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**LOCOMOTOR AND COLLISION CHARACTERISTICS OF RUGBY LEAGUE MATCH-
PLAY: ANALYSIS OF LEAGUE-WIDE PLAYER TRACKING AND EVENT DATA TO
EVALUATE LONGITUDINAL CHANGES.**

Gordon Rennie

A thesis submitted in partial fulfilment of the requirements of Leeds Beckett University for the
degree of Doctor of Philosophy

September 2024



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ABSTRACT

This thesis examines the longitudinal evolution of match-play characteristics in senior male professional rugby league at both domestic and international levels, with a particular focus on the impact of rule changes within the sport. The experimental chapters analyse whole-match, ball-in-play, and peak characteristics, and evaluate the variability of these segments using player locomotion and match-event data collected during the Rugby League World Cup and from domestic Super League competition. Throughout the thesis, the implications of rule changes within rugby league are discussed. Chapter 3 presents a systematic review of the literature as it relates to the effect of rule changes within football-code team sports and provides insights into how rule changes effect physical performance and technical-tactical events, injury incidence and prevention, match scoring or points awarded, and player development opportunities. A systematic review and meta-analysis published in 2019 identified a scarcity of research investigating the characteristics of international rugby league matches. The first published study in this thesis (Chapter 4) addresses this gap by analysing data from the 2017 Rugby League World Cup, thereby advancing the knowledge base of international match-play characteristics. Chapter 4 found that international-level rugby league competition exposes forwards to higher collision rates during defensive phases of play, while backs experience higher collision rates during attacking phases, which has implications for training drill design. Chapter 4 also presents a practical method for estimating peak average speed and collision frequency using slope and intercept values derived from international rugby league matches, which may assist coaches in the planning of technical-tactical training. The 2019 systematic review and meta-analysis also noted a bias, with significantly more published studies from the southern hemisphere ($n = 27$) than from the northern hemisphere ($n = 3$). The second and third published studies (Chapters 5 and 6, respectively) therefore analysed data collected from the highest level of northern hemisphere competition, the Super League. Chapter 5 analysed player locomotion and match-event data collected across three years of Super League competition and revealed changes in match duration and ball-in-play duration, particularly in response to rule changes implemented due to the COVID-19 pandemic. Season 2020, divided into pre- and post-pandemic interruption, showed reduced average speeds and increased collision rates upon the return to competitive matches. Chapter 6 analysed match-event data collected from seven seasons of Super League competition, including over 1,000,000 tackle events, and for the first time demonstrated significant positional variability in collision-based events. These findings suggest that training approaches tailored to specific playing positions would be beneficial.

DECLARATION

I hereby confirm that this is my own work. The thesis, or any part thereof, has not been previously submitted for any degree or comparable award.

A handwritten signature in cursive script, appearing to read "Gordon Rennie", is written above a horizontal line.

Gordon Rennie

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Firstly, I'd like to express my deepest gratitude to my director of studies, Professor Ben Jones, and my supervisor, Dr Dan Weaving. Your leadership and encouragement have helped me grow as a person and develop as a researcher. You've both challenged and inspired me, guiding me through every step of this journey. I'm forever indebted to you both for your expertise and unwavering support. Thank you.

Thank you to my employer, Catapult Sports, for funding this PhD on a part-time basis and for allowing me the freedom to embark on such an ambitious journey. My sincere thanks also go to every study participant for sacrificing your time to take part in my work. I hope the findings of this thesis and the studies included have been of benefit to you all in your quest to become the best performers you can possibly be.

Life as a part-time and remote researcher after a 10-year break from academia has been challenging. To the fantastic CARR group, I would have loved to have been more present in person at Headingley, but the 217 miles between us never once felt like a barrier. Thank you to each of you for always being at the end of a phone call or email. I'd also like to extend a special thank you to my co-authors, especially Dr Nicholas Dalton-Barron, Brian Hart, and Dr Lucy Chesson. I have learned more from you than you'll ever know, and for your friendship I am forever grateful.

I was once told that only three groups of people will read your thesis: your supervisors, your examiners, and your parents. To Mum and Dad, rest assured, I have no plans to quiz either of you on the contents of this thesis, so if you stopped reading at the table of contents, you are forgiven! I owe you both an enormous debt of gratitude. Thank you for raising me, for all of your sacrifices, and for providing me with an environment in which I could grow into the man I have. I hope you are both very proud.

The biggest thanks of all goes to my wonderful wife. Katy, you unconditionally kept me going over the course of this journey. Through every wobble, every moment of self-doubt, you were there – like you always are. The best mother, the best wife, and the best friend anyone could ever ask for. I struggled to find a single word to describe why I am thankful – words like *endurance* and *tolerance* came to mind – but in the end, I think I'm most grateful to you for your love. Without you, this and so many other adventures simply wouldn't be possible.

Finally, I'd like to dedicate this thesis, and everything in it, to my two incredible children, Lottie and Harri. When Daddy (and Mummy) embarked on this journey, Lottie, you were a baby, and Harri, you were a wish. In the six years since, you've both taught me more than I will probably ever be able to teach you. But I hope this shows you that with love, purpose, and a determination to be better every day, you can achieve your dreams. And who knows, one day, Daddy might actually become a *"hit-ball doctor"*!

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Rennie, G., Dalton-Barron, N., McLaren, S. J., Weaving, D., Hunwicks, R., Barnes, C., Emmonds, S., Frost, B., Jones, B. (2019). Locomotor and collision characteristics by phases of play during the 2017 rugby league World Cup. *Science and Medicine in Football*, 4(3):225-232.

Rennie, G., Hart, B., Dalton-Barron, N., Weaving, D., Williams, S., Jones, B. (2021). Longitudinal changes in Super League match locomotor and event characteristics: A league-wide investigation over three seasons in rugby league. *PLoS One*, 2;16(12): e0260711.

Rennie, G., Weaving, D., Hart, B., Dalton-Barron, N., Jones, B. (2022). Tackle and ball carrier demands of rugby league: a seven-year league-wide study including over 1,000,000 tackle events. *Journal of Science and Medicine in Sport*, 25(10):850-854.

Rennie, G., Chesson, L., Weaving, D., Jones, B. (2024) The effects of rule changes in football-code team sports: a systematic review. *Science and Medicine in Football*, 9(3):199-212.

ADDITIONAL PUBLICATIONS CONTRIBUTED TO DURING CANDIDATURE

- Dalton-Barron, N., Palczewska, A., McLaren, S.J., Rennie, G., Beggs, C., Roe, G. & Jones, B. (2020) A league-wide investigation into variability of rugby league match running from 322 Super League games. *Science and Medicine in Football*, 5(3):225-233.
- Dalton-Barron, N., Palczewska, A., Weaving, D., Rennie, G., Beggs, C., Roe, G., & Jones, B. (2022) Clustering of match running and performance indicators to assess between- and within-playing position similarity in professional rugby league. *Journal of Sports Sciences*, 40(15):1712-1721.
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- Paul, L., Davidow, D., James, G., Ross, T., Lambert, M., Burger, N., Jones, B., Rennie, G. & Hendricks S. (2022) Tackle Technique and Changes in Playerload™ During a Simulated Tackle: An Exploratory Study. *Journal of Sports Science and Medicine*, 21(3):383-393.
- Whitehead, S., Dalton-Barron, N., Rennie, G. & Jones, B. (2021) The peak locomotor characteristics of Super League (rugby league) match-play. *International Journal of Performance Analysis in Sport*, 21(6):981–992.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
AFL	Australian Football League
AGR	Away Goal Rule
AIS	Australian Institute of Sport
ANOVA	Analysis of variance
APCS	Additional Permanent Concussion Substitute
API	Application Programme Interface
BIP	Ball-in-play
BOP	Ball-out-of-play
CI	Confidence interval
CL	Confidence Limit
CV	Coefficient of Variation
DIMAYOR	Division Mayor del Futbol Profesional Colombiano
EJSS	European Journal of Sports Sciences
ELV	Experimental law variation
EPTS	Electronic performance and tracking systems
ES	Effect Size
FIFA	Fédération Internationale de Football Association
GLONASS	GLObal NAVigation Satellite System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning Systems
HARKing	Hypothesizing After Results are Known
HDOP	Horizontal dilution of precision
HIA	Head Injury Assessment
HSD	Honestly significant difference
HSR	High speed running
ICC	Intraclass correlation coefficient
IFAB	International Football Association Board
IFT	Intermittent Fitness Test
ILR	Increase of load reduction
IMA	Inertial movement analysis
IMU	Inertial measurement unit
IRT	Intermittent Recovery Test
JSAMS	Journal of Science and Medicine in Sport
JSS	Journal of Sports Sciences
KPI	Key performance indicator
LNR	Ligue Nationale de Rugby
MEMS	Micro-Electrical Mechanical Systems

MLR	Major League Rugby
MSSE	Medicine and Science in Sports and Exercise
NRL	National Rugby League
NSWPL	New South Wales Premier League
OR	Offside rule
PCL	Posterior cruciate ligament
PLoS	Public Library of Science
PLslow	PlayerLoad TM slow
PRISMA	Preferred Reporting Items of Systematic Reviews and Meta-analyses
PRL	Premiership Rugby Limited
PTB	Play-the-ball
RCT	Randomised controlled trial
RFL	Rugby Football League
RFU	Rugby Football Union
RHIE	Repeated high intensity effort
RLWC	Rugby League World Cup
ROR	Revised offside rule
RPE	Rating of perceived exertion
RR	Rate ratio
SD	Standard deviation
SEM	Standard error of measurement
SWC	Smallest worthwhile change
TMA	Time Motion Analysis
TMO	Television match official
UEFA	Union of European Football
VAR	Video assistant referee
VHSR	Very high speed running
WSL	Women's Super League
XFL	Extreme Football League
XML	Extensible markup language
IMA	Inertial movement analysis
IMU	Inertial measurement unit
IRT	Intermittent Recovery Test

CHAPTER 1: INTRODUCTION AND AIMS

1.1 Background and Overview of Thesis

The Betfred Super League, the highest level of rugby league competition in Europe, began in 1996 replacing the previously named First Division, which ran between 1895 and 1996. The move from First Division to Super League in 1996 saw the sport enter full-time professionalism which brought a significant change in the timing of competitive fixtures moving from a traditional winter season to a spring and summer season. The present Super League season typically begins late February and concludes early September in the form of a Grand Final which is played between the remaining two sides following a play-off series including the top six sides.

Since the inception of this project in advance of season 2018, fifteen unique teams have participated within the twelve team Super League, through the process of promotion and relegation, with eleven of the fifteen an ever present in the competition. At the time of writing this thesis during the 2024 campaign, eleven of the participating twelve teams are based in England and one is based in southern France. Of the eleven participating sides presently based in England, one is based in London whilst ten are based in the north of the country, which geographically and culturally reflects the sports overwhelming heartland close to its origin within the United Kingdom.

In preparation for 2017 Rugby League World Cup (RLWC) and 2018 Super League season, the Rugby Football League (RFL), signed a league-wide athlete tracking agreement with Australian based wearable microtechnology provider Catapult. Catapult was founded in 2006 and was born out of a partnership between the Australian Institute of Sport (AIS) and the Cooperative Research Centres with the objective of maximising the performance of Australian athletes ahead of the Sydney Olympics. This league-wide athlete tracking agreement primarily centred around the provision of Global Navigation Satellite Systems (GNSS) technology to the England Rugby League national team and the twelve annual participating Super League teams for an initial period of three years (Catapult, 2017). Part of the service provision between RFL and Catapult includes an applied research support collaboration with Leeds Beckett University which was a first of its kind within league-wide wearable microtechnology agreements. Two research students, one full-time and one part-time, collaboratively worked on the project operationally named 'Project SL-Catapult'. Dr Nicholas Dalton-Barron was a full-time doctorate student who submitted a thesis in January 2021 entitled *'The Design of a League-Wide Data Management System*

to Evaluate the Match Characteristics of Rugby League’, which included the following publications:

- Dalton-Barron, N., Whitehead, S., Roe, G., Cummins, C., Beggs, C., & Jones, B. (2020). Time to embrace the complexity when analysing GPS data? A systematic review of contextual factors on match running in rugby league. *Journal of Sports Sciences*, 38(10), 1161–1180. <https://doi.org/10.1080/02640414.2020.1745446>
- Dalton-Barron, N., Palczewska, A., McLaren, S. J., Rennie, G., Beggs, C., Roe, G., & Jones, B. (2021). A league-wide investigation into variability of rugby league match running from 322 Super League games. *Science and Medicine in Football*, 5(3), 225–233. <https://doi.org/10.1080/24733938.2020.1844907>
- Dalton-Barron, N., Palczewska, A., Weaving, D., Rennie, G., Beggs, C., Roe, G., & Jones, B. (2022). Clustering of match running and performance indicators to assess between- and within-playing position similarity in professional rugby league. *Journal of Sports Sciences*, 40(15), 1712–1721. <https://doi.org/10.1080/02640414.2022.2100781>

The present thesis was written as a part-time research student working full-time for Catapult as a sports scientist specialising in the application of wearable microtechnology within sport and with a background as a full-time strength and conditioning coach within professional rugby union. Working full-time whilst concurrently conceptualising research questions and methods, analysing and interpreting data, and authoring manuscripts has proven to be a rewarding and fulfilling challenge which has tested transferrable life-skills such as prioritisation and time management.

Project SL-Catapult was unique insofar as advancements in cloud-based processing allowed for the aggregation of league-wide player positional tracking data into a centralised cloud database underpinned by what is known as a ‘Parent-Child’ data architecture. Catapult are experienced suppliers of microtechnology at a league-wide level having supplied the Australian Football League (AFL) since 2016 and presently the National Rugby League (NRL), Ligue Nationale de Rugby (LNR), Premiership Rugby Limited (PRL), Extreme Football League (XFL), and Division Mayor del Futbol Profesional Colombiano (DIMAYOR). The first iteration of the league-wide centralised database solution had previously been implemented within AFL and represented a hierarchical relationship with the league OpenField™ software account (i.e., Parent) and each independent club teams OpenField™ software accounts (i.e., Child) which are connected using the concept of tags. OpenField™ is the name given to the proprietary software provided by Catapult. Tags are

applied within each OpenField™ software account signifying league, team and player identification numbers which enables successful migration of player positional tracking data from Child to Parent software accounts.

The AFL imposed strict data management and governance over clubs including data segmentation (e.g., “Quarter 1”, “Quarter 2”, “Quarter 3”, and “Quarter 4”) and standardised settings (i.e., consistent speed thresholds) across all OpenField™ software accounts. This data governance was critical in the AFL league-wide centralised project since only summary data was permitted to be extracted by the league during the data migration process. However, the collaboration between RFL, Leeds Beckett University and Catapult was unique at the project’s commencement owing to the migration of summary and raw 10 Hz data; the latter unlocking the possibility of a greater granularity of analysis including for example ball-in-play (i.e., attack, defence, and transition) phases of play.

Although migration of raw player tracking data was performed in the Parent-Child OpenField™ proprietary software, the accessibility and manipulation of summary and raw data was limited within proprietary software therefore it was necessary to explore and move to an alternative data extraction and interrogation process. The second iteration of Project SL-Catapult’s centralised data management involved the use of ‘Catapult Connect’ (Catapult, 2018) which is Catapult’s application programme interface (API). Using the Catapult Connect API, all summary and raw positional tracking data were extracted through R (R, 2023) which allowed subsequent data manipulation, transformation, and loading steps within the R platform. The advantage of this approach was that all participating club sides had the autonomy and capability of collecting and analysing data in line with their individual philosophy and, upon their routinely performed cloud sync, all raw data would be retrievable in R for analyses and interrogation. Whilst this approach was undoubtedly challenging, it is arguable that allowing all participating club sides the freedom to have choice over their settings, speed thresholds, and data segmentation, likely increased collaboration and reduced any potential for resistance within the project.

The advantage of homogenous data stratification, processing and reporting at league level unlocked not only research insights which would benefit coaches and physical preparation staff but allowed stakeholders at league level (e.g., social media, marketing, and commercial teams) to leverage innovative strategies and projects around the use of player tracking data. The Super League are continual innovators and regularly implement technological initiatives such as on-field video review as early as 1996 (five years before rugby union and some twenty-two years before association football). Standardised processing, filtering and segmentation of player tracking data allowed social media and marketing teams the opportunity to demonstrate to a captivated public audience the physical qualities of the athletes in the sport with regular infographics and content created

highlighting the players which covered the greatest distances and achieved the highest peak speeds during matches. This off-field project evolved from online social media posts to multiple real-time broadcast initiatives in collaboration with Sky Sports (BskyB, London, United Kingdom) including two 'Magic Weekend' events (Magic Weekend is two days of back-to-back fixtures, three per day, broadcast live on television from a neutral venue) and two Grand Final contests. The standardised nature and consistency of the data collected for research and broadcast purposes allowed data comparisons to be made by broadcasters therefore greatly enhancing this aspect of the project.

World events including the coronavirus pandemic, resulting in a worldwide lockdown, had a significant impact upon the project. Questions regarding player proximity to fellow players and the potential spread of the virus during training and matches were proposed by the RFL. Given the league-wide nature of the data collected within Project SL-Catapult, the research group were able to support and work with stakeholders at club and league level to monitor player proximity using wearable microtechnology whilst also informing the RFL Laws Committee at league level of events resulting in player incursions (Jones et al., 2021b) which contribute most to player interactions with fellow players. An example of a consequent intervention was the temporary removal of scrums during match-play.

This research project and thesis was funded by Catapult. The research chapters which contribute to the body of this thesis are in response to real-world questions which have arisen by practitioners in the field, and it is hoped that the findings of each chapter have proven useful and that the summary discussion to conclude the thesis will prove beneficial for all stakeholders including coaches, backroom staff, players, and sports legislative bodies.

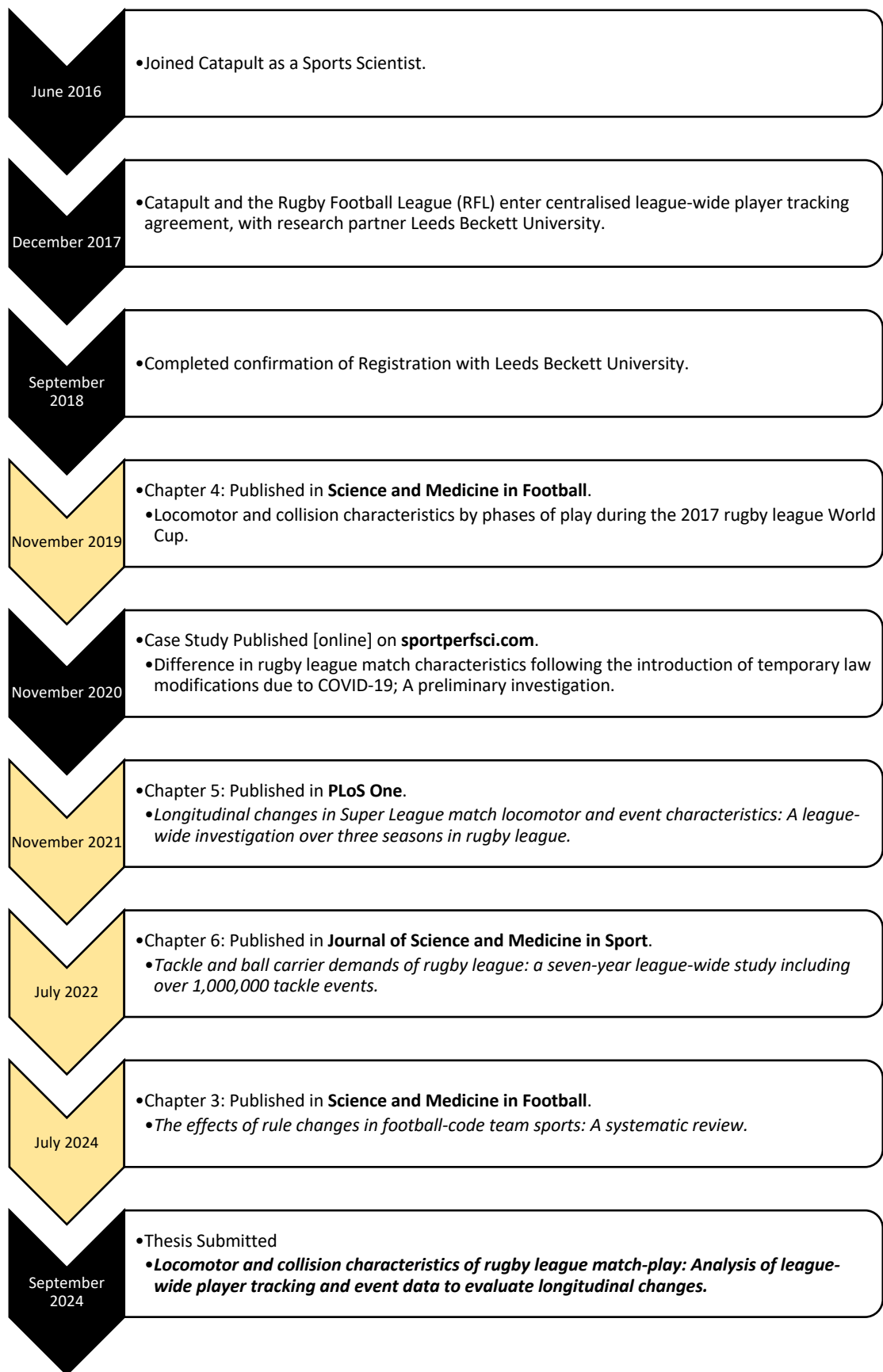


Figure 1: Infographic showing project milestones and research timeline (Rennie, 2024).

1.2 Introduction

Rugby league is a contact-based football-code team sport played in several countries worldwide at both domestic and international levels (Brewer and Davis, 1995, Gabbett et al., 2008a). It is played professionally in Europe, in the Super League, governed by the RFL, and in Australasia, in the NRL, under the governance of the Australian Rugby League Commission (Twist et al., 2014).

Rugby league's origins trace back to the mid-1890's (Brewer and Davis, 1995). The Rugby Football Union (RFU) was formed in 1871, with the first laws of rugby approved in June of that year (Dunning and Sheard, 2005). Fourteen years later, in August 1895, representatives from twenty-two RFU member clubs met in Huddersfield, United Kingdom, to form the Northern Rugby Football Union following an ongoing dispute with the RFU regarding player pay and committee representation (Fagan, 2007). This schism is heralded as the birth of rugby league, albeit the name 'rugby league' was adopted by the sport several years later 1922 (Baker, 1995). The sport is currently played with 13 players per side and 4 interchangeable players (Gardner et al., 2015), with a limit of 8 interchanges permitted per team, and is characterised by intermittent and high-intensity locomotion and collision activities which are separated by periods of low-intensity (Weaving et al., 2019b). Senior male rugby league is played over two 40 minute halves separated by a 10 minute rest interval (Glassbrook et al., 2019). The 13 players are commonly divided into two predominant playing groups, namely forwards and backs (Gissane et al., 2003). Playing position are often further categorised as props, loose forwards, second-rows, hooker, halves, centres, wingers and fullback (Dalton-Barron et al., 2022).

The objective of rugby league is to outscore the opponent in the form of tries (i.e., placing the ball behind the oppositions 'try' line) and goals (Gabbett et al., 2008a). During rugby league match-play, each team in possession is allowed six consecutive tackles, known as a "set", with the aim of advancing the ball forward to achieve this points scoring objective (Gissane et al., 2003). After a successful tackle, the attacking team initiates a play-the-ball (PTB), with the defending team required to retreat at least 10 m towards their own try line in accordance with the 10 m rule (Gabbett et al., 2008a, Meir et al., 2001). If a team remains in possession following the sixth tackle, the ball is turned over to the opposing team so they can begin their set of six tackles. During the sixth set, the attacking side will typically execute a strategic kick down field followed by a 'kick-chase' by teammates to gain advantageous field position and apply pressure to the opponent now in possession.

Rugby league matches last 80 minutes, which is similar to other football codes such as soccer (~90 minutes) and rugby union (~80 minutes) whilst being substantially shorter in duration than Australian rules football (~120 minutes) and longer than Gaelic Football (~60

minutes). The dimensions of a rectangular rugby league pitch are 68 m wide from touchline-to-touchline and 112 to 122 m long (including the in-goal area) which is equal to 224 to 244 m² per player. This is considerably smaller than that of an Australian rules football oval (i.e., 110 to 155 m wing-to-wing and 135 to 185 m goal-to-goal; 324 to 625 m² per player) and soccer pitch (i.e., 64 to 75 m touchline-to-touchline and 100 to 110 m goal line to goal line; 291 to 375 m² per player). Due to the shorter playing duration and smaller pitch area, the locomotor characteristics of rugby league (median [lower quartile – upper quartile]; 4073 [3282 – 4714] m for props to 7943 [7626 – 8311] m for fullbacks; (Dalton-Barron et al., 2020b) are typically lower than that of soccer (mean ± standard deviation [SD]; 10032.18 ± 466.14 m; (Oliveira et al., 2021) and Australian rules football (mean ± SD; 12897 ± 1601 m; (Johnston et al., 2018). Figure 2 provides a visual indication of field dimensions across different team sports (Torres-Ronda et al., 2022). In addition to a larger playing area within alternative football codes, the physical characteristics in the form of tackles and ball carries must be considered when analysing the overall match characteristics of rugby league (Weaving et al., 2019b).

