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The use of GPS to analyse the worst-case scenario of movement demands using fixed epochs versus rolling averages and the impact of climate and travel on the male England Rugby Sevens team during the World Rugby Sevens Series

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Abstract

Introduction. Analysing and quantifying movement demands using global positioning systems (GPS) traditionally uses fixed-time epochs (FIXED). However, research has indicated FIXED underestimates movement demands versus rolling averages (ROLL). Rugby sevens athletes are also exposed to travel and climatic demands during the World Rugby Sevens Series, which research has reported to affect performance. **Methods.** This study compared; FIXED *vs.* ROLL, to quantify worst-case scenarios and analysed travel and climatic impacts on movement demands. 18 male England Rugby Sevens players wore 10 Hz GPS units during 52 games, with peak values of relative total distance (RTD) and relative high-speed running (>5 $m.s^{-1}$; RHSR) recorded over 60-420 s using FIXED and ROLL epochs. Travel (duration, direction, time zones crossed) and climatic data (temperature, relative humidity, humidex) were collected and analysed against whole game relative distance and peak 1, 3 and 5-minute RTD and RHSR. **Results.** For each epoch, there was a difference between methods (60-420 s) ($p < 0.001$), with RTD and RHSR values decreasing as epoch length increased. FIXED always underestimated ROLL at each epoch for RTD (10-12%) and RHSR (12-20%). Whole game relative distance increased for temperature, relative humidity, and travel direction West ($p < 0.05$), and decreased following travel direction East and humidex ($p < 0.05$). Peak 5-minute RTD increased following travel direction West and relative humidity ($p < 0.05$) and decreased following travel Eastward ($p < 0.05$). Travel and climate did not significantly affect peak 1 and 3-minute RTD and peak 1, 3 and 5-minute RHSR. **Conclusion.** This is the first study in rugby sevens reporting an underestimation of the worst-case scenario using FIXED *vs* ROLL epochs. Information on the worst-case scenario is an important component in formulating training prescription. Travel and climatic factors can also influence performance, which may be independent of the effects on the worst-case scenario.

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…………………………………………... 15/04/2022

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.

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

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List of abbreviations

AIC = Akaike information criterion

BIP = Ball in play

CK = Creatine kinase

CMJ = Countermovement jump

COD = Change of direction

CV = Coefficient of variation

EHI = Exercise heat illness

GNSS = Global navigation satellite system

GPS = Global positioning system

FIXED = Fixed epoch method

HDOP = Horizontal dilution of precision

HH = High heat

HIR = High-intensity running

HSR = High-speed running

ICC = Intraclass correlation

KPI = Key performance indicator

MH = Moderate heat

RD = Relative distance

RHSR = Relative high-speed running

ROLL = Rolling average method

RTD = Relative total distance

S1 = Study 1

S2 = Study 2

SD = Standard deviation

SEE = Standard error of the estimate

TD = Total distance

TE = Total error

TEM = Total error of measurement

TMA = Time-motion analysis

VP = Vapour pressure

WCS – Worst-case scenario

WGRD = Whole game relative distance

WRWRSS = World Rugby Women’s Sevens Series

WRSS – World Rugby Sevens Series

Chapter 1.0 - Introduction:

Rugby sevens is a modified version of rugby union, involving teams of seven players playing seven-minute halves (Henderson, Harries, Poulos, Fransen, & Coutts, 2018). It is an intermittent sport, compromising of high-intensity activities, interspersed by periods of rest or lower intensity (Suarez-Arrones, Nunez, Portillo, Mendez-Villanueva, 2012). It generally involves an increased amount of relative high-intensity running (HIR) and relative distance (RD) covered in a game at a higher velocity in comparison to rugby fifteens (Higham, Pyne, Anson, & Eddy, 2012). Male rugby sevens players cover between 1,100-2,486 m per match, with the RD being between 78.6-121.4 m.min^{-1} (Ball, Halaki, & Orr, 2019). Enhancing the understanding of these movement demands analysed during training and competition can allow coaches and practitioners to develop specific and individualised training sessions according to the demands experienced (Higham, Pyne, Anson, Hopkins, & Eddy, 2016).

The World Rugby Sevens Series (WRSS) of 2018-2019 involved 10 tournaments, in 10 different countries (Dubai, Cape Town, New Zealand, Australia, USA, Canada, Hong Kong, Singapore, England and France), across an 8-month period. Tournaments last 2-3 days, with a maximum of 3 games played each day, and are grouped into competitions with 5-6 days between each back-to-back tournament (Fowler, Murray, Farooq, Lumley, & Taylor, 2019). Long-haul travel is therefore a requirement of the WRSS, as athletes must travel for long periods of time, whilst crossing multiple time zones, which could impair their performance and recovery due to effects of jet-lag (Fowler et al., 2019). The location of the tournaments of the WRSS also result in athletes having to perform in different climatic conditions to their home country, which could also hinder performance (Ozgunen et al., 2010; Wakabayashi, Oksa, & Tipton, 2015).

To date, there is limited research on the movement demands of rugby sevens athletes with the majority reporting average demands over half or a whole-game (Granatelli et al., 2014; Portillo et al., 2014; Ross, Gill, & Cronin, 2015b; Suarez-Arrones et al., 2014; Van den berg, Malan & de Ridder, 2017). For example, research on international rugby sevens players from the 2012-2013 WRSS indicated that the mean total distance (TD) covered by forwards was 1452 ± 243 (108 m.min^{-1}) and for backs was 1420 ± 332 (103 m.min^{-1}) (Ross et al., 2015b). TD has been shown to decrease by 11.2% between the first (643 ± 70 m) and second half (578 ± 77 m) (Granatelli et al., 2014), which is similar to other studies where a decrease in TD between halves has been reported (Portillo et al., 2014; Suarez-Arrones et al., 2014; Van den Berg et al., 2017). Positional differences have also been reported for average high-speed running (HSR) distance covered at more than 5 $m.s^{-1}$ for forwards (252 ± 103 m) and backs (249 ± 130 m) (Ross et al., 2015b), as well as average sprinting values (>20 km/h) of 8.3 ± 3.5 $m.min^{-1}$ and 11.2 ± 3.4 $m.min^{-1}$ for forwards and backs respectively (Suarez-Arrones et al., 2014). The number of accelerations and HSR completed in the first half compared to second has been shown to decrease in both forwards and backs (Peeters, Carling, Piscione, & Lacome, 2019). For example, Higham et al. (2012) recorded a 16% reduction in the accelerations completed per minute over 4 $m.s^{-2}$ in the second half compared to the first. Due to the high-intensity nature of a rugby sevens match, substitutes are also regularly used to maintain the intensity from the first to second half (Van den Berg et al., 2017), with substitutes being made in the second half having higher work-rates and work-rest ratios than starting players (Higham et al., 2012). Despite the data collected by global positioning systems (GPS) being useful in determining the workload and demand experienced by players during a game, measuring movement demands using half or whole-game averages may result in the peak demands not being accurately detected (Delaney et al., 2018). Recent research has highlighted that when these longer epoch lengths are used there is a decrease in the intensity of the movement demands recorded, meaning the training loads prescribed may not be accurate (Cunningham et al., 2018; Doncaster, Page, White, Svenson, & Twist, 2020; Sheppy et al., 2020).

Understanding the peak periods of a game, known as the worst-case scenario (WCS) is essential to allow coaches to develop and prescribe appropriate training for players (Doncaster et al., 2020). Due to the intermittent nature of a rugby sevens game, it is unlikely that match activities will fall within a pre-defined period and therefore it is likely that the peak movement demands will be underestimated when fixed epochs are used (Cunningham et al., 2018; Sheppy et al., 2020). Current research by Cunningham et al. (2018) analysed the difference between using fixed epochs and rolling averages to assess the WCS in Rugby Union, concluding that TD was underestimated by 11-12% when using fixed epochs compared to rolling averages (Cunningham et al., 2018). Similarly, in international women's rugby union, fixed epochs underestimated TD and HSR by 8-25% and 10-26% respectively when compared to a rolling average (Sheppy et al., 2020). To date, there is limited research within rugby sevens with only a few papers analysing the WCS using rolling averages. For example, Murray and Varley (2015) used a rolling average to analyse the peak 1-minute of play and recorded a TD of 183 ± 30 $m.min^{-1}$ and HSR of 86 ± 30 $m.min^{-1}$. Peeters et al. (2019) also used a 1-minute rolling average to assess the peak 1-minute period of play and highlighted that during the minute following the peak 1-minute period TD and HSR decreased. Further research has also been undertaken using a 2-minute rolling average where it was highlighted that the peak 2-minute period of play for RD and metabolic power was significantly different to the pre-peak period, post-peak period and match average (Furlan et al., 2015).

Despite some research being completed on analysing the WCS using rolling averages, currently there are no studies examining the difference between fixed vs rolling epochs in rugby sevens, providing an area for more research to be completed in.

As mentioned above, the competition structure and schedule of the WRSS schedule involves the athletes being exposed to a large amount of travel between tournaments (Fowler et al., 2019). Long-haul travel involving multiple time zones being crossed can result in jet-lag due to the synchronisation of the circadian rhythm being disrupted (Fowler, Duffield, Lu, Hickmans, & Scott, 2016). Consequently, jet lag has been reported to cause disturbances in sleep at night, an increase in tiredness during the day (Beaumont et al., 2004), an increase in subjective fatigue (Fowler, Duffield, & Vaile, 2015), a reduction in concentration and motivation and a reduction in physical performance (Chapman, Bullock, Ross, Rosemond, & Martin, 2012). Alongside this, spending long periods of time travelling in cramped conditions with difficulty sleeping, as well as being exposed to mild hypoxia can also cause perceptual travel fatigue (Reilly et al., 2007b). For example, Fowler, McCall, Jones and Duffield (2017a) analysed footballers during the FIFA 2014 World Cup who travelled 19 hours, covering 14,695 km eastward over 11 time zones. It was concluded that long-haul travel caused jet-lag which lasted for up to 5 days post-travel, subsequently lowering the players mean wellness and their ability to train (Fowler et al., 2017a). Furthermore, physical performance has also been shown to be impaired, as a reduction in countermovement jump and maximal sprint performance was recorded three and four days after long-haul travel in physically active individuals (Fowler et al., 2017b). Alongside long-haul travel, research has also highlighted that the direction of travel should be considered when planning recovery, as it has been recommended for every time zone crossed eastward one day should be allocated and half a day allowed for each time zone crossed westward (Reilly et al., 2007b). According to this research the England rugby sevens team did therefore not have enough time for recovery during the tournaments in Hamilton (New Zealand) and Hong Kong as more time zones were crossed eastward than days allowed to recover prior to competing.

To date, there is limited research on the effect of travel on rugby sevens athletes during the WRSS. For instance, Mitchell, Pumpa and Pyne (2017) demonstrated that long-haul travel (> 5 hours) can impair an athlete's lower body power by reducing peak power output by 9.4% (± 3.5%) and mean power by 5.6% (± 2.9%). Furthermore, the movement demands following long-haul travel have also been shown to increase with rugby sevens athletes completing 13% (960 m ± 520 m) more TD per tournament compared to short-haul travel (Mitchell et al., 2017). Similarly, Fuller, Taylor and Raftery (2015) also analysed the effect of different travel lengths and time zones crossed (≤ 3 hrs and ≤ 2 time zones, ≥ 10 hours and ≤ 2 time zones or ≥ 10 hours and ≥ 6 time zones) on rugby sevens players over several WRSS. However, it was concluded that despite the travel duration and time zones crossed prior to competition, players' performance and injury risk was not affected (Fuller et al., 2015), contrasting Mitchell et al. (2017). The impact on performance reported by Fuller et al. (2015) was assessed using the tournament ranking and therefore performance was not directly measured like in Mitchell et al. (2017) where performance was quantified using GPS and measuring lower-body power using countermovement jumps (CMJ). The research on the impact travel has on rugby sevens athletes during the WRSS is contradicting and limited therefore more research is needed in this area to understand its potential impact.

Travelling to multiple tournaments situated around the world during the WRSS can also result in athletes experiencing different environmental conditions, which could alter performance (Taylor, Thornton, Lumley, & Stevens, 2019a). When environmental conditions are hot, both skin and core temperature can increase, leading to heat stress (Girard, Brocherie, & Bishop, 2015). In combination with other factors, such as hypohydration, reductions in performance can ensue (Ozgunen et al., 2010). For example, Ozgunen et al. (2010) highlighted that footballers covered significantly less distance during the second half of a football game compared to the first half, with more distance covered walking when competing at a high climatic temperature (36 ± 0°C) compared to moderate temperature (34 ± 1°C). Higher temperatures have been reported to be beneficial for short-term power output and the first set of sprints during repeated sprinting due to an increase in muscle temperature increasing the muscle contraction rate (Girard et al., 2015). However, continued repeated sprints and intermittent efforts performed in the heat, like during rugby sevens has been shown to begin to cause a decrement in performance (Girard et al., 2015). The increased core and skin temperature caused by the athlete experiencing heat stress results in a reduction in voluntary muscle activation and increased strain on the metabolic and cardiovascular system (Girard et al., 2015). Pre-season football training in temperatures of 30.9 ± 2.1°C has been indicated to impair performance, with O'Connor et al. (2020) reporting a decrease in TD and HSR due to the increase in solar radiation. This indicates that higher environmental temperatures increasing core temperature can negatively influence intermittent team-sport performance in both pre-competition training and competition (Ozgunen et al., 2010; O'Connor et al., 2020).

Competing in colder climatic conditions during tournaments of the WRSS could also impact the movement demands of athletes. Cooler environments (≤ 20°C) have been shown to impair performance as there is a dose-dependent relationship between the decrease in muscle performance and the cooler the temperature (Oksa, Rintamaki, & Rissanen, 1997). Reductions in performance are present when exercising in the cold due to a change in the neural drive, as the altered muscle electrical activity results in an increase in the activation of the antagonist muscle compared to the agonist muscle (Racinais, Cocking, & Periard, 2017; Racinais & Oksa, 2010). This physiological change in the interaction between the antagonist-agonist ratio can result in an impairment in performance due to the reduction in conduction velocity when exposed to colder environmental temperatures (Racinais et al., 2017; Racinais & Oksa, 2010). Wakabayashi et al. (2015) highlighted that temperatures below 27°C can impair maximal isometric voluntary contractions due to a reduction in muscle fibre contraction, subsequently limiting the force produced (Wakabayashi et al., 2015). The effects of temperatures below ≤ 20°C have also been shown to impair drop jump performance by reducing the flight time and average force production, which continued to decrease alongside the reduction in temperature (Oksa et al., 1997). The climatic conditions for both hot and cold environments can therefore result in a reduction in performance. Therefore, when travelling around the world for the WRSS the constantly changing environment may create issues for the rugby sevens players when competing.

To date, there is limited research analysing environmental temperature in rugby sevens players. Taylor et al. (2019a) reported that there was not a significant difference in core temperature over two tournaments of the WRSS, London (13.8 – 22.3°C) and Singapore (21.4 – 27°C). Further research in male and female rugby sevens tournaments highlighted that peak core temperatures are linked to the time played within a match (Fenemor et al., 2021; Henderson, Chrismas, Stevens, Coutts, & Taylor, 2020), with Taylor et al. (2019a) recording peak core temperature during the last match of a day. All three studies reported that players had peak core temperature values ≥39°C (Fenemor et al., 2021; Henderson et al., 2020; Taylor et al., 2019a) which has previously been shown to be associated with impaired intermittent sprint performance (Girard et al., 2015). Games during the WRSS are of a high-intensity and can occur at any point during the day with ~2-3 hours between the back-back matches (Schuster et al., 2018). The environmental conditions and body temperature will change throughout a day resulting in players competing in different in conditions for each game depending on the time of day (West, Cook, Beaven, & Kilduff, 2017). Thermoregulation is therefore essential for the players to ensure that they can compete in constantly changing conditions but also maintain their performance throughout the intense days during a WRSS tournament. This highlights the importance of undertaking further research to analyse the effect of temperature on rugby sevens performance during tournaments of the WRSS as the current research in this area in very limited. As can be seen above the combination of both the travel and climatic demands during the WRSS can negatively affect performance variables. In particular, it can be anticipated that the travel and climatic demands of the WRSS will affect the peak demands during competition which are a key factor of rugby sevens performance due to it being an intermittent sport.

The aims of this current study were threefold; 1) to compare fixed *vs*. rolling epochs to calculate the worst-case scenario of movement demands (relative HSR and relative TD) during rugby sevens games from the WRSS 2018-2019, 2) to analyse the impact of travel during the WRSS on worst-case scenario outputs of 1, 3 and 5-minute relative total distance and high-speed running and the movement demand of whole game relative distance, and 3) to analyse the impact of climate during the WRSS on worst-case scenario outputs of 1, 3 and 5-minute relative total distance and high-speed running and the movement demand of whole game relative distance.

Chapter 2.0 – Review of Literature

2.1 - Rugby sevens and assessing movement demands.

2.1.1 - Physiological demands and responses to rugby sevens match play

Rugby sevens is an intermittent sport involving repeated high-intensity efforts followed by periods of rest (Ross, Gill, & Cronin, 2014). It is an adaptation of rugby union consisting of seven players playing two seven-minute halves (fourteen-minute games) with a two-minute half-time period on a normal rugby union sized pitch (Granatelli et al., 2014). International rugby sevens players are on average 1.83 m ± 0.06 m tall, 89.7 kg ± 7.6 kg in mass, with lean mass averaging at 51.7 kg/mm$^{0.14}$ ± 4.5 kg/mm$^{0.14}$ and average VO^{2max} values of 53.8 mL.kg^{-1}.min^{-1} ± 3.4 mL.kg^{-1}.min^{-1} (Higham, Pyne, Anson, & Eddy, 2013). Due to rugby sevens being a high-intensity intermittent sport there is a heavy reliance on both the aerobic and anaerobic energy pathways during matches (Higham et al., 2013). The anaerobic system is vital for the short-term high-intensity repeated bouts during rugby sevens (Higham et al., 2016), which can result in blood lactate levels reaching 11.2 mmol.L^{-1} after a match (Granatelli et al., 2014). Creatine kinase (CK) levels are also affected by the high-intensity nature of a rugby sevens tournament, with West et al. (2014) reporting a ~250% increase in CK after day 1 and a 500% increase after matches on day 2. This highlights the importance of the aerobic energy pathway to ensure players can recover during a game amongst the high-intensity activity, as well as during the ~2-3 hours available between back-to-back matches (Ross et al., 2014; Schuster et al., 2018). Despite this West et al. (2014) recorded a decrease in neuromuscular fatigue over a competition by ~26% following tournament one, with a reduction still present by ~8% 5 days later prior to tournament two. This exemplifies the physiological stress of each match during a tournament on rugby sevens players and indicates that players are not always fully recovered prior to the next tournament.

During rugby sevens there is also fewer players competing on the same size pitch as rugby union, meaning the absolute running demands are higher for rugby sevens players when compared to rugby union (Suarez-Arrones et al., 2012). Suarez-Arrones et al. (2012) estimated that if the match duration of rugby sevens was extended to 80 minutes like rugby union, then rugby sevens players would cover ~9,000 m compared to the average distance of 4,662–6,389 m that has previously been reported to be covered during a male rugby union game. Furthermore, rugby sevens players are more uniform in performance and physiological characteristics as when analysing these factors, a low CV (2.5 - 11.9%) was reported indicating there are similarities between players (forwards and backs) compared to rugby fifteens where the differences between positions are more prominent (Granatelli et al., 2014; Higham et al., 2013).

2.1.2 - Movement demands of rugby sevens

During rugby sevens quantifying the movement patterns of players during matches is essential to understand the movement demands athletes' experience. Recording the movement demands during a rugby sevens game can help in understanding how frequently different activities are undertaken and measure the physical loads players experience (Ross, Gill, & Cronin, 2015a). By understanding this coaches and practitioners can then use this data to help improve performance by developing training drills and programmes specific to the match demands experienced as well as creating drills for each individual position (Jones, West, Crewther, Cook, & Kilduff, 2015; Ross et al., 2015a). Monitoring the movement demands during training can also ensure that the athletes are performing at the correct level of physiological stress to ensure the intended training effects are being achieved, whilst also avoiding any injuries or overtraining (Cunningham et al., 2018).

2.1.3 - Video time-motion analysis (TMA)

Video TMA is a common method used to quantify the physiological demands and movement patterns of team sports, allowing practitioners to design training programmes specific to the sport or playing position (Deutsch, Kearney, & Rehrer, 2007; Dobson & Keogh, 2007). The data for video TMA is collected using either singular or multiple cameras set-up which are elevated between 3-20 m above the pitch (Dobson & Keogh, 2007). The process of video TMA involves either one or multiple researchers to code and analyse the data collected, which can cause several problems associated to the validity and interrater reliability of this method (Barris & Button, 2008). Firstly, interrater reliability of video TMA may be reduced due to the subjectivity of the method as researchers may interpret games differently (Dobson & Keogh, 2007), however, interrater reliability and validity can be enhanced when experienced analysts are used who have adequate knowledge on the sport (Duthie, Pyne, & Hooper, 2003). Video TMA also has other limitations, with research typically analysing small samples due to it being a time consuming and laborious process (Barris & Button, 2008). Furthermore, the categorisation of movement patterns by researchers is a subjective method which varies in reliability depending on which movement pattern is being categorised (Duthie et al., 2003). Despite research grouping movement patterns similarly according to movement activities, there are differences between studies in naming the movement categories, therefore different studies should be compared with caution due to the interrater reliability being unknown (Dobson & Keogh, 2007).

