T., Masimla, W., Jokoet, I., & Lambert, M. (2006). Fitness and body composition profiling of elite junior South African rugby players. *South African Journal of Sports Medicine*, *18*(2), 38-45.

Duthie, G., Pyne, D., & Hooper, S. (2003). Applied physiology and game analysis of Rugby Union. *Sports medicine*, *33*(13), 973-991.

Eaton, C., & George, K. (2006). Position specific rehabilitation for Rugby Union players. Part I: Empirical movement analysis data. *Physical Therapy in Sport*, *7*(1), 22-29.

Gabbett, T. J. (2006). Skill-based conditioning games as an alternative to traditional conditioning for rugby league players. *The Journal of Strength & Conditioning Research*, *20*(2), 306-315.

Gabbett, T. J. (2016). The training—injury prevention paradox: should athletes be training smarter and harder?. *British journal of sports medicine*, *50*(5), 273-280.

Gabbett, T. J., Jenkins, D. G., & Abernethy, B. (2012). Physical demands of professional rugby league training and competition using microtechnology. *Journal of science and medicine in sport*, *15*(1), 80-86.

Gastin, P., Williams, K. (2010) Accuracy of 1Hz versus 5Hz HPS devices to measure movement patterns in team sport activities. *Journal of Science and Medicine in Sport.* 13(1), 32

Haakma, M. L. (2021). *Exploring and analysing the notion of worst case scenario in professional Rugby Union* (Doctoral dissertation, The University of Waikato).

Hartwig, T. B., Naughton, G., & Searl, J. (2011). Motion analyses of adolescent Rugby Union players: a comparison of training and game demands. *The Journal of Strength & Conditioning Research*, *25*(4), 966-972.

Hill-Haas, S. V., Dawson, B., Impellizzeri, F. M., & Coutts, A. J. (2011). Physiology of small-sided games training in football. *Sports medicine*, *41*(3), 199-220.

Howe, S. T., Aughey, R. J., Hopkins, W. G., Cavanagh, B. P., & Stewart, A. M. (2020). Sensitivity, reliability and construct validity of GPS and accelerometres for quantifying peak periods of rugby competition. *Plos one*, *15*(7), e0236024.

Huggins, R. A., Giersch, G. E., Belval, L. N., Benjamin, C. L., Curtis, R. M., Sekiguchi, W., ... & Casa, D. J. (2020). The validity and reliability of global positioning system units for measuring distance and velocity during linear and team sport simulated movements. *The Journal of Strength & Conditioning Research*, *34*(11), 3070-3077.

Ille, N., Erber, R., Aurich, C., & Aurich, J. (2014). Comparison of heart rate and heart rate variability obtained by heart rate monitors and simultaneously recorded electrocardiogram signals in nonexercising horses. *Journal of Veterinary Behavior*, *9*(6), 341-346.

Johnston, R. J., Watsford, M. L., Kelly, S. J., Pine, M. J., & Spurrs, R. W. (2014). Validity and Interunit Reliability of 10 Hz and 15 Hz GPS Units for Assessing Athlete Movement Demands. *Journal of Strength and Conditioning Research*, *28*(6), 1649–1655. https://doi.org/10.1519/jsc.0000000000000323

Johnston, R. J., Watsford, M. L., Pine, M. J., Spurrs, R. W., Murphy, A. J., & Pruyn, E. C. (2012). The validity and reliability of 5-Hz global positioning system units to measure team sport movement demands. *The Journal of Strength & Conditioning Research*, *26*(3), 758-765.

Johnston, R. J., Watsford, M. L., Pine, M. J., Spurrs, R. W., Murphy, A. J., & Pruyn, E. C. (2012). The validity and reliability of 5-Hz global positioning system units to measure team sport movement demands. *The Journal of Strength & Conditioning Research*, *26*(3), 758-765.

Jones, M. R., West, D. J., Crewther, B. T., Cook, C. J., & Kilduff, L. P. (2015). Quantifying positional and temporal movement patterns in professional Rugby Union using global positioning system. *European Journal of Sport Science*, *15*(6), 488-496.

Jones, M. R., West, D. J., Harrington, B. J., Cook, C. J., Bracken, R. M., Shearer, D. A., & Kilduff, L. P. (2014). Match play performance characteristics that predict post-match creatine kinase responses in professional Rugby Union players. *BMC sports science, medicine and rehabilitation*, *6*(1), 38.

Jones, M. R., West, D. J., Harrington, B. J., Cook, C. J., Bracken, R. M., Shearer, D. A., & Kilduff, L. P. (2014). Match play performance characteristics that predict post-match creatine kinase responses in professional Rugby Union players. *BMC sports science, medicine and rehabilitation*, *6*(1), 1-7.

Knechtle, B., Knechtle, P., Wirth, A., Alexander Rüst, C., & Rosemann, T. (2012). A faster running speed is associated with a greater body weight loss in 100-km ultra-marathoners. *Journal of sports sciences*, *30*(11), 1131-1140.

Lacome, M., Piscione, J., Hager, J. P., & Carling, C. (2016). Analysis of running and technical performance in substitute players in international male Rugby Union competition. *International journal of sports physiology and performance*, *11*(6), 783-792.