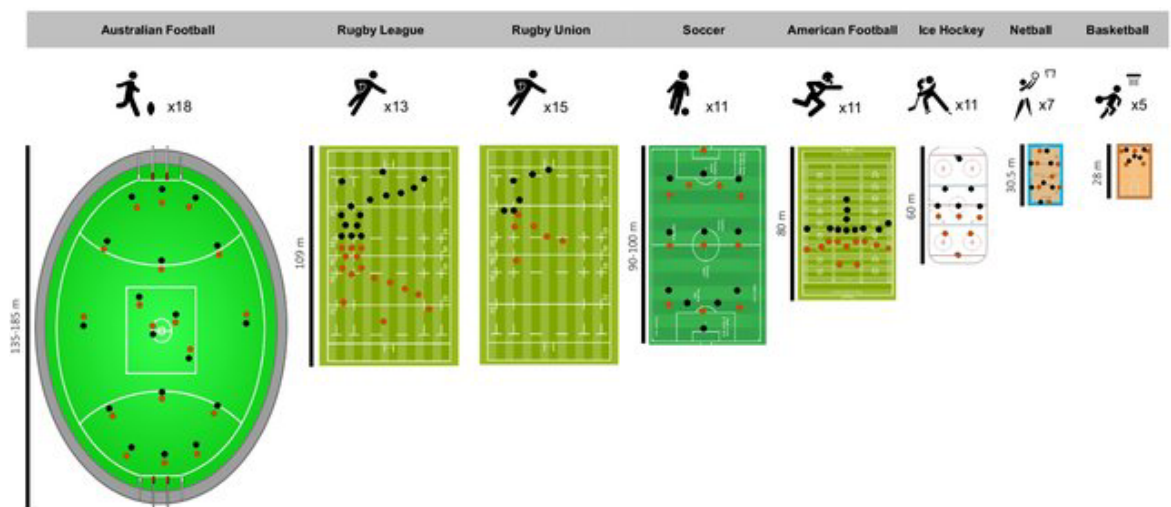


Figure 2: A comparison of field size across different team sports (Torres-Ronda et al., 2022)

The number of players per team is represented by the figure above each field.

Quantification of physical match characteristics in rugby league has been extensively explored through the application of time-motion analysis (TMA) throughout the past three decades (Dalton-Barron et al., 2020b, Glassbrook et al., 2019, Hausler et al., 2016, Johnston et al., 2014a). The earliest implementation of TMA within rugby league research dates back to 1993 which, through manual coding of video footage from two professional matches in Australia, revealed that distances covered ranged from (mean ± SD) 6530 ± 690 m for props, to 6764 ± 449 m for hookers, to 6750 ± 156 m for wingers, and to 7921 ± 473

m for half-backs (Meir et al., 1993). This approach has been shown to be moderately reliable within rugby union (Duthie et al., 2003), however due to its labour-intensive nature the application of this methodology has been limited. Moreover, due to advancements in microtechnology, wearable player tracking devices incorporating GNSS and Micro-Electrical Mechanical Systems (MEMS) (e.g., accelerometers, magnetometers, and gyroscopes) have become commonplace within rugby league (Cummins et al., 2013, Twist et al., 2014). Microtechnology devices are preferred by practitioners and researchers due to their ease of data collection, portability, and relative low-cost (Gray et al., 2018) as well as their ability to monitor athletes in real-time (Barrett, 2017, Cunneen and Borges, 2020, Weaving et al., 2017b). Microtechnology devices have been used by all professional teams competing in the Super League and the NRL since 2010 and 2009, respectively (Johnston et al., 2014a) which provides the opportunity for league-wide data analysis (Dalton-Barron et al., 2020a). Single team studies, which are commonly undertaken due to accessibility and convenience (Teddle and Yu, 2007) are not unusual within rugby league research (Dalton-Barron et al., 2020b, Glassbrook et al., 2019) but are problematic due to inherent small sample sizes which is one of three factors, alongside significance level and the magnitude of the treatment effect, which affects statistical power (Beck, 2013). Moreover, the generalisability of findings from studies containing individual teams are limited since data obtained from a single team is non-random (Dalton-Barron et al., 2020b) and is likely influenced by certain tactics which influence match and training characteristics.

Although locomotor characteristics of rugby league are lower than other football-code team sports, rugby league players are exposed to between 28 (23 to 32) and 45 (38 to 52) collisions during a whole-match as an outside back or wide-running forward, respectively (Gabbett et al., 2012). The volume of collision events is an important consideration when analysing match characteristics as there is an inverse relationship between peak match speed (measured in meters per minute; $\text{m}\cdot\text{min}^{-1}$) and collision events (Johnston et al., 2019b). When zero collisions are experienced, peak match average-speed for NRL playing forwards is $164.1 \pm 18.6 \text{ m}\cdot\text{min}^{-1}$ and for Super League playing forwards is 164.5 ± 14.2 ; whereas when three-or-more collisions are experienced, peak match speed for NRL playing forwards is reduced to $127.1 \pm 18.6 \text{ m}\cdot\text{min}^{-1}$ and for Super League playing forwards is reduced to $120.6 \pm 25.8 \text{ m}\cdot\text{min}^{-1}$ (Johnston et al., 2019b). A similar trend is observed when zero collisions are experienced for NRL playing backs (mean \pm SD; zero collisions: $166.7 \pm 18.1 \text{ m}\cdot\text{min}^{-1}$ vs. three-or-more collisions: $132.6 \pm 23.8 \text{ m}\cdot\text{min}^{-1}$) and Super League playing backs (zero collisions; $170.8 \pm 17.6 \text{ m}\cdot\text{min}^{-1}$ vs. three-or-more collisions; $109.6 \pm 31.6 \text{ m}\cdot\text{min}^{-1}$) thus demonstrating that player running volume reduces in the presence of increased collision exposure (Johnston et al., 2019b). To tolerate these physiological and mechanical exposures, whilst maximising physical performance, players

require a wide range of well-developed physical qualities such as repeated-sprint ability, speed, muscular strength and power, and maximal aerobic fitness (Johnston et al., 2014b, Speranza et al., 2017). These physical qualities have been shown to relate to technical performance. Tackling ability in semi-professional rugby league players is notably related to both lower-body and upper-body strength, as well as upper-body power (Gabbett, 2016, Speranza et al., 2015a). Athletes demonstrating greater lower-body power make a significantly higher proportion of dominant tackles during match-play (Gabbett et al., 2011, Speranza et al., 2015b).

As a sport, rugby league is characterised by its continuous evolution, often marked by rule changes and structural adjustments aimed at enhancing spectator engagement and improving player safety. The first documented rule change within rugby league was during the inaugural 1895 breakaway season (Fagan, 2007). In the seasons which preceded the inaugural Northern Rugby Football Union (i.e., rugby league) season, the scrum half was permitted to follow the ball as it progressed through the opposition forwards during the scrum however in 1895 the defending scrum half would be ruled offside if they moved past their own team's forward players during the scrum. In addition to the newly introduced offside rule, the lineout was abolished, playing numbers were reduced from 15 to 13, and a play-the-ball (PTB) was introduced after a completed tackle. The season which followed included further rule changes (e.g., in the event a defending player deliberately knocked the ball on a free kick would be awarded instead of a scrum formed). Since the mid-1950s, economists have stressed the importance of the uncertainty-of-outcome in sport and its role in maintaining spectator interest (Borland, 2003, Budzinski and Pawlowski, 2014, Rottenberg, 1956). Changes to competition rules are one method of achieving this uncertainty amongst spectators (Hon and Parinduri, 2016) with the objective of ensuring that competitiveness still exists (Eckard, 2017). Rule changes have become increasingly common as rugby league has continued to evolve. For example, the 2019 Super League season included rule changes intended to increase the speed of match play by reducing the number of player interchanges and introducing a 'shot-clock' (i.e., play must be restarted within 35 seconds for a scrum and 30 seconds for a drop-out). Season 2019 also introduced an additional 10 minutes of playing time (referred to as 'Golden Point') in the event of a tied score upon full-time, meaning teams would compete for two additional 5 minute periods to determine a winner decided by the side which scored next.

Moreover, in response to restrictions in place as a consequence of the COVID-19 global coronavirus pandemic, the 2020 Super League season was suspended for 141 days (15th March 2020 to 2nd August 2020) and upon return saw further rule changes introduced including the removal of scrums, which was a temporary rule change to reduce the risk of SARS-CoV-2 transmission (Jones et al., 2020, Jones et al., 2021a), and the introduction of

the colloquially named 'six-again' rule. Prior to the introduction of the 'six-again' rule, ruck infringements were penalised with awarding of a traditional penalty, where teams were given the option of kicking into touch (i.e., kicking the ball out of play to gain field position), restarting an attacking set from the penalty spot, or a penalty shot at goal. Under the revised 'six-again' rule implementation, the referee awarded an automatic reset of the defending team's tackle count to a full six tackle allocation. Rule changes in rugby league serve multiple purposes, including improving player performance and match continuity, ensuring safety, elevating participation, enhancing enjoyment, and accommodating technological progress (Eaves et al., 2008b). Rule changes continue to be implemented within the sport. Ahead of Super League 2024 season, an '18th Player Interchange' was made more readily available (i.e., this additional interchange can be activated following two failed head injury assessments (HIAs) rather than three, or when a player is deemed ineligible to return to the field by any injury caused by serious foul play which leads to an opponent being dismissed or sent to the sin bin).

1.3 Statement of the Problem(s)

Understanding the characteristics of rugby league match-play is important for researchers, coaches and players as improved knowledge of players physical qualities facilitate improved training design for athletes playing at the highest levels (Glassbrook et al., 2019) and can assist applied sports scientists to evaluate whether training prescription is appropriate to the rigours of competition (Gabbett, 2012). A systematic review and meta-analysis investigating the characteristics of professional rugby league match-play, published in 2019, identified that most studies within rugby league are completed using data collected from NRL competition ($n = 27$), with only 10% of the pool of evidence undertaken using data collected from Super League competition ($n = 3$), and one using international matches (Glassbrook et al., 2019). Previous studies have demonstrated differences between competitions (i.e., NRL vs. Super League) (Twist et al., 2014) levels of competition (i.e., elite vs. semi-elite) (Sirotic et al., 2009). Players participating in Super League competition were found to record higher average speed than those in the NRL (Super League: $95.8 \text{ m}\cdot\text{min}^{-1}$ vs. NRL: $90.2 \pm 8.3 \text{ m}\cdot\text{min}^{-1}$, $p < 0.05$) however players within the NRL competition were found to report greater high-speed distance (Super League: $6.1 \pm 1.7 \text{ m}\cdot\text{min}^{-1}$ vs. NRL: $7.8 \pm 2.1 \text{ m}\cdot\text{min}^{-1}$, $p < 0.05$) (Twist et al., 2014). Elite players recorded higher average speed (elite: $108.9 \pm 10.6 \text{ m}\cdot\text{min}^{-1}$ vs. semi-elite: $102.3 \pm 9.7 \text{ m}\cdot\text{min}^{-1}$, $p < 0.01$) and high-speed distance (elite: $36.7 \pm 9.8 \text{ m}\cdot\text{min}^{-1}$ vs. semi-elite: $29.6 \pm 7.8 \text{ m}\cdot\text{min}^{-1}$, $p < 0.01$) during the first half of matches (Sirotic et al., 2009). Due to the differences documented between competitions and levels of match-play, it is reasonable to speculate that international match

characteristics may differ from elite domestic. Therefore, considering the dearth of literature surrounding international match characteristics, this aspect of performance including whole-match, attacking and defensive phases, and peak characteristics remains unknown and requires investigation.

Another problem that the sport of rugby league faces, which contributes to the challenge of generalising study findings across competitions, is that differences in rules exist between competitions. Differences between rules manifested ahead of the 2024 World Club Challenge (which is contested between the winners of the 2023 Super League and the winners of the 2023 NRL) into a controversial decision to implement international rules, rather than enforcing the tighter Super League rules related to increased sanctions for accidental head and neck contact. This episode highlights a problem the sport of rugby league faces which is that occasionally different rules are applied within different playing tournaments at elite domestic level, and between elite domestic and international level, therefore findings from research investigating match-play characteristics with players and teams participating in one playing population cannot easily be generalised across teams, levels or competitions. In light of recent literature reporting the effects of the introduction of the colloquially termed “six-again” rule within NRL competition (Delves et al., 2022b), it is reasonable to expect that rule changes can influence match characteristics. Due to the lack of match-characteristics related literature within Super League competition (Glassbrook et al., 2019), a problem which must be addressed is that of analysing and presenting generalisable match characteristics literature using data specific to Super League competition.

The within-player and between-player, between-position, between-match, and between-team variability of locomotor characteristics from 322 Super League rugby league matches have recently been reported (Dalton-Barron et al., 2020a), however a limitation of this study is that it only included displacement characteristics and therefore the variability of collision-based variables such as tackles and ball carries remains unknown and requires investigation. The lack of this information makes it difficult for governing bodies, coaches, players and researchers to interpret what a meaningful deviation from normal is.

Microtechnology is a valid method of detecting collisions within rugby league (Hulin et al., 2017), however a problem that practitioners operating within rugby league must navigate is that microtechnology cannot distinguish between the type of collision a player is involved in. Therefore, the frequency of distinct tackle events, ball carries and tackler involvements which players are exposed to during match-play are unknown and require investigation. Moreover season-to-season variability of match events (i.e., tackle events, ball carries, and tackler involvements) is also yet to be determined and requires exploration in order to determine when meaningful change has occurred. Understanding longitudinal

changes in match-play characteristics, including changes from season-to-season, enables coaches to make more informed decisions regarding preparation strategies for their players. Rule changes add to this challenge and continue to be introduced on an annual and occasionally mid-season basis however often their effects are not quantified within literature. By leveraging league-wide datasets, this project has the capability to overcome the common issue within sports science of inherently small sample sizes (Sands, 2008) often resulting in underpowered studies (Abt et al., 2020).

The prevalence and quality of research into the effects of rule changes within football-code team sports remains broadly unknown. For example, coaches and backroom staff would benefit from knowing if the implementation of rule changes effect areas of performance such as physical characteristics, match scoring, or injury incidence. Improved knowledge of this area better positions coaches and researchers to make better informed decisions and therefore understanding how rule changes impact the various aspects of match-play within football-code team sports is an area which requires investigation and summary presentation. Therefore, the chapters contained within this thesis aim to contribute findings towards these areas in which the literature is currently lacking.

1.4 Aims

The aims of the chapters within this thesis are:

1. To present and summarise the existing research examining the effects of rule changes within football-code team sports characterised by their invasion-based and continuous match-play, with a specific emphasis on methodological quality (Chapter 3).
2. To describe locomotor and collision characteristics of international rugby league matches (including whole-match, attacking and defending phases of play, ball-in-play periods, and peak characteristics) and describe the within-player and between-player variability of these characteristics (Chapter 4).
3. To quantify the differences in match events and locomotor characteristics between the 2018, 2019 and 2020 Super League seasons in response to rule changes implemented by the sport's governing body (Chapter 5).
4. To describe the highest frequency of collision-based events (i.e., tackle events, ball carries and tackler involvements) for playing positions within professional rugby league over a multi-year period, including within-player, between-match, between-season, between-player, and between-position variability (Chapter 6).

CHAPTER 2: LITERATURE REVIEW

2.1 Overview of the Chapter

The following review of literature has two key aims. Firstly, to critically evaluate the current evidence relating to the usefulness, validity and reliability of GNSS and MEMS devices used within football-code team sports; and secondly, to provide an overview of the match characteristics (i.e., locomotor and collision characteristics) of international, elite domestic, and sub-elite rugby league including the various methods for quantifying these match characteristics available to the practitioner.

Section 2.2 will focus upon the application of electronic performance and tracking systems (EPTS) within rugby league. Section 2.2.1 will discuss the usefulness, validity, and reliability of global positioning system receivers (section 2.2.1.1) followed by inertial measurement units (IMUs) (section 2.2.1.2). Section 2.2.1.1.1 will discuss validity and reliability of global positioning receivers within the context of EPTS and present insight into total and speed-based threshold distance (section 2.2.1.1.2), peak and instantaneous speed (section 2.2.1.1.3), and GNSS derived acceleration and deceleration metrics (section 2.2.1.1.4). Section 2.2.1.2.1 will discuss the usefulness and reliability of IMUs within the context of EPTS and present insight into the application of IMUs within rugby football codes (section 2.2.1.2.2). Increased understanding of the application of wearable microtechnology within rugby league aids in informing the selection of methods utilised in the subsequent experimental chapters.

Section 2.3 will discuss the physical characteristics of rugby league match-play. Section 2.3.1 will provide an overview of the locomotor characteristics of match-play, section 2.3.2 will present collision characteristics, and section 2.3.3 will provide an insight into the technical-tactical characteristics of rugby league. Section 2.3.4 will discuss the contextual factors which may influence performance characteristics. These contextual factors contribute to the variability of data in rugby league match-play within-players and between-players, between-matches, between-positions, and between-seasons which will be discussed in section 2.3.5.

2.2 Electronic Performance and Tracking Systems (EPTS)

Before any measure is implemented, a number of key theoretical and technical attributes (e.g., conceptual and measurement model, validity, reliability, responsiveness, interpretability, respondent and administrative burden, alternative forms, and cultural and

language adaptation) must be considered (Impellizzeri and Marcora, 2009). Atkinson and Nevill (1998) postulate reliability both absolute terms (i.e., the degree to which repeated measurements vary for individuals) and relative terms (i.e., the degree to which individuals maintain their position in a sample with repeated measurements). Absolute reliability is important when assessing the standard error of measurement (SEM) present within a measure and is usually assessed through typical error (expressed as coefficient of variation [CV]) (Atkinson and Nevill, 1998). Relative reliability is important for comparing a measure between individuals and is usually assessed through correlation (expressed as intraclass correlation coefficient [ICC]) (Atkinson and Nevill, 1998). There are three main types of validity to consider: content validity, construct validity (including convergent and discriminant validity), and criterion validity (including predictive, concurrent, and postdictive validity) (Impellizzeri and Marcora, 2009). The following sections will evaluate commonly used methods, and their associated measures, used to quantify physical characteristics of rugby league match-play, with reference to these considerations.

2.2.1 Usefulness, validity, and reliability of EPTS

2.2.1.1 Global positioning system receivers

Global Positioning Systems (GPS) is a satellite navigation network, originally developed for military purposes (Cummins et al., 2013), that provides location and time information of positional tracking devices (Malone et al., 2017). Each satellite in the GPS constellation is equipped with an atomic clock, with the GPS receiver synchronising its clock with the satellites atomic clock (Larsson, 2003). The satellites continuously transmit precise time information to the GPS receiver at the speed of light (Silva et al., 2023). The GPS receiver calculates signal travel time by comparing the time given by a satellite within the GPS receiver (Larsson, 2003). The distance to the satellite is then determined by multiplying the signal travel time by the speed of light (Schutz and Herren, 2000). By calculating the distances to at least four satellites, the precise position can be trigonometrically determined (McLellan et al., 2011). Although four satellites are the minimum required, published literature within the discipline of sports science will often advocate the connection of 10 or more satellites to a GPS receiver (Weston et al., 2015).

GNSS is a collective term used to encompass all satellite navigation systems (Li et al., 2015); including GPS, which was developed and is operated by the United States Department of Defense; GLObal NAVigation Satellite System (GLONASS), developed and operated by the Russian Federation; Galileo, developed and operated by the European Union; and BeiDou, developed and operated by China. The quality and accuracy of the

GNSS data collected is influenced by several factors including the number of satellites available to the receiver. The theoretical minimum number of satellites required is four (Witte and Wilson, 2004), however it has been suggested that devices connected to less than six satellites would have weaker connection (Malone et al., 2017, Weston et al., 2015). By increasing the number of satellites available during tracking, GNSS receivers (i.e., multi-constellation) are more sensitive than GPS receivers (i.e., single constellation) in quantifying the physical characteristics of team-sport movements (Jackson et al., 2018). In addition to number of satellites, the geometrical organisation of the satellites is of importance for signal quality and accuracy and is measured by horizontal dilution of precision (HDOP) (Buchheit et al., 2014a) with values typically ranging from 1.0 to 50.0 (Varley et al., 2012b) but should not exceed 2.0 (Tahsin et al., 2015). Multi-constellation GNSS enabled devices achieve lower HDOP than GPS only devices (0.67 ± 0.06 vs. 0.89 ± 0.04 , Effect Size [ES] = 1.85 ± 0.16 , $p < 0.001$) (Jackson et al., 2018) which may indicate better signal quality. However, it is important to acknowledge that a good HDOP value does not guarantee more accurate positional data since HDOP measures a single source of error (i.e., satellite configuration). A more common issue within an urban and indeed elite sport environment is that of multipathing (see Figure 3) which occurs when satellite signals are reflected from building or stadium surfaces (i.e., grandstands) (Groves et al., 2013, Kumar et al., 2013, Zhang et al., 2018). HDOP is calculated purely from the geometrical organisation of the satellites (Malone et al., 2017), therefore multipathing does not change the HDOP values reported and remains an issue within many elite sport environments.

Distance is the most frequently reported variable derived from wearable technology within rugby league research (Hausler et al., 2016). GNSS devices can calculate distance, and speed, using either positional differentiation or the Doppler-shift method (Cummins et al., 2021). GNSS devices determine their location (i.e., latitude and longitude) by computing the distance between each satellite and the receiver, triangulating the receiver's location (Malone et al., 2017). Positional differentiation involves calculating distance from the change in receiver location with each satellite signal (Varley et al., 2017). Positional differentiation enables the calculation of receiver speed using the concept of distance divided by time (Cardinale and Varley, 2017). However, greater accuracy and lower error rates are found when speed is calculated using the Doppler-shift method (Cormier et al., 2023, Malone et al., 2017, Townshend et al., 2008). The Doppler-shift method refers to the change in frequency of the satellite signal (Howe et al., 2020) and calculates velocity by measuring the rate of change of the radio frequency signals due to the movement of the receiver (McLellan and Lovell, 2013, Schutz and Herren, 2000). Distance can then be derived through multiplying this almost instantaneous velocity by time (Malone et al., 2017).

Commercially available wearable athlete tracking systems usually calculate distance via positional differentiation and velocity via the Doppler-shift method (Malone et al., 2017).

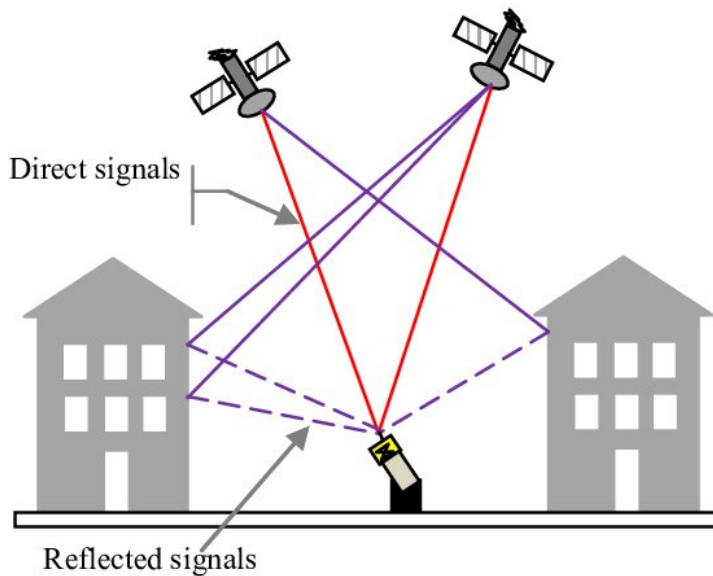


Figure 3: Principle of multipath signal (Kumar et al., 2013)

The use of wearable athlete tracking devices (see Figure 4) to quantify the external load of team-sport athletes, for both research and practice, has increased substantially in recent years (Lacome et al., 2018, Malone et al., 2017). Given their widespread use it is important that the limitations of satellite derived data are understood to make appropriate inferences and decisions from the data.

2.2.1.1.1 Validity and reliability

The validity and reliability of GPS receivers from the perspective of their use in athlete tracking has been demonstrated extensively within the context of athlete tracking solutions (Clavel et al., 2022, Cormier et al., 2023, Crang et al., 2021a, Crang et al., 2021b, Crang et al., 2024, Delaney et al., 2018a, Luteberget and Gilgien, 2020, Luteberget et al., 2023, Malone et al., 2017). Various factors have been shown to impact validity and reliability including sampling rate (Johnston et al., 2014c), type of movement (Duffield et al., 2010), number of satellites (Oliva-Lozano and Muyor, 2022), and data processing methods used (Thornton et al., 2019). The validity and reliability of the most commonly used GPS-derived locomotive variables, such as: total distance, speed-based threshold distances, maximum speed, instantaneous speed, and acceleration metrics have been reviewed by Crang et al. (2021b) and is summarised below.