To date, there is only one study which uses video TMA to measure the activity profiles of rugby sevens players (Rienzi, Reilly, & Malkin, 1999), with other rugby sevens studies using video TMA to quantify match activities (e.g., ball carries, contact, passes, scrums, tackles, ball-in-play, rest duration etc) and global positioning systems (GPS) to measure movement data (Ross et al., 2015b; Suarez-Arrones et al., 2014). Rienzi et al. (1999) analysed 30 different matches and organised the player movement activities into seven categories; walking, jogging, moving sideways, high-intensity running, walking backwards, jogging backwards and static poses which differs from the activity categories used within recent research in rugby union (Deutsch et al., 2007; Duthie et al., 2003; Duthie, Pyne, & Hooper, 2005; Roberts, Trewartha, & Stokes, 2006). During a 14-minute rugby sevens game players spent on average 861.4 ± 143.8 seconds in activity and 203.1 ± 46.5 seconds stationary (Rienzi et al., 1999). Only 6.3% of the time in activity involved the players completing high-intensity running, with forwards undertaking significantly more jogging and static poses per game in comparison to the backs (Table 2.1) (Rienzi et al., 1999). The amount of time spent active in each of the 7 activity categories also decreased from the first to second half, indicating the players were fatigued as there was a significant decrease in the amount of sideways moving and jogging in the second half (Table 2.2) (Rienzi et al., 1999).

Table 2.1. Comparison of work-rate frequencies per game between forwards and backs from Rienzi et al. (1999).

TABLE I.—*Comparison of work-rate frequencies per game between forwards and backs.*

Activity	Total (mean±SD)	Forwards (mean±SD)	Backs (mean±SD)	p value
Walking	73.4±17.7	77.8±22.0	70.1±13.3	ns
Jogging	55.6±12.7	61.4±13.5	51.2±10.3	<0.05
Move sideways	35.6±10.3	34.2±10.2	36.7±10.6	ns
High intensity running	18.5±7.3	17.7±6.3	19.2±8.1	ns
Walking backwards	36.4±10.0	39.9±9.1	33.8±10.2	ns
Jogging backwards	6.3±3.2	6.2±4.0	6.4±2.5	ns
Static	51.6±14.5	62.1±12.6	43.6±10.3	<0.01

Table 2.2. Comparison of work-rate frequencies per game between first and second half from Rienzi et al. (1999).

TABLE III.—*Comparison of work-rate frequencies per game between first and second half.*

Activity	First half (mean±SD)	Second half (mean±SD)	p value
Walking	38.4±10.8	35.5±8.7	ns
Jogging	29.1±8.3	25.7±5.7	<0.05
Move sideways	18.9±7.1	15.8±5.4	<0.05
High intensity running	9.7±3.8	8.8±4.6	ns
Walking backwards	18.3±5.7	17.2±6.4	ns
Jogging backwards	3.3±2.5	3.0±1.7	ns
Static	26.4±8.8	24.4±7.8	ns

As mentioned above, other research on rugby sevens only used video TMA to assess the quantity of match activities such as scrums, tackles, passes, contacts etc rather than the movement demands of the rugby sevens players which was measured using GPS (Ross et al., 2015b; Suarez-Arrones, 2014). When using video TMA to analyse the number of tackles performed Suarez-Arrones et al. (2014) highlighted that forwards completed 7.4 ± 1.8, with backs carrying out 4.1 ± 2.4 tackles, which is higher than the tackles recorded by Ross et al. (2015b); 2.68 ± 2.59 and 2.41 ± 2.52, for forwards and backs respectively. It was concluded that forwards were involved in more defensive situations e.g., rucks whereas backs completed more passing and carrying of the ball compared to forwards (Ross et al., 2015b). Currently research within video

TMA in rugby sevens is limited, with more research being completed alongside the development of GPS rather than using the traditional method of video TMA.

2.2 - Global positioning system (GPS)

2.2.1 - GPS to assess movement demands.

Recent research into the movement demands of team sports has seen an increase in the use of GPS technology due to its ability to provide live data in comparison to video TMA (Baris & Button, 2008; Beato, Coratella, Stiff, & Iacono, 2018; McLellan, Lovell, & Gass, 2011). GPS was initially only used in the military (Cummins, Orr, O'Connor, & West, 2013), until 1997 where it was first used to track athletic movement (Schutz & Chambaz, 1997). The latest developments in GPS have resulted in team sports such as rugby union, rugby league, football, hockey, netball, basketball, lacrosse, Australian football, and American football (Crang et al., 2020; Cummins et al., 2013) using GPS to measure the demands experienced during team sports. GPS is a system which tracks multiple athletes using satellites and GPS receivers to calculate the movement demands during activity (Malone, Lovell, Varley, & Coutts, 2017). It has traditionally been used within team sports to measure accelerations, decelerations, total distance (TD) and velocity, however recent advances in GPS technology involving the combination with other sensors such as gyroscopes, magnetometers and tri-axial accelerometers can allow the load and activity demands of players to be measured (Crang et al., 2020; Cummins et al., 2013). Furthermore, continued research has resulted in a progression from 1 and 5 Hz GPS units previously used, to 10 Hz and more recently ≥15 Hz GPS technology, which has increased the validity and reliability of GPS, enhancing the ability to quantify external load and prepare athletes for the demands of sport (Beato et al., 2018; Beato & de Keijzer, 2019; Coutts & Duffield, 2010; Jennings, Cormack, Coutts, Boyd, & Aughey, 2010a; Johnston, Watsford, Kelly, Pine, & Spurrs, 2014; Nikolaidis, Clemente, Van der Linden, Rosemann, & Knechtle, 2018; Rampini et al., 2014).

2.2.2 - GPS in rugby sevens

GPS has been more frequently used within rugby sevens over the years, due to the developments in GPS technology as well as the increased popularity of rugby sevens since its inclusion in the 2016 Olympics (Ball, Halaki, & Orr, 2019). During training and matches GPS units are worn by players within their game shirt or a vest situated underneath their shirt, which positions the units between the players scapulae, reducing movements during a game (Theodoropoulos, Bettle, & Kosy, 2020). The use of GPS within rugby sevens training and games allows information to be collected on the movement patterns of players such as distance, high-speed running, and peak speed and therefore the demands experienced by players (Beato et al., 2018; Varley, Fairweather, & Aughey, 2012b). Quantifying this during a game using GPS provides real-time data and analysis, allowing informed decisions to be made during a game or immediately after and therefore removing the issues with time-consuming methods of video TMA as mentioned above (Beato et al., 2018; Cummins et al., 2013). Monitoring the demands with GPS during training and matches can help with identifying the load that individual players are experiencing and therefore can inform decisions on when to substitute players, potentially reducing the risk of injury when the load is higher (Van den Berg et al., 2017). Following a game, the movement demands quantified using GPS can aid coaches and practitioners to develop and prescribe training sessions specific to the demands of competition to improve performance (Granatelli et al., 2014; Hoppe, Baumgart, Polglaze, & Freiwald, 2018). GPS can therefore provide numerous positive benefits when used within rugby sevens matches such as informing in-game decisions, aiding with the design of game specific training programmes, and reducing the risk of injury (Beato et al., 2018; Granatelli et al., 2014; Hoppe et al., 2018; Van den Berg et al., 2017)

To date, research within rugby sevens using GPS is still limited, with the vast amount of research on GPS in rugby union being used to help analyse and understand rugby sevens GPS data. When categorising the movement velocities during a rugby sevens game the majority of research has coded movement into 6 activity areas; standing and walking (0 - 6 $km.h^{-1}$), jogging (6 - 12 $km.h^{-1}$), cruising (12 - 14 $km.h^{-1}$), striding (14 - 16 $km.h^{-1}$), high-intensity running (18 - 20 $km.h^{-1}$) and sprinting (>20 $km.h^{-1}$) (Portillo et al., 2014; Suarez-Arrones et al., 2012; Suarez-Arrones et al., 2014) based off research completed on the use of GPS in elite rugby union (Cunniffe, Proctor, Baker, & Davies, 2009). Other research in rugby sevens has also based movements velocities off of research in rugby union (Reid, Cowman, Green, & Coughlan, 2013; Coughlan, Green, Pook, Toolan, & O’Connor, 2011) and has categorised movement into 6 areas; standing/non-purposeful movements (0 - 0.05 $m.s^{-1}$), walking (0.5 - 1.7 $m.s^{-1}$), jogging (1.7 - 3.6 $m.s^{-1}$), medium-intensity running (3.6 - 5.0 $m.s^{-1}$), high-intensity running (5.0 - 6.7 m.s^{-1}), and maximal speed running/sprinting (>6.7 m.s^{-1}) (Van den Berg et al., 2017). Some studies however did not categorise movement velocities into 6 subsections and instead divided movement into low-speed areas <18.0 km.h^{-1} or high-speed areas >18 km.h^{-1} (Clarke, Anson, & Pyne, 2015; Ross et al., 2015b, Suarez-Arrones et al., 2016). As a result of the research within rugby sevens being relatively new there is therefore not a generalised set of categories for classifying movement velocities within rugby sevens, further explaining why research from rugby union is used to analyse the data. Despite this all the movement velocity categories follow a similar pattern of classifying high-intensity running/high-speed running as being ≥5 m.s^{-1} or ≥18.0/18.1 km.h^{-1} and therefore this allows GPS data from different rugby sevens papers to be compared. Furthermore, even though rugby sevens games are shorter than rugby union it has been indicated that the same velocity thresholds can be used as the categories represent the varying movement demands during intermittent team sports, which both rugby sevens and rugby union are (Clarke et al., 2015; Cunniffe et al., 2009; Van den Berg et al., 2017).

Quantifying the HSR (high-speed running) demands according to the above thresholds of >18.1 km/h or >5 m.s^{-1} has indicated that male rugby sevens players cover an average distance of 190.3 m when reported in a meta-analysis (Ball et al., 2019). However, other research has reported values on HSR distance that are both higher (Ross et al., 2015b) and lower (Suarez-Arrones et al., 2012) than the distance highlighted by Ball et al. (2019) making it difficult to compare data when different HSR thresholds are used (Table 2.3). One study measuring the positional differences indicated a small difference in distance covered at <5 m.s^{-1}, with forwards covering marginally more distance than backs during a single game (Ross et al., 2015b) (Table 2.3). Contrastingly, when measuring the relative high-speed running (RHSR) distance (5 - 6 m.s^{-1}) it was reported that backs covered more metres per minute than forwards over 22 international rugby sevens games (Higham et al., 2016). Differences between halves have also been reported, with Suarez-Arrones et al. (2016) recording a 25.6% decrease in the RHSR distance above 18 km.h^{-1} (Table 2.4), however Ball et al. (2019) indicated no significant difference (p = 0.34) between halves. Furthermore, when late substitutions are made during a game Murray and Varley (2015) highlighted there is an increased amount of mean HSR completed when compared against players who had completed a whole game.

Another key GPS metric of rugby sevens is sprinting, with research reporting that forwards completed 4.0 ± 1.3 sprints and backs 4.3 ± 1.8 sprints in the first half, compared to 2.5 ± 1.9 and 4.2 ± 1.3 sprints respectively in the second half (Suarez-Arrones et al., 2014). A large decrease in sprints between the first and second half in the forwards was therefore highlighted, with backs performing a higher maximum sprint distance in a game compared to forwards (Suarez-Arrones et al., 2014). Similar values have also been reported in other research, indicating athletes completed between 3.8 – 5.2 sprints in the first half and 3.5 - 3.8 sprints in the second half (Suarez-Arrones et al., 2012; Suarez-Arrones et al., 2016).

When analysing the TD using GPS in rugby sevens, a meta-analysis by Ball et al. (2019) reported that male athletes cover between 1,100 – 2,486 m per game, which is consistent with TD recorded in other studies (Table 2.3). Similar to HSR distance, during a singular match the difference in TD between backs and forwards was small, however when analysed over a tournament consisting of six games it was reported than forwards covered more TD than backs (Ross et al., 2015b). Contrastingly, when comparing the relative distance (RD) during a game between forwards and backs, backs covered more distance per minute than forwards (Higham et al., 2016; Suarez-Arrones et al., 2014) (Table 2.3), with RD averaging between 78.6 – 121.4 $m.min^{-1}$ in male rugby sevens players (Ball et al., 2019). Other research studying TD and RD measured by GPS has divided the data into the first and second halves. A non-significant difference (p = 0.111) was reported for mean TD between the first and second half of a rugby sevens game, despite a 11.2% decrease in mean TD (Granatelli et al., 2014), which is similar to a meta-analysis which also recorded a non-significant difference (p = 0.053) for TD between halves despite reporting a decrease (Ball et al., 2019). Despite this, one study by Van den Berg et al. (2017) indicated than the mean distance covered in the first half was significantly different ($p < 0.05$) to the mean distance in the second half, highlighting the contrasting and limited amount of research on movement demands within rugby sevens. Positional differences between halves, indicated that backs covered more TD and RD than forwards per half (Granatelli et al., 2014), with a significant difference ($p < 0.05$) between halves being reported for RD in backs (Suarez-Arrones et al., 2014) (Table 2.4). Most studies had a greater RD recorded in the first half compared to the second except for Van den Berg et al. (2017) (Table 2.4), however despite this all studies reported a non-significant difference in

RD between the first and second half (Furlan et al., 2015; Granatelli et al., 2014; Van den Berg et al., 2017) (Table 2.4). TD and RD therefore varies between matches and can be further influenced by the score, opponents, and substitutes (Murray & Varley, 2015).

Table 2.3. Whole match movement demands summary for rugby sevens

Study	Variable	Whole Team	Forwards	Backs
Higham et al., 2016	RHSR (5-6 $m.s^{-1}$)		8.9 ± 4.8 $m.min^{-1}$	10.2 ± 6.2 $m.min^{-1}$
	RD		96 ± 12 $m.min^{-1}$	103 ± 14 $m.min^{-1}$
Ross et al., 2015b	TD	Pool: 1446 ± 299 m Cup: 1423 ± 285 m	1452 ± 243 m	1420 ± 332 m
	HIR (≥5 $m.s^{-1}$)	Pool: 254 ± 123 m Cup: 246 ± 117 m	252 ± 103 m	249 ± 130 m
Granatelli et al., 2014	TD	1221 ± 118 m		
Suarez-Arrones et al., 2012	TD	1580.8 ± 146.3 m		
	HIR (18.1 – 20 km/h)	79.5 ± 37.2 m		
Couderc et al., 2017	TD	1429.1 ± 170.6 m		
	RD	87.2 ± 11.1 $m.min^{-1}$		
Suarez-Arrones et al., 2014	RD	102.3 ± 9.8 $m.min^{-1}$	97.7 ± 6.8 $m.min^{-1}$	107.4 ± 10.3 $m.min^{-1}$
Blair, Body, & Croft, 2017	TD	1574.4 ± 267.4 m		
Van den Berg et al., 2017	TD	1100.8 m		

Table 2.4. Summary of movement demands by half for rugby sevens

Study	Variable	First half	Second Half	Difference
Granatelli et al., 2014	TD	Whole team: 643 ± 70 m Backs: 677 ± 60 m Forwards: 599 ± 60 m	Whole team: 578 ± 77 m Backs: 615 ± 87 m Forwards: 540 ± 51 m	11.2% reduction, but not significantly different (*p* =0.111)
	RD	91.4 ± 13.6 $m.min^{-1}$	78.5 ± 18.3 $m.min^{-1}$	No significant difference (*p* = 0.200)
Furlan et al., 2015	RD	98 ± 11 $m.min^{-1}$	90 ± 10 $m.min^{-1}$	Significantly less distance (*p* = 0.032)
	HIR (<4.21 $m.s^{-1}$)	27 ± 8 $m.min^{-1}$	27 ± 8 $m.min^{-1}$	No significant difference (*p* = 0.809)
Higham et al., 2012	RD	120 ± 19 $m.min^{-1}$	113 ± 16 $m.min^{-1}$	5% reduction
	Relative HIR (5-6 $m.s^{-1}$)	9.9 ± 4.5$m.min^{-1}$	9.0 ± 3.8 $m.min^{-1}$	10% reduction
Murray and Varley, 2015	HSR (4.17-10 $m.s^{-1}$)	28.3 ± 10.6 $m.min^{-1}$	19.2 ± 7.6 $m.min^{-1}$	1.17% decrease
	RD	103 ± 15 $m.min^{-1}$	86 ± 19 $m.min^{-1}$	1.24% decrease
Suarez-Arrones et al., 2014	TD	Forwards: 745.2 ± 105.5m Backs: 895.9 ± 184.2m	Forwards: 762.4 ± 111.5 m Backs: 820.4 ± 135.4 m	(*p* = 0.66) (*p* = 0.16)
	RD	Forwards: 97.7 ± 9.7 $m.min^{-1}$ Backs: 112.1 ± 15.7 $m.min^{-1}$	Forwards: 97.6 ± 6.5 $m.min^{-1}$ Backs: 102.8 ± 7.1 $m.min^{-1}$	(*p* = 0.98) (*p* = 0.05)
	HIR (18.1-20 km/h)	Forwards: 5.1 ± 1.9 $m.min^{-1}$ Backs: 5.7 ± 2.1 $m.min^{-1}$	Forwards: 3.3 ± 2.2 $m.min^{-1}$ Backs: 4.66 ± 2.0 $m.min^{-1}$	(*p* = 0.12) (*p* = 0.14)
Suarez-Arrones et al., 2016	RD	112.1 ± 10.4 $m.min^{-1}$	112 .1 ± 9.3 $m.min^{-1}$	
	HSR (>18.0 km/h)	21.9 ± 9.9 $m.min^{-1}$	16.3 ± 5.9 $m.min^{-1}$	25.6% decrease

Table 2.4. Continued. Summary of movement demands by half for rugby sevens

Van den Berg et al., 2017	TD	596.8 m	504 m	Significant difference ($p < 0.05$)
	RD	78 $m.min^{-1}$	79.7 $m.min^{-1}$	Non-significant difference ($p = 0.780$)
	% Of time in HIR (5.1 – 6.7 $m.s^{-1}$)	5.74 %	6.08 %	Non-significant difference ($p = 0.670$)

2.2.3 - Validity and reliability of GPS

It is crucial that GPS units are both valid and reliable to ensure that the data collected when monitoring sporting activity is of a high quality and can be accurately quantified (Vickery et al., 2014). To date, previous research has compared data recorded from GPS against criterion measures such as a tape measure, trundle wheel pedometer, timing gates, radar guns and Vicon to assess the validity of GPS and whether it accurately measures what it intends to measure (Crang et al., 2020; Scott, Scott, & Kelly, 2016). The reliability of the GPS units to be able to reproduce results is also important so that data can be compared between different players wearing different GPS units (Heale & Twycross, 2015; Hopkins, 2000). It is however difficult to compare different sampling rates of GPS units due to the differences in model of GPS and the method used to analyse the validity and reliability (Rampini et al., 2014). The validity and reliability of GPS can be affected by the speed and intensity of the task, the sampling rate and the type of exercise being completed (Rampini et al., 2014) and therefore it is essential to have a high validity and reliability to allow practitioners to use the data collected to improve performance (Crang et al., 2020).

Improvements in GPS technology has led to the development of 10 Hz GPS units which are more commonly used within team sports due to the increased validity and reliability compared to lower sampling GPS (Table 2.5) (Johnston, Watsford, Pine, Spurrs, & Sporri, 2013; Nikolaidis et al., 2018; Rampini et al., 2014; Scott et al., 2016). Research has commonly indicated that the accuracy of GPS increases alongside the sampling rate of units, with Rampini et al. (2014) highlighting that 10 Hz GPS had a lower typical error for TD, HSR, very-high-speed running, metabolic power, time at high metabolic power and time at very-high metabolic power compared to 5 Hz GPS, making it more accurate (Table 2.5). There is a vast amount of research supporting the reliability and validity of 10 Hz GPS for measuring TD during both team sport circuits and linear activities over short to moderate distances as the values reported by GPS were not significantly different from the criterion measures (Table 2.5) (Johnston et al., 2014; Rampini et al., 2014; Vickery et al., 2014). 10 Hz GPS has also been proven to be a valid measure of TD during change of direction courses, however when the changes in direction became tighter, the validity began to reduce (Vickery et al., 2014). Despite 10 Hz GPS units providing more valid and reliable results than 1 Hz and 5 Hz, caution should still be taken when measuring instantaneous velocity as accuracy has been shown to be reduced during accelerations above 4 m.s^{-2} (Akenhead, French, Thompson, & Kayes, 2014). The reliability during instantaneous velocity is however 6-fold more reliable than 5 Hz GPS units, indicating that 10 Hz GPS is more reliable and sensitive for use within team sport (Varley et al., 2012b). Recent research analysing the 10 Hz STATSports Apex units (the units used within this study) highlighted the units are valid when measuring distance during a 400 m trial, 128.5 m circuit and 20 m trial as well as instantaneous speed (ICC = 0.96) when compared to the criterion measures (Beato et al., 2018). The 10 Hz Apex units also have excellent inter-unit reliability for peak velocity over sprint distances of 5-30 m (Table 2.5) (Beato & de Keijzer, 2019). When comparing the higher sampling rate units (15 Hz and 18 Hz) to 10 Hz GPS, the literature has shown that they provide the same results as higher sampling units, suggesting the increase in sampling rate is unnecessary when 10 Hz GPS is both valid and reliable for use in team sports (Scott et al., 2016). Research has therefore indicated that 10 Hz GPS units are valid and reliable to assess movement demands during team sports, however it is difficult to compare data between models due to the differences in manufacturing (Beato & de Keijzer, 2019).