Larsson, P. (2003). Global positioning system and sport-specific testing. *Sports medicine*, *33*(15), 1093-1101.

Maddison, R., & Ni Mhurchu, C. (2009). Global positioning system: a new opportunity in physical activity measurement. *International Journal of Behavioral Nutrition and Physical Activity*, *6*(1), 1-8.

Malone, J. J., Lovell, R., Varley, M. C., Coutts, A. J. (2017) Unpacking the Black Box: Applications and Considerations for Using GPS Devices in Sport. *International Journal of Sports Physiology and Performance.* 12(2), 18-26

Maud, P. J., & Shultz, B. B. (1984). The US national rugby team: a physiological and anthropometric assessment. *The Physician and Sportsmedicine*, *12*(9), 86-99.

McCarra, A. (2020). Physical Demands of Rugby Union, and the difference between the senior and junior game. *Setanta College.*

McKenzie, A. D., Holmyard, D. J., & Docherty, D. (1989). Quantitative analysis of rugby: factors associated with success. *J Hum Mov Stud [Internet]*, *17*, 101-13.

McLean, D. A. (1992). Analysis of the physical demands of international Rugby Union. *Journal of sports sciences*, *10*(3), 285-296.

McNeff, J.G. (2002) The global positioning system. *IEEE Transactions on Microwave theory and techniques, 50(3),* pp. 645-652.

Nicholas, C. W. (1997). Anthropometric and physiological characteristics of Rugby Union football players. *Sports Medicine*, *23*(6), 375-396.

Nikolaidis, P. T., Clemente, F. M., van der Linden, C. M., Rosemann, T., & Knechtle, B. (2018). Validity and reliability of 10-Hz global positioning system to assess in-line movement and change of direction. *frontiers in physiology*, *9*, 228.

Novak, A. R., Impellizzeri, F. M., Trivedi, A., Coutts, A. J., & McCall, A. (2021). Analysis of the worst-case scenarios in an elite football team: Towards a better understanding and application. *Journal of Sports Sciences*, 1-10.

Oliva-Lozano, J. M., Martín-Fuentes, I., Fortes, V., & Muyor, J. M. (2021). Differences in worst-case scenarios calculated by fixed length and rolling average methods in professional soccer match-play. *Biology of Sport*, *38*(3).

Owen, A., Twist, C., & Ford, P. (2004). Small-sided games: the physiological and technical effect of altering pitch size and player numbers. *Insight*, *7*(2), 50-53.

Owen, C., Till, K., Weakley, J., & Jones, B. (2020). Testing methods and physical qualities of male age grade Rugby Union players: A systematic review. *Plos one*, *15*(6), e0233796.

Owen, S. M. (2019). *Match-play demands of a Super Rugby team* (Doctoral dissertation, Stellenbosch: Stellenbosch University).

Parak, J., & Korhonen, I. (2013). Accuracy of Firstbeat Bodyguard 2 beat-to-beat heart rate monitor. *White Pap Firstbeat Technol Ltd*.

Pollard, B. T., Turner, A. N., Eager, R., Cunningham, D. J., Cook, C. J., Hogben, P., & Kilduff, L. P. (2018). The ball in play demands of international Rugby Union. *Journal of science and medicine in sport*, *21*(10), 1090-1094.

Quarrie, K. L., Handcock, P., Toomey, M. J., & Waller, A. E. (1996). The New Zealand rugby injury and performance project. IV. Anthropometric and physical performance comparisons between positional categories of senior A rugby players. *British journal of sports medicine*, *30*(1), 53-56.

Rampinini, E., Alberti, G., Fiorenza, M., Riggio, M., Sassi, R., Borges, T. O., & Coutts, A. J. (2015). Accuracy of GPS devices for measuring high-intensity running in field-based team sports.

Rampinini, E., Alberti, G., Fiorenza, M., Riggo, M., Sassi, R., Borges, T. O., Coutts, A. J. (2015) Accuracy of GPS Devices for Measuring High-intensity Running in Field-based Team Sports. *International Journal of Sports Medicine.* 36(1), 49-53

Read, D. B., Jones, B., Phibbs, P. J., Roe, G. A., Darrall-Jones, J. D., Weakley, J. J., & Till, K. (2017). Physical demands of representative match-play in adolescent Rugby Union. *The Journal of Strength & Conditioning Research*, *31*(5), 1290-1296.

Read, D. B., Jones, B., Phibbs, P. J., Roe, G. A., Darrall-Jones, J., Weakley, J. J., & Till, K. (2018). The physical characteristics of match-play in English schoolboy and academy Rugby Union. *Journal of sports sciences*, *36*(6), 645-650.

Read, D. B., Jones, B., Phibbs, P. J., Roe, G. A., Darrall-Jones, J. D., Weakley, J. J., & Till, K. (2017). Physical demands of representative match-play in adolescent Rugby Union. *The Journal of Strength & Conditioning Research*, *31*(5), 1290-1296.