2.2.1.1.2 Total and speed-based threshold distance

GNSS receivers accurately quantify total distance during a range of human locomotion activities including those with frequent changes of direction (Linke et al., 2018, Nikolaidis et al., 2018, Padulo et al., 2019, Rampinini et al., 2015, Rawstorn et al., 2014, Vickery et al., 2014), continuous movements that do not incorporate frequent directional change (Beato et al., 2018, Edgecomb and Norton, 2006, Nikolaidis et al., 2018, Petersen et al., 2009), and circuits which replicate typical team sport movements (Jennings et al., 2010, Johnston et al., 2014c, Linke et al., 2018, Muñoz-López et al., 2017, Willmott et al., 2019). Validity improves as the distance travelled increases (Jennings et al., 2010, Muñoz-López et al., 2017, Petersen et al., 2009), while frequent directional change appears to degrade accuracy (Duffield et al., 2010, Jennings et al., 2010, Vickery et al., 2014). Barr et al. (2019) demonstrated reliability for 15 Hz units (SPI HPU, GPSports, Canberra, Australia) devices by reporting CV as 1.4% (1st Units: 4073 ± 189 vs. 2nd Units: 4108 ± 175). Direct comparisons between published literature are challenging due to method differences, filtering processes, sampling rates, and hardware used. For example, Vickery et al. (2014) demonstrated differences in distance outputs between 10 Hz (MinimaxX S4, Catapult, Melbourne, Australia) and 15 Hz (SPI-ProX, GPSports, Canberra, Australia) GPS units, however the MinimaxX S4 device was true 10 Hz technology whereas the SPI-ProX was a 5 Hz chip interpolated to 15 Hz (Hausler et al., 2016). Interpolation is suggested to enhance measurement accuracy compared to raw 5 Hz (Rawstorn et al., 2014), however Johnston et al. (2014c) found that true 10 Hz GPS devices measured movement with greater validity and interunit reliability than interpolated 15 Hz technology. The recommended minimum sampling rate of GPS athlete tracking devices, to minimise error, when quantifying total distance is 10 Hz (Crang et al., 2021b).

Discretising, often referred to as banding, distance into speed-based thresholds (e.g., walking through to sprinting) is common practice amongst practitioners (Cummins et al., 2013). Although application of speed-based threshold distances is popular (Oliva-Lozano and Muyor, 2022, Weaving et al., 2022), particularly within the context of rehabilitation and injury risk reduction strategies (Buchheit, 2019), the discretisation of a continuous variable into a categorical one can result in a large amount of information loss through oversimplification of data (Crang et al., 2021b). Due to associated financial costs of high-speed three-dimensional (3D) motion analysis equipment, the body of literature assessing validity using this apparatus is relatively small (Crang et al., 2021b, Duffield et al., 2010). The most used criterion method to evaluate distance measurement accuracy is implementation of a predefined movement circuit with known spatial arrangements (Buchheit et al., 2014a,

Castillo et al., 2021, Hoppe et al., 2018, Rampinini et al., 2015, Rawstorn et al., 2014). Segmentation algorithms or change point analysis used to discretise data (Corbett et al., 2019) also influence the validity of outcome measures therefore the appropriateness of algorithms used for this purpose should also be validated (Crang et al., 2021b).

When performing repeated straight-line running activities over a pre-measured 70 m course, GNSS devices accurately measure total distance and high-speed running distance (running speed > 4.17 m·s⁻¹) however validity significantly reduces when the defined very high-speed running zone (running speed >5.56 m·s⁻¹) was achieved (Rampinini et al., 2015). Use of interpolated devices (e.g., devices estimated from a known 5 Hz data point to and unknown 15 Hz value) does not appear to improve validity (Linke et al., 2018). When performing a team sport-specific circuit, 18 Hz GPS devices demonstrated enhanced validity and reliability than 10 Hz devices (criterion: 129.6 m entire circuit; 10 Hz GPS 126.9 ± 0.6 m; 18 Hz GPS 127.6 ± 0.3 m) however the statistical significance of these differences was not determined (Hoppe et al., 2018). Interestingly, Hoppe et al. (2018) reported that 10 Hz GPS devices connected to *most likely* a greater number of satellites than the 18 Hz devices (10 Hz: 12.5 ± 0.5 vs. 18 Hz: 9.6 ± 0.5, ES = 5.6) suggesting perhaps additional factors contribute to positional quality beyond those of satellite count and HDOP (e.g., orientation of GPS antenna within the wearable device). It is important for researchers and practitioners to interpret the outcome of validation studies in light of the reference methods used (Luteberget et al., 2023). Two reference systems recently shown to demonstrate profound differences in measured distance (+6% to -17%), leading Luteberget et al. (2023) to state that choice of criterion measure and reference system has a substantial impact accuracy assessments of tracking technology systems. Advances in microtechnology facilitate higher sampling rates, multi-constellation GNSS receivers, and positional correction through real-time kinematics therefore further investigation is required to substantiate the effects of these enhancements.

2.2.1.1.3 Peak and instantaneous speed

The association between high-speed running exposures and injury risk underscores the importance of accurate assessment of maximum speed within an athlete tracking setting (Malone et al., 2017). During straight line sprinting protocols, GNSS devices have been shown to accurately measure maximum speed (Akenhead et al., 2014, Barr et al., 2019, Beato et al., 2018, Clavel et al., 2022, Cormier et al., 2023, Varley et al., 2012b). Straight line sprinting within the context of human performance is a relevant protocol since maximum speed is often achieved by an athlete during a straight-line sprint in a relatively open space (Crang et al., 2021b).

A limitation within literature investigating the efficacy of GNSS technology to measure maximum speed is the use of timing gates as a criterion measurement (Hoppe et al., 2018). Timing gates are incapable of measuring instantaneous peak speed since they calculate average speed by measuring time over a set distance (Crang et al., 2021b) therefore use of three-dimensional motion analysis or a radar gun may be more suitable.

Clavel et al. (2022) utilised a Stalker Pro II Sports Radar Gun sampling at 46.875 Hz as a criterion measurement of maximum speed. During each sprint, the athlete wore two Vector S7 devices with the aim of concurrently determining validity (i.e., microtechnology device in comparison to radar gun) and inter-unit reliability (i.e., microtechnology devices in comparison to one another). These authors established that criterion maximum speed was $8.84 \pm 1.06 \text{ m}\cdot\text{s}^{-1}$ whilst Vector S7 device one reported $8.81 \pm 1.06 \text{ m}\cdot\text{s}^{-1}$ and Vector device two reported $8.81 \pm 1.05 \text{ m}\cdot\text{s}^{-1}$. From a validity perspective, this equates to a standardised mean bias of -0.05 (-0.11 to 0.01), from the perspective of interunit reliability this equates to an intraclass correlation coefficient of 0.99 (0.98 to 1.00) with sensitivity reported as 'good'.

When comparing different microtechnology GNSS manufacturers to a criterion 2.56 kHz MuscleLab speed laser, Crang et al. (2024) reported a $7.1 \pm 1.0 \text{ m}\cdot\text{s}^{-1}$ criterion measurement of maximum speed alongside a $7.0 \pm 1.0 \text{ m}\cdot\text{s}^{-1}$ by Vector S7 (Catapult Sports, Melbourne, Australia) and $7.4 \pm 1.0 \text{ m}\cdot\text{s}^{-1}$ by Apex Pro (Statsports, Newry, Northern Ireland) devices. For instantaneous speed, the MuscleLab speed laser recorded an average instantaneous speed of $5.7 \pm 1.8 \text{ m}\cdot\text{s}^{-1}$ whilst the Vector S7 reported $5.7 \pm 1.7 \text{ m}\cdot\text{s}^{-1}$ and the Apex Pro device recorded $5.7 \pm 1.7 \text{ m}\cdot\text{s}^{-1}$ whilst the MuscleLab speed laser $5.7 \pm 1.7 \text{ m}\cdot\text{s}^{-1}$. Apex Pro and Vector S7 reported a RMSE of 0.16 ± 0.02 and 0.15 ± 0.04 , respectively (Crang et al., 2024) with the authors concluding that practitioners can be confident of the peak and instantaneous speed measures provided by both providers during straight line running.

Validity of instantaneous speed varies when specific components of straight-line movement are assessed (Barr et al., 2019, Varley et al., 2012b). For example, Varley et al. (2012b) found when using 5 Hz devices that decelerations were inaccurately measured when starting speed was high ($5\text{-}8 \text{ m}\cdot\text{s}^{-1}$) with CV as percentage ($33.2 \pm 1.64\%$) reported lower when 10 Hz devices were analysed ($11.3 \pm 0.44\%$). From a reliability standpoint, Varley et al. (2012b) reported a CV as a percentage for 5 Hz as $31.8 \pm 2.99\%$ whereas for 10 Hz devices this was reported as $6.0 \pm 0.33\%$ therefore demonstrating superior validity and reliability with devices sampling at a higher rate. Inter-unit reliability of 15 Hz devices (SPI HPU, GPSports, Canberra, Australia) was demonstrated with a CV as 1.0% (1st Units: $8.84 \pm 0.14 \text{ m}\cdot\text{s}^{-1}$ vs. 2nd Units $8.83 \pm 0.12 \text{ m}\cdot\text{s}^{-1}$). Reliability improves significantly when peak speed is attained through straight-line sprinting with CV ranging from 7.5 to 9.2% (Johnston et al., 2012). However, during frequent change of direction and low intensity running using

15 Hz devices, reliability is less clear with CV ranging from 5.4% to 20.9% (Vickery et al., 2014). Further research using non-interpolated technology is required during activities which encompass frequent change of direction.

2.2.1.1.4 GNSS derived acceleration and deceleration metrics

Within the context of team sports, movements performed during training and match-play often require athletes to accelerate, decelerate, and change direction (Delaney et al., 2018a). Moreover, acceleration and deceleration profiles have been associated with indicators of muscle damage (Gastin et al., 2019, Young et al., 2012) and are regularly reported variables during studies investigating the match characteristics of football-code team sports (Kempton et al., 2015b, Varley et al., 2014). In addition to literature using acceleration and deceleration events to describe match characteristics, Nedelec et al. (2014) reported decreases in neuromuscular performance and increases in perceived muscle soreness, which was dependent on number of sprints and changes of direction performed during match-play, in the 72 hour period post-match. Acceleration and deceleration events and distances are generally derived from the GNSS chip housed inside the wearable device, through measures of change in instantaneous speed (Crang et al., 2021b).

Use of three-dimensional motion capture (VICON Vantage 5; Oxford Metrics Ltd, Oxford, United Kingdom at 100Hz) as a criterion measurement of acceleration has shown that acceleration data extracted from 10 Hz GNSS devices is valid (Delaney et al., 2019). However, when compared to raw GNSS data (mean bias raw units: -0.23 (-0.28 to -0.18), mean bias standardised units: -1.16 (-1.41 to -0.90), ES: Moderate), validity appears to reduce when data is exported from manufacturers software (mean bias raw units: -0.74 [-0.79 to -0.69]), mean bias standardised units: -3.77 (-4.02 to -3.51), ES: Very Large) (Delaney et al., 2019). This may be explained by filtering and smoothing techniques applied to the raw data by different manufacturers (Crang et al., 2021b).

Starting speed effects the accuracy of the detection of acceleration events, with higher starting velocities (3-5 m·s⁻¹ and 5-8 m·s⁻¹) showing improved validity than lower starting velocities (1-3 m·s⁻¹) when using both 5 Hz and 10 Hz devices (Varley et al., 2012b). This finding has important implications since magnitude of acceleration is greater at lower starting velocities (Crang et al., 2024), high initial acceleration appears to compromise the validity of 5 Hz and interpolated 15 Hz devices (Barr et al., 2019, Varley et al., 2012b), with 10 Hz devices providing a greater degree of validity when compared (Akenhead et al., 2014, Varley et al., 2012b). Using a laser sampling at 2000 Hz (optoNCDT ILR 1191, Micro-Epsilon Messtechnik GmbH & Co, Germany), Akenhead et al. (2014) demonstrated that the validity

and reliability of 10 Hz GPS devices (MinimaxX S4, Catapult Sports, Melbourne, Australia) for the measurement of instantaneous speed inversely related to acceleration noting that detection of accelerations which exceed $4 \text{ m}\cdot\text{s}^{-2}$ are compromised (mean bias during $0\text{-}1 \text{ m}\cdot\text{s}^{-2}$ accelerations: $0.12 \pm 0.27 \text{ m}\cdot\text{s}^{-1}$, mean bias during $1\text{-}2 \text{ m}\cdot\text{s}^{-2}$ accelerations: $0.08 \pm 0.31 \text{ m}\cdot\text{s}^{-1}$, mean bias during $2\text{-}3 \text{ m}\cdot\text{s}^{-2}$ accelerations: $0.02 \pm 0.35 \text{ m}\cdot\text{s}^{-1}$, mean bias during $3\text{-}4 \text{ m}\cdot\text{s}^{-2}$ accelerations: $-0.10 \pm 0.28 \text{ m}\cdot\text{s}^{-1}$, mean bias during $>4 \text{ m}\cdot\text{s}^{-2}$ accelerations: $-0.40 \pm 0.62 \text{ m}\cdot\text{s}^{-1}$). Using a laser sampling at 50 Hz (LAVEG Sport, Jenoptik, Jena, Germany), Varley et al. (2012b) demonstrated acceptable validity for 10 Hz GPS devices (MinimaxX S4, Catapult, Melbourne, Australia) to capture accelerations at a starting speed of $1\text{-}3 \text{ m}\cdot\text{s}^{-1}$, $3\text{-}5 \text{ m}\cdot\text{s}^{-1}$, and $5\text{-}8 \text{ m}\cdot\text{s}^{-1}$ (CV $5.9 \pm 0.23\%$, $4.9 \pm 0.21\%$, and $3.6 \pm 0.18\%$, respectively). However, validity was substantially lower to when measuring decelerations from an initial speed of $5\text{-}8 \text{ m}\cdot\text{s}^{-1}$ (CV $11.3 \pm 0.44\%$) with overestimation of magnitude of acceleration of $8.9 \pm 0.8\%$ (Varley et al., 2012b).

The frequency of acceleration and deceleration efforts are amongst the most common measures reported by sport scientists (Aughey, 2011), with reliability generally dependent upon the threshold set (Buchheit et al., 2014b, Delaney et al., 2018a). Delaney et al. (2018a) demonstrated that 5 Hz GPS devices (SPI HPU, GPSports, Canberra, Australia) displayed suitable reliability when detecting low ($1\text{-}2 \text{ m}\cdot\text{s}^{-2}$) and moderate ($2\text{-}3 \text{ m}\cdot\text{s}^{-2}$) intensity (5.1% [4.0 to 6.9%] and 3.7% [2.9 to 5.0%], respectively) however detection of high ($>3 \text{ m}\cdot\text{s}^{-2}$) intensity efforts were less reliable (13.2% [10.5 to 18.1%]). When compared to 10 Hz GNSS devices (OptimEye S5, Catapult Sports, Melbourne, Australia), reliability of acceleration effort detection was similar at low and moderate intensity (4.4% [3.4 to 6.0%]) and 5.3% (4.2 to 7.3%), respectively) but were less reliable when measuring high intensity efforts (5.9% [4.7 to 8.2%]) (Delaney et al., 2018a). Detection of deceleration efforts using the same 5 Hz and 10 Hz devices was suitable at low, moderate, and high intensity thresholds (5 Hz: 4.6% (3.7 to 6.3%) vs. 10 Hz: 3.3% (2.6 to 4.5%), 5 Hz: 4.8% (3.8 to 6.6%) vs. 10 Hz: 5.2% (4.1 to 7.2%), 5 Hz: 6.5% (5.2 to 8.9%) vs. 10 Hz: 4.8% (3.8 to 6.6%), respectively) (Delaney et al., 2018a).

Various data processing methods have also been shown to alter summary metrics of acceleration data, with Ellens et al. (2024) reporting significant differences in raw, custom-processed, and manufacturer-processed acceleration variables. An alternative GNSS derived acceleration metric which demonstrates superior reliability is average acceleration (Thornton et al., 2019). Thornton et al. (2019) analysed the inter-unit reliability of three GNSS devices (Evo, GPSports, Canberra, Australia; OptimEye S5, Catapult Sports, Melbourne, Australia; and Apex, Statsports, Newry, Northern Ireland). The authors identified differences in inter-reliability between manufacturers. The Evo and OptimEye S5 devices were found to have a CV less than 5% for low intensity (CV%; $\pm 95\%$ CL, Evo: 4.2% ; ± 1.5 ,

OptimEye S5: 3.4%; ± 1.6), moderate intensity (Evo: 2.7%; ± 1.5 , OptimEye S5: 3.1%; ± 1.6), and high intensity (Evo: 1.4%; ± 1.5 , OptimEye S5: 2.1%; ± 1.6) acceleration distances (Thornton et al., 2019). However the Apex device demonstrated poorer inter-unit reliability when measuring acceleration meters at low intensity (8.6%; ± 1.5), moderate intensity (19.7%; ± 1.5), and high intensity (6.6%; ± 1.5) (Thornton et al., 2019). Average acceleration by comparison was reliable for both Evo and Apex devices (1.2%; ± 1.5 , 3.6%; ± 1.5) during this study. Although average acceleration provides a more reliable alternative to traditional acceleration efforts and distances, differences between manufacturers are evident (Delves et al., 2022a, Thornton et al., 2019). Raw acceleration efforts ($>2 \text{ m}\cdot\text{s}^{-2}$) (Evo: 3.8 ± 2.8 vs. Apex: 10.0 ± 7.6 , ES -1.1 (-1.4 to -0.7)) and raw average acceleration (Evo: $0.37 \pm 0.11 \text{ m}\cdot\text{s}^{-2}$ vs. Apex: $1.19 \pm 0.27 \text{ m}\cdot\text{s}^{-2}$, ES -3.72 (-4.95 to -2.50)) was significantly higher when reported using the Apex devices (Delves et al., 2022a). Coaches, practitioners and researchers must consider the effects of data processing methods upon summary variables and how different techniques used can alter the quantification of match characteristics.

2.2.1.2 Inertial Measurement Units (IMUs)

The body of literature within the context of quantifying match characteristics in football-code team sports has mostly concentrated on the use of displacement metrics such as total distance and high-speed running distance (Cummins et al., 2013). This is an observation consistent with research outputs within rugby league specifically (Hausler et al., 2016). Inertial sensors (including accelerometers, gyroscope and magnetometer), often referred to as IMUs, typically sample at higher rates than GNSS receivers (e.g., 100 Hz compared to 5-15 Hz) and are considered as having a notable advantage in that they do not rely on satellite connectivity which can be influenced by external factors (Crang et al., 2024). Inertial measurement units have emerged as a tool with the potential to measure stride related variables during human locomotion and reflect changes in running gait such as postural control (Akenhead et al., 2017).

The most common use of IMUs is the calculation of accelerometer-derived accumulated load metrics such as PlayerLoadTM (Catapult Sports, Melbourne, Australia) (Cormack et al., 2013, Kempton et al., 2015c, Page et al., 2015, Scott et al., 2013) and Body Load (GPSports, Canberra, Australia) (Cunniffe et al., 2009). Derived from the tri-axial accelerometer, PlayerLoadTM is a composite vector magnitude expressed as the square root of the sum of the squared instantaneous rates of change in acceleration in each of the 3 planes divided by 100 (Boyd et al., 2011, Weaving et al., 2019a). Body Load (measured as G-force) is the collation of all forces imposed on an athlete, including accelerations,

decelerations, changes of direction and impacts from both the player-to-player collision and contact with the ground (e.g., foot strikes and falls) (Cummins et al., 2013).

2.2.1.2.1 Reliability of IMUs

PlayerLoad™ when captured using MinimaxX S4 devices (Catapult Sports, Melbourne, Australia) has been shown to be a reliable variable with values obtained during trials demonstrated to not differ significantly (184.7 ± 25.2 vs. 186.4 ± 27.6 , $p = 0.943$) during an incremental treadmill running protocol (Barrett et al., 2014). Barreira et al. (2017) calculated PlayerLoad™ using IMU data captured with Viper (Statsports, Newry, Northern Ireland) devices in multidirectional movements and revealed moderate-to-high reliability with values during trials not differing significantly during jogging (trial 1: 13037.8 ± 2309.7 vs. trial 2: 12448.0 ± 1803.4 , $p = 0.118$), side cutting (trial 1: 2861.0 ± 507.9 vs. trial 2: 2773.7 ± 422.9 , $p = 0.260$), striding (trial 1: 655.2 ± 172.7 vs. trial 2: 652.3 ± 159.5 , $p = 0.929$), or sprinting (trial 1: 1442.2 ± 280.4 vs. trial 2: 1385.4 ± 324.4 , $p = 0.102$).

Contrasting findings have been reported for inter-device reliability in relation to the measurement of PlayerLoad™ with Nicolella et al. (2018) demonstrating effect sizes (Cohen's d ; 95% CI) of small (0.54; 0.34–0.74) to large (1.20; 1.08–1.30). PlayerLoad™ calculated using proprietary software has been shown to be 15% lower than when compared to manual calculation using published formula, although intra-device reliability was considered excellent with CV ranging from 0.01% to <3.0% (Nicolella et al., 2018). Boyd et al. (2011) demonstrated within-device reliability of 1.01% and between-device reliability of 1.10%. Kelly et al. (2015) used SPI ProX II (GPSports, Canberra, Australia) devices and reported 1.87-2.21% intra-unit reliability whereas Krasnoff et al. (2008) found CV of 0.6% for intra-unit and 9.5-34% inter-unit reliability. Different methodologies may explain such contrasting outcomes (e.g., Kelly et al. (2015) utilised a purpose-built mechanical device capable of reproducing highly consistent impacts whilst Krasnoff et al. (2008) measured reliability using a HS 260 (IKA Works, Inc, Wilmington, NC) reciprocating shaker) as well as different statistical analysis techniques used.

The noise (i.e., coefficient of variation) of PlayerLoad™ is lower than the signal (i.e., smallest worthwhile difference) (Boyd et al., 2011), suggesting that IMUs can detect changes or differences in physical activity during football-code team sports. However, it is important to note that absolute output values by EPTS can be influenced by the type of filtering utilised by the wearable manufacturer (Malone et al., 2017). Although the low signal-to-noise ratio supports the use of accelerometer metrics, their large between-player variation limits their comparisons between individuals (Barrett et al., 2016).

In addition to PlayerLoad™, inertial sensors are also capable of reliably detecting explosive movements (Luteberget et al., 2018) including jumps (Spangler et al., 2018). Luteberget et al. (2018) analysed Catapult Sports proprietary algorithm, termed Inertial Movement Analysis (IMA), and demonstrated that OptimEye S5 devices could reliably measure low intensity (device 1: 416.5 ± 97.7 vs. device 2: 417.2 ± 97.2 2.7, CV = 2.7%), medium intensity (device 1: 120.3 ± 31.6 vs. device 2: 120.4 ± 31.7 , CV = 4.6%), and medium-plus-high intensity (device 1: 189.2 ± 55.8 vs. device 2: 189.7 ± 56.4 , CV = 3.1%) actions. When analysing jumps detected by using Catapult Sports proprietary algorithms, Spangler et al. (2018) demonstrated an accuracy of 99.3% with a sensitivity of 95.8% and a specificity of 99.7% therefore concluding that practitioners can monitor jumping-based workloads with confidence.

2.2.1.2.2 Application of IMUs in rugby football codes

Derivates of PlayerLoad™ metrics and custom variables using IMUs have proven useful within rugby union (Chambers et al., 2015, Chambers et al., 2019, Couderc et al., 2023, Lokteff et al., 2020, MacLeod et al., 2018, Menzies et al., 2024, Reardon et al., 2016, Roe et al., 2016a, Tierney et al., 2020) and rugby league (Gabbett et al., 2010, Hulin et al., 2017) for the purposes of collision-based event detection.

Roe et al. (2016a) reported that PlayerLoad™ and PlayerLoad™ slow (PLslow), which is defined as PlayerLoad™ captured at 2 ms^{-1} or less, demonstrated a *very large* relationship with total collisions in the forwards whilst PLslow demonstrated the largest (*large*) relationship with collisions in the backs. These authors suggested that based on the strong relationship in both forwards and backs, PLslow may provide the most useful metric for measuring collision-based activity in both positional groups within rugby union. Scrum event detection during rugby union has been shown to be accurate within both training (87.6%; sensitivity 0.89, specificity 0.87) and match-play (93.6%; sensitivity 0.94, specificity 0.94) situations, however accuracy is compromised in scrum situations involving five or less players which may have implications in training specifically (Chambers et al., 2019).

In addition to scrum events, IMUs have also been shown to quantify the number of collisions (MacLeod et al., 2018, Reardon et al., 2016) and more recently contact involvements (defined as a tackle, ball carry and hitting a ruck) using Catapult Sports proprietary algorithms (Couderc et al., 2023, Menzies et al., 2024). MacLeod et al. (2018) compared collision events captured by Viper (Statsports, Newry, Northern Ireland) devices with video coded tackles and carries. These authors reported that EPTS could accurately, sensitively and specifically identify collision events (93.3%, 93.8% and 92.8%, respectively). A retrospective analysis using players from a single professional rugby union side in elite

French competition demonstrated a significant correlation ($r = 0.75$, $p < 0.001$) between collision events per minute detected by Vector S7 (Catapult Sports, Melbourne, Australia) microtechnology ($1.02 (\pm 0.54)$) and those coded by a video analyst ($0.79 (\pm 0.37)$) (Couderc et al., 2023). Couderc et al. (2023) also reported mean intensity of collisions using gravitational force (g force) and reported that backs ($8.5 g (\pm 2.9 g)$) experienced significantly greater collisions than forwards ($7.8 g (\pm 2.4 g)$) which is attributed to more frequent bouts of acceleration and high-speed running efforts performed by backs which increase impact force of collisions. Menzies et al. (2024) reported a sensitivity for attacking ruck hit (Forward: 74.5%, Back 75.2%), defensive ruck hit (Forward: 80.6%, Back 70.2%), ball carry (Forward 90.0%, Back 87.0%) and tackle made (Forward 80.3%, Back 70.7%) when comparing the Catapult contact involvement algorithm against those coded by video analysts. However, it's important to note that these studies were performed using single team observations therefore the generalisability of findings should be applied with caution. Additionally, weather and surface conditions have not been reported in any study cited above investigating the relationship between IMU and notational contact detection. The firmness of the ground could have a substantial influence on the magnitude of collisions experienced in rugby union match-play and therefore should be considered in future research (Tierney et al., 2020).