Table 2.5. Validity and reliability of 10 Hz GPS units

Study	Participants	Methods	Criterion Measure	Validity	Reliability
Akenhead et al., 2014	Custom aluminium monorail	15 x 10 m linear sprints	Laser	Smooth acceleration SEE = 0.12 – 0.32 Raw acceleration SEE = 0.17 – 0.36	Smooth acceleration – TE = 0.05-0.12, CV = 0.7-9.1% Raw acceleration – TE = 0.11-0.44, CV = 1.8-47.4%
Bataller-Cervero et al., 2019	8 male amateur team sport players	10 x 20 m or 21 x 40 m	Tape measure Radar gun Timing gates	Instantaneous velocity – bias = -0.07 ± 0.22, STE = 0.22	Instantaneous velocity ICC = 0.99
Beato et al., 2018	20 male and female physically active university students	Intraclass correlation for criterion vs Apex Vpeak. 400 m track 128.5 m team sport circuit 20 m linear running trial	Radar gun Measuring tape	400 m bias = 1.05 ± 0.87% 128.5 m circuit bias = 2.3 ± 1.1% 20m bias = 1.11 ± 0.99%	ICC for Vpeak= 0.96
Beato and de Keijzer, 2019	10 male team sports players	Inter-unit reliability Linear sprint distances of 5-10, 10-15, 15-20 and 20-30 m.	Measuring tape		5 -10 m ICC = 0.96 10-15 m ICC = 0.95 15-20 m ICC = 0.95 20-30 m ICC = 0.97 Sprints overall = 0.99
Castellano et al., 2011	9 trained male athletes	7 x 15 m and 6 x 30 m linear runs	Tape measure Electronic timing gates	Bias 15 m sprint = 11.9% Bias 30 m sprint = 6.5%	15 m CV = 1.3% 30 m CV = 0.7%

Table 2.5. continued. Validity and reliability of 10 Hz GPS units

Study	Participants	Method	Criterion Measure	Validity	Reliability
Hoppe et al., 2018	6 male athletes	10 bouts of team sport circuit	Trundle wheel Tape measure Timing gates	25.1 m sprinting with COD TEE = 1 ± 0.1 10m walking with COD TEE = 0.7 ± 0.1 129.6 entire circuit TEE = 4.2 ± 0.5 Sprinting TEE = 0.5 – 1.1	25.1 m sprinting with COD TE = 0.9 ± 0.1 10 m walking with COD TE = 0.6 ± 0.1 129.6 entire circuit TE = 3.4 ± 0.6 Sprinting TE = 0.5 – 1.2
Johnston et al., 2014	8 trained men	8 repetitions of a 165 m team sport simulation circuit Inter-unit reliability (between 2 10 Hz units)	Tape measure Timing lights	<1% error in total distance when GPS compared to actual total distance. Average peak speed when actual and GPS values compared (*r* = 0.89-0.91 for two units)	Total distance TEM = 1.30% Peak speed TEM = 1.64%
Nikolaidis et al., 2018	Study 1 (S1) – track and field athletes, 6 females, 2 males Study 2 (S2) - 20 female soccer players	S1 – 5 laps of a 200 m track S2 – 20 m shuttle run endurance test	Tape measure	Bias between GPS and actual distance S1 – less than ~1% S2 – less than ~5%	S1 – Intra-unit reliability ICC = 0.833 Inter-unit reliability CV = 1.31%-2.20% S2- Intra-unit reliability of 2^{nd} & 3^{rd} stage, ICC = 0.718 and 5^{th}, 6^{th}, 7^{th} & 8^{th} ICC = 0.831. Inter-unit reliability CV = 2.08-3.92%

Table 2.5. continued. Validity and reliability of 10 Hz GPS units

Study	Participants	Method	Criterion Measure	Validity	Reliability
Rampini et al., 2014	8 male football players	Soccer simulation – intermittent running, 7 x 70 m	Radar gun	High-speed running CV = 4.7% Very high-speed running = 10.5% Total distance CV = 1.9% Mean metabolic power CV = 2.4% Time spent at high metabolic power CV = 4.5% Time spent at very high metabolic power = 6.2%	
Roe et al., 2017	9 male, rugby union players	3 x 40 m sprints	Radar gun	Velocity max TEE = 1.87 – 1.95%	Velocity max ICC = 0.95-0.96
Varley et al., 2012b	3 athletes	80 bouts of straight-line runs. Intra-unit reliability	Laveg laser	Constant velocity CV = 3.1 – 8.3% Acceleration CV = 3.6 – 5.9% Deceleration CV = 11.3%	Constant velocity – CV = 2.0 – 5.3% Acceleration = 1.9 – 4.3% Deceleration CV = 6.0%

2.3 - Worst-case scenario (WCS)

2.3.1 - Worst-case scenario of movement demands in rugby

Traditionally movement demands during rugby union, rugby league and rugby sevens have been quantified as absolute values over a whole match or by halves (Table 2.3 and 2.4) however, using these average values during training can result in the peak demands being underestimated (Cunningham et al., 2018; Delaney et al., 2015). The worst-case scenario (WCS) is known as the most demanding aspect of play within a given epoch length and needs to be accurately measured to be able to be used. By correctly quantifying and understanding these demands coaches and practitioners can then plan training sessions to simulate the WCS of match play, allowing players to train and adapt to the most intense periods of competition (Cunningham et al., 2018; Furlan et al., 2015). Research has indicated that athletes should be training at the intensity of the WCS or higher to fully prepare athletes for competition and reduce injury risk (Cunningham et al., 2018; Doncaster, et al., 2020; Gabbett, 2016) as training under the intensity of the WCS i.e., by using average demands could result in athletes being underprepared (Sheppy et al., 2020). To be able to accurately quantify the WCS and avoid underestimation a more sensitive method needs to be used (Delaney et al., 2015). To date, the most common method used to calculate the WCS is using smaller fixed epochs (1-10 minutes) (Cunningham et al., 2018; Granatelli et al., 2014; Jones et al., 2015; Kempton, Sirotic, & Coutts, 2015), or ball in play (BIP) time (Reardon, Tobin, Tierney, & Delahunt, 2017; Pollard et al., 2018), with recent literature focusing on rolling averages (1-10 minutes) (Cunningham et al., 2018; Furlan et al., 2015; Johnston, Devlin, Wade, & Duthie, 2019a; Johnston et al., 2019b).

In rugby union, Jones et al. (2015) used averages over 10-minute blocks to assess the movement patterns during a game, reporting that there was an increase during the final 10-minutes of play in both high-speed distance and high-intensity sprinting. Furthermore, the RD completed during the first 10-minute block of the first and second half (75.3 $m.min^{-1}$ and 74.3 $m.min^{-1}$), was higher than the average RD for each half (67.6 $m.min^{-1}$ and 64.7 $m.min^{-1}$) as well as the final 10-minutes of each half (62.0 $m.min^{-1}$ and 61.8 $m.min^{-1}$) (Jones et al., 2015). In rugby league a decrease in HSR and TD following the peak 5-minutes of a game was recorded and similarly to Jones et al. (2015) a decrease after the first 10-minutes of each half was reported which could be explained by fatigue (Kempton et al., 2015). Cunningham et al. (2018) also used fixed epochs (1-5 minutes) to quantify the WCS in rugby union concluding that as the duration of the epoch reduced from 5-minutes to 1-minute the intensity of the running demands increased from 14.9 ± 9.1 $m.min^{-1}$ to 49 ± 22.4 $m.min^{-1}$ for HSR and 90.4 ± 13.9 $m.min^{-1}$ to 148.1 ± 22.1 $m.min^{-1}$ for RD respectively.

Another method used to provide a more in-depth analysis is using BIP times, for example Reardon et al. (2017) analysed the WCS which was regarded as the longest bout of BIP time in elite rugby union players. Using BIP times Reardon et al. (2017) reported that the WCS involves both alternating periods of high and low intensity activity and is generally higher in intensity than research has previously reported when using only average demands. Pollard et al., 2018 also concluded that relative total distance (RTD) and HSR were significantly higher when recorded using BIP times BIP period also increased as the BIP period shortened from 90 seconds to 30-60 seconds (Pollard et al., 2018) which is similar to previous research using fixed epochs (Cunningham et al., 2018). This research using smaller time periods of BIP further emphasises the underestimation of the WCS when quantified using whole game or half game averages. The only studies to use BIP times in rugby sevens are Ross et al. (2015b), Ross et al. (2015a) and Carreras, Kraak, Planas, Martin and Vaz (2013) however BIP time was not used as a method to analyse the WCS and was just presented as the amount of time spent within each BIP length.

To date, there is only one paper which assesses the uses of fixed epochs to analyse the temporal patterns of fatigue during a rugby sevens game (Granatelli et al., 2014). A 1-minute fixed epoch was used reporting that rugby sevens players experience transient fatigue as following an increase in the RD on the 2^{nd}, 7^{th}, and 11^{th} minute of a play a decrease in RD was recorded (Granatelli et al., 2014). This highlights that rugby sevens players must pace themselves during a game due to the high-intensity glycolytic characteristics of a rugby sevens match (Granatelli et al., 2014). Despite research using fixed epochs allowing more informed decisions to be made than whole-game or half averages, due to rugby sevens being an intermittent and high-intensity sport, the peak intensities will occur at random points within a game and therefore will not fall within a pre-defined period (Furlan et al., 2015). Further analysis into the WCS of movement demands during rugby has therefore focused on the use of rolling averages instead of fixed epochs.

The limited literature analysing rugby sevens using smaller defined epoch lengths (fixed epochs and BIP times) further exemplifies the minimal research that has been completed in this area. It could be suggested that due to rugby sevens games being played at a higher intensity than rugby union or rugby league, the WCS may be underestimated by a larger amount and could therefore lead to training not adequately preparing athletes for the demands of competition (Cunningham et al., 2018). There is therefore a gap within the literature to further analyse rugby sevens match performance to develop an understanding to optimally prepare athletes for rugby sevens competitions.

However, it could be questioned why research on the WCS is warranted in rugby sevens when there is already WCS research that has been completed in rugby fifteens. As highlighted already there is currently little research supporting the use of the WCS in identifying a different training stimulus in comparison to game averages and peak efforts. The WCS could be viewed as an average of multiple individual WCS and therefore in games of a longer duration e.g., rugby fifteens vs rugby sevens it could be indicated to be similar to game average. It is important however to acknowledge that the WCS reports a different intensity in comparison to game averages. An advantage in rugby sevens is the games being shorter in length, which results in a reduction in the pacing requirements to maintain high intensity performance. This increased intensity and shorter duration could allow the rolling WCS to provide a better understanding of the high intensity periods in a game compared to full game averages. In turn this therefore can allow training prescription to be specifically adapted, exemplifying the benefits of assessing the WCS in shorter duration rugby sevens games (Higham et al., 2016).

Despite research indicating the benefits of the WCS, recent research has suggested the concept and definition of the WCS is variable and may lead to athletes being underprepared when designing training programmes based off of it (Novak, Impellizzeri, Trivedi, Coutts & McCall, 2021). Novak et al. (2021) highlights that preparing training sessions off a univariate WCS e.g., singular variables such as high-speed running and total distance may not provide a sufficient training stimulus. It was suggested that the WCS should be considered alongside other parameters as it is a multivariate scenario involving a mixture of both contextual factors and physical activity, which when combined with the internal load will provide a more accurate representation of the WCS (Novak et al., 2021). Contextual factors such as the period prior to the WCS, the stage of season/tournament and minutes competed by the player have all also been indicated to affect the WCS analysis (Novak et al., 2021; Oliva-Lozano, Rojas-Valverde, Gomez-Carmona, Fortes & Pino-Ortega, 2020).

Despite the critiques against the WCS this study did not intend to focus on the potential multivariate factors experienced under Novak et al. (2021) definition of the WCS. Instead, the study aimed to focus directly on the movement demands of the WCS, with initial analysis considering the analytical differences between two processes (FIXED vs ROLL). It was also based off of historical data and therefore information on internal load could not be collected and included to analyse the internal response to the WCS as suggested by Novak et al. (2021).

2.3.2 - Using rolling averages for assessing worst-case scenarios

To date the most recent literature has used rolling averages which have been identified as being a more precise method for quantifying the WCS in comparison to fixed length epochs (Cunningham et al., 2018; Varley, Elias, & Aughey, 2012a). The rolling average is calculated in a bespoke software using the raw instantaneous data collected from GPS devices which can sample at various rates. For example, if a 1-minute rolling average is calculated using a 10 Hz GPS device (ten samples per second) then a 600-sample epoch length is created and applied throughout the whole match (Whitehead, Till, Weaving, & Jones, 2018). The rolling average would therefore calculate epochs of 0-600, 1-601, 2-602, etc and the peak 1-minute is then obtained from this in comparison to fixed epochs which calculate 1-600, 601-1200, 1201-1800, etc (Whitehead et al., 2018). Gradually more research has been completed in rolling averages in sports such as soccer (Delaney et al., 2018; Doncaster et al., 2020; Fereday et al., 2020), rugby union (Cunningham et al., 2018; Delaney et al., 2017; Howe, Aughey, Hopkins, Cavanagh, & Stewart, 2020; Sheppy et al., 2020), rugby league (Delaney et al., 2015; Johnston et al., 2019a; Johnston et al., 2019b) and rugby sevens (Furlan et al., 2015).

Following the increase in research on using just rolling averages to assess movement demands instead of pre-defined periods of time, current research has begun to compare the two methods of quantifying peak periods of play. Initial research in rolling averages was completed in soccer where a 5-minute fixed epoch and a rolling average was used to analyse peak high velocity running (≥4.17 m/s) (Varley et al., 2012a). It was highlighted that when using a fixed epoch there was an underestimation of peak distance (≤25%) and an overestimation in distance during the 5-minutes after the peak period when compared to the rolling average (Varley et al., 2012a). The 5-minute fixed epochs used in this study led to WCS data not being accurately measured and the true value not being obtained meaning interpretations made from this data could result in transient fatigue not being recognised during a match (Varley et al., 2012a). More recent research analysing WCS in soccer using fixed epochs (1-10 minute) vs rolling averages stated that both HSR distance and RTD was underestimated by ~12-25% and ~7-10% respectively when compared to a rolling average (Fereday et al., 2020). Both these studies highlighted that rolling averages should be used compared to fixed epochs as they provide a more accurate quantification of the peak intensities, which can then be used to prescribe training and monitor the demands experienced (Fereday et al., 2020; Varley et al., 2012a).

This trend was also reported in rugby union where both a fixed epoch (1 - 5 minutes) and a rolling average was used to analyse HSR distance (>5 $m.s^{-1}$) and RD during a rugby game (Cunningham et al., 2018). The fixed epochs underestimated HSR distance by up to ~20% and RD by up to ~11%, with differences being more pronounced for HSR as the epoch length increase (Cunningham et al., 2018). Research within women's rugby union also supports the conclusions made by Cunningham et al. (2018) as fixed epoch lengths (1-10 minutes) underestimated RTD by ~8-25% and ~10-26% for HSR distance when compared to rolling averages (Sheppy et al., 2020). Both Cunningham et al. (2018) and Sheppy et al. (2020) concluded that as the length of the epoch increased the intensity of the WCS decreased emphasising the importance of rolling averages for quantifying the WCS instead of fixed epochs and whole or half games. Furthermore, a similarity amongst most of the research comparing fixed vs rolling averages has identified that HSR distance is generally underestimated by a larger amount than RTD or TD, indicating that the use of rolling averages is particularly important, especially when assessing the WCS demands of HSR (Fereday et al., 2020).

2.3.3 - Rolling averages for assessing worst-case scenarios in rugby sevens

To date, there is minimal research which has been completed quantifying the peak demands during rugby sevens, with only a few papers using a rolling average as a method of analysis (Furlan et al., 2015; Murray and Varley, 2015; Peeters, Carling, Piscione, & Lacome, 2019). Unlike rugby union (Cunningham et al., 2018; Sheppy et al., 2020) and football (Fereday et al., 2020; Varley et al., 2012a) there is also no comparison of the two different methods used to analyse the peak demands (fixed epoch vs rolling average) making the literature within this area limited.

Research on rugby sevens using a rolling average to quantify the peak 1-minute period of play has reported that players cover peak RHSR distances of 86 ± 30 $m.min^{-1}$ and peak RTD of 183 ± 30 $m.min^{-1}$ (Murray & Varley, 2015). These distances recorded were also shown to increase when the athletes were competing against a higher-level opponent, indicating that the preparation for competition may alter when rugby sevens athletes are competing against a team of a higher quality (Murray & Varley, 2015). When compared to other research this study showed that the rolling averages used to quantify the peak demands here are higher than previously shown within other rugby sevens studies using whole-game averages. Further research in rugby sevens by Furlan et al. (2015) used a 2-minute rolling average to identify the peak periods of play, reporting that there was a significant reduction in performance following the peak period in both RD and metabolic power. This study indicated that rugby sevens players pace themselves during a game and experience transient fatigue as highlighted by the sudden changes in intensity following the peak period (Furlan et al., 2015). Utilising this information on peak metabolic power and peak RD can inform practitioners allowing them to create training sessions to replicate the high-intensity periods of competition (Furlan et al., 2015). Peeters et al. (2019) also used a 1-minute rolling average like Murray and Varley (2015) and further analysed players into positional differences of forwards and backs. It was reported that during a peak 1-minute period of play backs covered 184 ± 23 m and 55 ± 36 m of TD and high-speed distance respectively and forwards covered 176 ± 26 m and 63 ± 26 m (Peeters et al., 2019). A reduction in running intensity was also recorded following the peak 1-minute period of play indicating that the players are fatigued (Peeters et al., 2019). This conclusion is consistent with the findings in other studies using rolling averages as well as fixed epochs, suggesting the need to develop specific training programmes to prepare athletes for the demands of the WCS (Furlan et al., 2015; Granatelli et al., 2014; Peeters et al., 2019).

The use of rolling averages to analyse performance does have its disadvantages as a bespoke software needs to be developed to allow for the specific metrics to be run through the system. Despite this, once this bespoke software is created it allows a much more in-depth analysis to be completed compared to rolling averages (Cunningham et al., 2018; Fereday et al., 2020; Sheppy et al., 2020; Varley et al., 2012) and is particularly advantageous in intermittent, high-intensity team sports like rugby sevens (Furlan et al., 2015).

2.4 - Travel

2.4.1 - Travel demands in rugby sevens

Rugby sevens athletes are exposed to a vast amount of transmeridian travel when competing in the World Rugby Sevens Series (WRSS) as the locations of each tournament are situated in different geographical locations (Leduc et al., 2021). The WRSS involves 5 competitions, with each competition consisting of 2 tournaments (10 tournaments over a whole WRSS) in different countries with each tournament separated by a week (Table 2.6). Within each tournament which typically lasts between 2-3 days athletes must compete in 5-6 games with roughly 2-3 hours available between each match (Leduc et al., 2021; Schuster et al., 2018). Teams must then travel again to compete in the second tournament meaning teams will experience different travel requirements before the first tournament but will undergo the same journey when travelling to the second tournament of a competition (Fuller et al., 2015). Following each competition there is a break of roughly 4 weeks before the next competition commences in a different continent (Leduc et al., 2021). In the week before each tournament rugby sevens athletes therefore must complete a large amount of travel ranging from 1 hour to >24 hours (Mitchell et al., 2017) whilst crossing multiple time zones followed by further travel between each tournament, which may lead to the athletes facing jet-lag and travel fatigue (Fuller et al., 2015). Furthermore, the demands experienced from both matches and long-haul travel to each tournament has been indicated as a reason for the increased number of injuries during rugby sevens matches compared to rugby fifteens (Robineau et al., 2020).

Table 2.6. Organisation of the tournaments into competitions during the 2018-2019 World Rugby Sevens Series

Competition Number	Tournaments
1	Dubai – 30th November/1st December Cape Town – 8th/9th December
2	Hamilton – 26th/27th January Sydney – 2nd/3rd February
3	Las Vegas – 1st/2nd/3rd March Vancouver – 9th/10th March
4	Hong Kong – 5th/6th/7th April Singapore – 13th/14th April
5	London – 25th/26th May Paris – 1st/2nd June

2.4.2 - Physical and cognitive impact of travel on team sports

The travel demands during a season for team-sport athletes are therefore unavoidable resulting in studies researching into the impact that travelling has on the psychological, physiological, and key performance indicators of athletes. The two main consequences of travel typically experienced by athletes are jet lag and travel fatigue. Travel fatigue occurs after a long-haul journey caused by the stressors of travel such as cramped conditions, lack of sleep during flight, prolonged exposure to mild hypoxia and the travel schedule (Fowler et al., 2015; Fowler et al., 2017a ; Reilly, Waterhouse, & Edwards, 2009). It generally results in headaches increasing in frequency, disorientation, and extreme tiredness (Reilly et al., 2009). Further side effects of travel fatigue can result in physiological changes such as increased blood coagulation, hypohydration and a shift of fluid to the lower extremities (Fowler, Duffield, Lu, Hickmans, & Scott, 2016) but adverse effects will reduce a few days after arrival (McGuckin, Sinclair, Sealey, & Bowman, 2014). Jet lag is caused when time zones are crossed quickly during transmeridian travel resulting in the internal circadian rhythms not being synchronised with the time zone of the destination (Fowler et al., 2016; Fowler et al., 2017a; Janse Van Rensburg, Fowler, & Racinais, 2020). The side effects of jet lag happen when the body is trying to resynchronise the internal clock e.g., melatonin secretion and body temperature, with the external signals e.g., the lightdark cycle at the new destination (Forbes-Robertson et al., 2012; Fowler et al., 2016). Common symptoms of jet lag are being tired during daytime, reduced sleep during the night, a reduction in physical and mental performance, reduced motivation, and reduced concentration (Chapman et al., 2012; Forbes-Robertson et al., 2012). The length of time required for overcoming symptoms of jet-lag may be different for each individual and dependent on the number of time zones which have been crossed during travel (Chapman et al., 2012). Previous research has indicated that irrespective of the direction travelled (west or east) a day is needed per time zone crossed during the journey (Lee & Galvez, 2012). This is contradictory to other studies which have indicated that recovery from jet-lag should be altered according to the direction of travel, with Fowler et al. (2017b) highlighting that journeys east require a day for each hour time difference and travel west needing half a day for each hour different. The research on recovery from travel and its side-effects of jet-lag and travel fatigue are therefore contradicting highlighting an area where more research needs to be completed.