Read, D. B., Till, K., Beasley, G., Clarkson, M., Heyworth, R., Lee, J., ... & Jones, B. (2019). Maximum running intensities during English academy Rugby Union match-play. *Science and Medicine in Football*, *3*(1), 43-49.

Reardon, C., Tobin, D. P., & Delahunt, E. (2015). Application of individualized speed thresholds to interpret position specific running demands in elite professional Rugby Union: a GPS study. *PloS one*, *10*(7), e0133410.

Reardon, C., Tobin, D. P., Tierney, P., & Delahunt, E. (2017). The worst case scenario: Locomotor and collision demands of the longest periods of gameplay in professional Rugby Union. *PLoS one*, *12*(5), e0177072.

Rico-González, M., Ortega, J. P., Nakamura, F. W., Moura, F. A., & Los Arcos, A. (2021). Identification, computational examination, critical assessment and future considerations of spatial tactical variables to assess the use of space in team sports by positional data: A systematic review. *Journal of Human Kinetics*, *77*, 205.

Rigg, P., & Reilly, T. (1988). A fitness profile and anthropometric analysis of first and second class Rugby Union players. *Science and football*, 194-200.

Roberts, S. P., Trewartha, G., Higgitt, R. J., El-Abd, J., & Stokes, K. A. (2008). The physical demands of elite English Rugby Union. *Journal of sports sciences*, *26*(8), 825-833.

Roe, G., Darrall-Jones, J., Black, C., Shaw, W. (2017) Validity of 10-Hz GPS and Timing Gates for Assessing Maximum Velocity in Professional Rugby Union Players. *International Journal of Sports Physiology and Performance.* 12(6), 836-839

Roe, G., Darrall-Jones, J., Black, C., Shaw, W., Till, K., & Jones, B. (2017). Validity of 10-HZ GPS and timing gates for assessing maximum velocity in professional Rugby Union players. *International journal of sports physiology and performance*, *12*(6), 836-839.

Scott, M. T., Scott, T. J., & Kelly, V. G. (2016). The validity and reliability of global positioning systems in team sport: a brief review. *The Journal of Strength & Conditioning Research*, *30*(5), 1470-1490.

Sheppy, E., Hills, S. P., Russell, M., Chambers, R., Cunningham, D. J., Shearer, D., ... & Kilduff, L. P. (2020). Assessing the whole-match and worst-case scenario locomotor demands of international women's Rugby Union match-play. *Journal of science and medicine in sport*, *23*(6), 609-614.

Smart, D. J., Hopkins, W. G., & Gill, N. D. (2013). Differences and changes in the physical characteristics of professional and amateur Rugby Union players. *The Journal of Strength & Conditioning Research*, *27*(11), 3033-3044.

Sullivan, C., Bilsborough, J. C., Cianciosi, M., Hocking, J., Cordy, J., & Coutts, A. J. (2014). Match score affects activity profile and skill performance in professional Australian Football players. *Journal of science and medicine in sport*, *17*(3), 326-331.

Tee, J. C., Lambert, M. I., & Coopoo, W. (2016). GPS comparison of training activities and game demands of professional Rugby Union. *International Journal of Sports Science & Coaching*, *11*(2), 200-211.

Thornton, W. R., Nelson, A. R., Delaney, J. A., Serpiello, F. R., & Duthie, G. M. (2019). Interunit reliability and effect of data-processing methods of global positioning systems. *International Journal of Sports Physiology and Performance*, *14*(4), 432-438.

Varley, M. C., Elias, G. P., & Aughey, R. J. (2012). Current match-analysis techniques' underestimation of intense periods of high-velocity running. *International Journal of Sports Physiology and Performance*, *7*(2), 183-185.

Varley, M. C., Fairweather, I. F. W., & Aughey1, 2, R. J. (2012). Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *Journal of sports sciences*, *30*(2), 121-127.

Vaz, L. M. T., Gonçalves, B. S. V., Figueira, B. E. N., & Garcia, G. C. (2016). Influence of different small-sided games on physical and physiological demands in Rugby Union players. *International Journal of Sports Science & Coaching*, *11*(1), 78-84.

Venter, R. E., Opperman, E., & Opperman, S. (2011). The use of Global Positioning System (GPS) tracking devices to assess movement demands and impacts in Under-19 Rugby Union match play: sports technology. *African Journal for Physical Health Education, Recreation and Dance*, *17*(1), 1-8.

Waldron, M., Harding, J., Barrett, S., & Gray, A. (2021). A new foot-mounted inertial measurement system in soccer: reliability and comparison to global positioning systems for velocity measurements during team sport actions. *Journal of Human Kinetics*, *77*(1), 37-50.

Whitehead, S., Till, K., Weaving, D., & Jones, B. (2018). The use of microtechnology to quantify the peak match demands of the football codes: a systematic review. *Sports medicine*, *48*(11), 2549-2575.

Yamamoto, W., Takemura, M., Iguchi, J., Tachibana, M., Tsujita, J., & Hojo, T. (2020). In-match physical demands on elite Japanese Rugby Union players using a global positioning system. *BMJ Open Sport & Exercise Medicine*, *6*(1).