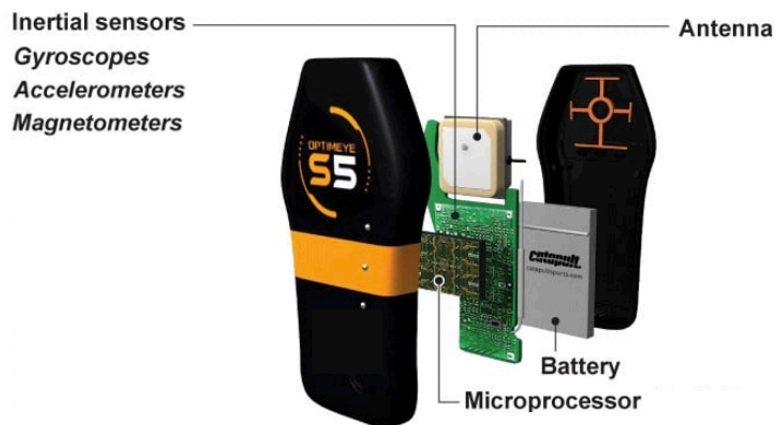


Figure 4: EPTS device including inertial system (Lokteff et al., 2020)

2.3 Quantifying Rugby League Match Characteristics

The outcome of a rugby league match is related to the performance of both competing teams, however performance in this context cannot be directly quantified through a single variable due to the multifactorial nature of match-play (e.g., score-line, positions of players on the pitch, or environmental conditions) (Dalton-Barron et al., 2020b). Quantification of

the physical characteristics of rugby league is further complicated and thus difficult to determine due to the differences in methods used within studies (Sirotic et al., 2011).

Three constructs relevant to match-play performance are physical (i.e., locomotor and collision characteristics), technical (i.e., individual's skill), and tactical (i.e., interaction with other individuals) (Impellizzeri and Marcora, 2009). These constructs of performance are closely related. For example, players and coaches frequently make tactical decisions that affect player positioning on the field and player locomotion characteristics, and therefore improved knowledge of their relationship may enhance coaches understanding of why an athlete has completed a particular movement (Dalton-Barron et al., 2020b). Research within football-code team sports (i.e., soccer) has shown that match status (i.e., win, draw, lose) and location (i.e., home, away), level of opposition (i.e., top, middle bottom), and match halves impact the physical and technical characteristics of players (Castellano et al., 2011, Lago-Peñas and Lago-Ballesteros, 2011, Lago et al., 2010, Rampinini et al., 2009). Gaining a better understanding of these constructs as they relate to match-play allows coaches to increase the specificity and effectiveness of their training and preparation practices (Cummins et al., 2013).

2.3.1 Locomotor characteristics

Attempts to better understand the locomotor characteristics of physical performance within football-code team sports, through the application of time-motion analysis methods, date back to the mid-1970's (Reilly and Thomas, 1976). Time-motion analysis encapsulates the quantification of players movement characteristics and includes notational analysis, manual video-based analysis, semi-automated and video-computerised analysis systems, and more recently microtechnology in the form of GPS devices (Cunneen and Borges, 2020). The earliest attempt within the context of rugby league to understand the locomotor characteristics of match-play using notational analysis techniques took place in the early-1990's and included analysis of four positional groups across two matches (Meir et al., 1993). Advances in TMA methodologies (e.g., the widespread use of microtechnology devices containing GNSS or local positioning systems [LPS]) allows researchers and practitioners to collect, analyse and report data from rugby league matches on a large scale. This increase in the accessibility of technology has facilitated a substantial increase in research in this area.

Distance covered is the most common variable reported within studies investigating the physical match characteristics of rugby league (Glassbrook et al., 2019). A systematic review and meta-analysis (Hausler et al., 2016) reported that junior (mean [95% CI]; 2669 [2557 to 2780] m) players covered substantially less ($p < 0.001$) distance than elite (6619

[6235 to 7003] m) and sub-elite (6219 [5640 to 6799] m) players, however, there were no significant differences between elite and sub-elite levels. It must be noted though that junior match-play data presented in this review is drawn from one study in which playing time was lower than that of elite and sub-elite level (low-standard junior 30 ± 8 minutes to high-standard junior 36 ± 6 minutes) (Johnston et al., 2015b). A more appropriate variable to account for the vast difference in match duration is average speed which was significantly different ($p = 0.04$) between elite players ($92 [90 \text{ to } 94] \text{ m}\cdot\text{min}^{-1}$) and sub-elite players ($90 [86 \text{ to } 90] \text{ m}\cdot\text{min}^{-1}$), with both covering significantly more ($p < 0.002$) than junior players ($80 [74 \text{ to } 85] \text{ m}\cdot\text{min}^{-1}$) (Hausler et al., 2016). A more recent meta-analysis by Glassbrook et al. (2019) demonstrated that 70% of studies analysing match characteristics of rugby league included total distance and reported pooled means of 5367 (95% CI: 4990 to 5745) m for forwards, 7057 (95% CI: 6552 to 7562) m for adjustables, and 7064 (95% CI: 6641 to 7488) m for backs (Glassbrook et al., 2019). The results of this meta-analysis are presented in Table 1. Although forwards cover significantly less ($p < 0.001$) distance than the other reported positional groupings used within the meta-analysis, a limitation of the positional groupings is the overlap of positions within literature. For example, qualifying studies have considered half-backs within the adjustables positional subgroup (Austin and Kelly, 2014, Gabbett et al., 2012, Gabbett, 2013b) whereas other qualifying studies included half-backs in the backs positional subgroup (Austin and Kelly, 2013)). In addition to measures of total distance, wearable microtechnology provides researchers and coaches with the ability to categorise running into thresholds or zones however comparisons between studies are challenging due to the application of different methods used. For example, Weaving et al. (2017a) labelled high speed running distance as $5 \text{ to } 7 \text{ m}\cdot\text{s}^{-1}$ and sprint distance as $>7 \text{ m}\cdot\text{s}^{-1}$ whereas Dempsey et al. (2018) labelled running as $>65\%$ of a players maximum speed. No significant difference was found when comparing the pooled mean total distance covered by adjustables and backs ($p = 0.983$) (Glassbrook et al., 2019). However, in one study comparing different levels of competition (NRL vs. New South Wales Premier League [NSWPL]), researchers reported significant differences between elite (i.e., NRL) players and semi-elite (i.e., NSWPL) players high-intensity running (elite: $36.7 \pm 9.8 \text{ m}$ vs. semi-elite: $29.6 \pm 7.8 \text{ m}$, $p = 0.001$) and very high-intensity running (elite: $14.4 \pm 5.1 \text{ m}$ vs. semi-elite: $11.5 \pm 3.8 \text{ m}$, $p = 0.007$) distance (Sirotic et al., 2009). This research is supported by findings by McLellan and Lovell (2013) who reported that elite players covered substantially greater sprint distance than semi-elite (i.e., Queensland Cup) and junior (i.e., National Youth Competition) players (elite: $413 \pm 60 \text{ m}$ vs. semi-elite: $298 \pm 52 \text{ m}$, junior $237 \pm 48 \text{ m}$, $p < 0.05$).

Table 1: Descriptive locomotor characteristics of rugby league match-play, data extracted from Glassbrook et al. (Glassbrook et al., 2019) systematic review and meta-analysis.

Positional Group	Forwards	Adjustables	Backs	All Positions
Playing time (minutes)	57.7 [54.1, 61.3]	74.9 [70.5, 79.2]	83.4 [79.0, 87.8]	64.8 [59.5, 70.1]
Total distance (m)	5367 [4990, 5745]	7057 [6552, 7562]	7064 [6641, 7488]	6215 [5741, 6688]
Average speed (m·min ⁻¹)	92.0 [89.0, 95.0]	99.0 [95.3, 102.8]	87.8 [84.1, 91.4]	94.0 [90.3, 97.6]
Slow-speed running distance (m)	4826 [4385, 5267]	7056 [6467, 7644]	6173 [5688, 6659]	5895 [5367, 6422]
High-speed running distance (m)	335 [268, 401]	474 [389, 559]	563 [486, 640]	380 [288, 472]
RHIE Bouts (n·min ⁻¹)	0.22 [0.18, 0.25]	0.17 [0.13, 0.21]	0.14 [0.11, 0.18]	0.18 [0.16, 0.21]

Data presented as mean and 95% confidence intervals

Slow-speed running distance <5 m s⁻¹

High-speed running distance >5 m s⁻¹

Differences in total distance covered are most likely a consequence of significantly less ($p < 0.001$) time on-field since backs generally have a longer playing time during the match than forwards and thus have a more time to accumulate distance. Given the differences in playing time (Cummins and Orr, 2015, Dempsey et al., 2018, Evans et al., 2015, Glassbrook et al., 2019, Twist et al., 2014, Waldron et al., 2011) and use of interchanges in rugby league, it is especially important to consider the average running speed of match-play, alongside the total distance, when comparing between positional groups. Average speed (measured in meters per minute; m·min⁻¹) is the second most popular variable reported within rugby league match-play research (Glassbrook et al., 2019). Meta-analysis by which included 19 of 30 studies (63%), reported pooled means of 92.0 (95% CI: 89.0 to 95.0) m·min⁻¹ for forwards, 99.0 (95% CI: 95.3 to 102.8) m·min⁻¹ for adjustables, and 87.8 (95% CI: 84.1 to 91.4) m·min⁻¹ for backs (Glassbrook et al., 2019). Forwards reported significantly less ($p = 0.004$) average speed than adjustables. Both forwards ($p = 0.079$) and adjustables ($p < 0.001$) reported significantly higher average speed than backs.

Average speed, presented regularly within literature as 'relative distance' and occasionally as 'work rate', is often presented alongside cumulative metrics in absolute terms whereby data are reported per a whole- or half-match (Cummins et al., 2013). This method of analysis provides useful insight into the volume players are expected to perform when analysing cumulative metrics and has been shown to highlight differences between levels of match-play (McLellan and Lovell, 2013, Read et al., 2017) and between positional

categories (Austin and Kelly, 2013, Gabbett et al., 2012). Conversely, recent research has demonstrated that there is little difference between positional categories (forwards vs. backs) or playing level (professional vs. semi-professional (Johnston et al., 2019a). Whilst useful for providing insight into the volume characteristics, the whole- or half-match approach does not represent the peak intensities of match-play and therefore application of bespoke methods (e.g., moving averages, segmental and 'ball-in-play') are required to understand peak characteristics players may be required to perform (Whitehead et al., 2018).

Fixed-time epochs (e.g., 0-5, 6-10 minutes etc) reported approximately 20-25% underestimation of peak high-speed running distance than a rolling average 5 minute time epoch (Varley et al., 2012a). Using a rolling average method to extract peak average speed, peak average acceleration, and peak average accelerometer load, Johnston et al. (2019a) revealed little difference between playing standards, with only *small* differences in average speed (professional forwards $167.2 \pm 23.4 \text{ m}\cdot\text{min}^{-1}$ vs. semi-professional forwards $161.1 \pm 13.1 \text{ m}\cdot\text{min}^{-1}$; ES: 0.35; 0.15 to 0.55). These authors also revealed no difference in peak average speeds between positional categories at professional level (professional forwards $167.2 \pm 23.4 \text{ m}\cdot\text{min}^{-1}$ vs. professional backs $168.0 \pm 32.0 \text{ m}\cdot\text{min}^{-1}$), however there was significantly ($p < 0.05$) greater peak average speed for backs than forwards in semi-professional competition with *small to moderate* differences (semi-professional forwards $161.1 \pm 13.1 \text{ m}\cdot\text{min}^{-1}$ vs. Semi-professional backs $167.5 \pm 13.4 \text{ m}\cdot\text{min}^{-1}$; ES range: 0.60-0.39). Method differences, particularly the application of linear mixed-effects models within the statistical analysis, in addition to increased perception of professionalisation within the semi-professional rugby league match-play, and different microtechnology devices used could explain different findings between this study and previous literature. During international rugby union, the fixed-time method underestimated average speed (~11%) and high-speed running values (up to 20%) compared to the rolling average method (Cunningham et al., 2018), which is an important consideration for future research aiming to determine peak match characteristics. Ball-in-play (BIP) analyses is an important consideration within rugby league due to the intermittent nature of the sport with the ball shown to be in play for approximately 57% of the duration of matches (mean \pm SD; Whole-match: 84.5 ± 3.0 minutes vs. BIP: 47.9 ± 4.1 minutes) (Gabbett, 2015). Moreover, BIP analyses is important within the context of rugby league due to the large difference in average speed when using this technique (Whole-match: 86.7 ± 9.8 vs. BIP: 125.1 ± 16.1 , ES: 2.88) (Gabbett, 2015).

The ability to accelerate and decelerate are important attributes for successful performance in many team sports including rugby league (Delaney et al., 2018a, Delves et al., 2022b). The number of acceleration and deceleration efforts completed by players are popular variables within the applied team sport setting, however these are not commonly

analysed variables within the literature. A mere 10% of studies within rugby league published literature reported pooled mean total accelerations ($>2.78 \text{ m}\cdot\text{s}^{-2}$) of 58.7 (95% CI: 24.0 to 93.4) for forwards, 78.3 (29.2 to 127.4) for adjustables, and 65.8 (16.7 to 114.9) for backs and pooled mean total decelerations ($<-2.78 \text{ m}\cdot\text{s}^{-2}$) of 69.2 (95% CI: 51.9 to 86.5) for forwards, 93.3 (95% CI: 68.8 to 117.8) for adjustables, and 82.7 (95% CI: 58.3 to 107.1) for backs (Glassbrook et al., 2019). The application of thresholds (e.g., $>3.5 \text{ m}\cdot\text{s}^{-2}$) to capture high-intensity accelerations within team sports is common however recently continuous variables such as acceleration density have been proposed (Delaney et al., 2016a). The approach of using thresholds in this manner (i.e., discretising a continuous variable into a categorical one) is problematic (Carstensen, 2020) particularly in the context of continuous acceleration variables since low intensity, moderate intensity, and high intensity acceleration meters have shown smallest worthwhile change (SWC) of 4.9%; ± 1.3 , 8.9%, ± 1.3 , and 34.8%; ± 1.3 , respectively; whereas acceleration density demonstrated an SWC of 1.8%; ± 1.3 (Thornton et al., 2019). Recent research supports this finding and has shown that discretised acceleration metrics have shown *good* to *poor* reliability whereas average acceleration demonstrated *good* inter-device reliability (Crang et al., 2021a). Acceleration density, commonly referred to as average acceleration, is measured in meters per second squared ($\text{m}\cdot\text{s}^{-2}$) and is calculated by taking the absolute value of all acceleration and negative acceleration (i.e., deceleration) data, and averaging over the duration of the defined period (Delaney et al., 2018a). Acceleration density is more reliable (CV: 1.2% [90% CI: 1.0 to 1.7%]) than traditional low to high acceleration and deceleration counts which range from 4.4 – 5.9% CV and 3.3 – 4.8% CV, respectively (Delaney et al., 2018a). Acceleration density is an increasingly popular variable being reported within male and female rugby league literature (Cummins et al., 2021, Delves et al., 2022b). Elite level female rugby league players participating in National Rugby Women's League have demonstrated peak acceleration density values during 60 s epochs of $0.72 \pm 0.02 \text{ m}\cdot\text{s}^{-2}$ for forwards, $0.77 \pm 0.02 \text{ m}\cdot\text{s}^{-2}$ for adjustables, and $0.77 \pm 0.02 \text{ m}\cdot\text{s}^{-2}$ for backs within the literature (Cummins et al., 2021). Adjustables and backs reported significantly greater ($p \leq 0.05$) acceleration density in these 60 s epochs than forwards. The mean acceleration of elite male rugby league players participating in NRL was reported in 2019 as $0.91 \pm 0.07 \text{ m}\cdot\text{s}^{-2}$, 2020 as $1.02 \pm 0.10 \text{ m}\cdot\text{s}^{-2}$, and 2021 as $1.06 \pm 0.07 \text{ m}\cdot\text{s}^{-2}$ (Delves et al., 2022b). The substantially greater ($>0.6 \text{ SD}$) mean acceleration in 2020 and 2021 season than in season 2019 was attributed to the introduction of the 'six-again' rule.

2.3.2 Collision characteristics

In addition to the commonly applied measurements of athlete locomotion, microtechnology devices contain tri-axial accelerometers, gyroscopes and magnetometers and have been shown to provide a valid and reliable means of quantifying collision characteristics of performance during rugby league matches (Hulin et al., 2017). Collisions in the form of ball carries and tackles can also be derived from TMA which, whilst adding to the granularity of possible analysis, adds to the complexities of aggregating findings across studies.

Of the 30 studies included within Glassbrook et al. (2019) meta-analyses, 10 studies reported collisions with a pooled average (95% CI) for the whole squad of 25.6 (21.2, 29.9). However, the range of collisions reported is considerable (17.9 (17.2, 18.6) (Gabbett, 2013b) to 43.0 (41.6, 44.4) (Murray et al., 2014)). Such vast differences may be explained by contextual factors including turnaround of matches, sample size included with the study, and year of investigation in the event the sport may have been subjected to rule changes between included manuscripts. The ranges in the values reported for collision characteristics of match-play for the 'whole-squad' could also be due to the differences in physical characteristics between positions and positional groups (Austin and Kelly, 2013, Glassbrook et al., 2019, Hausler et al., 2016, Kempton et al., 2015a, Sirotic et al., 2011, Waldron et al., 2011). For example, typically during male rugby league matches forwards are involved in more collisions than backs (Weaving et al., 2019b). This is an important consideration, as *being tackled* and *tackling* are the most common injury mechanisms during rugby league match-play. *Being tackled* accounts for 28% of injuries among male players and 38% of injuries among female players during match-play, with greater burden ($p < 0.01$) than other injury mechanisms, while *tackling* accounts for 25% of injuries among male players and 20% of injuries among female players (Scantlebury et al., 2024). Data exclusion or missing data is also an important consideration as this could result in an over- or under-representation of certain positions within the data set, and thus effect the overall averages reported. Missing data is common in longitudinal data sets but can be dealt with through appropriate analysis techniques, such as linear mixed-effects models (Cnaan et al., 1997, Krueger and Tian, 2004).

Wearable technology has been shown to provide a valid means of capturing collision events within rugby league (Gabbett et al., 2010, Hulin et al., 2017), albeit the validity of microtechnology to detect tackle events within female rugby league matches has been shown to be lower than during male rugby league matches (Cummins et al., 2022). Glassbrook et al. (2019) presents 'low-impact' collisions as those captured by microtechnology between zero to 8 g and 'high-impact' collisions as those recorded between 8 g to 15 g (Cummins and Orr, 2015, Gabbett et al., 2012, Gabbett, 2013b,

Gabbett, 2013a, Varley et al., 2014). Whilst Cummins and Orr (2015) utilised a wearable technology provider which reports gravitational force of collisions (SPI-Pro X II, GPSports, Canberra, Australia), other researchers have previously utilised a microtechnology (e.g., MinimaxX or OptimEye, Catapult Sports, Melbourne, Australia) which reports accumulated PlayerLoad™ within the algorithmically detected tackle event (Duthie et al., 2020, Gabbett, 2013b, Varley et al., 2014). This is a further limitation of synthesising IMU related findings within literature. The application of IMUs specifically within rugby league is further discussed in later in this chapter (section 2.3.1.2.2).

Repeated High Intensity Efforts (RHIEs) are a popular measurement of high-intensity effort within rugby league and defined as three or more qualifying efforts (i.e., acceleration, deceleration, or high-speed efforts) or events (i.e., collisions) with less than twenty-one seconds rest between each effort (Austin et al., 2011, Hausler et al., 2016, Johnston et al., 2014a). Differences in total RHIE exposure has been demonstrated at playing level, within contextual phases of play (i.e., attack vs. defence), game state (i.e., winning vs. losing) and have been shown to reflect playing positional differences as well as relate to physical qualities demonstrated by players. Differences in the frequency of RHIEs have been shown to reflect game status (i.e., players playing in a whole match when compared to those interchanged).

During a standardised RHIE test protocol, Gabbett and Wheeler (2015) analysed the relationship between the speed in the first 10 m sprint of the RHIE bout, the average speed across all four sprints in the RHIE bout, and the percentage speed decrement across the entire RHIE bout with measures of an individual player's upper body strength, upper body endurance, lower body strength, and maximal aerobic power. These authors reported that players with a greater initial speed over the first 10 m of the test had a higher average speed over the entire bout ($r = 0.75$) and had a negative relationship with speed decrement during the test ($r = -0.76$) suggesting better ability to maintain speed in the presence of fatigue. Gabbett and Wheeler (2015) also categorised players as first- and second-grade level, revealing a significant difference in percentage of speed decrement between levels (mean \pm SD; first-grade: $-2.36 \pm 10.3\%$ vs. second-grade: $-4.70 \pm 2.05\%$, ES = 1.63). This may be explained in part due to the substantially different athletic profile of first- and second-grade players which is emphasised by the difference reported in lower body strength characteristics (first-grade: 162.0 ± 17.9 kg vs. second-grade: 184.0 ± 29.7 kg, ES = 0.90). Quantifying physical attributes at different levels of rugby league is of particular interest to coaches. Previous research has shown that international level female players demonstrate superior physical qualities compared to those in the Women's Super League (WSL), with significant differences evident in countermovement jump height (International: 29.1 ± 4.7 cm vs. WSL: 24.8 ± 4.9 cm, ES = 0.96 [0.48 to 1.43], $p = 0.00$), speed over 10 m

(International: 1.93 ± 0.11 s vs. WSL: 2.07 ± 0.14 s, ES = 0.92 [0.46 to 1.38], $p = 0.00$), 20 m (International: 3.36 ± 0.17 s vs. WSL: 3.63 ± 0.26 s, ES = 0.90 [0.35 to 1.25], $p = 0.00$), 30 m (International: 4.73 ± 0.25 s vs. WSL: 5.16 ± 0.41 s, ES = 0.83 [0.39 to 1.27], $p = 0.00$), 40 m (International: 6.17 ± 0.34 s vs. WSL: 6.71 ± 0.61 s, ES = 0.61 [0.16 to 1.07], $p = 0.01$) and Modified Yo-Yo IRT1 (International: 763.0 ± 301.9 m vs. WSL: 522.7 ± 284.8 m, ES = -0.51 [-0.03 to -0.99], $p = 0.04$) (Scantlebury et al., 2022).

Elite level players and sub-elite level players complete a similar amount of RHIEs during matches, with both performing significantly more ($p < 0.01$) than junior level players (Hausler et al., 2016). A meta-analysis completed by Hausler et al. (2016) reported that elite players (10.8 [9.2-12.4]; $r^2 = 80.7\%$) and sub-elite players (10.0 [8.8-11.3]; $r^2 = 91.56\%$) have similar RHIE characteristics whilst both performing significantly ($p < 0.001$) more bouts than junior level players (4.4 [3.5-5.3]; $r^2 = 55.73\%$). This may be attributed to junior level players not being physically capable of producing the necessary high-speed or acceleration outputs to register qualifying efforts. From the perspective of playing position, hit-up forwards perform a significantly greater ($p < 0.05$) number of RHIEs (12 ± 3) when compared to adjustables (6 ± 3) and outside backs (5 ± 1) (Austin et al., 2011). Since hit-up forwards typically perform more bouts, they consequently have the shortest average recovery time between bouts (376 ± 205 s) (Austin et al., 2011). Black and Gabbett (2014) analysed the frequency of RHIEs and reported that players when interchanged performed RHIE bouts at a higher rate than whole-match player of the same position. In receipt of this information, coaches are in a position to make more informed preparation, selection and interchange decisions.

RHIE bouts are more prevalent when defending as opposed to attacking during rugby league match-play. Gabbett et al. (2014) analysed the rate of RHIEs in attack and defence and revealed almost double the requirement to perform RHIEs when defending (one RHIE bout every 4.9 ± 5.1 minutes when defending vs. one RHIE bout every 9.4 ± 6.1 minutes when attacking). However, whilst Gabbett et al. (2014) demonstrated that defending elicits a greater RHIE response than attacking; Gabbett (2013b) revealed that successful teams at elite level complete more frequent RHIEs, including more efforts per bout, than less-successful teams at the same level. This contrast in findings seems unintuitive since it would be reasonable to speculate that successful teams spend more time attacking whereas less-successful teams spend more time defending, however Black and Gabbett (2014) support the suggestion that successful teams perform more RHIEs than those less-successful. These authors analysed data with respect to game state and players at sub-elite level on a winning side were shown to produce a greater frequency of RHIE bouts than players within losing teams (one RHIE bout every 5.7 ± 3.1 minutes when winning vs. one RHIE bout every 8.2 ± 2.8 minutes when losing).

This information provides coaches with strategic support in terms of repeatedly attacking defensive players which could have a profound effect on match outcomes. Gabbett (2008) demonstrated that residual fatigue as a consequence of performing RHIEs elicits reductions in tackling technique within rugby league players. Compromised technique during the action of tackling an opponent could result in a reduction in dominant tackles and increased number of missed tackles (Gabbett and Ryan, 2009), which could have negative implications such as more points conceded (Johnston et al., 2015d) or increased risk of injury.