The adverse effects that travel can have via travel fatigue and jet-lag have then been investigated further to see whether it affects performance in team-sport athletes. Current research is limited but has focused on sports such as football, rugby league and rugby sevens, with some research also simulating travel to investigate its effects (Fowler et al., 2015, Fowler et al., 2016; Fowler et al., 2017a; Fullager et al., 2016; McGuckin et al., 2014; Mitchell et al., 2017). Early research by McGuckin et al. (2014) researched the effect of short-haul travel (1-3 hours time difference) on the physiological, psychological and performance measures of Australian rugby league players. The study reported that symptoms of travel fatigue were present as players had an increase in stress and reduced alertness after travel to away games compared to home matches (McGuckin et al., 2014). The TD covered was also significantly higher at home games compared to away, but there was no physiological difference in strength (hand-grip strength test) or power (CMJ) between home and away games indicating short-haul travel may not hinder performance (McGuckin et al., 2014). Fowler, Duffield, and Vaile (2014) also examined the effects of short-haul travel on performance, using Australian soccer players who competed at home and away during a season. It was reported that sleep and perceptual measures (stress, fatigue, muscle soreness, sleepiness) were not affected by short-haul travel as there was no significant difference when away matches were compared to home (Fowler et al., 2014). There was however an increase in the perceptual travel fatigue after travel to an away match compared to a home game, but this was indicated to not affect performance (Fowler et al., 2014). This research supports the conclusions of McGuckin et al. (2014), suggesting that short-haul travel will only result in travel fatigue and may therefore not have a detrimental effect on team sport performance.

Long-haul travel eastward over 19 hours, crossing 11 times zones has been reported to impact player preparedness during the 2014 FIFA World Cup (Fowler et al., 2017a). On the first day after travel players indicated a reduction in sleep, overall functioning, wellness, and an increase in fatigue, with jet-lag symptoms occurring for up to 5 days following long-haul (Figure 2.1) (Fowler et al., 2017a). Collectively these side-effects of long-haul travel may result in players not managing the demands of training and therefore may not be optimally prepared for competition (Fowler et al., 2017a). Fullager et al. (2016) also reported a reduction in sleep during long-haul travel but indicated that the footballers were able to sleep more after arrival and therefore the effect on perceptual factors was limited.

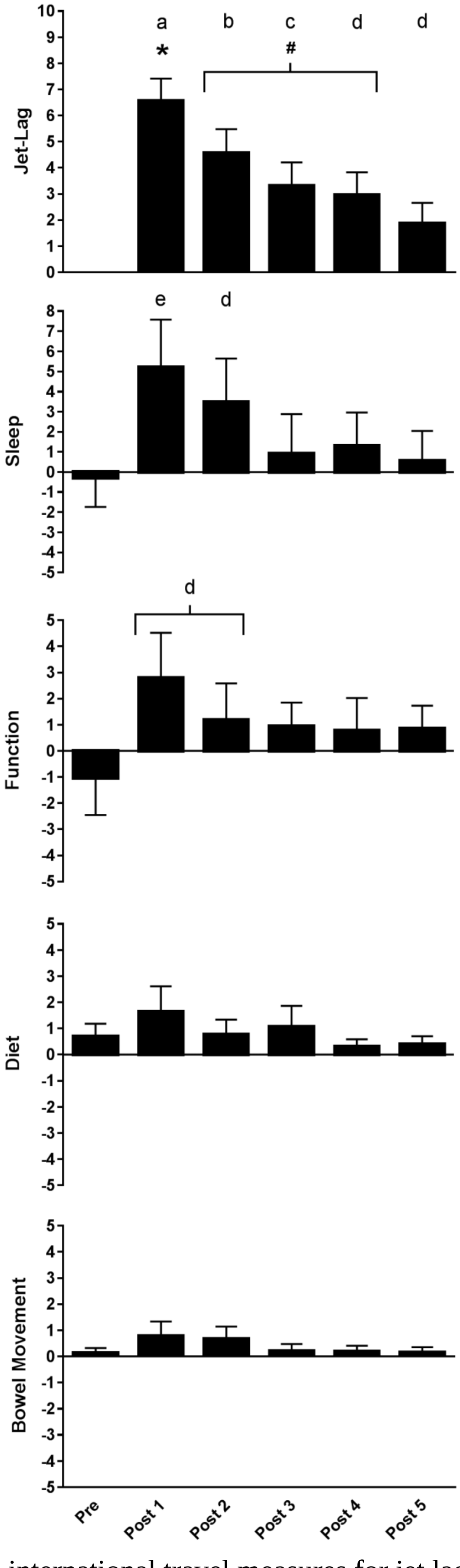

Figure 2.1. Pre and post international travel measures for jet lag, sleep, function, diet, and bowel movement from Fowler et al. (2017a).

The difference between the effects of domestic travel of 5-hours (short-haul travel) to international travel 24-hours in length (long-haul) by simulating travel conditions has also been compared for team sports athletes (Fowler et al., 2015). Fowler et al. (2015) indicated that international journeys can have a significant effect on team sport performance compared to domestic travel as a reduction in intermittent sprint performance was recorded in the afternoon of the day after travel. This reduction could have a detrimental impact on sporting performance as it is a key component within team sports as games generally involve fluctuations in intensity (Duffield & Fowler, 2017). Fowler et al. (2015) also reported that leg power was not impaired after domestic or international travel when undertaking CMJ, supporting the conclusions of McGuckin et al. (2014) in short-haul travel. A similar pattern has also been demonstrated in rugby league players during the 2015 World Club Series where 25-hours of long-haul travel crossing 11 time zones (Sydney to London) was completed (Fowler et al., 2016). A significant difference was not recorded for muscle strength (assessed using the adductor squeeze test) despite subjective jet-lag still being reported on the eighth day after travel (Fowler et al., 2016). Despite these studies testing the effect of long or short-haul travel on physiological variables, using tests such as adductor squeezes, CMJ and hand-grip strength tests are not ecologically relevant to team sport performance making the true effect on team sport athletes still unclear (Fowler et al., 2016; Fowler et al., 2017b).

As well as impacting performance, studies have also shown travel to increase the risk of illness in team sports as highlighted by research in upper-respiratory symptoms after long-haul travel in rugby league players (Fowler et al., 2016). It was revealed that there was a significant increase in the reports of upper respiratory symptoms on day 6 after long-haul westward travel when compared to the reports prior to travelling (Fowler et al., 2016). However, the impact of this increase on sporting performance in team sport athletes is still unknown as performance impacts were not recorded in the study. Schwellnus et al. (2012) also measured the illness risk within rugby union during the Super 14 tournament. The study reported that there was a 2-3-fold increase in the number of illnesses (respiratory, gastrointestinal and infections) when travel duration was more than 5 hours (Schwellnus et al., 2012). However, it was concluded that due to the illnesses occurring on the outward journey and not on the journey back home that travelling was not responsible for the increase in illness and may be caused by the environmental conditions at the tournament (Schwellnus et al., 2012). This assumption highlights another factor which could be detrimental for team sport athletes who are constantly travelling during a season and further demonstrates the inconsistency of the research within this area.

2.4.3 - Impact of the direction of travel (east vs west) on team sport performance

As mentioned above, research has indicated different recovery times may be needed to overcome the symptoms of jet-lag, with differences being present when travelling eastwards compared to westward (Fowler et al., 2017b). This is due to studies indicating that jet-lag effects may be more severe after travelling in an eastward direction compared to west (Janse Van Rensburg et al., 2020). When travelling east the circadian clock needs to undergo a phase advance, whereas travel to the west involves a phase delay in the circadian rhythm (Eastman & Burgess, 2009). The natural human circadian rhythms are longer than 24 hours (24-26 hours) and there will be a natural daily change in a human's circadian rhythm with it normally extending (Eastman & Burgess, 2009; Leatherwood & Dragoo, 2012; Reilly & Edwards, 2007a). It is therefore easier for humans to be able to delay their circadian rhythms when travelling west rather than advance them when travelling east, as they can extend within their normal circadian clock (Eastman & Burgess, 2009; Reilly & Edwards, 2007a). A longer period of time is therefore normally needed to allow the body to recover following travel east, due to the body needing to recover from jet-lag by resynchronising the internal and external cues (Leatherwood & Dragoo, 2012). Consequently, disrupting the circadian rhythm can have a direct impact on athletic performance as it has been suggested that performing at different times of the day after travel when an athletes' physiological conditions are not at their optimum can impair sporting performance (Leatherwood & Dragoo, 2012; Lo, Aughey, Hopkins, Gill & Stewart, 2019a).

Current research by Fowler et al. (2017b) studied the difference between long-haul travel either eastward or westward over 21 hours and crossing 8 time zones on team-sport performance. It was reported that there was a larger effect following eastward travel within the first 72 hours on measures of fatigue, sleep and maximal and intermittent sprint performance compared to westward travel which had insignificant effects (Fowler et al., 2017b). There was also a reduction after travel in both the east and west direction for CMJ performance and 5 and 20 m sprint performance which lasted for four and three days after travel respectively (Fowler et al., 2017b). This contradicts previous research which did not record a reduction in lower-body power after travel and indicates that reductions in performance may be present regardless of the direction of travel (Fowler et al., 2017b). It should be acknowledged however that this study did not follow elite athletes over a tournament/competition, instead using physically active trained men, and therefore the relevance to team-sport athletes such as the rugby sevens team during the WRSS may be limited.

Research analysing the effects of long-haul travel crossing numerous time zones on key performance indicators (KPI) has also been analysed in Super Rugby (Lo, Aughey, Hopkins, Gill & Stewart, 2019b). Lo et al. (2019b) concluded that following travel westward there was either an improvement or no change in performance but following eastward travel a reduction in performance was recorded. This conclusion aligns with previous research on travelling eastward *vs* westward as the ability of the body to advance the circadian rhythm following travel eastward can result in jet lag being more severe (Leatherwood & Dragoo, 2012). Further research has also been completed in Super Rugby due to the large amount of travel undertaken during a season which is similar to rugby sevens. Following an analysis of 21 years of data in Super Rugby, Lo et al. (2019a) highlighted that in 1996, for every 10 matches played travel east would result in an increased chance of losing of 1.0 extra match and travel west resulting in a win of 0.1 extra matches. In 2016, there was an increased chance in winning 0.9 extra matches following westward travel and following travel eastward 0 extra matches were won, indicating the detrimental effect that travelling eastward can have on match outcomes in the Super League (Lo et al., 2019a). The conclusions from Super Rugby further exemplify the negative impact that travel can have on both match outcome and KPIs following travel east compared to west, highlighting the importance of preparing athletes for these demands prior to travel.

Within rugby sevens some studies have analysed whether the direction of travel impacts the athletes, with Leduc et al. (2021) highlighting that total sleep time was similar regardless of the direction travelled but following westward travel a reduction in the efficiency and quality of sleep was reported. This conclusion opposes previous research highlighting that eastward travel results in worsened sleep disruption and symptoms of jet-lag compared to westward travel (Lee & Galvez, 2012). Further research within rugby sevens indicated a non-significant difference post-travel between east and west for lower-body power but reported an increase in TD and HSR by 13% and 5% respectively following westward travel compared to eastward (Mitchell et al., 2017).

The studies above exemplify the inconsistent conclusions within the literature on the direction of travel (eastward *vs* westward) and the minimal research within rugby sevens. Some studies highlighted that eastward travel resulted in a detriment to performance and sleep (Fowler et al., 2017b; Lo et al., 2019a; Lo at el., 2019b), whereas other research has concluded similar to detriments to performance and sleep regardless the direction of travel (Fowler et al., 2017b; Leduc et al., 2021). These conclusions highlight the differing impact that the direction travel can have on an athletes' sleep and performance, illustrating the importance of preparing an athlete for these travel demands. Furthermore, due to the intense travel schedule that rugby sevens athletes experience during the WRSS it is even more important to understand the directional travel effects imposed on these athletes. This knowledge will then allow for strategies to be implemented pre and post travel to allow the rugby sevens athletes to be optimally prepared for the demands of travelling either eastward or westward.

2.4.4 - Travel impacts on rugby sevens athletes and performance

To date, there is minimal research that has been completed into the effects of travel on rugby sevens athletes with studies analysing the impact on different areas such as sleep (Leduc et al., 2021), risk of injury, (Fuller et al., 2015) lower-body power and match demands (Mitchell et al., 2017). In particular, there is a gap within current literature on the effect of travel on the movement demands of rugby sevens athletes which is the focus of this study, with only one paper investigating the effect on the running requirements of performance (TD and HSR) (Mitchell, et al., 2017). Using international rugby sevens athletes Mitchell et al. (2017) reported an overall decrease in peak lower-body power over a tournament of -9.4% ± 3.5% and -5.1% ± 8.4% for long-haul compared to short haul travel respectively. The athletes also experienced a decrease post long-haul travel in both mean power -2.2% ± 1.7% and peak power -4.3% ± 3.0% indicating that travel, especially long-haul travel can impair lower-body power measured via CMJ (Mitchell et al., 2017). The demands of the match (TD and HSR >5 $m.s^{-1}$) were also quantified using GPS software and indicated that athletes undertaking long-haul travel completed 960 ± 520 m additional distance over each tournament and 12 ± 13 m more HSR than athletes undertaking short-haul travel (Mitchell et al., 2017). A reduction in performance can therefore be caused following long-haul travel in rugby sevens athletes, attributed to travel fatigue, neuromuscular fatigue and jet lag which may consequently impair their cognitive performance (Mitchell et al., 2017).

Further research into the effects of travel on rugby sevens athletes during the WRSS has focused on whether the injury risk is increased after long-haul travel (≥10 hours travelling and crossing ≥6 time zones) (Fuller, Taylor, & Raftery, 2015). When compared to two other lengths of travel (≤3 hours travel, ≤2 time zones crossed or ≥10 hours travel, ≤2 time zones crossed) long-haul travel crossing multiple time zones was shown to not be significantly different and did not increase the injury risk (Fuller et al., 2015). The athletes completing long haul travel and crossing multiple time zones also did not lower their standard of performance during the WRSS as when assessing the final tournament rankings, it indicated that performance was not impaired following long-haul travel. This is contradictory of Mitchell et al. (2017) however, this should be considered with caution as the study did not measure any physiological variables, or movement demands e.g., HSR or TD) and therefore the impact on performance is not directly measured.

The most recent study on the effects of travel is by Leduc et al. (2021) analysing the impact on sleep during two legs of the WRSS. Leduc et al. (2021) reported that athletes sleep quantity and quality was not affected by jet-lag during the period prior to competition but there was a change to sleep when athletes were competing or relocating to the next tournament. The effect of altered sleep on performance is however unknown as movement demands and fatigue experienced during games was not quantified in this study, which is similar to Fuller et al. (2015). Furthermore, due to the studies on rugby sevens athletes focusing on the effects of travel on different areas it makes the research difficult to compare and therefore the true effect on performance during the WRSS is still unknown. Despite this, Leduc et al. (2021) indicated that the minimal effect of long-haul travel on sleep may be due to the rugby sevens players being elite athletes and therefore they are less effected and adapted to the stressors of long-haul travel. This is similar to previous research in footballers where Fowler et al. (2017a) highlighted that the effects of jet-lag were reduced on day 1 after arrival in more experienced players. This could therefore explain the minimal effect of long-haul travel on sleep (Leduc et al., 2021) and performance (Fuller et al., 2015) as the athletes are constantly travelling during the WRSS and so may be experienced in travelling long distances and crossing multiple time zones.

2.5 - Climate

2.5.1 - Climatic conditions during the World Rugby Sevens Series

As highlighted above the WRSS involves tournaments situated in different continents across the world and therefore includes a vast amount of international travel during competition stages. Consequently, the varied locations of the WRSS will result in differing climatic conditions at each tournament (Taylor et al., 2019a) which could affect the athletes' performance during matches. During the World Rugby Women's Sevens Series (WRWSS) Henderson et al. (2020) highlighted the inconsistent climatic conditions for game days as individuals may be competing in different seasons compared to their home country (e.g., summer compared to winter). This is similar for the 2018-2019 male WRSS with tournaments being held in Dubai, Cape Town, Hamilton, Sydney, Las Vegas, Vancouver, Hong Kong, Singapore, London, and Paris during different parts of the year and over different seasons (Table 2.7). Due to the limited research on the effect of climate on team sports there is also only a few papers focusing on the area of rugby sevens, providing an area where more research is needed.

Table 2.7. Dates and seasons of the World Rugby Sevens Series 2018-2019

Tournament	Date	Season
Dubai	30th November /1st December 2018	Winter
Cape Town	8th/9th December 2018	Summer
Hamilton	26th/27th January 2019	Summer
Sydney	2nd/3rd February 2019	Summer
Las Vegas	1st/2nd/3rd March 2019	Winter
Vancouver	9th/10th March 2019	Winter
Hong Kong	5th/6th/7th April 2019	Spring
Singapore	13th/14th April 2019	Spring
London	25th/26th May 2019	Spring
Paris	1st/2nd June 2019	Summer

2.5.2 - Impact of climate and humidity on performance

As a result, on the varying locations of tournaments and competitions during an athlete's season literature has begun to identify the effects of being exposed to different environmental conditions on performance. Most of the research completed within this area focuses on exercise being completed in hot-dry or hot-humid conditions with very little research analysing the impact of colder environmental conditions. Furthermore, literature has simulated environments in laboratory-controlled conditions which does not reflect the high-intensity intermittent nature of team-sports (Ozgunen et al., 2010). When exercising in the heat there are numerous challenges for athletes which may lead to a decrease in performance. Activity in the heat results in an increased requirement for thermoregulatory control, with blood flow to the skin being essential to be able to regulate temperature (Gonzalez-Alonso, Crandall, & Johnson, 2008). An increase in sweat rate occurs when exercising in high temperatures, which if not replaced can result in dehydration and a decrease in the volume of the blood which consequently increases core temperature (Gonzalez-Alonso et al., 2008; Sawka, Wenger, Young, & Pandolf, 1993). As the exercise continues and heat-stress increases, cardiac output can rise due to the increases stress on the thermoregulatory and metabolic demands of the body (Sawka et al., 1993). Core body temperature will then continue to rise if the accumulation of metabolic heat is higher than what the body can remove, leading to an imbalance which could then have detrimental effects on sporting performance.

Girard et al. (2015) reviewed literature on sprinting, highlighting that higher environmental temperatures can benefit singular sprinting performance due to the contractile and biomechanical properties of the muscles being enhanced. However, when these sprints are recurring in the form of repeated sprints (≤60 second recovery) and intermittent sprints (60–300 seconds recovery) it has been indicated that higher climatic conditions do not enhance but diminish performance (Girard et al., 2015). Intermittent sprint performance decreased when exercise caused core temperature to exceed 39°C (hyperthermia), whereas repeated sprints decreased when there was an increase in both core temperature and climatic conditions (Girard et al., 2015). Intermittent sprinting is a key component of team sports highlighting the negative impact exercising in the heat can have when core temperature is increased beyond 39°C.

Ozgunen et al. (2010) looked at the climatic effect on soccer in a high heat index (HH) environment (ambient temperature = 36 ± 0°C, heat index = 49 ± 1°C, relative humidity = 61 ± 1%) compared to a moderate heat index (MH) environment (ambient temperature = 34 ± 1°C, heat index = 35 ± 1°C, relative humidity = 38 ± 2%). The soccer players mean peak core temperatures during the MH and HH matches were 39.1 ± 0.4°C and 39.6 ± 0.3°C respectively, reaching core temperatures that could detriment performance (Girard et al., 2015; Ozgunen et al., 2010). It was reported that the TD undertaken in the second half of the HH match was significantly lower than the first half, with the MH match showing no significant differences between halves (Ozgunen et al., 2010). A higher percentage of the HH game was also completed walking, with high-speed running distance being lower during both the first and second half for the HH match (194 ± 97 m and 132 ± 52 m) compared to the MH match (203 ± 46 m and 180 ± 82 m) (Ozgunen et al., 2010). This study therefore demonstrates the reduction in physical performance that can occur when competing in a high temperature and humidity and the greater fatigue experienced within a HH game compared to a MH game (Ozgunen et al., 2010). Similarly, to Ozgunen et al. (2010), Austin, Collins, Huggins, Smith and Bowman (2021) researched the effect of different environmental conditions on female soccer player during training sessions. It was concluded that an increase in the wet bulb globe temperature resulted in a reduction in the GPS intensity (external load) and an increase in the internal physiological load. Austin et al. (2021) therefore supports the conclusions of Ozgunen et al. (2010) that elevated heat stress can reduce external performance variables in training and highlights the importance of planning training according to the climatic variables to achieve the maximal training effects.