2.3.3 Technical-tactical qualities

Football-code team sport preparation is complex as players are frequently trained in group settings which are designed to develop team cohesion, physical fitness and technical-tactical skills (Manzi et al., 2013). Technical and tactical skill execution is a critical component of achieving success in rugby league. For example, physical and technical qualities are closely linked to successful performance amongst elite rugby players whom have been shown to possess superior tackling technique (Speranza et al., 2015a), draw and pass proficiency (Gabbett et al., 2011), and anticipatory skill (Gabbett et al., 2008b). Any attempt to understand the match characteristics of rugby league, and measure the success of performance, without considering the execution of technical and tactical skills is likely to be incomplete. The purpose of quantifying technical match characteristics (i.e., performance analysis) is to assess the performance of an individual or team whilst identifying strengths or weaknesses in their performance analysis (Hughes and Bartlett, 2002) and are often utilised as a measurement of technical-tactical performance (Parmar et al., 2018). A key performance indicator (KPI) within the context of rugby league match-play is defined as a selection or combination of action variables aimed at delineating various aspects of a player's performance (Parmar et al., 2017) and include actions such as tackles, ball carries and PTBs.

Opta Sports (Stats Perform, London, UK) is the commercial provider of match eventing data within the Super League, as well as other team sports. Whilst literature supporting the reliability of commercial match event providers is limited, one study in did soccer find very high inter-rater reliability (ICC range = 0.88–1.00) for assessing different match actions (e.g., assists, clearances, dribbles, key passes) of outfield players (Liu et al., 2013). Within the AFL, a very high level of agreement (ICC range = 0.95–1.00) in assessing the counts of different actions (e.g., disposals, handballs, kicks, tackles) between author coded events and events coded by a commercial provider (Champion Data, Melbourne, Australia) was reported (Robertson et al., 2016a). Whilst preliminary, and low in sample

size, this data suggests that the reliability of assessing action counts is acceptable for commercial match-event providers. Using Opta provided data collected within rugby league, specifically the Super League during this project, I undertook an in-house data quality assessment of these commercially provided match event characteristics captured during two halves of Super League match-play across two different matches. This included the synchronisation of a timeline of match events overlaid with match-play video footage to determine my agreement with the commercial provider of match event characteristics. A Kappa value of 0.978 was calculated suggesting almost perfect agreement with the commercial match eventing provider. However, it is important to note that this has not been peer reviewed nor published and therefore the reliability of Opta coded events within rugby league remain unknown.

Gabbett and Hulin (2018) analysed the skill involvements of NRL teams over a ten-year period and found successful teams (defined as those placing in the top four of the competition) completed more PTBs while unsuccessful teams (defined as those placing in the bottom four of the competition) accrued a greater number of missed tackles and ineffective tackles within the period analysed. A greater number of PTBs by successful teams may be explained by this performance indicator occurring during an attacking action and therefore are likely to be performed more by successful teams. These specific action types are usually monitored using notational analysis.

The frequency of player actions, captured using notational analysis techniques, are often reported at both individual and team level (Travassos et al., 2013). Advancements in technology (e.g., improvements in purposely designed tagging and analysis software) have enhanced the use of notational analysis (Wright et al., 2012) and emergence of commercial match event data providers have generally improved their accessibility and enhanced their use within research (e.g., Parmar et al. (2018) used Opta Sports (Stats Perform, London, UK) within rugby league, Kempton et al. (2015c) used Champion Data (Melbourne, Australia) within Australian rules football, and Kempton et al. (2017) used Prozone (Sydney, Australia) within rugby league). This emergence of commercial match event data providers has provided the practical possibility for researchers to perform innovative longitudinal analysis using large league-wide datasets. Non-metric multidimensional analysis of an eleven-year period demonstrated that between 2005 and 2011, NRL teams showed a similarity of team profiles, but that team profiles substantially evolved and were relatively dissimilar between the 2012 and 2016 seasons (Woods et al., 2018). These changes in team profiles may be attributable to rule changes implemented within the league (Woods et al., 2018) and also are speculated to be attributable to the largest coach turnover in league history which occurred at the end of the 2011 season (Gabbett and Hulin, 2018). Indeed,

Woods et al. (2018) suggest that introduction of new coaches is likely to have led to implementation of novel preparation methods and technical-tactical game plans.

Literature quantifying technical match characteristics (i.e., performance analysis), applying notational analysis techniques, are categorised as 'what' and 'how' studies (den Hollander et al., 2018). Basic notational analysis (e.g., number of passes, tackles, or sets) are considered 'what' studies which typically are recorded in a linear sequence of 'what', 'who', 'when' and 'where' (Colomer et al., 2020) whereas 'how' studies investigate why these actions are taking place (den Hollander et al., 2018). For example, a 'what' study may report the number of tackles performed (Gabbett, 2004) whilst a 'how' study will define the number of tackles within the context of match-play (e.g., possession, level of opposition, or interchange players) with a view of understanding why these actions have occurred.

When analysing average speed within the context of team possession, Gabbett et al. (2014) found an increase whilst defending when compared to attacking in average speed (mean \pm SD; $109.0 \pm 16.0 \text{ m}\cdot\text{min}^{-1}$ vs. $82.0 \pm 12.0 \text{ m}\cdot\text{min}^{-1}$; ES [90% CI] = 1.35 [0.55 to 2.12]) and high-speed running (HSR) distance (mean \pm SD; $5.3 \pm 3.7 \text{ m}\cdot\text{min}^{-1}$ vs. $3.9 \pm 3 \text{ m}\cdot\text{min}^{-1}$; ES [90% CI] = 0.39 [-0.32 to 1.09]). However, these findings are related to a single professional domestic club and therefore may not be generalisable across a league or indeed international rugby league. When analysing level of team (i.e., successful vs. less-successful), Hulin and Gabbett (2015) demonstrated that during peak periods hit-up forwards within successful teams accumulate lower total distance (mean \pm SD; high-success: $111 \pm 15 \text{ m}\cdot\text{min}^{-1}$ vs. low-success: $121 \pm 24 \text{ m}\cdot\text{min}^{-1}$, $p = 0.02$, ES = 0.5 ± 0.4) and HSR distance (high-success: $10 \pm 4 \text{ m}\cdot\text{min}^{-1}$ vs. low-success: $13 \pm 6 \text{ m}\cdot\text{min}^{-1}$, $p = 0.01$, ES = 0.6 ± 0.4) than those in less-successful teams. During peak periods, hit-up forwards from successful teams were involved in greater number of collisions (high-success: 7.1 ± 2.3 vs. low-success: 5.7 ± 1.8 , $p = 0.03$, ES = 0.6 ± 0.4) than those in less-successful teams (Hulin and Gabbett, 2015). Adjustables from successful teams performed a greater number of RHIE bouts than those from less successful teams (high-success: 0.6 ± 0.3 vs. low-success: 0.3 ± 0.3 , $p = 0.05$, ES = 0.5 ± 0.4) in the five minute period following peak periods (Hulin and Gabbett, 2015). These findings led the authors to comment that technical and tactical effectiveness, rather than activity profiles alone, contribute to the team success. Given the importance of technical and tactical effectiveness, it's important to consider that technical skill performance adjustables playing a whole match have been shown to diminish in the final 5 minutes of each half compared with the initial 5 minute periods, suggesting accumulated and transient fatigue (Kempton et al., 2015a).

Individual performance within the context of player interchanges have been investigated with a particular emphasis on the running characteristics experienced by players who play a whole match and those who are interchanged (Cummins et al., 2018,

Waldron et al., 2013). Adjustables (hooker, half-back, five-eighth) were found to demonstrate moderate to very large decreases for total distance (mean \pm SD; whole-match: 8.0 ± 1.1 km vs. interchange: 4.2 ± 2.2 km, $p < 0.001$, ES = -2.18 [-2.67, -1.80]), HSR distance per minute (whole-match: 19.3 ± 5.6 m \cdot min $^{-1}$ vs. 14.2 ± 7.2 m \cdot min $^{-1}$, $p = 0.031$, ES = -0.78 [-1.18, -0.39]) and moderate intensity accelerations per minute (whole-match: 2.1 ± 0.3 vs. interchange: 1.9 ± 0.4 , $p = 0.014$, ES = -0.57 [-0.96, -0.17]) when comparing players who played a whole-match versus those interchanged (Cummins et al., 2018). Conversely, these authors noted small increases for very high intensity accelerations per minute (whole-match: 2.8 ± 1.3 vs. interchange: 3.3 ± 0.9 , $p = 0.092$, ES = 0.45 [0.06, 0.84]) and small increases for very high intensity decelerations per minute (whole-match: 3.0 ± 1.4 vs. interchange: 3.3 ± 0.9 , $p = 0.492$, ES = 0.25 [-0.13, 0.64]).

2.3.4 Contextual Factors

Understanding the physical characteristics of rugby league match-play has implications from an athlete preparation perspective, including training prescription and implementation of player monitoring strategies (Kelly and Coutts, 2007). It is however important to understand how different components interact to form context which may rationalise and explain individual and team physical performance characteristics (Dalton-Barron et al., 2020b). For example, level of opposition (Gabbett, 2013b) and timing of fixtures during season (Twist et al., 2014) may impact physical running characteristics, therefore knowledge of this allows coaches to plan and periodise more effectively leading into certain matches or periods of competition (Dalton-Barron et al., 2020b). Through analyses of data collected using the MinimaxX GPS device (Team 2.3; Catapult Innovations, Melbourne, Australia), which sampled at 5 Hz, Gabbett (2013b) compared the activity profiles when players competed against the highest-ranked (Top 4) and lowest-ranked (Bottom 4) teams, taking into consideration if the players team either won or lost the match. Significantly greater ($p < 0.05$) high-speed running distance (mean \pm SD; Top 4: 300.6 ± 31.6 m vs. Bottom 4: 393.3 ± 36.9 m, ES = 0.55) and high-speed running distance per minute (Top 4: 4.7 ± 0.3 m \cdot min $^{-1}$ vs. Bottom 4: 5.7 ± 0.4 m \cdot min $^{-1}$, ES = 0.57) was reported when lower-ranked teams were the opposition, whilst significantly greater ($p < 0.05$) rating of perceived exertion (Top 4: 8.5 ± 0.2 au vs. Bottom 4: 7.9 ± 0.2 au, ES = 0.66) was reported when these players played against higher-ranked teams. The number of mild, moderate, and heavy collisions were similar ($p > 0.05$, ES = 0.00 to 0.28) irrespective of where the opposition placed. These findings therefore suggest that high intensity locomotor characteristics are greater when playing against lower-ranked teams whilst player perception is greater playing against higher-ranked teams, and whilst collision characteristics appear similar, leads

researchers to therefore speculate if players psychologically perceive effort to be greater when they play higher-ranked opposition. A limitation of this research is that it included teams from a single team and therefore generalisability of findings is problematic. Twist et al. (2014) analysed data from both NRL and Super League competitive matches and categorised performances into early-season, mid-season, and late-season phases. These authors reported that average speed was not significantly different ($p = 0.782$, $ES = -0.01$ to 0.48) across the seasons however a main effect for group revealed a significant difference ($p = 0.023$, $ES = -0.38$) between leagues (NRL early-season $91.4 \pm 8.0 \text{ m}\cdot\text{min}^{-1}$, mid-season $91.5 \pm 9.0 \text{ m}\cdot\text{min}^{-1}$, late-season $87.6 \pm 7.6 \text{ m}\cdot\text{min}^{-1}$ and Super League early-season $91.9 \pm 18.0 \text{ m}\cdot\text{min}^{-1}$; mid-season $95.6 \pm 13.3 \text{ m}\cdot\text{min}^{-1}$, late-season $98.2 \pm 21.9 \text{ m}\cdot\text{min}^{-1}$). It is important when analysing match-play characteristics to note that large between-player, between-position, and between-match variability has been reported for total distance and high-speed running distance during rugby league matches (Kempton et al., 2015c, Dalton-Barron et al., 2020a), and therefore accurately estimating future match running characteristics based on historical data is not without challenges. The prevalence of within-player, between-player, between-match, between-position and between-season variability in rugby league match-play analysis will be discussed later in this chapter.

A contextual factor within the context of rugby league match-play is any variable which provides information about the state of the match at any given time and include information such as situational-related (i.e., possession, scoreline, or player location on the field) and environmental-related conditions (i.e., venue, temperature, or weather) (Dalton-Barron et al., 2020b). As such, Paul et al. (2015) state that match running characteristics may be explained by an almost infinite number of contextual factors affecting variability of performance related outcome measures. Changes in head coach and support staff are also contextual factors which may influence match-play characteristics (Sousa et al., 2024) and injury risk (Ekstrand et al., 2023). Although the frequency of head coach change and potential impact of these changes is yet to be analysed within rugby league specifically, a change in head coach mid-season within soccer appears to briefly improve performance, but with reductions in medium-long term success (Sousa et al., 2024). From the perspective of player injury which consequently impacts upon player availability, changes in fitness coach and team doctor have been shown to significantly increase the burden of hamstring injury which is perhaps due to newly introduced training and preparation philosophies imposed by new staff members (Ekstrand et al., 2023). The generalisability of these findings in soccer may not transcend to other football codes such as rugby league and therefore further research is required to determine the contextual effect of coaching and support staff changes within rugby league.

One common statistical approach to data analysis within football-code team sports, such as rugby league, is the use of general linear models to determine changes or differences in match characteristics (Dalton-Barron et al., 2020b), yet general linear models are limited as they do not by their very nature consider nor account for the covariance of data (Balague et al., 2017). Trewin et al. (2017) systematically investigated situational-related and environmental-related contextual factors upon match running characteristics in association football and concluded that both types had the potential to influence match running performance. For example, within association football, attacking players reported 71% greater high-speed running distance when their team is in-possession compared to out-of-possession (mean \pm SD; in-possession 566 \pm 104 m vs. out-of-possession 331 \pm 83 m, $p < 0.05$), whereas central defenders reported 156% greater high-speed running distance when their team is out-of-possession compared to in-possession (in-possession 179 \pm 93 m vs. out-of-possession 459 \pm 74 m, $p < 0.05$) (Di Salvo et al., 2009). The evidence supporting both situational-related and environmental-related contextual factors influence on performance supports the assertion that linear regression modelling is limited (Trewin et al., 2017). Linear modelling may as a consequence provide a one-dimensional perspective of match characteristics since they only contain fixed effects (Paul et al., 2015), thus adding support to the use instead of mixed effects models which allow researchers to control for both fixed and random effects.

Within rugby league match-play specifically, Dalton-Barron et al. (2020b) identified 15 studies which investigated the influence of contextual factors upon match locomotor characteristics and reported the influence of individual fitness qualities (Delaney et al., 2016b, Gabbett et al., 2013, Kempton and Coutts, 2016), match result (i.e., win / loss) (Delaney et al., 2016b, Gabbett, 2013b, Kempton and Coutts, 2016, Murray et al., 2014), team strength (Hulin et al., 2015, Kempton et al., 2017) and opposition strength (Delaney et al., 2016b, Gabbett, 2013b, Kempton and Coutts, 2016), match conditions (Delaney et al., 2016b, Kempton and Coutts, 2016, Murray et al., 2014, Quinn et al., 2015, Twist et al., 2014), technical and tactical characteristics (Cummins et al., 2018, Delaney et al., 2016b, Gabbett, 2012, Gabbett et al., 2014, Kempton and Coutts, 2016, Waldron et al., 2013), spatial/temporal characteristics (i.e., first and second halves or time epochs) (Bradley et al., 2016, Delaney et al., 2016b, Gabbett et al., 2014, Hulin et al., 2015, Kempton and Coutts, 2016, Twist et al., 2014, Waldron et al., 2013), and nutritional interventions (Bradley et al., 2016). Understanding the influence of these various situational-related and environmental-related contextual factors upon locomotor characteristics during matches should form the basis of the training and recovery process (Dalton-Barron et al., 2020b), however rugby league is characterised by locomotor and collision activity and therefore further research is

needed to understand how contextual factors explain the contact-based characteristics of the sport.

A consistent finding within rugby league is that individuals possessing superior fitness qualities demonstrate greater average speed (Delaney et al., 2016b, Kempton and Coutts, 2016) and high-speed running distance (Gabbett et al., 2013, Kempton and Coutts, 2016), which is in keeping with other football-code team sports such as association football (Buchheit et al., 2010), rugby union (Swaby et al., 2016), and Australian rules football (Ryan et al., 2017). Using 15 Hz GPS devices (SPI HPU, GPSports, Canberra, Australia), Delaney et al. (2016b) reported that players exhibiting superior intermittent running ability (measured using the 30:15 Intermittent Fitness Test (IFT) demonstrated *very likely large* increases in both average speed (ES \pm 90% CI; 0.59 [0.18 to 0.82]) and metabolic power (0.56 [0.16 to 0.80]) during rugby league matches. Cardiorespiratory and metabolic conditioning is important within the context of football-code team sports since a strong aerobic capacity allows athletes to efficiently recover between intermittent bouts therefore enabling players to produce greater physical outputs (Tomlin and Wenger, 2001). Maximal aerobic capacity when measured within the pre-season period may change over time during the competitive season (Booth et al., 2018, Dalton-Barron et al., 2020b) and therefore this facet of performance is in and of itself a contextual factor. Whilst regular maximal aerobic fitness testing during the competitive season is inappropriate (Dalton-Barron et al., 2020b), alternative cardiorespiratory measurements such as heart rate response to standardised activities may provide suitable estimates of player fitness. Using twenty-two elite rugby league players playing within the NRL, Scott et al. (2018) demonstrated acceptable reliability in the assessment of average heart rate during the first 30 seconds (ICC 0.91; 0.78-0.94) of, and heart rate recovery in the 60 seconds (ICC 0.80; 0.61-0.90) and 120 seconds (ICC 0.84; 0.69-0.92) following, a 4 minute individualised submaximal shuttle run test.

Inconsistent findings were reported between studies which investigated match results and how they relate to locomotor characteristics with one study showing that winning had no effect on average speed (Delaney et al., 2016b), another demonstrating that average speed was reduced (Kempton and Coutts, 2016), and two studies reporting an increase (Gabbett, 2013b, Murray et al., 2014). Inconsistent findings between studies may be attributed to coaches tactical instructions, player availability, or the margin of score differential (Dalton-Barron et al., 2020b). An important consideration when analysing how match result may influence running characteristics is that the outcome of a match (i.e., win / loss) is absolute however evolves throughout the course of a match whereby often teams are leading for periods of a match and behind for other periods. Using the final result as a covariate does not account for the changing nature of scoreline (Lago-Penas and Gomez-

Lopez, 2014) and therefore it may be more statistically appropriate to model the evolution of scoreline during matches in relation to concurrent physical performance characteristics than in relation to absolute match outcomes (Dalton-Barron et al., 2020b). Naturally, consistently more successful teams in terms of matches won will place higher on league table and therefore team strength and opposition strength, measured using league table position, are intrinsically linked to absolute match outcomes.

Using league position to define team success, previous literature has shown that players in successful teams have a tendency to produce lower high-speed running distance than those which are lower ranked (Hulin et al., 2015, Hulin and Gabbett, 2015, Kempton et al., 2017). For example, hit-up forwards from successful teams reported significantly ($p = 0.01$) lower average speed ($81 \pm 10 \text{ m}\cdot\text{min}^{-1}$ vs. $89 \pm 14 \text{ m}\cdot\text{min}^{-1}$, $ES = 0.6 \pm 0.4$), greater involvement in collisions (3.0 ± 1.4 vs. 2.3 ± 0.9 , $ES = 0.7 \pm 0.4$), and lower high-intensity running distance per minute ($2.9 \pm 1.6 \text{ m}\cdot\text{min}^{-1}$ vs. $4.1 \pm 2.7 \text{ m}\cdot\text{min}^{-1}$, $ES = 0.5 \pm 0.4$) than hit-up forwards from the less-successful teams (Hulin and Gabbett, 2015). Locomotor characteristics reported by successful teams, when playing in matches against less-successful teams, appears to generally be lower especially at higher intensities however final league position may not accurately reflect the undulating performance, or form, of a team throughout their entire competitive campaign (Dalton-Barron et al., 2020b). Given the limitations of using a team's absolute league position as a measurement of success, previous literature has also utilised an approach to take into consideration recent form (i.e., number of wins in most recent five matches) of a team as a measurement of success, with the authors reporting a *possibly small* reduction in average speed ($ES = 0.12$ (0.02 to 0.22)) and a *likely small* reduction in metabolic power when facing more-successful opponents (Delaney et al., 2016b). These contrasting findings suggest that final league position does not necessarily reflect the quality of opposition at the time of the fixture and which could be explained by playing or coaching personnel changes (Dalton-Barron et al., 2020b).

A reduction in average speed ($ES = 0.31$ (0.23-0.39)) and high-speed running distance ($ES = 0.35$ (0.27-0.43)) was reported when rugby league teams played away from their home location in one study (Kempton and Coutts, 2016), a finding which is in keeping with other football-code teams sports such as association football (Castellano et al., 2011) and Australian rules football (Ryan et al., 2017). Reduced locomotor characteristics reported across football codes when competing away from home may add credibility to the phenomenon known as "home advantage" within the context of sporting competition however further research is required to understand which factors contribute to this specifically (e.g., influence of supporters, familiarity with surroundings, or lessened travel requirements when playing at home) (Pollard and Pollard, 2005). In addition to match location, the timing of fixtures within the season has also been investigated in both Super

League and NRL competition. Twist et al. (2014) reported that locomotor characteristics increased within the Super League and reduced within the NRL as the season progressed which may be explained by changes in player fitness or fatigue over time. However, further research to substantiate this is required. Other environmental factors which may affect locomotor characteristics as the season progresses include temperature since Super League generally begins in February with the regular season drawing to a close late-summer, which may result in increased physiological strain during warmer periods (Girard et al., Periard et al., 2015).

Primarily due to television broadcast requirement, rugby league fixtures regularly take place on three, and sometimes four, different days per week (i.e., Thursday through to Sunday). This invariably leads to regular changes in number of days between matches, with short turnaround times providing inconsistent results in relation to their influence on locomotor characteristics during matches. When short turnarounds are experienced (i.e., less than seven days), locomotor characteristics have been found to increase (Delaney et al., 2016b, Murray et al., 2014), which is surprising, whilst another study demonstrated that average speed and high-speed running distance reduced when shorter turnarounds were experienced (Kempton and Coutts, 2016), a finding which is perhaps expected. A contextual factor which may explain inconsistent findings is player availability and player rotations in terms of selection (Cunniffe et al., 2011), therefore this should be accounted for when modelling this contextual factor (Dalton-Barron et al., 2018), however it is also possible that players are able to perform at varying levels of intensity whilst experiencing symptoms of neuromuscular fatigue (Roe et al., 2016b).

Technical and tactical factors (e.g., attack, defence and transition) and how they relate to match locomotor and collision characteristics are important considerations for coaches when preparing their players for competition. Generally, increases in average speed are accepted by coaches during defensive phases of play and this belief is supported within research (Gabbett et al., 2014). However, since defensive phases require defending players to retreat 10 m following each tackle whereas an attacking player will often carry the ball from more than 10 m depth, it is reasonable to speculate that high-speed running may in fact be greater in attack than in defence, albeit further research is needed. Gabbett (2012) investigated the exposure to sprint efforts and demonstrated that 78.7% of sprints were performed without the ball compared to 21.3% when in possession of the ball.

Generalisability of the studies included by Dalton-Barron et al. (2020b) is challenging since 80% of the studies included data collected from a single team and five of the fifteen studies within their review investigated a single contextual factor. Although the above studies have demonstrated differences between these covariates, there is also the

presence of natural variability within- (i.e., match-to-match) and between-seasons (i.e., season-to season).

2.3.5 Variability: Within-players and between-players, between-matches, between-positions, and between seasons

The analysis and interpretation of player tracking data collected utilising wearable microtechnology is widespread, yet there is a poor understanding of the variability of this data within football-code team sports (Kempton et al., 2015c). Since rugby league match performance characteristics (i.e., locomotion and collision-based variables) are a product of many different contextual factors, these are likely subject to high variability (Dalton-Barron et al., 2020a). Moreover, performance within football-code team sport matches is a multifactorial construct (Atkinson, 2002), which is stochastic in nature, and therefore inherent variability of match performance related variables is to be expected (McLaren et al., 2016). Quantifying the variability of physical performance within football-code team sports can be a useful way to highlight changes that appear normal and those which seem higher or lower than usual (Oliva-Lozano et al., 2020).

Several studies using participants within football-code team sports demonstrated that as speed of player locomotion increases, match-to-match variability of displacement characteristics also increases. Within professional soccer the match-to-match variability of total distance is relatively stable and has ranged from 2.4% (Rampinini et al., 2007) to 5.3% (Al Haddad et al., 2018) whilst the variability for HSR distance has varied considerably with values reported at 9.2% (Mohr et al., 2003), 14.4% (Rampinini et al., 2007), 17.7% (Gregson et al., 2010), 19.8% (Carling et al., 2016), and 53% (Al Haddad et al., 2018). Within Australian rules football, Kempton et al. (2015c) similarly reported considerable match-to-match variability for HSR distance ($\text{HSR} > 4 \text{ m}\cdot\text{s}^{-1}$; CV range = 12% to 14%) and very HSR distance ($\text{VHSR} > 5.5 \text{ m}\cdot\text{s}^{-1}$; CV range = 15% to 21%).

Within professional rugby league, Kempton et al. (2014) also observed high variability amongst players participating in the NRL competition for both HSR distance ($> 4.2 \text{ m}\cdot\text{s}^{-1}$; CV = 15%) and VHSR distance ($> 5.8 \text{ m}\cdot\text{s}^{-1}$; CV = 37%). A limitation of this study within professional rugby league is that it sampled participants from a single team and therefore the findings may not be generalisable at league-wide level. To overcome this limitation, Dalton-Barron et al. (2020a) analysed the variability of player locomotion data collected by 11 teams, across 322 professional rugby league matches, over a two-year period. Dalton-Barron et al. (2020a) stratified data per whole-match; ball-in-play; and attack, defence and transition phases of play. These authors reported large within-player and between-player variability, as well as large between-position variability for total distance and HSR distance

(CV = >10%). In keeping with previous research within rugby league (Kempton et al., 2014) and other football-code team sports, Dalton-Barron et al. (2020a) reported that higher running speeds demonstrated higher variability with total distance between-match variability ranging from 4% to 29% and HSR distance between-match variability ranging from 14% to 51%. Unsurprisingly, large between-position variability was observed for whole matches and distinct phases of play which is likely attributed to fundamental differences in role of each positional category during match-play (Dalton-Barron et al., 2020a). Although generalisability of single team studies is a limitation, these authors reported a lack of between-team variability for whole matches, ball-in-play and transition phases (CV = <5%) which has important implications when interpreting previous research conducted with data sampled from only one team. However, with specific reference to attacking and defensive phases, these authors reported high variability between-teams (CV = 16% and 18%, respectively) which they speculate is likely due to the interaction with technical performance indicators (e.g., line breaks, missed tackles, or offloads) (Dalton-Barron et al., 2020a).

Understanding how physical characteristics vary within- and between-players, between-matches, between-positions, and between-seasons is an important consideration when applying reference values to match-play performance characteristics (McLaren et al., 2016) and when interpreting real changes or differences in match characteristics (Dalton-Barron et al., 2020a, Oliva-Lozano et al., 2020). Although variability of locomotion variables is now documented at league-wide level, the variability of distinct collision-based events (e.g., ball carries and tackles) remain unknown and requires investigation.

2.4 Rule Changes within Football-Code Team Sports

Rugby league match-play characteristics and injury risk have been shown to be influenced by numerous contextual factors including playing level (Sirotic et al., 2009, McLellan and Lovell, 2013), competition (Twist et al., 2014), and gender (Scantlebury et al., 2024). For instance, Twist et al. (2014) reported that Super League players exhibited higher average running speeds (Super League: $95.8 \text{ m}\cdot\text{min}^{-1}$ vs. NRL: $90.2 \pm 8.3 \text{ m}\cdot\text{min}^{-1}$, $p < 0.05$), whilst NRL players covered greater high-speed running distances (Super League: $6.1 \pm 1.7 \text{ m}\cdot\text{min}^{-1}$ vs. NRL: $7.8 \pm 2.1 \text{ m}\cdot\text{min}^{-1}$, $p < 0.05$). Although the NRL and Super League are considered the two premier rugby league competitions globally, the rules governing each league often differ meaning that international competition can also have different rules from domestic level competition.

Across football codes more broadly, rule changes are regularly introduced by governing bodies with varied objectives: to reduce injury risk (Stokes et al., 2021), promote faster or more intense gameplay (League, 2019), enhance player safety (Jones et al.,

2021b), or accommodate commercial, technological, or sociocultural developments (Arias et al., 2011).

Recent rule changes in rugby league (such as the introduction of a shot clock, golden point rules, and limits on interchanges) have aimed to increase game speed and reduce stagnation (League, 2019). However, their effects remain largely unquantified within the Super League playing group. Delves et al. (2022b) investigated the introduction of the "Six-Again" rule in the NRL, observing increases in acceleration characteristics and BIP durations. A limitation of this study is that it used data from a single team participating in the NRL competition, and differences between teams (Woods et al., 2018) and competitions (Twist et al., 2014) raise questions about generalisability. As this rule has since been adopted in the Super League, its effects warrant investigation within this competition.

While rule changes are often introduced with a clear aim, their consequences are typically multifaceted affecting not only gameplay and performance metrics but also training demands and injury risk. Arias et al. (2011), in a comprehensive review of rule modifications in sport, noted that many studies fail to articulate or evaluate the original objectives of such changes. They found that fewer than 30% of studies reviewed included a clear pre-implementation empirical evaluation, underlining the need for more reflective, evidence-informed policymaking.

The structure and function of rules shape interactions between players, time, space, and equipment. Modifications to these dimensions, whether structural (e.g., game duration, player numbers) or functional (e.g., tackle height, restart procedures), can significantly alter match characteristics (Vahed et al., 2014) and may also directly or indirectly influence injury rates (Livingston and Forbes, 2002, Putukian, 2004), necessitating robust analysis and evaluation.

In rugby union, Stokes et al. (2021) assessed the effects of lowering legal tackle height and found changes in tackler behaviour, but no significant difference in concussion incidence (RR = 1.31, 95% CI = 0.85 to 2.01, $p = 0.21$). This is notable given the tackle area is consistently reported as the most injurious event in both rugby codes (Hopkinson et al., 2020, Tee et al., 2019). This is particularly relevant within rugby league, as seen during the 2024 World Club Challenge between the 2023 NRL and Super League champions. At the time, Super League had implemented stricter tackle height enforcement, leading to 16 players being charged and 9 banned in Round One of the 2024 competition. However, international rule, subjectively considered lenient by comparison, were applied in the Challenge match, resulting in fewer sanctions. This discrepancy not only caused confusion for coaches, players and spectators but also underscored the practical and ethical complexities of implementing and enforcing rule changes across competitions within the

same sport. Crucially, no published studies had yet quantified the effects of these stricter tackle height rules in rugby league, reinforcing the need for systematic evaluation.

Other rugby league rule changes, such as interchange limits, also highlight potential benefits. Gabbett (2005) found that introducing a 12-interchange limit significantly reduced injury rates (72.5 [58.2 to 86.8] vs. 51.0 [33.8 to 68.1] injuries per 1,000 playing hours, RR = 0.70 [0.65 to 0.75], $p < 0.05$). Similar changes (i.e., reduced number of interchanges) were implemented in Super League competition in 2019, but their effects have not yet been analysed.

Rule changes are thus an often under-considered but critical factor shaping match events and the broader performance landscape. Woods et al. (2018), using non-metric multidimensional scaling, showed a marked shift in NRL performance characteristics following 2012 rule changes, highlighting increases in run metres and kick return metres, and decreases in missed tackles and tackle breaks. These shifts underscore how rule changes may explain variations traditionally attributed to player or tactical evolution alone.

Accordingly, understanding how rule changes influence performance data is vital for sports scientists, performance analysts, coaches, and policymakers. The systematic review presented in Chapter 3 synthesises literature on rule changes across football codes. It classifies rule changes, assesses intended and unintended consequences, and critiques methodological approaches. This broader perspective complements the empirical findings from preceding chapters and provides actionable guidance for stakeholders considering future rule changes.

2.5 Chapter Summary

This review of literature aimed to critically evaluate the current evidence relating to the usefulness, validity and reliability of GNSS and MEMS devices used to track players within football-code team sports. The second aim was to provide an overview of the locomotor and collision characteristics of rugby league match-play.

This review demonstrated that wearable microtechnology, in the form of GNSS devices and MEMS, provides a reliable and valid method of measuring player locomotion and collision characteristics. It also highlighted that there is a dearth of research into these characteristics specifically within the context of international rugby league match-play which requires investigation to support and inform researchers, coaches and players physical preparation strategies.

It demonstrated that there is a substantial bias within literature to rugby league match-play within the southern hemisphere (i.e., NRL) than the northern hemisphere. Additionally, the review demonstrated that most studies within the context of rugby league

match-play include participants from a single team which makes the generalisability of findings problematic. There is a clear need for research investigating the locomotor and collision characteristics specific to elite northern hemisphere competition, however the Super League is constantly in a state of evolution with a particular focus on changes to rules for example with the intention of enhancing the speed of matches or improving player welfare. As a result, the effectiveness of rule changes within Super League competition must be determined to evaluate the success of the governing bodies strategic aims.

This review has also identified studies specifically within rugby league which have observed changes in locomotor characteristics have attributed this to rule changes implemented by governing bodies. In addition to locomotor characteristics (i.e., average acceleration) measured using GPS technology, non-metric multidimensional analysis has shown changes within NRL team profiles between the period of 2012 and 2016 which was attributed to high rates of coach turnover and rule changes. The quality of research related to the topic of rule changes and the potential transferability of findings across football code team sports remains unclear and requires systematic evaluation.

Although advances in wearable microtechnology provides a valid and reliable method of collecting collision-based variables, GPS and MEMS devices are unable to specify the nature of the contact which has taken place and therefore frequency of specifically tackle events (including ball carries and tackler involvements) remains unknown and requires investigation. In addition to understanding these characteristics descriptively which can assist coaching strategies and players training and recovery processes; the within-player, between-match, between-season, between-player, and between-position variability of these events remains unknown. Therefore, certainty over when a meaningful change of exposure in collision-based events has occurred is challenging. The gaps in current knowledge which have been identified during this review of literature will be addressed in the subsequent chapters of this thesis. The aims of which are:

1. To present and summarise the existing research examining the effects of rule changes within football-code team sports characterised by their invasion-based and continuous match-play, with a specific emphasis on methodological quality (Chapter 3).
2. To describe locomotor and collision characteristics of international rugby league matches (including whole-match, attacking and defending phases of play, ball-in-play periods, and peak characteristics) and describe the within-player and between-player variability of these characteristics (Chapter 4).
3. To quantify the differences in match events and locomotor characteristics between the 2018, 2019 and 2020 Super League seasons in response to rule changes implemented by the sport's governing body (Chapter 5).

4. To describe the highest frequency of collision-based events (i.e., tackle events, ball carries and tackler involvements) for playing positions within professional rugby league over a multi-year period, including within-player, between-match, between-season, between-player, and between-position variability (Chapter 6).

CHAPTER 3: THE EFFECTS OF RULE CHANGES IN FOOTBALL-CODE TEAM SPORTS: A SYSTEMATIC REVIEW

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Abstract

Rule changes within football-code team sports aim to improve performance, enhance player welfare, increase competitiveness, and provide player development opportunities. This chapter aimed to review research investigating the effects of rule changes in football-code team sports. A systematic search of electronic databases (PubMed, ScienceDirect, CINAHL, MEDLINE, and SPORTDiscus) was performed to August 2023; keywords related to rule changes, football-code team sports, and activity type. Studies were excluded if they failed to investigate a football-code team sport, did not quantify the change of rule, or were review articles. Forty-four studies met the eligibility criteria. Four different football codes were reported: Australian rules football ($n = 4$), rugby league ($n = 4$), rugby union ($n = 16$), soccer ($n = 20$). The most common category was physical performance and match-play characteristics ($n = 20$). Evidence appears at a high risk of bias partly due to the quasi-experimental nature of included studies, which are inherently non-randomised, but also due to the lack of control for confounding factors within most studies included. Rule changes can result in unintended consequences to performance (e.g., longer breaks in play) and effect player behaviour (i.e., reduce tackler height in rugby) but might not achieve desired outcome (i.e., unchanged concussion incidence). Coaches and governing bodies should regularly and systematically investigate the effects of rule changes to understand their influence on performance and injury risk. It is imperative that future studies analysing rule changes within football codes account for confounding factors by implementing suitable study designs and statistical analysis techniques.

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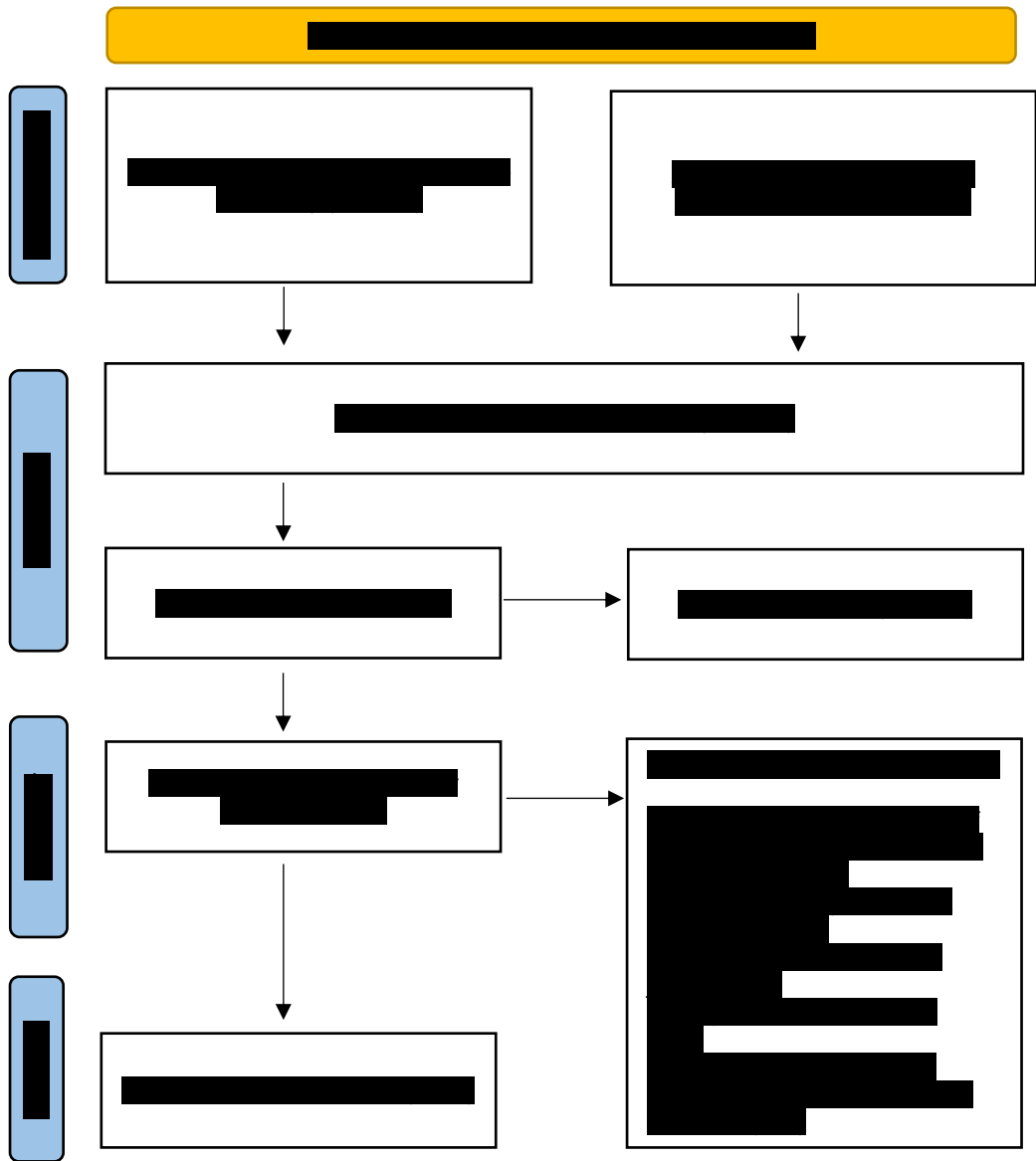


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3.3.4.4 [REDACTED]

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CHAPTER 4: LOCOMOTOR AND COLLISION CHARACTERISTICS BY PHASES OF PLAY DURING THE 2017 RUGBY LEAGUE WORLD CUP

Rennie, G., Dalton-Barron, N., McLaren, S.J., Weaving, D., Hunwicks, R., Barnes, C., Emmonds, S., Frost, B. & Jones, B. (2020) Locomotor and collision characteristics by phases of play during the 2017 rugby league World Cup. *Science and Medicine in Football*, 4(3):225-232

The content for this chapter has been published in *Science and Medicine in Football*.

The manuscript can be accessed at: <https://doi.org/10.1080/24733938.2019.1694167>.

Abstract

Understanding differences in locomotor and collision characteristics between phases of play can help rugby league coaches develop training prescription. There are no data currently available describing these differences at the elite international level. The aim of this study was to determine the differences in average speed ($\text{m}\cdot\text{min}^{-1}$), high-speed running ($>5.5 \text{ m}\cdot\text{s}^{-1}$) per minute and collision frequencies per minute ($\text{n}\cdot\text{min}^{-1}$) between attack and defence during the 2017 Rugby League World Cup (RLWC). Microtechnology data were collected from 24 male professional rugby league players from the same international squad across six matches of the RLWC. Data were then subject to exclusion criteria and stratified into forwards ($n = 9$) and backs ($n = 7$) before being analysed with linear mixed-effects models. When comparing attack with defence, forwards and backs had substantially slower average speeds (effect size [ES]; $\pm 90\%$ confidence limits: $-2.31; \pm 0.31$ and $-1.17; \pm 0.25$) and substantially greater high-speed distance per minute ($1.61; \pm 0.59$ and $4.41; \pm 1.19$). Forwards completed substantially more collisions per minute when defending ($2.75; \pm 0.32$) whilst backs completed substantially more when attacking ($0.63; \pm 0.70$). There was greater within- and between-player variability for collision frequency (CV range; 25–28%) and high-speed distance (18–33%) per minute when compared to average speed (6–12%). There are distinct differences in locomotor and collision characteristics when attacking and defending during international rugby league match-play, yet the variability of high-speed running and collisions per minute is large. These data may be useful to plan or evaluate training practices.

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4.2 [Redacted]

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4.2.3 [Redacted]

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4.2.4 [REDACTED]

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[REDACTED] Log transformation reduces heteroscedasticity and improves the normality of residuals therefore making parametric statistical tests more robust. For example, one player runs 50 m whilst another in the same position runs 500 m. Without transformation, these values are considerable in range, however are much closer following transformation: $\text{Log}(50) = 3.91$ vs. $\text{Log}(500) = 6.21$. This step ensured that the model assumptions were met, improving the reliability of statistical tests.

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4.3 [REDACTED]

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Figure 6 illustrates the peak running intensities achieved by international rugby league players during RLWC competition by position, as a function of moving average duration.

[REDACTED]

Table 6: [REDACTED]

[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
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Table 7: [REDACTED]

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[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]

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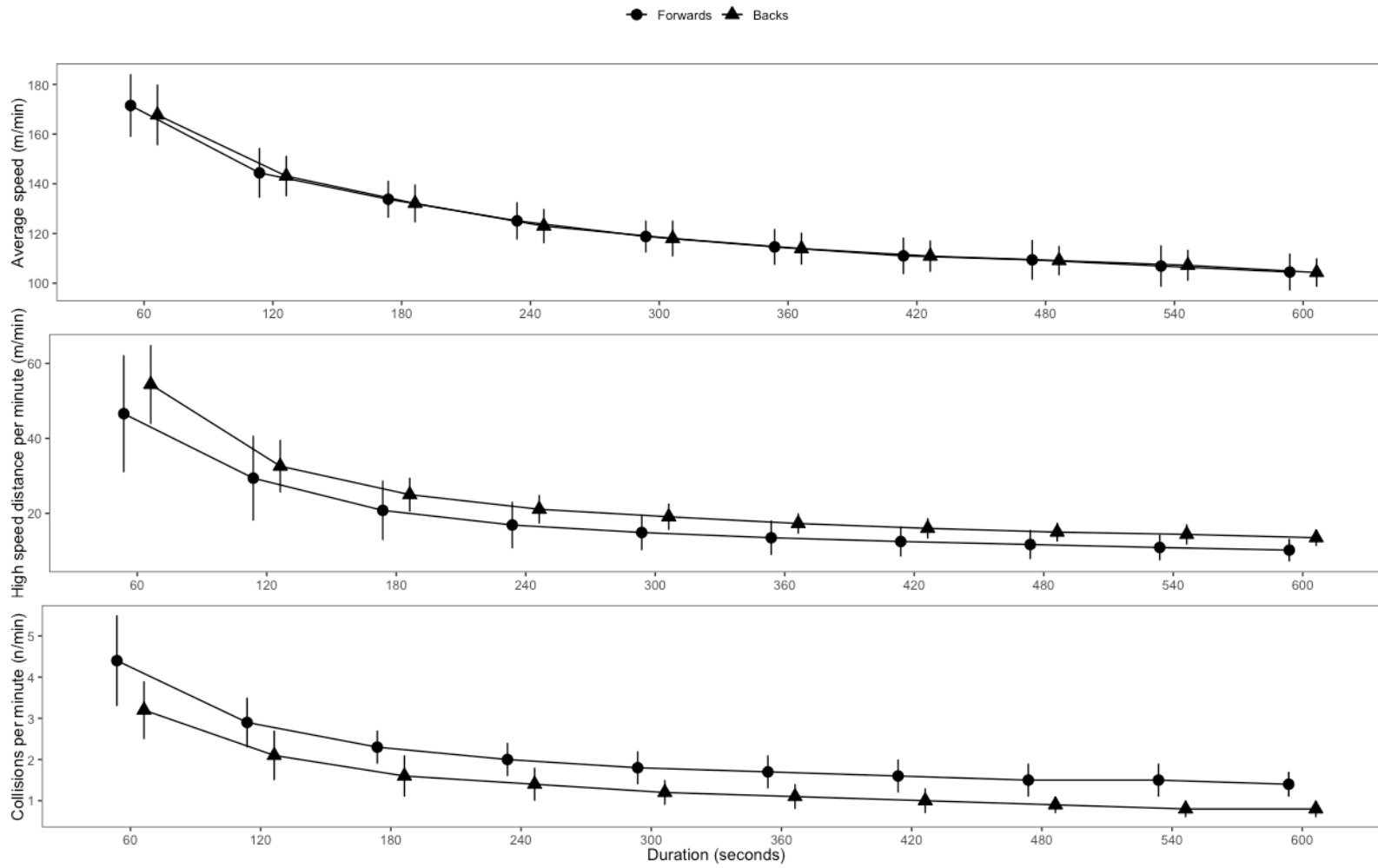


Figure 6: Peak running intensity achieved for each position, for each moving average duration.

Data are Mean \pm Within-Player SD.

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[REDACTED] Due to the elite nature of international competition, which inherently contains less teams, participants and smaller squad sizes, it is somewhat expected that studies within this population include smaller dataset for analysis than that of similar studies

investigating domestic level competition. A recent editorial within the sport of rugby union however demonstrated that international teams are capable of collaborating through a concept of coepetition within the sports medicine/science community (Ramirez-Lopez et al., 2020). [REDACTED]

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4.5 [REDACTED]

[REDACTED]

CHAPTER 5: LONGITUDINAL CHANGES IN SUPER LEAGUE MATCH LOCOMOTOR AND EVENT CHARACTERISTICS: A LEAGUE-WIDE INVESTIGATION OVER THREE SEASONS IN RUGBY LEAGUE

Rennie, G., Hart, B., Dalton-Barron, N., Weaving, D., Williams, S. & Jones B. (2021) Longitudinal changes in Super League match locomotor and event characteristics: A league-wide investigation over three seasons in rugby league. *PLoS One*, 16(12):e0260711

The content for this chapter has been published in *PLoS One*.

The manuscript can be accessed at: <https://doi.org/10.1371/journal.pone.0260711>.

Abstract

The 2019 and 2020 Super League seasons included several competition rule changes. This chapter aimed to quantify the difference between the 2018, 2019 and 2020 SL seasons for duration, locomotor and event characteristics of matches. Microtechnology and match event data were analysed from 11 Super League teams, comprising 124 players, from 416 competitive matches across a three-year data collection period. Due to an enforced suspension of league competition as a consequence of COVID-19 restrictions, and subsequent rule changes upon return to play, season 2020 was divided into season 2020^a (i.e. Pre-COVID suspension) and season 2020^b (i.e. Post-COVID suspension). Duration, locomotor variables, and match events were analysed per whole-match and ball-in-play (BIP) periods with differences between seasons determined using mixed-effects models. There were significant ($\rho \leq 0.05$) reductions in whole-match and BIP durations for adjustables and backs in 2019 when compared to 2018; albeit the magnitude of reduction was less during BIP analyses. Despite reduced duration, adjustables reported an increased average speed suggesting reduced recovery time between bouts. Both forwards and adjustables also experienced an increase in missed tackles between 2018 and 2019 seasons. When comparing 2019 to 2020a, adjustables and backs increased their average speed and distance whilst all positional groups increased average acceleration both for whole-match and BIP analyses. When comparing 2020^a to 2020^b, all positional groups experienced reduced average speed and average acceleration for both whole-match and BIP analyses. Forwards experienced an increased number of tackles and carries, adjustables experienced an increased number of carries, and backs experienced an

increased number of missed tackles when comparing these variables between season 2020^a and 2020^b. Rule changes have a greater effect on whole-match duration and locomotor characteristics than those reported during BIP periods which suggests the implemented rule changes have removed stagnant time from matches. Amendments to tackle related rules within matches (e.g., introduction of the 'six-again' rule) increases the number of collision related events such as carries and tackles.