One study analysed the effect of climatic conditions in Australia (61 ± 6% mean relative humidity, 30.9 ± 2.1°C mean ambient temperature and 718 ± 224 W/m^2 mean solar radiation) on team sport athletes (footballers) performance during training (O’Connor et al., 2020). It was concluded that an increase in the relative humidity decreased the percentage of high-speed running by 3.4% and increased exposure to solar radiation resulted in a decreased RD and percentage of high-speed running by -19.7 $m.min^{-1}$ and -10% respectively (O’Connor et al., 2020). These findings reflect Ozgunen et al. (2010), supporting the conclusion that an increase in humidity can negatively impact the movement demands in team sports. In comparison to other literature the ambient temperature recorded here did not impair the athlete’s performance during training but instead resulted in RD and high-speed running increasing by 19.7 m.min^{-1} and 3.5% (O’Connor et al., 2020). The increase in movement demands may be attributed to a higher muscle temperature however this further highlights the varied conclusions on different climatic conditions and the effect it has on team-sport performance (O’Connor et al., 2020).

From the minimal research on exercising in colder climates there is currently no research directly focusing on its impact on team sports. Similar to the research on hotter environments, literature within colder environments have been completed in climatic chambers and within laboratories to mimic the challenging environments. When muscles are cooled, the power produced may not be as high in comparison to warmer temperatures as the shortening and lengthening of muscle contractions are slower (Oksa, 2002). This decrease in contraction velocity can be attributed to a reduction in the hydrolysis of adenosine triphosphate as well as the calcium release and uptake from the sarcoplasmic reticulum being slower (Oksa, 2002; Wakabayashi et al., 2015). The decline of these functional properties of the muscle therefore results in a reduction in muscle performance in colder environments.

Early research by Oksa, Rintamäki and Rissanen (1997) demonstrated that cooling a muscle can cause a significant reduction in muscle performance when completing drop jumps. An initial decrease in performance was reported following cooling at an ambient temperature of 20°C and with the flight time of drop jumps continuing to decrease after the subjects were exposed to ambient temperatures of 15°C and 10°C (Oksa et al., 1997). A similar trend was also noted within a review by Wakabayashi et al. (2015) highlighting that a reduction in maximal voluntary isometric force was reported when muscle temperatures decreases below 27°C, with other literature highlighting a decrease of between 11-19% (Oksa, 2002).

Dynamic exercise is also affected by cooling and has been shown within literature to have a decrease in performance by ~2 - 10% for each degree of muscle temperature lost (Oksa, 2002). Research has therefore highlighted that muscle temperature and muscular performance has a dose dependent relationship, causing an increase or decrease in performance (Oksa, 2002). Despite these studies being important in demonstrating that a decrease in performance can be caused when performing in cooler environments, there is little ecological validity to team sport performance and therefore the findings should be considered with caution.

2.5.3 - Impact of climate on rugby sevens performance

To date the research on climatic influences within rugby sevens is limited, especially studies acknowledging the impact of different climatic conditions on performance during the WRSS. Currently, there is no literature focusing on the impact of colder climates during the WRSS (e.g., Vancouver), providing an area for research to be completed to help enhance rugby sevens performance. Research by Taylor et al. (2019a) is the only study to assess the different effects of warm and temperate environments on the core temperature of rugby sevens athletes during two tournaments of the WRSS, London (13.8-22.3°C) and Singapore (21.4-27°C). It was reported that the core temperature recorded throughout the matches of the two tournaments was not different despite different environmental conditions (Taylor et al., 2019a). Core temperature also increased throughout the day, with the highest core temperature (>39°C) being recorded during the last game of the day during both Singapore and London tournaments (Figure 2.2) (Taylor et al., 2019a). The increase in temperature could be associated with the multiple matches occurring within a day resulting in core temperature gradually increasing which could impair performance during the later games (Taylor et al., 2019a). However, previous research in rugby sevens athletes has indicated there is a circadian change in core temperature throughout the day, with core temperature being the lowest in the morning and peaking in the early evening (West, et al., 2017). This highlights the importance of implementing recovery strategies (e.g., cold-water immersion) during a tournament day to help prevent high core temperatures (Taylor et al., 2019a). The peak core temperatures beyond 39°C recorded in this study have also previously been shown to have a negative effect on intermittent sprinting performance (Girard et al., 2015) however, the effect within this study is unknown as Taylor et al. (2019a) did not quantify performance variables.

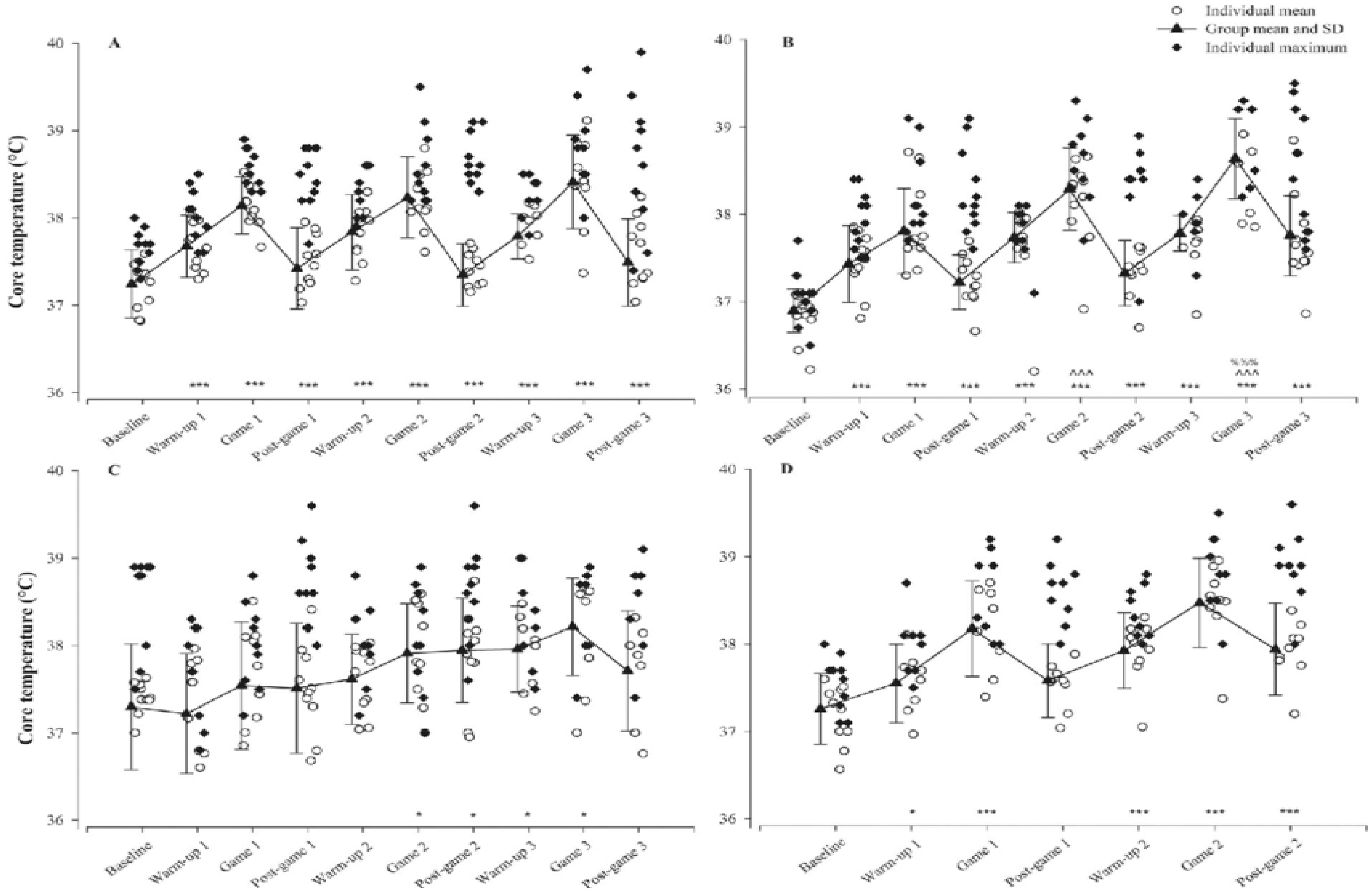

Figure 2.2. Average core temperature (°C) over Singapore day 1 (A) and day 2 (B) and London day 1 (C) and day 2 (D) from Taylor et al. (2019a)

The most recent analysis of core temperature changes during rugby sevens performance focuses on elite male rugby sevens athletes during a tournament in Fiji in hot and humid conditions (Fenemor et al., 2021). It was reported that core temperature post-game was significantly affected by total running distance, high-speed distance, playing minutes and the core temperature post warm-up (Fenemor et al., 2021). Further research has also been completed in the women's WRSS (WRWSS) tournament in Australia (Wet-bulb globe temperature = ≤20°C) (Henderson et al., 2020). Henderson et al. (2020) quantified the external load of rugby sevens players using GPS but concluded that there was no relationship between the peak core temperature and the GPS metrics measured. Both Fenemor et al. (2021) and Henderson et al. (2020) recorded core temperatures of ≥39°C during matches which has previously been shown to impair intermittent sprint performance (Girard et al., 2015). Henderson et al. (2020) also acknowledged a link between the peak core temperature and the amount of time played within a match, reflecting the results of Fenemor et al. (2021) who found a significant link and Taylor et al. (2019a) who recorded peak core temperatures during the last match of a day. Despite no differences being recorded between peak core temperatures and GPS metrics the findings of Henderson et al. (2020) should be considered with caution. This is due to physiological differences being present between genders which may lead to core temperature in females rising faster and resulting in a larger detriment to performance in comparison to males (Henderson et al., 2020).

A common conclusion from the research within rugby sevens is that athletes may benefit from preparing for the hotter environmental temperatures of tournaments by either acclimatising prior to an event or using cold-water immersion (CWI) strategies throughout a tournament day. By involving these into an athlete's tournament strategy it may enhance the thermoregulatory system and therefore consequently aid performance (Taylor et al., 2019a). One study analysed the benefit of using a cooling vest before and during a warm-up due to the potential of warm-ups to increase core temperature beyond 39°C in some athletes (Taylor, Stevens, Thornton, Poulos, & Chrismas, 2019b). It reported that athletes who utilised the cooling vest had a ~0.7°C average lower core temperature than individuals who did not wear one and led to core temperature not increasing beyond 39°C (Taylor et al., 2019b). The vest also did not interfere with the movement demands during the warm-up or CMJ performance after the warm-up, indicating that it only benefits the athletes by ensuring they do not reach core temperatures of ≥39°C which could have detrimental effects on their intermittent sprinting performance (Taylor et al., 2019b). The question of whether hot or cold climatic conditions affect rugby sevens athletes, and their performance is therefore still unknown due to the minimal to no literature in this area, indicating more research needs to be completed.

The purpose of this study is to quantify and compare the worst-case scenario, known as the most demanding period of play in male rugby sevens, comparing the fixed time epochs to the rolling average epochs. The study also aims to analyse the impact of different climatic conditions and travel demands on the movement demands during male rugby sevens matches. It is hypothesised that the fixed epoch method will underestimate the WCS in comparison to the rolling averages method. An increase and decrease in temperature in comparison to the home country temperature and long-haul travel is also hypothesised to have a negative impact on the movement demands of rugby sevens athletes.

3.0 - Methods:

3.1 - Participants

All participants were members of the England Rugby 7s team from the 2018-2019 World Rugby Sevens Series (WRSS) (*n* = 18, age: 25 ± 4 years; height: 183.9 ± 7.1 cm; body mass: 91.5 ± 8.8 kg). Permission was granted from the Rugby Football Union for the data to be collected and analysed and the Swansea University Ethics Committee provided ethical approval for the study to commence. At the time of data collection all participants were healthy and not injured as verified by the Rugby Football Union medical staff, allowing them to compete in the WRSS. The data set used in this study was a historical data set from 30th November 2018 to 2nd June 2019, which was used due to the impact of the COVID-19 pandemic preventing current data collection. Consequently, this limited the opportunity to add additional analysis measures such as internal load (e.g., core temperature, heart rate, measures of sleep, circadian genes) which would have been relevant and beneficial to the study. There was a total of 418 global positioning system (GPS) files recorded over the WRSS 2018-2019 with the high-speed running (HSR) threshold being set at >5m.s^{-1} as used in other studies in rugby sevens and rugby fifteens (Clarke et al., 2015; Suarez-Arrones et al., 2014; Van den Berg et al., 2017). Every player provided at least 1 GPS file, with the smallest amount of data provided by a singular athlete being 6 GPS files and the largest being 46 GPS files.

3.2 - Experimental Design

Data was collected between 30th November 2018 to 2nd June 2019 from 9 tournaments, involving 52 games (https://www.world.rugby/sevens-series/calendar/2019). Each athlete was assigned a GPS unit (STATSport, Northern Ireland) with a 10Hz augmented global navigation satellite system (GNSS), magnetometer, a 952Hz accelerometer and gyroscope (STATSport, 2020). The same unit was worn by the same player during every game to avoid inter-unit variation (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010b). The unit remained within a specially designed pocket of the playing shirt (Figure 3.1), allowing the unit to be positioned between the athletes' scapulae, on the upper thoracic spine reducing its movement and ensuring that only movements of the athletes' body were recorded (Theodoropoulos, Bettle, & Kosy, 2020).

The units were turned on prior to the game as recommended by the manufacturer. The players were familiar with wearing the devices due to the analysis that had been carried out in prior training sessions and therefore familiarisation was not needed. The raw data was downloaded post-games and analysed using the STATSports software, with the whole game relative distance (WGRD) (m.min^{-1}) being obtained for the travel and climatic analysis. The data was also exported and analysed for the worst-case scenario (WCS) using a bespoke software designed for this analysis.

Figure 3.1. Location of the STATSports unit situated within the playing shirt on the back between the scapulae.

A travel itinerary was recorded allowing data to be collected on the travel and climatic demands of the England Rugby Sevens team (Table 3.1). Following the end of the WRSS 2018-2019 climatic data on the temperature (°C), relative humidity (%), and humidex (°C) was also obtained for each individual game of each tournament.

Table 3.1. List of travel data collected throughout the WRSS.

Travel Data Collected	Units
Time zones crossed	Time zones
Travel direction	East or West
Time difference from the previous destination	Hours
Time travelled	Seconds

3.3 - GPS Units

The 10Hz GPS units from the Stats Sports Apex Series have been reported to be valid measures (Beato et al., 2018; Beato & Keijzer, 2019). The units have been proven to be reliable for peak velocity (ICC = 0.96) (Beato et al., 2018), sprint distances between 5-30m (ICC = 0.95-0.07) and overall sprints (ICC = 0.99) (Beato & de Keijzer, 2019). The 10Hz STATSports Apex units also showed excellent inter-unit reliability scores when compared to the STATSports Viper Pod units which ranged from good to excellent for sprints ranging between 5 - 30m (CV = 1.85%) (Beato & de Keijzer, 2019). Further research on inter-unit reliability indicated that the 10Hz STATSports Apex units were reliable when looking at software-derived data and raw processed data (raw data processed with customised software) for variables such as distance (CV = 0.3%; ±1.5%), relative speed ($m.min^{-1}$) (CV = 0.3; ±1.5%) and HSR > $5m.s^{-1}$ (CV = 1.9%; ±1.5%) (Thornton, Nelson, Delaney, Serpiello, & Duthie, 2019). The inter-unit reliability was however poor for moderate decelerations for the Apex units with a CV ranging from 72.8% ± 1.5% to 11.9%; ± 1.5% for soft-ware derived data and raw processed data respectively (Thornton et al., 2019).

Following each game data on the horizontal dilution of precision (HDOP) and the number of satellites for each GPS unit was also downloaded and an average was calculated for each game of every tournament (Appendix A). Across the nine tournaments the highest average HDOP value was recorded in Vancouver (1.3 ± 0.8), with the lowest in Dubai (0.4 ± 0.2) (Appendix A). A HDOP value of 1 is regarded as a low number and indicates a wide spread of satellites which increases the accuracy (Shergill, Twist & Highton, 2021). The tournament with the highest average satellite number was located in Dubai (20.1 ± 1.5) with the location with the lowest average satellite number being present in Hong Kong (15.4 ± 1.4) (Appendix A). In order to determine the position of the GPS unit using triangulation a minimum of 4 satellites are needed (Scott et al., 2016).

An increased number of satellites which are connected to the GPS units during a game can result in an increased accuracy of the GNSS signal (Beato et al., 2018). Tournaments situated in areas with tall buildings or within large stadiums can have the accuracy of the satellite signal reduced due to the GNSS signal being blocked, increasing the HDOP number (Scott et al., 2016; Shergill et al., 2021). It has also been indicated that an increase in the absolute humidity can decrease the accuracy in determining the location of the GPS units (Pishko, 2018). The HDOP values of the GPS units in this study were relatively low, with a high number of the satellites connected to the GPS units. This indicates an increased accuracy in the data collected and highlighting that the stadiums and environmental conditions that the athletes competed in did not affect the GPS data.

3.4 - Assessment of worst-case scenario (rolling average and fixed epochs)

The data obtained from each match was inserted into the bespoke software which analysed it using two different sampling methods: rolling (ROLL) and fixed (FIXED) length epoch. The method used to analyse the WCS using FIXED and ROLL methods of analysis followed that of Cunningham et al. (2018). The epoch length ranged from 60 to 420 seconds, increasing in increments of 60s and was defined by the user. To calculate the length of the epoch in samples the sampling rate was used which also allowed for missed samples, e.g., with a sampling rate of 10Hz and an epoch length of 60s the epoch length in samples would be 600. The rolling-epoch algorithm was calculated using the existing and 599 previous samples. Whereas the fixed-time epoch was obtained by using samples 1-600, 601-1200, 1201-1800 etc. From each analysis using both the ROLL and FIXED epochs, data was obtained on the distance (m) and the distance covered over $5m.s^{-1}$, also known as HSR for the length of the epoch. The relative WCS was then calculated for both relative total distance (RTD) ($m.min^{-1}$) and relative HSR distance (RHSR) ($m.min^{-1}$) by dividing each of the time epochs (60 – 420 seconds) by the corresponding time in minutes e.g., 60 seconds divided by 1-minute, 120 seconds divided by 2-minutes etc.

3.5 - Collection of travel data

A travel itinerary was recorded throughout the WRSS for the England Rugby Sevens team. Information on the time difference between the away tournament location and England (home country) as well as the departure and arrival time to each tournament destination was recorded. This data was then used to obtain additional travel metrics such as time difference (from previous destination), time zones crossed (from previous destination), travel direction across the meridian (east vs west) and the time travelled.

3.6 - Collection of climatic data

Climatic data was collected using Visual Crossing (https://www.visualcrossing.com/) a website which records climatic data from different weather stations across the world. Latitude and longitude were obtained for the stadium where games were played during each tournament allowing an average of the nearest weather stations to be used to collect the climatic data for each game. Throughout the WRSS the distance of weather stations from tournament locations ranged between 1km and 66km, and the number of weather stations over the WRSS from which the average was generated ranged from 2 weather stations to 11 weather stations (Appendix B). Data on temperature (°C) and relative humidity (%) was collected for each match. These climatic variables were recorded every 30 minutes to every 3 hours by the weather stations and the time closest to the start time of each game was used to obtain the climatic data.

Humidex was used to combine the variables of air temperature (°C) and relative humidity (%) to reflect the perceived temperature and was calculated using the following equation (Gerrett, Kingma, Sluijter, & Daanen, 2019; Ghani et al., 2017).

$$H = T + \frac{5}{9} * (vp - 10)$$

Where, H = Humidex T = temperature (°C), and vp = vapour pressure/atmospheric pressure of water vapour (mm Hg).

Where, $vp = 6.112 * 10^{\left(\frac{7.5*T}{(237.7+T)}\right)} * \frac{H}{100}$

Where, vp = vapour pressure, T = temperature (°C) and H = relative humidity (%).

The values obtained from calculating the Humidex are characterised into; 20 – 29 = little discomfort, 30 – 39 = some discomfort, 40 – 45 = great discomfort; avoid exertion, and above 45 = dangerous; heat stroke possible (Gerrett et al., 2019; Ghani et al., 2017).

3.7 - Data Analysis/Statistical analysis

The data set involved a group of participants over numerous games of the World Rugby Sevens Series. As a result of this, linear mixed models were used to analyse the data collected to study the effects on the dependent variable, with two separate liner mixed model analyses being completed within the data set (1. WCS analysis, 2. climatic and travel analysis). In the linear mixed model for the WCS random intercepts for player ID were specified for RTD and random effects of intercept, method and epoch for RHSR. For RTD the random effect of the player ID intercept was significant ($p < 0.001$), with the RHSR random intercepts of method and epoch being non-significant ($p = 0.426$) and significant ($p < 0.001$) respectively. For the analysis of climate and travel random intercepts of player and game code were specified to ensure that the uniqueness of each individual and each game was acknowledged (Appendix

C). The analysis was completed within Jamovi a statistical analysis software (The Jamovi Project, 2021).

For the analysis of the WCS a linear mixed model analysis was completed for each of the dependent variables (RHSR and RTD) with a follow up simple effects analysis completed to find the difference between methods at each time epoch (60 – 420 seconds). The linear mixed model analysis for the climatic and travel data involved dependent variables of WGRD, peak 1, 3 and 5-minute RHSR and peak 1, 3 and 5-minute RTD, with each of the climatic and travel variables being added in sequentially to test for the best model. A post-hoc analysis in the form of the Bonferroni test was then completed as a follow-up analysis to analyse whether there was a difference between travelling east vs west on peak 1, 3 and 5-minute RHSR, peak 1-, 3- and 5-minute RTD and WGRD. For both the linear mixed models completed the best model was determined using the Akaike information criterion (AIC) number, with the lowest AIC indicating the best fit for the model.