5.1 [REDACTED]

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Prior to analysis, inspection of normality was conducted per positional category through kernel density (Figure 7) and quantile-quantile (Figure 8) plots. [REDACTED]

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[REDACTED]

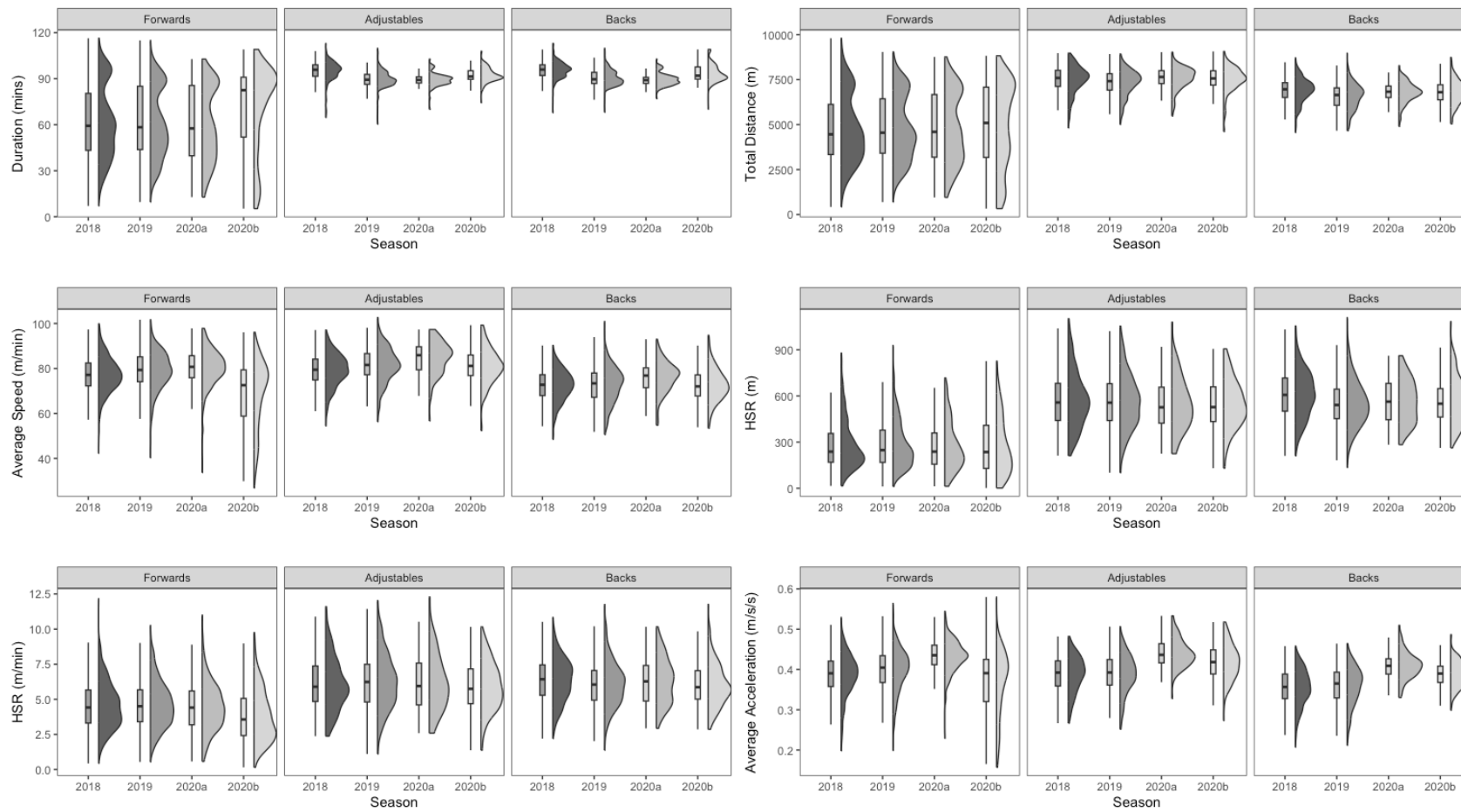


Figure 7: Kernel density estimations and boxplots of player locomotion dependent variables

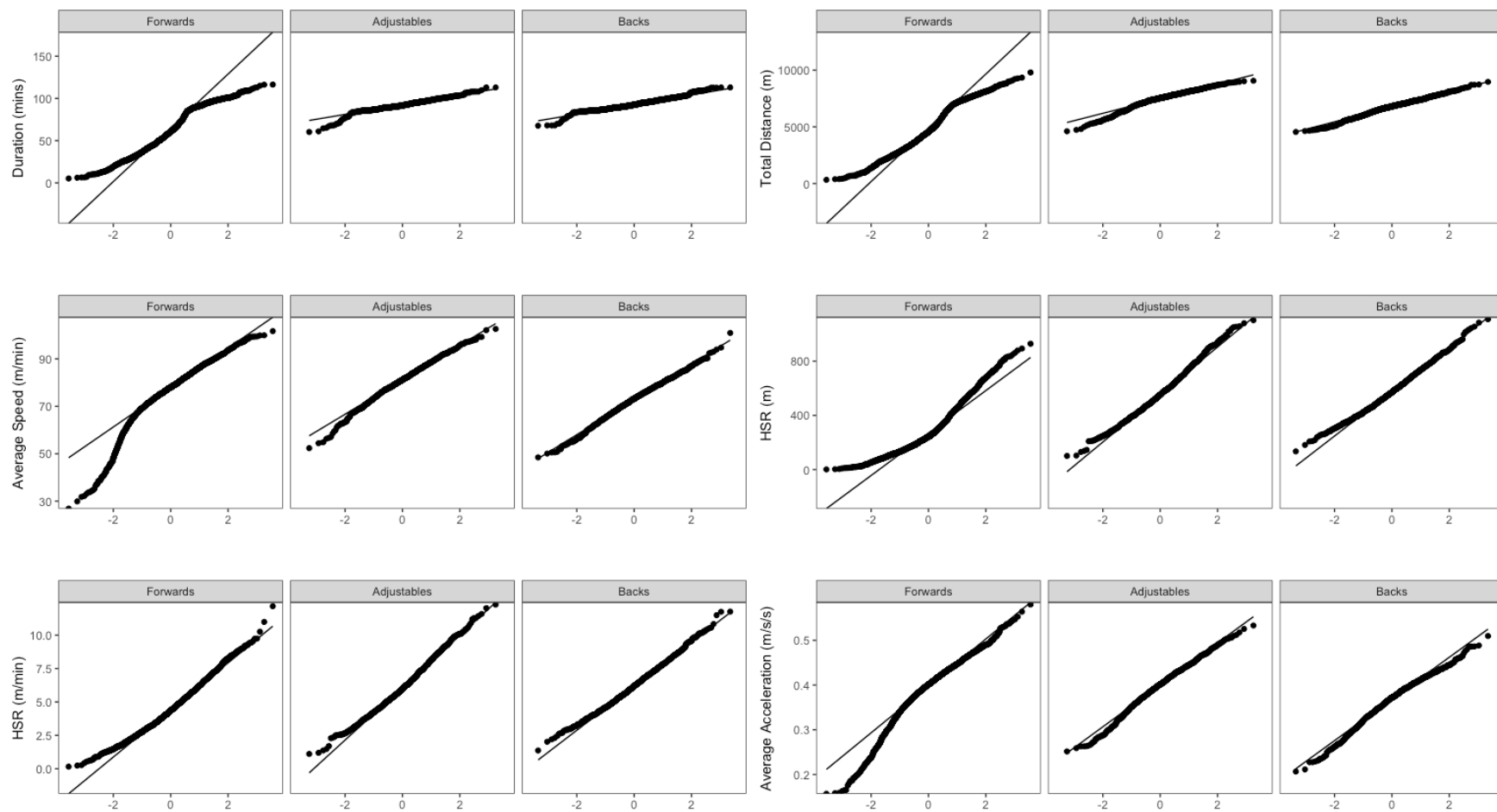


Figure 8: Quantile-quantile plots of player locomotion dependent variables

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[REDACTED]

5.3.1 [REDACTED]

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5.3.3 [Redacted]

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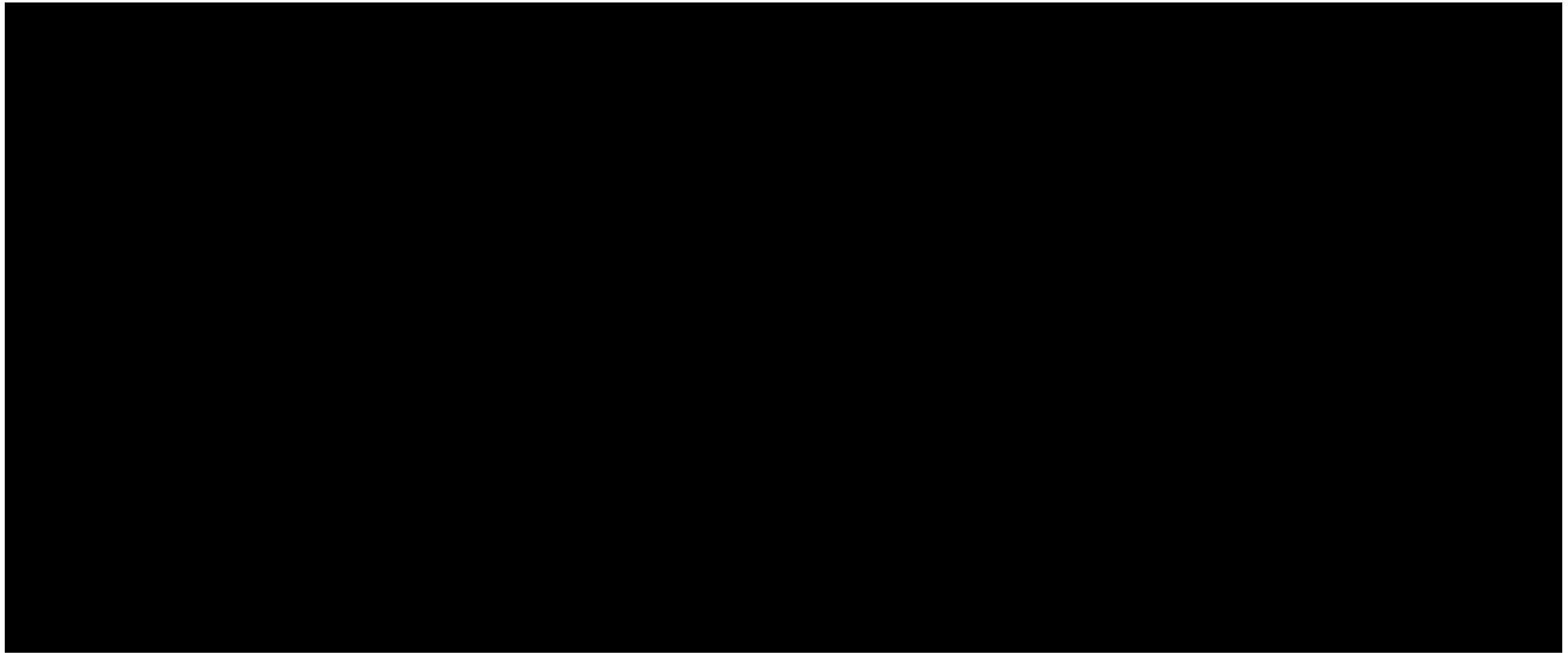


Figure 9: [Redacted]

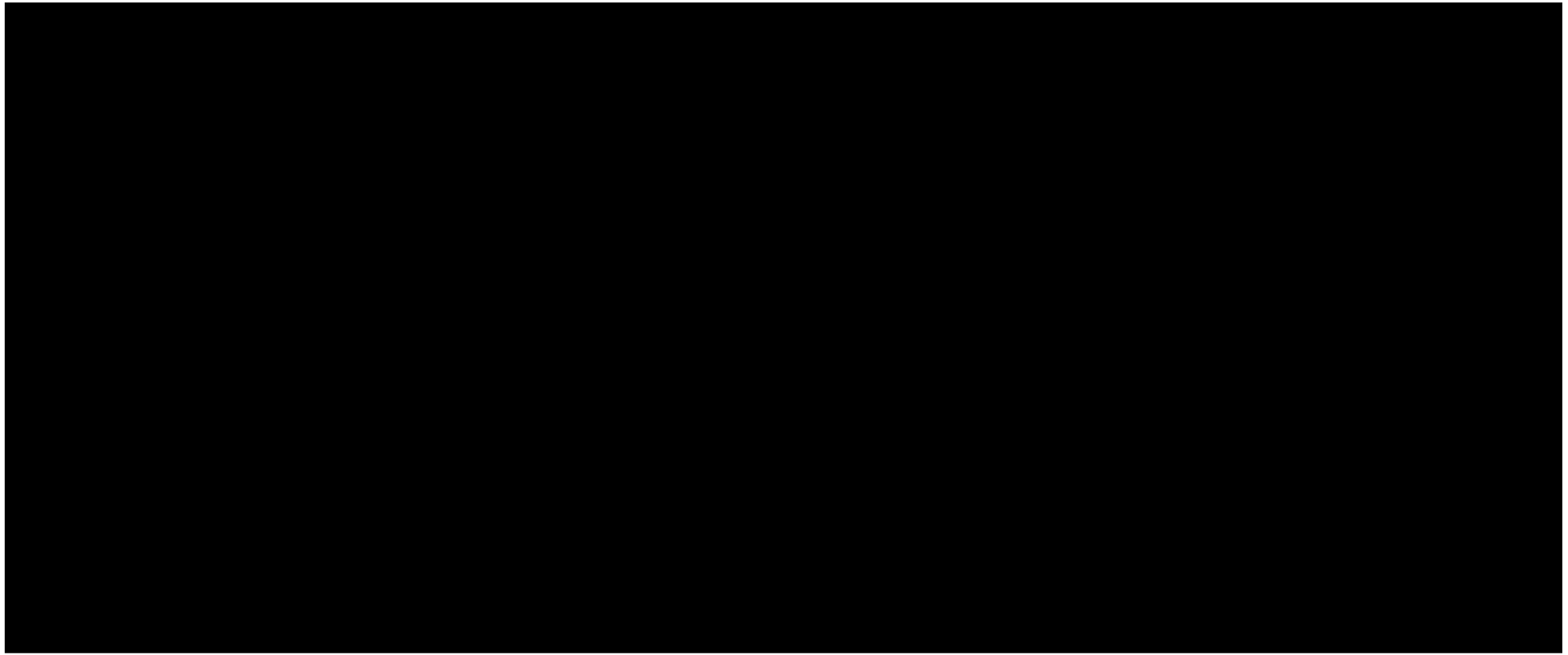


Figure 10: [Redacted]

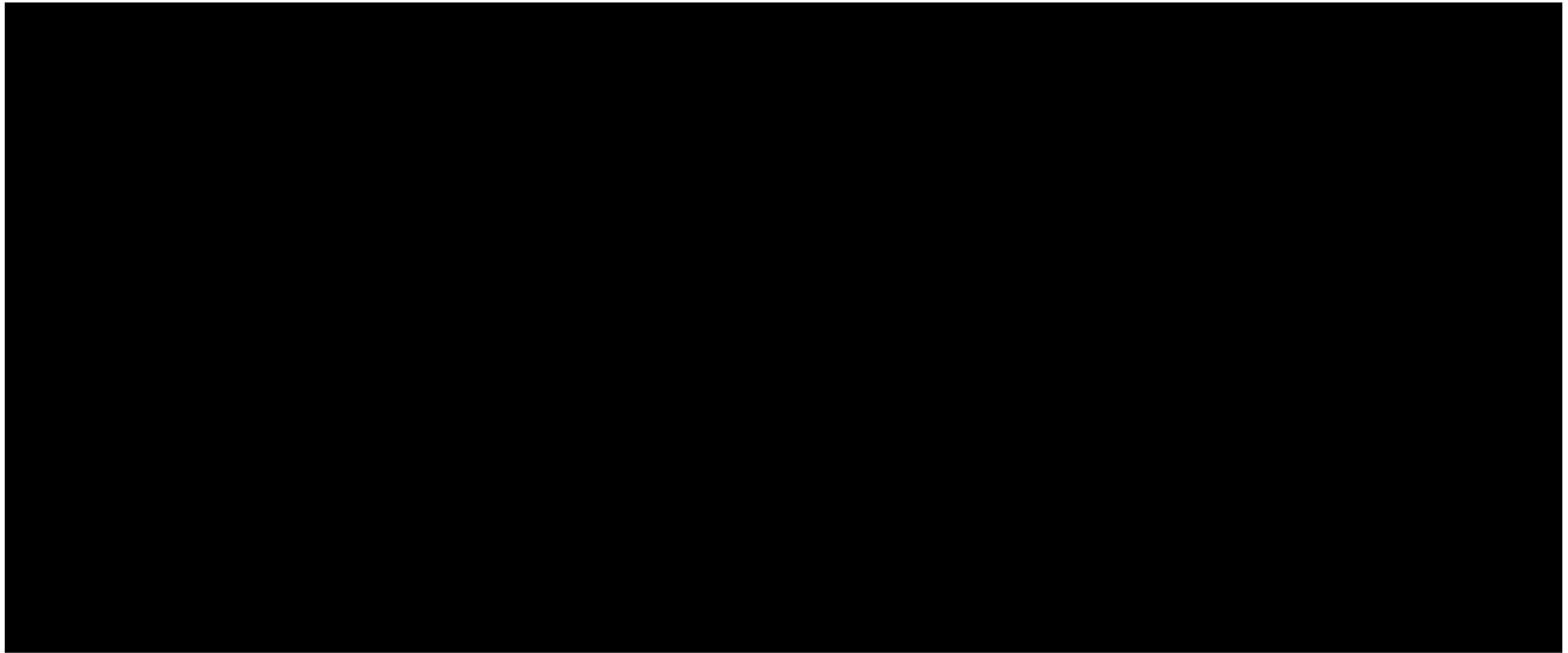


Figure 11: [Redacted]

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CHAPTER 6: TACKLE AND BALL CARRIER DEMANDS OF RUGBY LEAGUE: A SEVEN-YEAR LEAGUE-WIDE STUDY INCLUDING OVER 1,000,000 TACKLE EVENTS

Rennie, G., Weaving, D., Hart, B., Dalton-Barron, N. & Jones, B. (2022) Tackle and ball carrier demands of rugby league: a seven-year league-wide study including over 1,000,000 tackle events. *Journal of Science and Medicine in Sport*, 25(10):850-854.

The content for this chapter has been published in the *Journal of Science and Medicine in Sport*.

The manuscript can be accessed at: <https://doi.org/10.1016/j.jsams.2022.07.002>.

Abstract

Objectives: Describe the highest frequency and variability for tackle events in rugby league. Investigate seasonal differences in total tackle events per match over a seven-year period. **Design:** Retrospective observational. **Methods:** Tackle events (i.e., ball carrier events [attacker] and tackler involvements [defender]) from 864 male professional rugby league players competing in 1176 Super League matches from 2014 to 2020 were included. A series of linear mixed effect models were used to determine the frequency and variability during peak 1, 3, 5, 10, 20, 40 minutes and whole-match tackle events per player per match at a positional group level. Differences between seasons for the total number of tackle events per match were compared using a one-way analysis of variance and with Tukey's honestly significant difference test. **Results:** Tackle events were greatest for Props (51.5 [47.7–55.4] per match). Within-players, between-matches, and between-seasons variability was <10 % for tackle events. There were significantly less tackle events and tackler involvements per match in 2014 and a significantly more tackle events per match in season 2020b when compared with all other seasons. **Conclusions:** Large between-position variability in peak tackle events, ball carrier events, and tackler involvements would suggest that coaches should separate players into positional groups and prescribe training accordingly. Total number of tackle events, ball carrier events, and tackler involvements were significantly greater in season 2020b when compared to season 2014 to 2019 (inclusive) which may be a consequence of rule changes introduced to the sport.

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6.2.1 [Redacted]

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6.2.2 [Redacted]

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6.2.3 [REDACTED]

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6.3 [REDACTED]

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There was a significantly lower number of tackle events and tackler involvements per match in 2014 when compared with all other seasons (Figure 12). [REDACTED]

[REDACTED]

Table 12:

[Redacted Table Content]

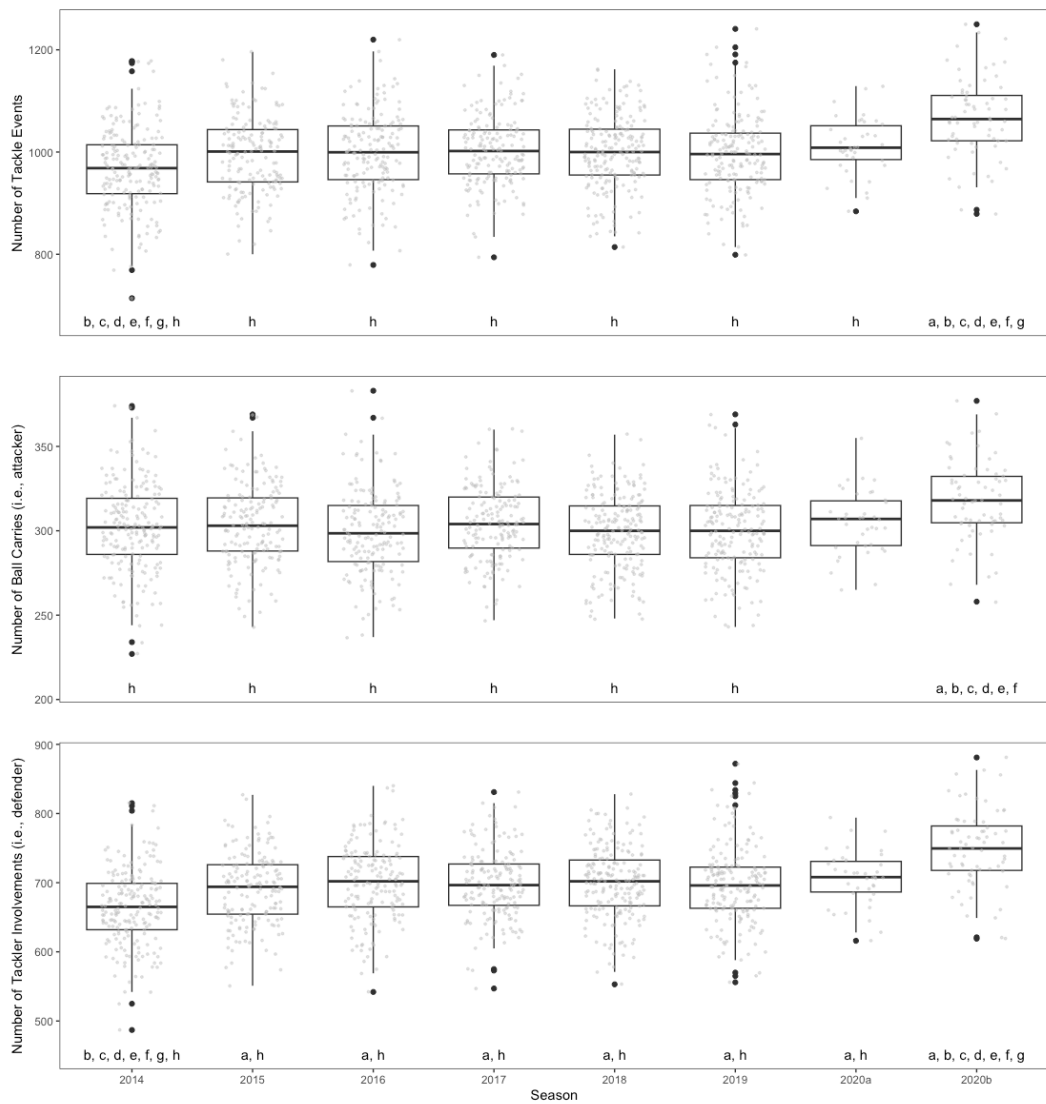


Figure 12: Boxplot of total number of tackle events, ball carries and tackler involvements per match

^a = significantly different from 2014; ^b = significantly different from 2015; ^c = significantly different from 2016; ^d = significantly different from 2017; ^e = significantly different from 2018; ^f = significantly different from 2019; ^g = significantly different from 2020a; ^h = significantly different from 2020b.

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6.5 [REDACTED]

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CHAPTER 7: GENERAL DISCUSSION

7.1 Introduction

This section summarises and discusses the findings and applications from the studies within this thesis that are relevant to coaches and practitioners involved in the sport of rugby league and applied researchers within football-code team sports. Limitations (see section 7.3), recommendations for future research (see section 7.4), and practical applications (see section 7.5) are also presented prior to conclusions (see section 7.6).

7.2 Overview of Studies

The overall aim of this thesis was to evaluate the match-play characteristics of senior male professional rugby league at both international and elite domestic level whilst considering both physical and technical-tactical performance impact. With specific reference to elite domestic rugby league competition (i.e., Super League), a particular line of investigation was the longitudinal evolution of match-play characteristics from the perspective of locomotor and collision-based variables and technical-tactical match events. Figure 13 presents the sequence of publications from this thesis. The following section will provide a summary of this thesis findings.

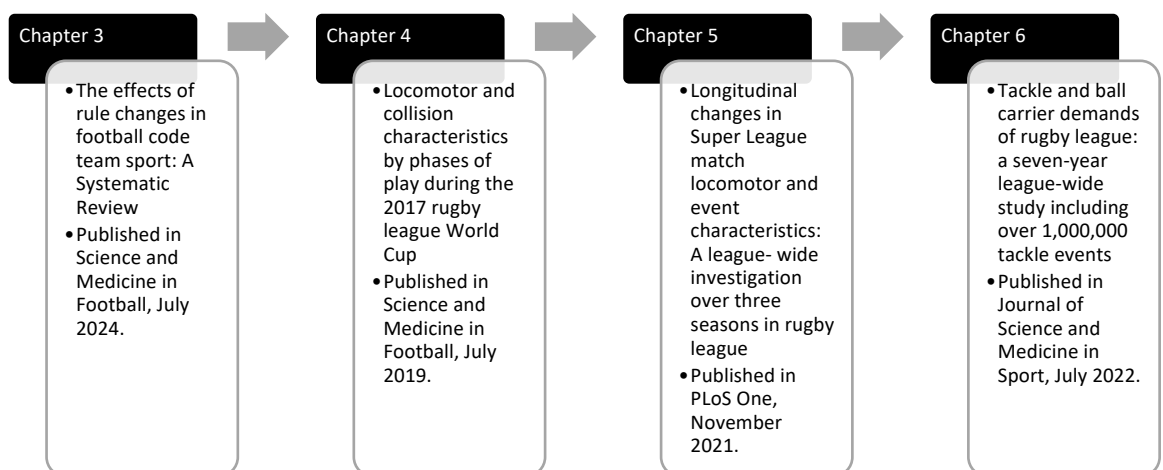


Figure 13: Flow diagram of experimental chapters produced within the current thesis (Rennie, 2024).