Chapter 4.0 - Results

4.1 - Fixed versus rolling epochs

The linear mixed model analysis highlighted that there was a significant main effect in the method used (FIXED vs ROLL) ($p < 0.001$) for both relative high-speed running (RHSR) and relative total distance (RTD), indicating that, across all epochs, there was a difference in the scores between the FIXED and ROLL method. There was an interaction effect of method x epoch ($p < 0.005$) for both RHSR and RTD, indicating that the difference between the two methods was dependent on the duration. As would be expected the beta values reported in Table 4.1 and 4.2 indicated a significant effect ($p < 0.001$) between the FIXED and ROLL methods for both RHSR and RTD when the 60 s epoch was compared across all other time epochs (120, 180, 240, 300, 360, 420 s).

The follow-up simple effects analysis, with the FIXED method as the baseline, indicated that there was a significant difference ($p < 0.001$) for each dependent variable (RTD and RHSR) between the FIXED and ROLL method at all time epochs (60 – 420 s). Analysis of the beta estimates highlighted that the ROLL method always produced higher values for RTD and RHSR than the FIXED method (Figure 4.1 and 4.2). The biggest (absolute) difference between the two methods was present at the 60 s time epoch for both RHSR and RTD, where the ROLL method reported higher values than the FIXED method by 7.39 $m.min^{-1}$ and 19.4 $m.min^{-1}$ respectively.

Further analysis of the WCS was completed by calculating the percentage difference between the FIXED and ROLL method at each epoch of the mean values for the RTD and RHSR. For RHSR the difference between the FIXED and ROLL method increased as epoch length increased, with the biggest difference of -20% occurring in the 360 s epoch (Table 3). However, the difference between methods did not increase as epoch length did for RTD, with the largest difference between methods at the 180 s epoch of -12% (Table 4.3). Peak speed and total distance was calculated by obtaining a mean from the players for each game. The tournament with the highest peak speed of 9.3 ± 1.6 $m.s^{-1}$ was the sixth game in Dubai, with the fourth game in Hong Kong having the highest average total distance of 1546.9 ± 425.3 m (Appendix D).

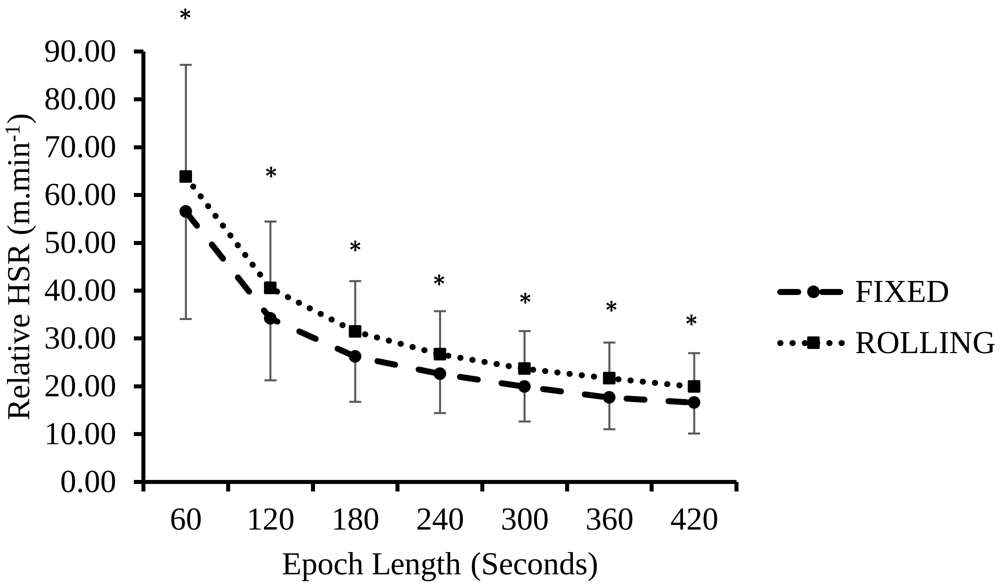

Figure 4.1 Fixed *vs.* rolling method at each epoch length for relative high-speed running

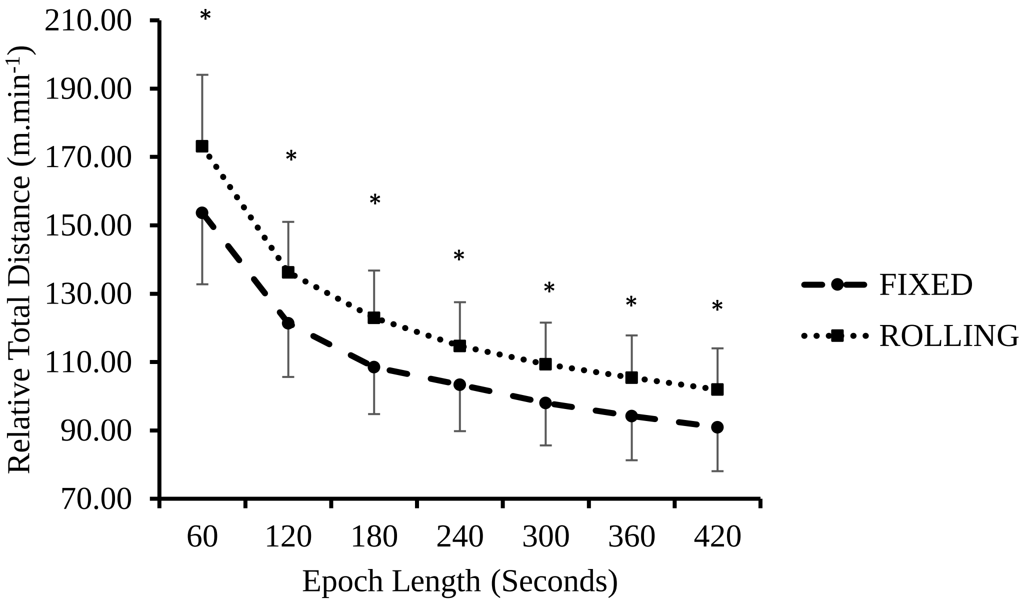

Figure 4.2. Fixed *vs.* rolling method at each epoch for relative total distance

Table 4.1. Table of fixed effects parameter estimates for relative high-speed running (RHSR).

				95% Confidence Interval				
Fixed factors	Effect	Estimate	SE	Lower	Upper	df	t	*p*
Method	ROLL – FIXED	4.962	0.383	4.21	5.7117	20.0	12.969	< .001
Epoch 1	120 – 60 s	-22.662	0.914	-24.45	-20.8695	18.8	-24.785	< .001
Epoch 2	180 – 60 s	-31.189	1.134	-33.41	-28.9661	17.5	-27.501	< .001
Epoch 3	240 – 60 s	-35.382	1.235	-37.80	-32.9610	17.1	-28.649	< .001
Epoch 4	300 – 60 s	-38.267	1.273	-40.76	-35.7713	17.0	-30.055	< .001
Epoch 5	360 – 60 s	-40.383	1.293	-42.92	-37.8492	16.9	-31.233	< .001
Epoch 6	420 – 60 s	-41.815	1.303	-44.37	-39.2611	16.8	-32.086	< .001
Method*epoch1	ROLL-FIXED*120-60 s	-0.952	1.106	-3.12	1.2159	5804.7	-0.860	0.390
Method*epoch2	ROLL-FIXED*180-60 s	-2.115	1.106	-4.28	0.0529	5804.7	-1.912	0.056
Method*epoch3	ROLL-FIXED*240-60 s	-3.176	1.106	-5.34	-1.0090	5804.7	-2.872	0.004
Method*epoch4	ROLL-FIXED*300-60 s	-3.522	1.106	-5.69	-1.3543	5804.7	-3.185	0.001
Method*epoch5	ROLL-FIXED*360-60 s	-3.305	1.106	-5.47	-1.1372	5804.7	-2.988	0.003
Method*epoch6	ROLL-FIXED*420-60 s	-3.959	1.106	-6.13	-1.7912	5804.7	-3.580	< .001

Table 4.2. Table of fixed effects parameter estimates for relative total distance (RTD)

				95% Confidence Interval				
Fixed effects	Effect	Estimate	SE	Lower	Upper	df	t	*p*
Method	ROLL – FIXED	13.8	0.334	12.72	14.03	5833.9	40.07	< .001
Epoch 1	120 – 60 s	-34.60	0.625	-35.82	-33.37	5833.9	-55.40	< .001
Epoch 2	180 – 60 s	-47.64	0.625	-48.87	-46.42	5833.9	-76.28	< .001
Epoch 3	240 – 60 s	-54.33	0.625	-55.55	-53.10	5833.9	-86.99	< .001
Epoch 4	300 – 60 s	-59.70	0.625	-60.92	-58.47	5833.9	-95.58	< .001
Epoch 5	360 – 60 s	-63.58	0.625	-64.80	-62.35	5833.9	-101.80	< .001
Epoch 6	420 – 60 s	-66.94	0.625	-68.16	-65.72	5833.9	-107.18	< .001
Method*epoch1	ROLL-FIXED*120-60 s	-4.60	1.249	-7.05	-2.15	5833.9	-3.68	< .001
Method*epoch2	ROLL-FIXED*180-60 s	-5.00	1.249	-7.45	-2.55	5833.9	-4.00	< .001
Method*epoch3	ROLL-FIXED*240-60 s	-8.11	1.249	-10.56	-5.66	5833.9	-6.49	< .001
Method*epoch4	ROLL-FIXED*300-60 s	-8.04	1.249	-10.67	-5.59	5833.9	-6.44	< .001
Method*epoch5	ROLL-FIXED*360-60 s	-8.22	1.249	-10.67	-5.78	5833.9	-6.58	< .001
Method*epoch6	ROLL-FIXED*420-60 s	-8.44	1.249	-10.89	-5.99	5833.9	-6.75	< .001

Table 4.3. Mean relative distance (RTD) and relative high-speed running (RHSR) and the percentage differences between the FIXED and ROLL methods

	Whole team relative HSR (m.min^{-1})		
Time Epoch	FIXED method	ROLL method	Difference %
60 s	56 ± 22	64 ± 23	-12
120 s	34 ± 13	41 ± 14	-17
180 s	26 ± 9	31 ± 11	-18
240 s	23 ± 8	27 ± 9	-17
300 s	20 ± 7	24 ± 8	-17
360 s	18 ± 7	22 ± 8	-20
420 s	17 ± 6	20 ± 7	-18
	Whole team relative total distance (m.min^{-1})		
60 s	154 ± 21	173 ± 21	-12
120 s	121 ± 16	136 ± 15	-12
180 s	109 ± 14	123 ± 14	-12
240 s	103 ± 14	115 ± 13	-10
300 s	98 ± 12	109 ± 12	-11
360 s	94 ± 13	105 ± 12	-11
420 s	91 ± 13	102 ± 12	-11

4.2 – Analysing the effect of climate and travel on peak 1-minute, 3-minute and 5-minute RTD and RHSR and the whole game relative distance.

For climate and travel, there was a non-significant change in peak 1, 3 and 5-minute RHSR for the time difference from previous destination/time zones crossed, travel direction across the meridian, time travelled, humidex, relative humidity and temperature (Table 4.4). This indicates that all of the climatic variables did not have an effect on the peak 1, 3 and 5-minute RHSR. For the covariate of travel direction, the beta estimates only compared travelling eastward to ‘no change’ and westward to ‘no change’ in travel direction and, therefore, a Bonferroni *post-hoc* test was completed to analyse whether there was a difference between travelling eastward compared to westward. *Post-hoc* test results indicated that there was a non-significant difference for travel direction eastward compared to westward on peak 1-minute (p = 1.00), 3-minute (p = 1.000) and 5-minute (p = 0.517) HSR.

Despite a non-significant effect for all the covariates on peak 1, 3 and 5-minute RHSR distance, analysis of the beta estimates indicated that an increase in the covariates of time difference from previous destination/time zones crossed and travel direction across the meridian for both east vs no change and west vs no change resulted in a reduction in the peak 1, 3 and 5-minute RHSR distance. An increase in temperature and relative humidity for peak 1-minute RHSR was also associated with a decrease in the peak 1-minute RHSR distance. The beta estimates also highlighted that an increase in the time travelled, and humidex led to an increase in the peak 1, 3 and 5-minute RHSR distance. Furthermore, increases in temperature and relative humidity resulted in the peak 3 and 5-minute RHSR distance increasing.

Further analysis was completed to analyse the effect that climate and travel variables had on the peak 1, 3 and 5-minute RTD. It was indicated that there was a non-significant difference in time difference from previous destination/time zones crossed, travel direction across the meridian, time travelled, humidex, relative humidity and temperature for peak 1-minute and 3-minute RTD (Table 4.4). Relative humidity and travel direction across the meridian had a significant effect on the peak 5-minute RTD, with temperature, humidex, time travelled and the time difference from previous destination/time zone crossed not having an effect on the peak 5-minute RTD (Table 4.4). Similar, to RHSR the travel direction beta estimates for RTD only compared differences based on ‘no change’ and so a *post-hoc* test was completed. The Bonferroni *post-hoc* analysis highlighted that there was a non-significant difference between east vs west travel direction for peak 1-minute and 3-minute RTD, however a significant difference ($p < 0.05$) was present for RTD at peak 5-minute. It was indicated that peak 5-minute RTD was significantly higher following travel westward compared to eastward, with travel eastward resulting in -5.43 $m.min^{-1}$ less peak 5-minute RTD.

Despite the peak 1-minute and 3-minute RTD not being significantly different for all covariates, the analysis of beta estimates indicated that increases in the humidex and travel direction across the meridian (east vs no change) resulted in a reduction in peak 1, 3 and 5-minute RTD. Additionally, non-significant increases in temperature and relative humidity resulted in an increase in the peak 1-minute, 3-minute and 5-minute RTD. Non-significant changes were also present following an increase in the time difference from the previous destination/time zones crossed and travel direction across the meridian (west vs no change) causing reductions in peak 1-minute RTD, with the time travelled increasing the peak 1-minute RTD covered. Beta estimates for peak 3-minute RTD indicated that increases in time travelled decreased the peak 3-minute RTD covered and increases in the time difference from the previous destination/time zones crossed and travel direction across the meridian (west vs no change) caused a reduction in the peak 3-minute RTD. Similarly, to peak 3-minute RTD, an increase in the travel direction across the meridian (west vs no change) caused the peak 5-minute RTD to decrease, with increases in the time travelled and time difference from previous destination/time zones crossed causing an increase in the peak 5-minute RTD covered.

When analysing the effect of the climatic and travel demands on whole game relative distance (WGRD) there was a significant difference in travel direction across the meridian (p = 0.024), humidex (p = 0.016), relative humidity, (p = 0.003) and temperature (p = 0.009). Both the time travelled (p = 0.290) and the time difference from the previous destination/time zones crossed (p = 0.139) did not have a significant effect on the WGRD covered. The analysis of travel direction was completed in the same way as previously indicated for RHSR and RTD. The results from the Bonferroni *post-hoc* analysis indicated that were was a significant difference between east vs west travel direction ($p < 0.05$) on WGRD. The WGRD reported for travel westward was higher than travelling eastward with the post-hoc beta analysis indicating a difference of -6.59 $m.min^{-1}$ between the two travel directions.

Analysis of beta estimates highlighted that an increase in humidex and travel direction (east vs no change) caused a reduction in WGRD. Even though time travelled had a non-significant difference on WGRD, the beta estimates indicated that an increase in time travelled also resulted in a reduction in WGRD. Further analysis of the beta estimates also indicated that an increase in relative humidity, temperature and travel direction (west vs no change) caused a significant increase in the WGRD.

Table 4.4 P-values from the fixed effect omnibus test for climatic and travel data.(* = significance)

	P Values						
	Peak 1-minute HSR ($m.min^{-1}$)	Peak 3-minute HSR ($m.min^{-1}$)	Peak 5-minute HSR ($m.min^{-1}$)	Peak 1-minute TD ($m.min^{-1}$)	Peak 3-minute TD ($m.min^{-1}$)	Peak 5-minute TD ($m.min^{-1}$)	Whole game relative distance ($m.min^{-1}$)
Temperature (°C)	0.337	0.994	0.956	0.775	0.469	0.060	0.009*
Travel direction across the meridian (East, west or no change)	0.564	0.261	0.075	0.472	0.093	0.025*	0.024*
Relative Humidity (%)	0.618	0.889	0.838	0.456	0.206	0.014*	0.003*
Humidex (°C)	0.345	0.929	0.922	0.886	0.532	0.088	0.016*
Time travelled (Seconds)	0.288	0.097	0.124	0.840	0.906	0.422	0.290
Time difference from previous destination/time zones crossed	0.149	0.086	0.148	0.986	0.717	0.183	0.139

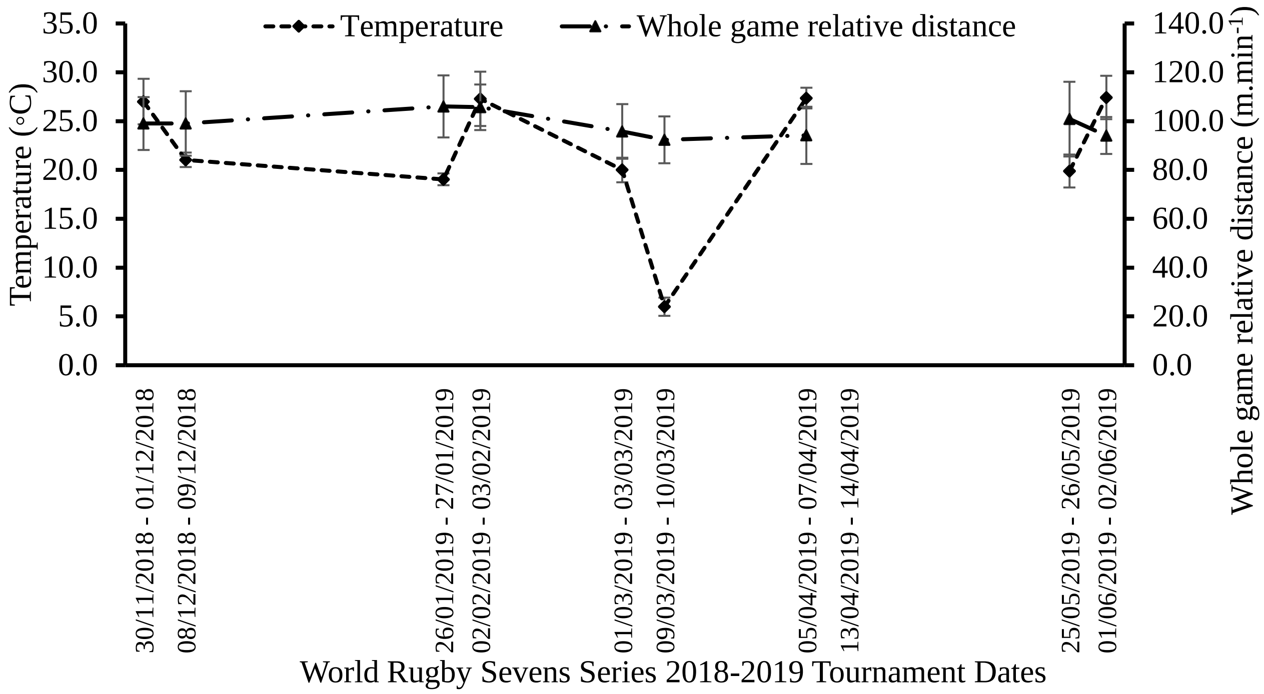

Figure 4.3. Mean temperature and whole game relative distance values for each tournament over the 2018-2019 season

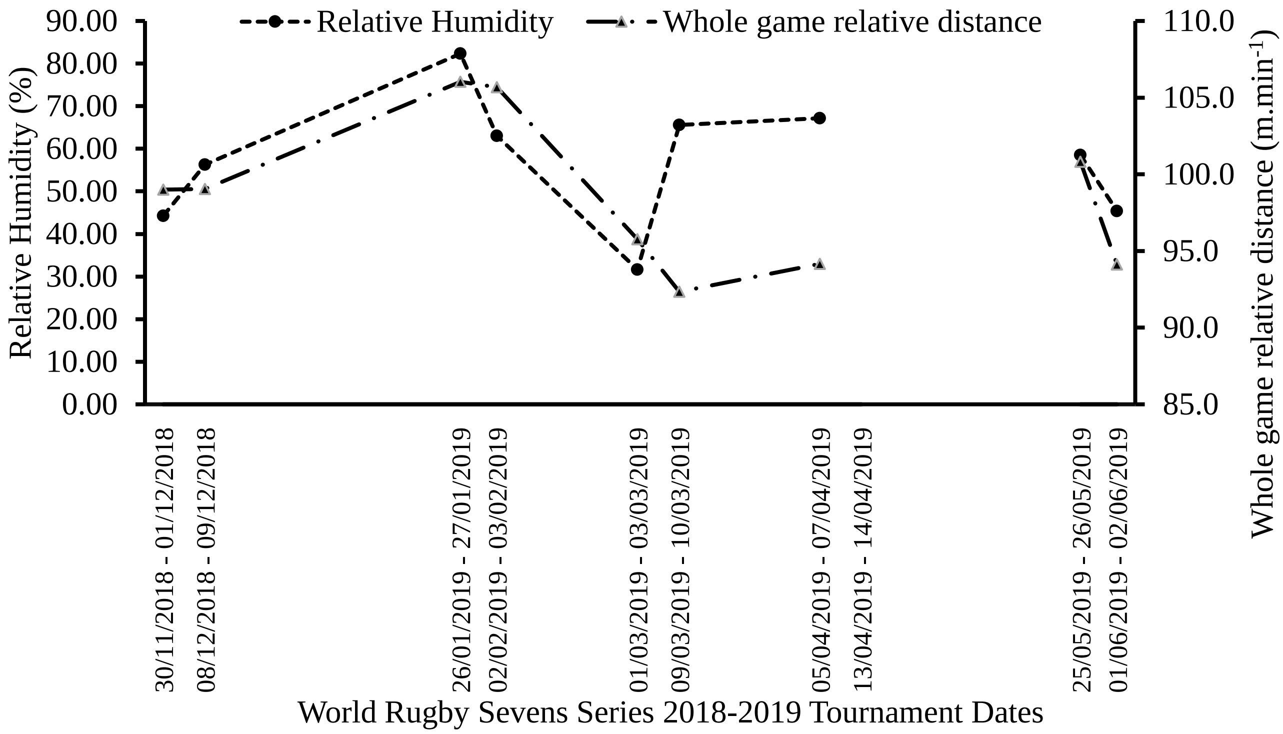

Figure 4.4. Mean relative humidity and whole game relative distance values for each tournament over the 2018-2019 season.

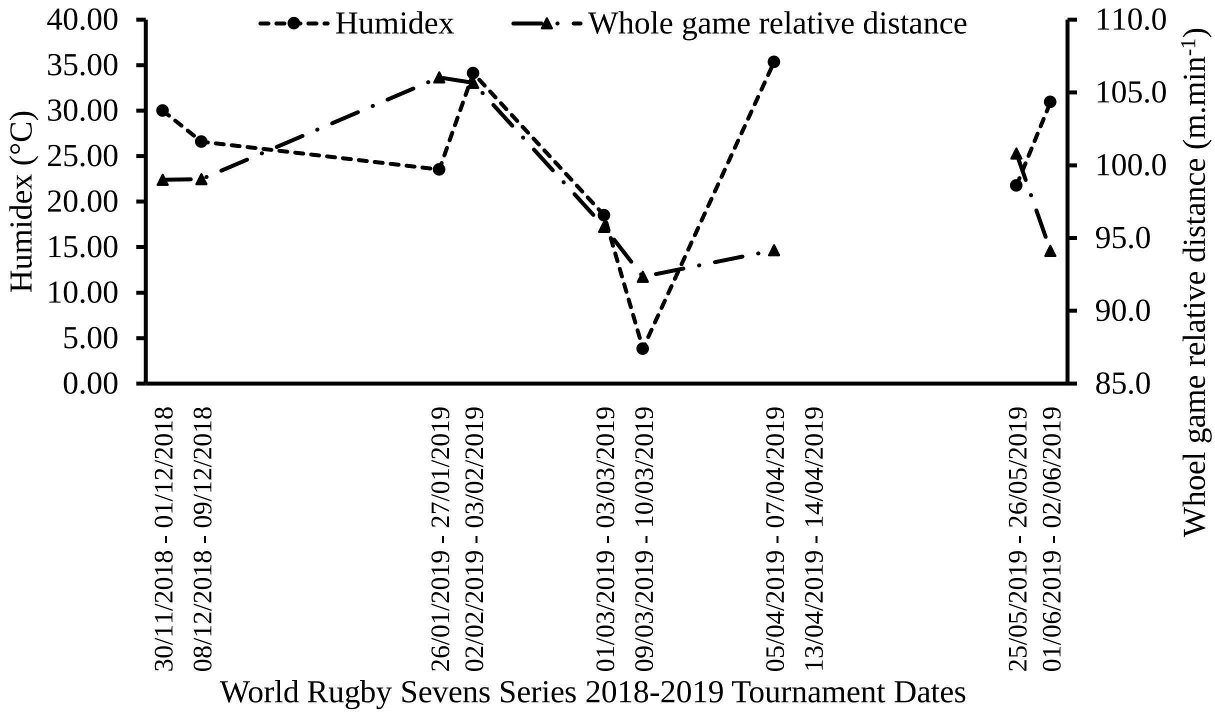

Figure 4.5. Mean humidex and whole game relative distance values for each tournament over the 2018-2019 season.

Table 4.5. Tournament locations, mean and SD for average temperature and humidity, travel time, travel direction, number of games per tournament and number of player files per tournament

Tournament	Average Temperature (°C)	Average Humidity (%)	Travel time (Seconds)	Travel time (Hours and Minutes)	Travel Direction (East, West, no change)	Number of games with data for each tournament	Number of individual player files for each tournament
Overall	21.0 ± 6.8	58.1 ± 17.4	29797 ± 25030	08:16:37 ± 06:57:10		5.7 ± 0.4	46.4 ± 13.2
Dubai	26.8 ± 2.6	44.8 ± 10.9	24600	06:50:00	East	6	53
Cape Town	21.1 ± 0.8	56.2 ± 2.9	34800	09:40:00	West	6	51
Hamilton	19.1 ± 0.7	81.7 ± 12.6	84900	23:35:00	East	6	53
Sydney	27.4 ± 3.0	62.3 ± 15.0	13200	03:40:00	West	6	56
Las Vegas	20.0 ± 1.3	32.0 ± 10.7	38700	10:45:00	West	6	49
Vancouver	6.0 ± 1.0	65.8 ± 2.9	10200	02:50:00	West	6	52
Hong Kong	27.4 ± 1.1	66.8 ± 2.9	42000	11:40:00	East	5	38
London	20.0 ± 1.8	57.9 ± 14.5	0	00:00:00	No Change	6	52
Paris	27.4 ± 2.3	45.3 ± 6.8	8220	02:17:00	East	5	14

Chapter 5.0 – Discussion

The primary aim of the current study was to compare the differences between two methods: fixed epochs *vs.* rolling averages in identifying the peak running demands (worst-case scenario) of the England Rugby Sevens team throughout the World Rugby Sevens Series (WRSS) 2018-2019. Secondly, the study also analysed the effect of travel and climatic demands throughout the WRSS on the movement demands of the England Rugby Sevens team. The main findings of this study indicated that there was a significant difference between the fixed and rolling method at each time epoch (60 – 420 s) for both relative total distance (RTD) and relative high-speed running (RHSR), with the rolling method consistently reporting higher values for the movement demands compared to the fixed method. The current study also reported that climatic and travel variables did not have a significant effect on the peak 1, 3 and 5-minute RHSR, and peak 1 and 3-minute RTD. However, there was a significant increase in peak 5-minute RTD for travel direction west and relative humidity, with travel east significantly reducing peak 5-minute RTD. Whole game relative distance (WGRD) was also significantly increased when there was an increase in temperature, relative humidity, and travel direction west and significantly decreased following an increase in humidex and travel direction east.

Cunningham et al. (2018) highlighted that using fixed epochs compared to rolling averages underestimated total distance covered in elite rugby union by 11-12%. The results of the current study are in line with Cunningham et al. (2018), as within rugby sevens it was highlighted that there was a 10-12% difference between fixed and rolling methods, with fixed always reporting lower values for RTD and RHSR. When comparing the findings of this study for both the peak fixed and rolling worst-case scenario (WCS) to the average RTD reported in rugby sevens athletes (Ball et al., 2019; Couderc et al., 2017; Suarez-Arrones et al., 2014), both the fixed and rolling demands reported exceeded the average RTD reported for a whole game. This highlights how using the average values to plan training can underestimate the peak game demands and result in athletes not being optimally prepared. In the current study, the values reported for both the fixed and rolling WCS for both the RTD and RHSR decreased as the epoch length increased from 60 seconds – 420 seconds, with the fixed method producing lower values at all epochs. These results are in line with previous studies by Cunningham et al. (2018) and Sheppy et al. (2020), where it was indicated that as the duration of the epoch increased, the intensity of the WCS decreased.

Previous research by Murray and Varley (2015) using a peak rolling 1-minute period of play reported values for total distance (TD) and HSR distances as 173 ± 21.0 $m.min^{-1}$ and 63.8 ± 23.4 $m.min^{-1}$ respectively. When compared to the same epoch length used in the current study, it was highlighted that the rolling values reported in Murray and Varley (2015) were higher than the values for RTD and RHSR in the current study. The higher values for HSR reported by Murray and Varley (2015) could be explained by threshold for HSR which was set at 4.17 – 10 $m.s^{-1}$ as opposed to >5 $m.s^{-1}$ used in the current study. The lower HSR threshold could, therefore, result in a larger amount of HSR being recorded during the international rugby sevens games, explaining the higher values recorded.

Peeters et al. (2019) also utilised a 1-minute rolling epoch, differentiating rugby sevens players by positions of forwards and backs for both total distance and HSR. The values reported for TD and HSR for the forwards were comparable to the overall peak values in the current study for the same 1-minute epoch length (176 ± 26 m and 63 ± 26 m vs 173.1 ± 21.0 m and 63.8 ± 23.4 m) for RTD and RHSR respectively (Peeters et al., 2019). However, the TD and HSR distanced reported for backs were greater than the overall values reported in the current study (184 ± 23 m and 55 ± 36 m vs 173.1 ± 21.0 m and 63.8 ± 23.4 m for RTD and RHSR respectively) (Peeters et al., 2019).

Overall, it has been highlighted that both fixed and rolling epochs are more accurate measures of rugby sevens game movement demands in comparison to using whole game averages. The rolling method of analysis has also been reported to be significantly more accurate than the fixed method at all epoch lengths. This allows for additional benefits when encompassing it into the prescription of training in comparison to traditional training sessions based on whole game averages. Gabbett (2006) indicated that to achieve the optimum results from training, the movement patterns and physiological pressures of the game need to be replicated in training. Understandably continuously replicating the peak demands of a game throughout training is impractical and could result in injury, therefore training should only form a section of an athletes training prescription (Delaney et al., 2017; Higham et al., 2016). However, injury risk could also increase if athletes train at the level of whole match averages resulting in athletes being underprepared for the peak demands of a match (Delaney et al., 2017; Gabbett, Jenkins and Abernethy, 2012). To ensure training is specific to rugby sevens, drills simulating game scenarios (e.g., small-sided games) should either replicate or exceed the physiological, physical, technical, psychological and tactical stressors of a rugby sevens match (Delaney et al., 2017; Higham et al., 2016). Therefore, accurately measuring the peak demands of a rugby sevens match using rolling averages can increase the specificity of training prescription, ensuring optimum training adaptations during match specific drills and thus enhancing performance.

Despite the advantages of the WCS compared to whole game averages, the WCS has been described by Novak et al. (2021) as a highly variable metric, that can be influenced by contextual and physical factors and has a limited use in formulating training prescription. It has been indicated that the WCS is a multivariate scenario involving physical factors and contextual factors such as activity in the period prior to the WCS, whether a player is a substitute or a starter, how long the players have played for and the time in which the WCS occurs (Novak et al., 2021) as well factors specific to rugby sevens such as the stage of the season/tournament. The WCS can occur at different points within a game and can be formed differently each time dependent on the occurrence of each of the different scenarios (Novak et al., 2021). Research by Novak et al. (2021) has highlighted the importance of the multivariate nature of the WCS which could be limited when the contextual factors above are not considered. The current study did not analyse all the contextual factors in response to relative high-speed running and relative total distance, due to the aim of the study being to compare the fixed vs rolling methods to assess the WCS of movement demands in rugby sevens athletes.

Novak et al. (2021) also suggested that having both external and internal methods of analysis will enhance the understanding of the physical and physiological demands athletes experience during competition. As a result of the study being based on historical data, additional internal responses i.e., heart rate and rating of perceived exertion could not be measured to assist in the understanding of the WCS.

This study reported that the only variables to be significantly affected by climatic and travel factors were peak 5-minute RTD and WGRD. With the other dependent variables of peak 1, 3 and 5-minute RHSR and peak 1 and 3-minute RTD not being significantly different as a result of the climatic and travel factors. In particular, beta analyses for WGRD indicated that an increase in temperature ($p < 0.05$) and relative humidity ($p < 0.05$) resulted in a significant increase in WGRD covered and increases in humidex ($p < 0.05$) led to a significant decrease in the WGRD. Humidex is calculated using the values of temperature and relative humidity and so it could be assumed that combining both temperature and relative humidity which results in an increase in WGRD would also lead to humidex increasing WGRD, however this was not the case in this study. It could be proposed that humidex causing a reduction in WGRD could be due to the combined effect of temperature and humidity together causing a detriment to performance. The results of this study indicating that humidex significantly decreases WGRD are in line with previous research by Ozgunen et al. (2010) in soccer players. Ozgunen et al. (2010) reported that total distance was significantly lower in the second half of a game in high heat and humidity (36 ± 0°C and 61 ± 1%) compared to a game in moderate heat and humidity (34 ± 1°C and 38 ± 2%). The reduction in WGRD could have several possible explanations, with the first being that a high humidex reduces the body's ability to cool down (Chmura, Konefal, Andrzejewski, Kosowski, & Chmura, 2017). This is a result of the body not being able to evaporate sweat from the skin as efficiently due to the increased water vapour present in the air in a high humidity and high heat (high humidex) environment, which can consequently lead to fatigue and performance impairment (Chmura et al., 2017). Secondly, it could be explained by an anticipatory response by the athletes to reduce their physical performance in order to maintain thermal homeostasis whilst exercising in conditions of a high humidex. This explanation has also been suggested by Ozgunen et al. (2010) and Tucker, Rauch, Harley and Noakes (2004), where a reduction in performance was reported under a high heat and relative humidity condition, compared to a cooler environment.

When acknowledging the effects of temperature individually, the average temperature over all of the 9 WRSS tournaments was 21.0 ± 6.8°C (Table 4.5). The current study did not record core temperature however data collected from previous research on rugby sevens games in London, Singapore, Sydney and Fiji (Fenemor et al., 2021; Henderson et al., 2020; Taylor et al., 2019a) reported a high core temperature (>39°C) following both warm-ups and matches. Core temperature has also been indicated to increase across a tournament (Fenemor et al., 2021), with Taylor et al. (2019a) also reporting peak core temperatures during the final game of a tournament. In the current study temperature has been reported to significantly increase WGRD ($p < 0.05$). Fenemor et al. (2021) highlighted that for every 1000m increase in total running distance, core temperature increased by 0.6°C, suggesting that the core temperature of the athletes in the current study will be increasing alongside the increase in WGRD. Rugby sevens practitioners should therefore consider monitoring the warm-ups to both preserve the beneficial increase in core and muscle temperature for performance but also to monitor core temperature to ensure it is not detrimental to intermittent sprint performance (Fenemor et al. 2021; Girard et al., 2015). In hotter temperatures cooling strategies have previously been highlighted to be beneficial in managing the rise in core temperature and so should be considered by practitioners to limit this increase core temperature throughout the day (Fenemor et al., 2021; Taylor et al., 2019b). The results from the current study also suggest that cooler temperatures may decrease the WGRD and therefore it is essential that practitioners focus on the warm-up and utilising different heat maintenance strategies to maintain muscle and core temperature throughout a tournament to benefit performance (Maughan & Shirreffs, 2004; West et al., 2016). Utilising these different strategies in both hot and cold temperatures may be beneficial for rugby sevens athletes as it is difficult to incorporate general acclimatisation strategies due to the intense nature of the WRSS involving training and travelling in different locations (Fenemor et al., 2021).

The significant increase in WGRD in higher temperatures is supported by O’Connor et al. (2020) where an increase in relative distance (RD) by 19.7 $m.min^{-1}$ was reported in footballers training in ambient conditions of 30.9 ± 2.1°C. A possible explanation for the increased WGRD could be due to an increase in muscle temperature as suggested by O’Connor et al. (2020). However, these results are contradictory of Mohr, Nybo, Grantham and Racinais (2012) who reported a decline in total distance in footballers playing a 90-minute game in temperatures of 43°C. The increase in WGRD recorded in this study could be due to rugby sevens games being shorter in length than a football game (14-minutes vs 90-minutes) and therefore the negative effects of performing in the heat for a prolonged period of time were not evident (Maughan & Shirreffs, 2004). Furthermore, despite previous research in rugby sevens displaying core temperatures >39°C only one study reported 1 athlete that displayed signs of environmental heat illness (EHI) (Fenemor et al., 2021) with the other study indicating that the athletes did not display any symptoms of EHI (Taylor et al., 2019a). These conclusions could suggest that rugby sevens athletes are not as susceptible to heat illness despite reports of high core temperatures, therefore explaining the increase in WGRD alongside an increase in temperature. Despite the results of O'Connor et al. (2020) displaying similar results to a rugby sevens game it must also be acknowledged that O'Connor et al. (2020) analysed performance in training and therefore the true 90-minute game effects were not analysed.

The current study did not report any significant differences in peak 1, 3 and 5-minute RHSR following an increase in temperature, unlike research by Girard et al. (2015) that indicated that increasing temperature begins to inhibit intermittent sprinting performance. Previous research in rugby sevens has reported high core temperature values beyond 39°C during rugby sevens matches and expected a decrease in intermittent sprinting performance with high core temperatures >39°C (Fenemor et al., 2021; Girard et al., 2015; Henderson et al., 2020; Taylor et al., 2019a) The beta analyses from the current study indicated that an increase in temperature at peak 3 and 5-minutes increased RHSR, with only peak 1-minute RHSR supporting the literature with a decrease in RHSR distance. Despite a decrease in peak 1-minute RHSR by -3.78 $m.min^{-1}$ being reported following an increase in temperature, it was not statistically significant; however, the decrease in peak 1-minute RHSR may still be of practical significance to coaches and practitioners.

Previous research analysing the individual effect of relative humidity of physical performance has indicated that an increase in relative humidity is associated with a reduction in HSR performance in footballers (O'Connor et al., 2020). Despite the findings of the current study having a non-significant effect on all RHSR variables, it was concluded that an increase in relative humidity decreased peak 1-minute RHSR, but increased RHSR distance at peak 3 and 5-minutes. The results for peak 1-minute RHSR further support the conclusion that relative humidity inhibits HSR performance (O'Connor et al., 2020); however, the results at peak 3 and 5-minutes contradicts previous research.

The current study also reported that an increase in relative humidity significantly increased the WGRD and peak 5-minute RTD. These conclusions oppose the results from O'Connor et al. (2020) who reported a decrease in distance covered per minute ($m.min^{-1}$) in footballers when relative humidity increased, however the change was not significant. The reason for this difference between this study and O'Connor et al. (2020) may be due to length of a football game and therefore the athletes are performing in a high humidity environment for a longer period of time compared to rugby sevens athletes. Furthermore, it is widely acknowledged that an increase in humidity limits evaporative cooling mechanism of the body, as it is more difficult for sweat to be evaporated into the environment, which can consequently increase core temperature (Chmura et al., 2017; Maughan, Otani, & Watson, 2012; O'Connor et al., 2020). There is currently little research that has been completed analysing the effect of relative humidity individually on sporting performance, with the majority of research analysing the combined effect of temperature and humidity on physical performance.

It must also be acknowledged that, in the current study, the reported values of temperature and humidity throughout the whole WRSS were averaged. This therefore involved a vast range of temperature and relative humidity values, with the lowest values of temperature and relative humidity being recorded in Vancouver and Las Vegas and the hottest temperatures and highest relative humidity in Sydney and Hamilton (Table 4.5).

Rugby sevens players in the current study were shown to cover significantly different WGRD and peak 5-minute RTD when travelling eastward compared to westward. The results from the current study indicated that -6.59 $m.min^{-1}$ less WGRD and -5.43 $m.min^{-1}$ less peak 5-minute RTD was covered following travel eastward compared to west. The main reason for this result may be due to research indicating that adapting the circadian rhythms following eastward travel compared to westward may be more challenging (Janse Van Rensburg et al., 2020). Similar trends have been previously reported in other research in rugby sevens where total distance and HSR increased following westward travel compared to eastward travel by 13% and 5% respectively (Mitchell et al., 2017). The current study did not however report a significant change in peak 1, 3 or 5-minute RHSR following eastward or westward travel.

Both the time travelled and time difference from the previous destination/time zones crossed in the current study did not have a significant effect on any of the performance variables of RHSR, RTD and WGRD recorded in this study. Despite a non-significant effect, beta analyses indicated that an increase in time travelled increased the peak 1, 3 and 5-minute RHSR. Data from Mitchell et al. (2017) supports this finding with ~11 ± 10% more HSR metres per game being covered after long-haul travel compared to short-haul travel. Mitchell et al. (2017) further confirm the results in this study as a non-significant effect was also reported for the RTD covered throughout the tournament between short and long-haul travel.

It would be expected that an increase in time zones/time difference from previous destination would result in jet lag which has been indicated to negatively affect performance and result in fatigue, reduced concentration and motivation (Chapman et al., 2012; Forbes-Robertson et al., 2012). An increase time difference from previous destination/time zones crossed from the previous destination was reported to result in a non-significant reduction in peak 1, 3 and 5-minute RHSR and peak 1-minute RTD, and non-significantly increase the WGRD and peak 3 and 5-minute RTD. A possible explanation for the changes in performance could be due to neuromuscular fatigue following travel and therefore practitioners should consider different strategies to be implemented into the athletes' schedule post travel to aid with recovery (Mitchell et al., 2017). Despite the time travelled and time zones crossed/time difference from previous destination not having a significant effect, there was a still change in performance that may be of practical significance to coaches and practitioners when analysing performance.

Overall, the climatic and travel variables were reported to have both positive and negative effects on the rugby seven athletes' performance. This highlights the challenges and environmental stressors that rugby seven athletes experience when competing in the WRSS and the importance of coaches and practitioners in preparing the athletes prior to the WRSS and creating strategies throughout to ensure optimum performance.

This study was the first to analyse the differences between fixed vs rolling epochs in rugby sevens athletes, highlighting that the fixed method underestimates RHSR and RTD at all epoch lengths in comparison to the rolling method. Furthermore, it has been indicated that climatic variables of temperature, relative humidity and humidex all have a significant effect of the WGRD, with relative humidity also significantly affecting the peak 5-minute RTD. Travel demands of travel direction across the meridian (east vs west) were also shown to significantly affect both the WGRD and peak 5-minute RTD distance throughout the WRSS. Practitioners should therefore use a rolling method when analysing the movement demands of a rugby sevens game and ensure that different strategies are used to help athletes both prepare, perform and recover from the different climatic and travel demands during the WRSS.

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Appendices:

Appendix A. Mean and SD for HDOP, quality of signal and satellite number for each tournament.

Tournament	Game Number	HDOP (Mean ± SD)	Quality of Signal (Mean ± SD)	Satellite Number (Mean ± SD)
Dubai	1	0.4 ± 0.1	336.5 ± 13.8	20.9 ± 1.1
	2	0.4 ± 0.2	338.2 ± 13.2	19.4 ± 1.2
	3	0.4 ± 0.1	334.2 ± 13.5	20.6 ± 0.8
	4	0.4 ± 0.2	337.0 ± 14.4	22.0 ± 1.1
	5	0.5 ± 0.3	332.4 ± 22.4	19.0 ± 1.1
	6	0.5 ± 0.2	334.6 ± 12.2	19.1 ± 1.0
	Average	0.4 ± 0.2	335.6 ± 15.3	20.1 ± 1.5
Cape Town	1	1.0 ± 0.6	321.5 ± 15.0	19.8 ± 1.2
	2	1.0 ± 0.5	307.0 ± 15.4	19.4 ± 1.4
	3	1.0 ± 0.7	311.7 ± 16.5	16.9 ± 0.6
	4	1.0 ± 0.6	316.7 ± 16.9	18.2 ± 0.8
	5	0.9 ± 0.4	301.9 ± 16.5	19.0 ± 1.7
	6	0.9 ± 0.6	308.7 ± 15.6	17.3 ± 1.1
	Averages	1.0 ± 0.5	310.9 ± 17.3	18.7 ± 1.6
Hamilton	1	0.6 ± 0.2	323.5 ± 16.2	17.8 ± 1.1
	2	0.4 ± 0.1	324.0 ± 16.1	17.2 ± 0.9
	3	0.6 ± 0.2	316.2 ± 18.3	16.8 ± 1.1
	4	0.6 ± 0.2	318.2 ± 15.5	18.2 ± 1.2
	5	0.4 ± 0.1	323.8 ± 13.5	18.5 ± 1.1
	6	0.7 ± 0.2	321.5 ± 13.3	15.9 ± 1.2
	Averages	0.5 ± 0.2	321.4 ± 16.1	17.5 ± 1.3

Appendix A continued. Mean and SD for HDOP, quality of signal and satellite number for each tournament.

Sydney	1	0.5 ± 0.2	16.8 ± 0.8
	2	0.5 ± 0.2	16.9 ± 1.2
	3	0.5 ± 0.3	20.3 ± 1.0
	4	0.5 ± 0.1	17.3 ± 0.8
	5	0.5 ± 0.2	16.8 ± 0.8
	6	0.5 ± 0.3	19.8 ± 1.2
	Averages	0.5 ± 0.2	18.2 ± 1.8
Las Vegas	1	0.6 ± 0.2	17.3 ± 1.0
	2	0.6 ± 0.2	18.0 ± 1.1
	3	0.4 ± 0.1	20.8 ± 1.4
	4	0.8 ± 0.2	16.9 ± 1.2
	5	0.5 ± 0.2	19.8 ± 0.8
	6	0.6 ± 0.2	19.2 ± 1.0
	Average	0.6 ± 0.2	18.5 ± 1.7
Vancouver	1	1.2 ± 0.7	18.9 ± 1.8
	2	1.0 ± 0.5	19.8 ± 1.0
	3	1.4 ± 0.8	18.6 ± 1.0
	4	1.3 ± 0.8	18.0 ± 1.2
	5	1.3 ± 0.6	20.6 ± 1.7
	6	1.3 ± 1.1	19.4 ± 1.2
	Average	1.3 ± 0.8	19.2 ± 1.5

Appendix A continued. Mean and SD for HDOP, quality of signal and satellite number for each tournament.

Hong Kong	1	0.7 ± 0.3	16.3 ± 1.2
	2	0.7 ± 0.2	15.9 ± 1.2
	3	1.0 ± 0.3	14.4 ± 1.3
	4		
	5	0.9 ± 0.2	14.9 ± 1.2
	Average	0.8 ± 0.3	15.4 ± 1.4
London	1	1.2 ± 0.6	17.7 ± 1.2
	2	1.3 ± 0.6	19.3 ± 1.4
	3	1.1 ± 0.4	19.6 ± 1.5
	4	1.0 ± 0.6	19.4 ± 1.2
	5	1.2 ± 0.5	18.8 ± 1.4
	6	1.0 ± 0.8	19.0 ± 1.1
	Average	1.1 ± 0.6	19.0 ± 1.5
Paris	1	1.1 ± 0.7	16.6 ± 1.3
	2	1.1 ± 0.7	17.4 ± 1.1
	3	0.8 ± 0.9	18.4 ± 1.1
	4	0.9 ± 0.7	17.5 ± 1.0
	5	0.9 ± 0.4	15.9 ± 1.1
	Average	0.9 ± 0.7	17.2 ± 1.4

Appendix B. Distance of weather stations from each stadium

Tournament Location	Weather Stations	Distance (km)
Dubai	Dubai International, AE	31
	OMDB	31
	Al Maktoum International Airport, AE	32
	OMDW	32
	Sharjah International, AE	37
Cape Town	OMSJ	38
	Cape Town Portnet, SF	2
	Molteno Reservoir, SF	3
	Ysterplant Saafb, SF	8
	Robben Island, SF	12
	Cape Town International, SF	19
	Fact	20
	EW3102 Duynefontein ZA	24
	Slangkop, SF	29
Hamilton	EW5565 Whatawhata NZ	7
	Port Taharoa, NZ	66
Sydney	Sydney Olympic Park AWS Archery Centre, AS	7
	EW2112 Seven Hills, AU	8
	Sydney Bankstown, AS	13
	Horsley Equestrian Centre, AS	15
	Canterbury Racecourse, AS	15
	Sydney Observatory Hill, AS	19
	Holsworthy Control Range, AS	21
	Sydney International, AS	22
	YSSY	23
	Terry Hills AWS, AS	26
	Gosford AWS, AS	54

Appendix B continued. Distance of weather stations from each stadium

Las Vegas	DW2751 Henderson NV US	4
	McCarran International Airport, NS US	13
	KLAS	14
	KLSV	15
	Las Vegas Henderson Airport, NV, US	16
	Las Vegas Nellis AFB, NV US	18
	Las Vegas Air Terminal, NV US	21
Vancouver	Vancouver Harbour CS BC, CA	1
	EW9431 North Vancouver CA	8
	CWWA	10
	West Vancouver AUT, CA	10
	Vancouver Sea Island CCG, CA	12
	Point Atkinson, CA	13
	Delta Burns Bog, CA	18
Hong Kong	Sha Tin, CH	14
	Waglan Island, CH	15
	EW2868 Sai Kung	16
	Cheung Chau, CH	20
	VHHH	28
	Hong Kong International, HK	28
	Ta Kwu Ling, CH	29
	Lau Fau Shan, CH	30
	Baoan International, CH	56
	ZGSZ	56
London	DW4121 London Heathrow UK	2
	Heathrow, UK	9
	Northolt, UK	12
	St James Park, UK	16
	Kenley Airfield, UK	25
	Charlwood, UK	36
	Farnborough, UK	36

Appendix B continued. Distance of weather stations from each stadium

Paris	CW1292 Coignieres FR	4
	Paris Montsouris, FR	7
	Velizy, FR	8
	Toussus Le Noble, FR	15
	Orly, FR	15
	Le Bourget, FR	20
	Trappes, FR	20

Appendix C. Random effects likelihood ratio tests (LRT) for each of the climatic and travel dependent variables

	P value	
	Player ID	Game Code
Whole Game Relative Distance	< 0.001	< 0.001
Peak 1-minute RHSR	0.0942	0.0730
Peak 3-minute RHSR	< 0.001	0.076
Peak 5-minute RHSR	< 0.001	0.016
Peak 1-minute RTD	0.204	0.128
Peak 3-minute RTD	< 0.001	< 0.001
Peak 5-minute RTD	< 0.001	< 0.001

Appendix D. Mean and SD for peak speed ($m.s^{-1}$) and total game distance (m).

Tournament	Game Number	Total Game Distance (m)	Peak Speed ($m.s^{-1}$)
Dubai	1	1074.2 ± 454.3	8.2 ± 1.0
	2	967.4 ± 346.7	8.3 ± 1.0
	3	1328.7 ± 328.2	8.4 ± 0.8
	4	1126.1 ± 434.2	8.3 ± 0.8
	5	1339.0 ± 222.5	8.5 ± 0.9
	6	1009.6 ± 365.5	9.3 ± 1.6
Cape Town	1	1330.1 ± 503.0	8.4 ± 0.8
	2	1126.0 ± 375.3	8.3 ± 0.8
	3	1258.7 ± 202.7	8.5 ± 0.6
	4	1243.3 ± 211.6	8.7 ± 0.8
	5	1314.9 ± 400.6	7.9 ± 0.9
	6	1372.6 ± 372.7	8.4 ± 0.9
Hamilton	1	1301.9 ± 444.7	8.6 ± 0.9
	2	1212.8 ± 414.0	8.4 ± 1.2
	3	1318.7 ± 525.4	8.3 ± 1.0
	4	1154.4 ± 404.3	8.0 ± 0.7
	5	1071.0 ± 398.3	8.1 ± 0.8
	6	1125.2 ± 309.9	8.6 ± 0.8

Appendix D continued. Mean and SD for peak speed (m.s^{-1}) and total game distance (m).

Sydney	1	1178.9 ± 327.4	8.5 ± 1.3
	2	1099.6 ± 250.3	8.0 ± 0.9
	3	1044.1 ± 404.7	8.2 ± 0.9
	4	1180.0 ± 401.2	8.6 ± 0.9
	5	1318.4 ± 295.0	8.1 ± 0.9
	6	1332.2 ± 526.0	8.4 ± 0.4
Las Vegas	1	1006.9 ± 400.1	7.9 ± 0.7
	2	1240.1 ± 364.7	8.3 ± 0.8
	3	1052.3 ± 338.6	8.1 ± 0.9
	4	1469.3 ± 391.8	8.3 ± 0.5
	5	1282.6 ± 401.3	8.5 ± 0.6
	6	1352.3 ± 445.7	8.0 ± 0.6
Vancouver	1	1081.7 ± 403.0	8.3 ± 0.9
	2	1102.8 ± 373.4	7.9 ± 0.9
	3	970.5 ± 328.9	8.4 ± 1.1
	4	1215.5 ± 412.4	8.1 ± 0.8
	5	1234.0 ± 423.4	8.1 ± 1.1
	6	1263.2 ± 366.9	8.6 ± 1.0

Appendix D continued. Mean and SD for peak speed (m.s^{-1}) and total game distance (m).

Hong Kong	1	1259.7 ± 425.3	8.5 ± 0.7
	2	1011.5 ± 378.3	8.0 ± 0.8
	3	1328.8 ± 443.4	8.8 ± 0.5
	4	1546.9 ± 425.3	9.2 ± 1.2
	5	1278.5 ± 357.5	9.0 ± 0.8
London	1	1153.6 ± 432.5	8.5 ± 0.9
	2	1098.6 ± 328.1	9.0 ± 0.7
	3	1202.4 ± 359.7	8.4 ± 0.9
	4	1517.9 ± 473.3	8.7 ± 0.7
	5	1099.6 ± 442.9	8.5 ± 1.2
	6	1009.7 ± 245.5	8.7 ± 0.7
Paris	1	1185.4 ± 372.7	8.6 ± 1.0
	2	1186.2 ± 433.3	9.0 ± 0.6
	3	990.6 ± 304.8	8.5 ± 0.8
	4	1163.0 ± 498.0	8.6 ± 0.2
	5	1071.4 ± 370.3	8.6 ± 0.2

Appendix E. Table of fixed effects parameter estimates for whole game relative distance

				95% Confidence Interval				
Fixed factors	Effect	Estimate	SE	Lower	Upper	df	t	*p*
Temperature (°C)	Temperature	6.191	2.274	1.735	10.647	43.4	2.723	0.009
Travel direction across the meridian 1 (East)	East – No change	-3.478	3.704	-10.737	3.782	49.5	-0.939	0.352
Travel direction across the meridian 2 (West)	West – No change	3.116	3.538	-3.819	10.052	45.8	0.881	0.383
Relative humidity (%)	Relative humidity	0.796	0.252	0.303	1.289	42.9	3.163	0.003
Humidex (°C)	Humidex	-3.949	1.573	-7.033	-0.865	43.5	-2.510	0.016
Time travelled (Seconds)	Time travelled	-1.39e-4	1.30e-4	-3.94e-4	1.15e-4	42.6	-1.072	0.290
Time difference from previous destination/time zones crossed (Hours/time zone)	Time difference from previous destination/time zones crossed	1.005	0.667	-0.302	2.313	42.4	1.507	0.139

Appendix F. Table of fixed effects parameter estimates for peak 1-minute relative HSR

				95% Confidence Interval				
Fixed factors	Effect	Estimate	SE	Lower	Upper	df	t	*p*
Temperature (°C)	Temperature	-3.784	3.898	-11.42	3.855	40.0	-0.971	0.337
Travel direction across the meridian 1 (East)	East – No change	-2.850	6.448	-15.49	9.788	47.9	-0.442	0.660
Travel direction across the meridian 2 (West)	West – No change	-5.765	6.088	-17.70	6.168	43.5	-0.947	0.349
Relative humidity (%)	Relative humidity	-0.217	0.431	-1.06	0.628	39.4	-0.503	0.618
Humidex (°C)	Humidex	2.581	2.699	-2.71	7.871	40.1	0.956	0.345
Time travelled (Seconds)	Time travelled	2.40e-4	2.23e-4	-1.97e-4	6.77e-4	40.2	1.077	0.288
Time difference from previous destination/time zones crossed (Hours/time zone)	Time difference from previous destination/time zones crossed	-1.687	1.146	-3.93	0.558	40.6	-1.473	0.149

Appendix G. Table of fixed effects parameter estimates for peak 3-minute relative HSR

				95% Confidence Interval				
Fixed factors	Effect	Estimate	SE	Lower	Upper	df	t	*p*
Temperature (°C)	Temperature	0.0129	1.650	-3.220	3.2460	38.9	0.00781	0.994
Travel direction across the meridian 1 (East)	East – No change	-4.5842	2.756	-9.986	0.8178	48.5	-1.66326	0.103
Travel direction across the meridian 2 (West)	West – No change	-3.4191	2.597	-8.510	1.6714	44.4	-1.31643	0.195
Relative humidity (%)	Relative humidity	0.0256	0.182	-0.332	0.3828	38.3	0.14059	0.889
Humidex (°C)	Humidex	0.1020	1.142	-2.137	2.3407	39.0	0.08932	0.929
Time travelled (Seconds)	Time travelled	1.60e-4	9.43e-5	-2.44e-5	3.45e-4	39.5	1.70146	0.097
Time difference from previous destination/time zones crossed (Hours/time zone)	Time difference from previous destination/time zones crossed	-0.8535	0.485	-1.804	0.0972	40.3	-1.75958	0.086

Appendix H. Table of fixed effects parameter estimates for peak 5-minute relative HSR

				95% Confidence Interval				
Fixed factors	Effect	Estimate	SE	Lower	Upper	df	t	*p*
Temperature (°C)	Temperature	0.0690	1.244	-2.370	2.508	40.5	0.554	0.956
Travel direction across the meridian 1 (East)	East – No change	-4.7185	2.073	-8.782	-0.655	50.2	-2.2761	0.027
Travel direction across the meridian 2 (West)	West – No change	-2.9207	1.958	-6.759	0.918	46.2	-1.4913	0.143
Relative humidity (%)	Relative humidity	0.0283	0.138	-0.241	0.298	40.0	0.2055	0.838
Humidex (°C)	Humidex	0.0851	0.862	-1.604	1.774	40.7	0.0988	0.922
Time travelled (Seconds)	Time travelled	1.12e-4	7.11e-5	-2.77e-5	2.51e-4	41.0	1.5697	0.124
Time difference from previous destination/time zones crossed (Hours/time zone)	Time difference from previous destination/time zones crossed	-0.5388	0.365	-1.255	0.177	41.6	-1.4743	0.148

Appendix I. Table of fixed effects parameter estimates for peak 1-minute relative TD

				95% Confidence Interval				
Fixed factors	Effect	Estimate	SE	Lower	Upper	df	t	*p*
Temperature (°C)	Temperature	1.0862	3.780	-6.322	8.49	41.4	0.2874	0.775
Travel direction across the meridian 1 (East)	East – No change	-7.6736	6.214	-19.852	4.50	48.9	-1.2350	0.223
Travel direction across the meridian 2 (West)	West – No change	-5.9025	5.900	-17.467	5.66	44.8	-1.0004	0.323
Relative humidity (%)	Relative humidity	0.3146	0.418	-0.505	1.13	40.9	0.7524	0.456
Humidex (°C)	Humidex	-0.3783	2.616	-5.506	4.75	41.6	-0.1446	0.886
Time travelled (Seconds)	Time travelled	4.38e-5	2.16e-4	-3.79e-4	4.67e-4	41.3	0.2030	0.840
Time difference from previous destination/time zones crossed (Hours/time zone)	Time difference from previous destination/time zones crossed	-0.0202	1.109	-2.195	2.15	41.4	-0.0182	0.986

Appendix J. Table of fixed effects parameter estimates for peak 3-minute relative TD

				95% Confidence Interval				
Fixed factors	Effect	Estimate	SE	Lower	Upper	df	t	*p*
Temperature (°C)	Temperature	1.754	2.403	-2.956	6.464	43.9	0.730	0.469
Travel direction across the meridian 1 (East)	East – No change	-7.271	3.940	-14.993	0.450	51.3	-1.846	0.071
Travel direction across the meridian 2 (West)	West – No change	-2.637	3.751	-9.988	4.714	47.3	-0.703	0.485
Relative humidity (%)	Relative humidity	0.341	0.266	-0.180	0.862	43.3	1.283	0.206
Humidex (°C)	Humidex	-1.047	1.663	-4.307	2.213	44.0	-0.629	0.532
Time travelled (Seconds)	Time travelled	1.62e-5	1.37e-4	-2.53e-4	2.85e-4	43.4	0.118	0.906
Time difference from previous destination/time zones crossed (Hours/time zone)	Time difference from previous destination/time zones crossed	0.257	0.705	-1.124	1.639	43.4	0.365	0.717

Appendix K. Table of fixed effects parameter estimates for peak 5-minute relative TD

				95% Confidence Interval				
Fixed factors	Effect	Estimate	SE	Lower	Upper	df	t	*p*
Temperature (°C)	Temperature	3.707	1.918	-0.0513	7.466	43.0	1.9332	0.060
Travel direction across the meridian 1 (East)	East – No change	-5.252	3.157	-11.4394	0.936	51.1	-1.6634	0.102
Travel direction across the meridian 2 (West)	West – No change	0.180	3.001	-5.7007	6.061	47.3	0.0600	0.952
Relative humidity (%)	Relative humidity	0.542	0.212	0.1259	0.957	42.5	2.5538	0.014
Humidex (°C)	Humidex	-2.318	1.327	-4.9197	0.284	43.1	-1.7464	0.088
Time travelled (Seconds)	Time travelled	-8.88e-5	1.10e-4	-3.04e-4	1.26e-4	42.7	-0.8104	0.422
Time difference from previous destination/time zones crossed (Hours/time zone)	Time difference from previous destination/time zones crossed	0.762	0.562	-0.3401	1.864	42.8	1.3550	0.183

Appendix L. Ethical approval

LEAD APPLICANT NAME: Eliza Ullersperger, Georgina Saunders

Swansea University
Prifysgol Abertawe

DISCIPLINE/DEPARTMENT: SPEX

PROJECT TITLE: Using GPS to analyse the worst-case scenario and the impact of climate

and travel demands on England Rugby 7's World Series.

APPLICATION REFFERENCE NUMBER: Eliza_Georgie_Ullersperger_Saunders_19-10-20

Date of review board: November **Date:** 17th November 2020

Committee members in attendance: Chairs

Dear Eliza & Georgina,

Thank you for your recent ethics application. This decision letter is to inform you that the ethics application for the above titled project has been reviewed and approved**.** The ethical approval number for this application is EUGS_23-10-20 approved from 17/11/20–end of approval 30/09/21. Please see reviewer document for more information.

This letter is for Swansea University, College of Engineering Research Ethics and Governance approval only. Local Health and Safety, in addition to appropriate risk assessment guidelines are required separate to this approval, unless otherwise stated herein, and must be adhered to.

Associated researchers must not deviate from the approved protocol or extend beyond the approval end date. Any desired deviations or approval date extensions are subject to the ethical approval amendment process. Upon completion of the approved project researchers responsible for this application must submit a final (short) statement to the ethical committee stating the completion of the project, unless a time extension is being requested through the amendment process.

Best of luck with your research.

Aynsley Fagan

(On behalf of the College of Engineering Research Ethics and Governance Chair)