7.2.1 Summary of overall findings

Glassbrook et al. (2019) identified a lack of research describing match-play characteristics of international level rugby league, and demonstrated a significantly lower number of publications from Super League ($n = 3$) than NRL ($n = 27$) competition. This lack of population-specific research on international and Super League level matches poses a challenge to coaches and sports science practitioners working within these competitions, as previous literature that included multiple rugby league competitions has demonstrated between-competition differences in match characteristics (Twist et al., 2014).

Chapter 4, the first published study within this thesis, addressed this gap by investigating international level match-play characteristics and revealed disparities in the locomotor and collision characteristics between attacking and defending phases of play at the 2017 RLWC, which is the pinnacle of international rugby league competition. Both forwards and backs demonstrated significantly lower average speeds when attacking than defending but covered substantially greater high-speed distances per minute during attack than during defensive phases of play. Forwards participating in this competition engaged in more collisions per minute when defending, while backs had a higher collision frequency when attacking, a finding that provides insight into the actions in which respective positional groups tend to experience collisions. For example, together these findings suggest that forwards are exposed to collisions mostly when tackling (i.e., defending) whereas backs are exposed to collisions when carrying the ball into contact (i.e., attacking). In addition to differences in the physical characteristics of phases of match-play, the findings of Chapter 4 underscore the positional differences in locomotor and collision characteristics during the highest level of rugby league matches, offering novel insights that can inform specific technical-tactical training modalities (e.g., goal-line attack versus goal-line defence drills) in international rugby league teams.

Research describing match-play characteristics within NRL competition was significantly more prevalent than research investigating Super League competition (Glassbrook et al., 2019). Therefore, this thesis sought to address this imbalance by analysing league-wide player locomotion and match-event data collected during Super League matches. In light of the implementation of several rule changes within the Super League rugby league competition in 2019 (i.e., a reduced number of interchanges from 10 to 8, the introduction of the shot-clock, and the addition of golden point in the event of a tied score), 2020_a (i.e., reduction in the shot-clock by five seconds; 30 seconds for a scrum and 25 seconds for a drop-out), and 2020_b (i.e., the temporary removal of scrums and the introduction of the “six-again” rule), the aim of Chapter 5 was to quantify differences over a three-year period for player locomotor characteristics and match events. Chapter 5, which

is the second published study within this thesis, was the first study at the time of publication to include league-wide data for both locomotor characteristics and match events across multiple league seasons. The Super League publicly stated ahead of the 2019 season that their intention was to elicit faster, more intense, and more dramatic matches, and consequently introduced the rule changes described above. During the 2020 season, match-play was suspended for 141 days following restrictions in response to the COVID-19 pandemic. Upon returning to competition (i.e., season 2020_b), a series of additional rule changes were implemented, including the colloquially termed “six-again” rule, which had already been implemented within the NRL competition, and the removal of scrums. Chapter 5 demonstrates that, from 2018 to 2020_b, the Super League achieved its objective of increasing the speed of matches for both adjustables and backs, a finding which is supported by increased average speed and average acceleration. When comparing characteristics and events from the 2018 season to those experienced in 2020_b for forwards; average speed, average acceleration, high-speed running distances, and high-speed running distances per minute reduced, alongside an increase in completed tackles. Increased exposure to collision-based events may help explain the reductions reported in locomotor characteristics within this positional group. Although average speed and average acceleration increased for adjustables and backs, backs experienced a reduction in high-speed running distances per minute, and both positional groups experienced an increase in ball carries. The increase in match-play events may be explained by the increase in BIP duration, as increased BIP duration provides more opportunities for match events such as tackles and ball carries to occur. The findings in Chapter 5 are consistent with previous research in collision-based sports, which demonstrated that locomotor characteristics (i.e., total distance, average speed) are almost certainly greater during non-contact periods than during periods of contact-based activity (Roe, 2017).

The locomotor and collision characteristics of international and Super League rugby league competition are described in Chapter 4 and Chapter 5, respectively. The variability of displacement (i.e., locomotion) variables within rugby league matches was the topic of previous research (Dalton-Barron et al., 2020a); however, these authors did not analyse collision-based events, which are an important consideration when understanding the physical attributes of rugby league performance (Weaving et al., 2019b, Johnston et al., 2019b). Chapter 6, the third published study from within this thesis, aimed to address this knowledge gap by describing the highest frequency and variability of tackle events, ball carries, and tackler involvements experienced during a range of time epochs up to and including whole matches during professional Super League rugby league over a seven-year period. A secondary aim of Chapter 6 was to investigate seasonal whole-match differences between seasons 2014 and 2020. Over 1,000,000 tackle events were included within the

analysis in Chapter 6, which was completed using a more granular level of positional groupings than previous chapters (i.e., Props, Hookers, Second rows, Loose forwards, Scrum-halves, Stand-offs, Wings, and Fullbacks), facilitated in part due to the larger volume of data analysed. During an entire rugby league match, Props were involved in the highest number of tackle events and ball carries and Hookers were involved in the highest number of involvements as a tackler. Within a 1 minute period, both Props and Loose forwards were involved in the highest number of tackle events; Props and Fullbacks were involved in the highest number of ball carries; and Props, Hookers, and Loose forwards were involved in the highest number of involvements as a tackler. Chapter 6 also revealed that during a match, forwards undertake 32 to 39 tackles and 6 to 15 ball carries, whilst backs undertake 7 to 21 tackles and 6 to 12 ball carries. This equates to approximately one tackle every 2 to 3 minutes and one ball carry every 6 to 13 minutes for forwards, or approximately one tackle every 4 to 11 minutes and one ball carry every 7 to 13 minutes for backs. Evans et al. (2015) reported similar frequencies per positional group in Super League, with forwards undertaking one tackle every approximately 2 to 3 mins and one ball carry every 5 to 7 mins, and backs undertaking approximately one tackle and one ball carry every 9 mins. The implications of the findings of these experimental chapters is discussed in later sections of this thesis from the perspective of their influence on policy (section 7.2.2) and applied practice (section 7.2.3).

When investigating the longitudinal characteristics of rugby league match-play, it is important to consider the impact that rule changes may have on performance. Chapter 3 systematically reviewed the literature investigating the effects of rule changes within football-code team sports. Four studies included within the systematic review investigated the effects of rule changes within rugby league. Chapter 3 revealed that studies investigating rule changes within football-code team sports can be broadly categorised into at least four themes, the effects of rule changes on: physical performance and technical-tactical events, injury incidence and prevention, match scoring or competition points awarded, and player development opportunities. With specific reference to rugby league, three of the four studies focused on physical performance and technical-tactical events, and one study related to the topic of injury incidence and prevention. Chapter 3 emphasised that the area of rule changes within football-code team sports is one that is growing, as evidenced by the highest number of studies published in a single calendar year occurring in 2022. From a methodological quality perspective, Chapter 3 also highlighted that studies relating to rule changes within football codes are at risk of bias. Several studies in this area did not account for confounding factors within their analyses, which may have contributed to reported changes, and should be accounted for using appropriate statistical methods (i.e., accounting for the covariance or hierarchical nature of data).

7.2.2 Implications of findings for policy makers

Policy makers regularly review laws and rules of competition with several objectives, including: improving performance, enhancing player welfare, increasing competitiveness, and providing player development opportunities. Specifically, within Super League, a reduction in whole-match average speed and average acceleration was observed for forwards when comparing match characteristics in 2020_b to those in 2020_a. A reduction in BIP average speed and average acceleration was observed for all positional categories in the same comparative period. This may have been a consequence of two rule changes implemented between 2020_a and 2020_b: firstly, the introduction of the “six-again” rule; and secondly, the temporary removal of scrums, which were removed from match-play with the objective of reducing the likelihood of SARS-CoV-2 transmission during matches (Jones et al., 2021b). Although the average speed of matches appears to have reduced in this specific pre- to post-pandemic period, an increase in the number of tackles for forwards was found, which has important implications and is of particular relevance to policy makers since the tackle event is the most injurious event during rugby league match-play (Hopkinson et al., 2020). Adjustables and backs reported an increase in the number of ball carries, and backs experienced an increase in the number of missed tackles, suggesting that all positional groups experienced greater collision-based involvements. Previous research supports these findings, having demonstrated that average running speed and average acceleration reduces as the number of collisions experienced increases (Johnston et al., 2015a, Johnston et al., 2019b).

Together, the findings of this thesis emphasise that governing bodies should be aware of the impact that rule changes can have on match activities, specifically tackle-related events, given their associated injury risk (Hopkinson et al., 2020) and concussion risk (Gardner et al., 2015). During NRL match-play, 94.5% of HIAs occurred during the tackle event, with 1.6 HIAs reported per 1,000 tackler involvements (Gardner et al., 2015). Considering the increase in tackler involvements reported within Chapter 6, it would be reasonable to speculate that the risk of head-related trauma during rugby league match-play may have also increased; however, further research is required to substantiate this speculation.

Policy makers are aware from previous research that reduced injury incidence (measured per 1,000 playing hours) was reported when the number of permitted interchanges was reduced from unlimited to a maximum of 12 during match-play (Gabbett, 2005). Reduced interchanges were considered in Chapter 5 of this thesis, and their effects on performance indicators, including match events, duration, and locomotor characteristics

were analysed. In addition to a reduction in available player interchanges, the 2019 Super League season witnessed other notable rule modifications including the introduction of a shot-clock, and the use of the 'Golden Point'. Chapter 5 reveals a reduction in match duration for adjustables and backs following these rule changes, coupled with an increase in the average speed of match-play for adjustables. The “six-again” rule, which allows the referee to award a new set of six tackles instead of a penalty when infringements occur around the ruck, was also introduced. The introduction of this rule was explored within the southern hemisphere, NRL competition, and was found to contribute to an increased average acceleration when the ball was in play (Delves et al., 2022b). The effects of implementing the “six-again” rule within Super League competition were investigated within this thesis with findings suggesting that ball carries and tackles increased for forwards, ball carries increased for adjustables, and missed tackles increased for backs following the introduction of this rule. In addition to the increased number of match events, the whole-match and BIP average speed and average acceleration reduced for all three positional groups following this rule change. Chapter 6 found that tackle events, ball carries, and tackler involvements all increased in 2020_b, which was the specific period analysed following the introduction of the “six-again” rule. This has important implications for policy makers since the ball carrier is almost twice as likely to be injured than the tackler (39 vs. 20 injuries per 1,000 hours) during a tackle (Tee et al., 2019). Increases in collision-based elements of rugby league performance are an important consideration for policy makers due to the heightened injury risk associated with tackle-related incidents.

7.2.3 Implications of findings for practice

The findings in Chapter 4 align with previous literature in Super League and NRL competition, which demonstrated greater high-speed running percentages in attack compared to defence (Sykes et al., 2009). This may be explained by the attacking and defending systems deployed during matches (i.e., defending players are required to retreat 10 m before advancing, with the objective of reducing the space available to the attacking team and tackling the player in possession). Since the retreating distance is enforced at 10 m, defending players do not cover sufficient distances to achieve what may be considered ‘high-speed’ running thresholds during defensive play. In contrast, attacking players approach the opposition from depth with the objective of generating sprint momentum, as this physical quality has been shown to better discriminate between players at differing levels (first-division: 610 (51) kg·m·s⁻¹ vs. second-division: 570 (46) kg·m·s⁻¹, $P \leq 0.05$) and is of considerable interest for coaches working in collision-oriented sports (Baker and Newton, 2008). The average speed and collision frequencies during attack and defence,

outlined in Chapter 4, are also in agreement with previous research which found that forwards completed greater average speeds (defence: $109 \text{ m}\cdot\text{min}^{-1}$ vs. attack: $82 \text{ m}\cdot\text{min}^{-1}$) and collision frequencies (defence = $1.9 \text{ n}\cdot\text{min}^{-1}$ vs. attack = $0.8 \text{ n}\cdot\text{min}^{-1}$) when defending (Gabbett et al., 2014). However, these authors reported greater high-speed distance per minute (defence = $5.3 \text{ m}\cdot\text{min}^{-1}$ vs. attack = $3.9 \text{ m}\cdot\text{min}^{-1}$) when defending, which contradicts the results within Chapter 4 of this thesis. The differences between findings could be due to the differences in high-speed thresholds or the large match-to-match variability of high-speed running (Kempton et al., 2014), which was not considered as a random effect within the statistical analyses of previous research. Understanding the positional and contextual differences in match-play characteristics has implications for planning physical and technical-tactical training in practice which highlights their importance for coaches and sports scientists working within the sport.

Describing the peak locomotor and collision characteristics experienced during competition is paramount for coaches and players to ensure that training and physical preparation is appropriately informed and suitably prescribed. The mean peak average speed achieved over a 5 minute window during the RLWC appears to be slightly higher than that previously reported in the Super League (Weaving et al., 2019b) and NRL (Johnston et al., 2019b). This could be explained by the lower number of match observations and the inclusion of a large proportion of knock-out fixtures during the RLWC compared to the domestic season, or by differences in the microtechnology used to determine the mean peak average speeds (Thornton et al., 2019). To support coaches in setting training targets for technical-tactical drills aimed at matching or exceeding the peak average speeds of matches, Delaney et al. (2018b) proposed quantifying the power-law relationship between the peak average speeds achieved across a range of durations during matches. By quantifying the slope (i.e., rate of decline of peak running intensity) and intercept values of the relationship between the change in peak average speed with the change in duration, practitioners can estimate the likely peak average speed for a given drill for each individual player. Chapter 4 contains the first attempt to replicate this novel method using a within-player approach and analysing data collected during international rugby league matches. This novel approach could assist coaches and sports science practitioners in planning the locomotor characteristics collision exposures during the training process and within applied practice.

The 2019 rule changes within the Super League competition had a greater effect on whole-match characteristics than on BIP periods (e.g., adjustables and backs experienced a reduction in whole-match duration in season 2019 compared to 2018; however, when data were analysed for BIP periods, the reduction in duration was of a lower magnitude). Forwards, a positional group more susceptible to interchanges, did not experience any

change in duration which is likely due to the shot-clock having a greater impact on positional groups that have longer overall match durations.

Average speed increased for adjustables from 2018 to 2019 which is likely due to reduced inactive time with the introduction of the shot-clock. Players are therefore likely to have reduced time between bouts, which has implications for training practices and for preparing players for the characteristics of match-play (Whitehead et al., 2018). Chapter 5 also revealed that forwards and adjustables recorded more missed tackles in the 2019 season when compared to 2018 which may be a symptom of reduced rest time during matches and reduced number of player interchanges available which potentially contributes to more within-match fatigue, however further research is required to substantiate this speculation. The observed increase in the number of missed tackles aligns with previous research in the NRL (Woods et al., 2018), suggesting more free-flowing matches with an increased prevalence of missed tackles. Understanding how changes to rules influence the physical characteristics of match-play is critical for coaches and sports scientists working with teams in a practical setting. In addition to describing the physical characteristics of Super League rugby league match-play, Chapter 5 provides coaches, researchers, and practitioners with insights into the influence that changes to competition rules can have on physical characteristics.

Chapter 6 revealed that significantly more tackles and tackler involvements per match were observed for season 2020_b in comparison to all other seasons. This may be a consequence of competition rule changes, including the removal of scrums and the introduction of the “six-again” rule. Chapter 6 analysed data over a seven-year period and revealed that the peak number of tackle events, ball carries, and tackler involvements across all time epochs between matches and seasons were relatively stable (<10% CV). Larger variability was observed for 1 minute peak ball carries (CV = 7.4% (4.6 – 12.3%)), and between-position variability was large (>10% CV) for all positional groups at all time intervals. The large between-position variability of collision-based match events, in combination with the large between-position previously reported for total and high-speed running distances (Dalton-Barron et al., 2020a), further emphasise that a position-specific preparation and training approach is merited. The most recent comparative period analysed within the experimental chapters of this thesis (i.e., 2020_a to 2020_b) is of particular interest as the results of both Chapter 5 (i.e., the increased BIP duration, reduced average speed and reduced average acceleration for all positional categories) and the findings of Chapter 6 (i.e., increased total number of tackle events, ball carries, and tackler involvements) suggest that the ball being in play for longer contributes to an increased volume of collision-related match events during matches rather than locomotion (i.e., running-based) variables. Understanding the evolution of rugby league match-play can assist coaches in ensuring

that players are appropriately prepared for matches, thereby mitigating the likelihood of reduced tackling technique due to fatigue (Austin et al., 2011), which may potentially increase the risk of injury (Hogarth et al., 2016).

The variability in tackler events, tackler involvements, and ball carries appear similar to those reported for displacement variables (e.g., distance, average speed, and average acceleration) in rugby league (Dalton-Barron et al., 2020a). Collectively, these findings can be used to determine if a worthwhile change in collision-orientated events has taken place, which is important for player management strategies. Chapter 6 presented, for the first time, summated tackle event data on a fixture-level basis. There were no significant differences from 2015 to 2020_a when analysing the total number of tackles, ball carries, and tackler events per match (i.e., the summated total number of tackle events during a match). However, there was a significant increase in the total number of tackles and tackler involvements when comparing season 2020_b to all other seasons. This finding may be explained by the rule changes implemented at the commencement of season 2020_b, which began following a 141-day suspension of fixtures due to COVID-19 restrictions, as outlined in Chapter 5. These changes in match-event characteristics are important for coaches to understand how the physical qualities and characteristics of rugby league match-play are evolving, which may be useful for training and physical preparation review and future planning.

7.3 Limitations

The limitation of Chapter 4 is the case study design of the chapter. Although case studies can serve as a powerful tool to bridge the science-practice gap (Halperin, 2018), these reports can lack generalisability to the wider population or sport. The results of Chapter 4 represent a specific cross-sectional example of a finals reaching team that is likely to differ for teams of different nationalities and between and within successive RLWCs. Moreover, since the sample size is restricted to a single team, this limited further analysis of interest such as more granular positional stratification. A limitation of Chapter 5 is that data derived from wearable technology is only available from season 2018 onwards and therefore typical season-to-season variability in the years preceding 2018, independent of the rule changes presented, is unknown. The unknown inter- and intra-reliability of Opta personnel when coding rugby league match events is a limitation within Chapter 5 and Chapter 6. Whilst inter-operator reliability of event coding has been demonstrated to be very good within soccer (Liu et al., 2013) and AFL (Robertson et al., 2016b), it is unclear if these findings transcend other sports and therefore future research should aim to determine this. Two additional limitations are present within Chapter 6. Firstly, the specific action of the tackler

(e.g., type of tackle completed) during the tackle event is not specified therefore the tackling player may be the tackler making initial contact, may use a dominant or non-dominant shoulder, or perform the role of a supporting tackler (Burger et al., 2020). Mechanical and physiological load associated with primary or supporting tacklers during the tackle event likely differs due to the kinematics of the tackle event. For example, within rugby union, tackles performed using the dominant shoulder have been shown to produce 13% greater force than those completed using the non-dominant shoulder (Seminati et al., 2017). Secondly, the tackle events collected using notational analysis do not provide a magnitude of the collision. Collisions of different intensity are likely to have different metabolic (e.g., fatigue) or mechanical (e.g., muscle damage) costs depending on the role of tackler.

Publication bias is a concept which refers to the selective publication of research studies based on their positive effect findings (Dickersin, 1990, Mesquida et al., 2023). A characteristic of publications bias is greater likelihood of statistically significant findings being published than null findings when research quality is of an equal standard (Franco et al., 2014). When analysing the effects of rule changes within football-code team sports, for example in Chapter 3, there is a possibility that research studies which have reported null findings were either not accepted for publication (Dickersin, 1990, Mesquida et al., 2023), or that authors of these papers did not submit work for publication because they felt their research did not show any positive effects. This phenomenon, often referred to as the file-drawer problem (Rosenthal, 1979), increases the likelihood that published results reflect Type I errors rather than true publication parameters, biasing effect sizes upwards (Franco et al., 2014). This is a limitation of the research process within biomedical (Song et al., 2010) and social sciences (Coursol and Wagner, 1986, Gerber and Malhorta, 2008), and influence any scientific field. Franco et al. (2014) included 221 studies within their analysis which categorised studies as *strong* (all or most hypotheses were supported), *null* (all or most hypotheses were not supported), or *mixed* (representing the rest). These authors reported that when *null* findings were reported that 10 out of 48 (20.8%) *null* results were published, while 56 out of 91 (61.5%) studies categorised as *strong* statistically were published within an academic journal. A recent study into the potential prevalence of publication bias within sports science publications, specifically within the *Journal of Sports Science (JSS)*, found that there was some indication of this phenomenon (Mesquida et al., 2023). The consequence of this in publication terms is a likely increase in false positive reporting (Wacholder et al., 2004) or the probability that a published significant finding is actually a Type I error (Mesquida et al., 2023). Twomey et al. (2021) reported that approximately 70% of studies published within three sports science journals (including *Medicine and Science in Sports and Exercise (MSSE)*, the *European Journal of Sport Science (EJSS)* and the *Journal of Science and Medicine in Sport (JSAMS)*) reported significant findings. This is in

agreement with Mesquida et al. (2023) who observed that 73% of studies published reported significant findings.

Additionally, the physiological response to external load was not investigated, therefore no information on internal load or response is reported in this thesis. The collection of internal loads (i.e., heart rate response) is challenging within collision-based team sports such as rugby league due to the anatomical location of traditional heart rate monitors. Indeed, World Rugby, the governing body for rugby union, does not permit the use of chest-worn heart rate monitors during official matches. Nonetheless, there is a need to understand dose-response by measuring an athlete's internal load, and the production of commercially available integrated heart rate GPS vests which do not require a chest-worn monitor may enable the collection of player heart rate data during matches.

7.4 Practical Applications

A range of practical applications are presented below:

- All positional groups within international rugby league registered greater average speed in defence when compared to attack, however; all positional groups complete greater high-speed running average speed in attack compared to defence. Such detail has implications for planning and prescribing training and preparation activities to address these facets of performance (i.e. attack and defence phases of play).
- Practitioners can confidently estimate the peak characteristics of international rugby league match-play using the equation provided in Chapter 4. This will allow practitioners to ensure that training drills and conditioning sessions are providing adequate stimulus thus preparing players for peak characteristics of match-play by providing specific insights to the most physically demanding periods of play.
- Match duration reduced for outside backs and fullbacks; average speed and average acceleration increased for adjustables, outside backs and fullbacks within Super League season 2019. The number of missed tackles increased within Super League season 2019 for all positional groups. Coaches and support staff should be aware of the effects of rule changes on duration, locomotor characteristics and match events and review their preparation strategies where appropriate.
- Governing bodies should be aware that rule changes can be effective in increasing the speed of matches and consider regular review of competition laws at all levels of competition.
- Understanding the exposure and frequency of tackle events, ball carries, and tackler involvements is paramount for practitioners to adequately prepare players to the characteristics of the rugby league match-play.

- Large between-position variability in peak tackles, carries, and tackler involvements indicates players in different positional groups should have bespoke training, playing and recovery schedules.
- Given the stable between-match variability within a positional group, practitioners should monitor for meaningful increases and decreases in tackle event exposure between matches and plan subsequent training accordingly.
- Total number of tackles, carries, and tackler involvements were significantly greater in season 2020_b than season 2014 to 2019 which may be a consequence of rule changes introduced to the sport ahead of competitive return following COVID-19 restrictions.

7.5 Recommendations for Future Research

The findings of this thesis emphasise the importance of further research on understanding the longitudinal evolution of rugby league match characteristics including the effects of rule changes applied during and between seasons. Future studies should focus on identifying *why* rule changes are merited, *what* rules are deemed necessary to be changed, and *how* the amendments which are imposed effect on-field outcomes. Understanding *why*, *what* and *how* rule changes effect performance outcomes and risk of injury could lead to improvements in training regimes and more effective injury risk reduction strategies. In order advance the knowledge base of international rugby league match characteristics, it is recommended that multiple nations participating within elite competition should collaborate on larger scale projects. This would increase degrees of freedom and allow more in-depth analysis including successful versus unsuccessful participants and a more granular level of positional categories. Furthermore, considering data from additional international competitions (e.g., 4 Nations) could prove to be a useful exercise, as the differences between types of international competition is yet to be established.

The frequency of collisions is established and discussed thoroughly in Chapter 5 and Chapter 6 however the magnitude of collisions remains unknown. One method to contextualise the magnitude of player collisions, specifically at the head, is in the form of head acceleration magnitudes and exposures which has the potential to be achieved using instrumented mouthguards (Tierney et al., 2021). Although this method of collision quantification remains in its infancy, instrumented mouthguards have been shown to provide good reliability (Jones et al., 2022) and it is therefore recommended that large scale projects utilising data obtained from multiple teams wearing instrumented mouthguards are undertaken in order to understand player head accelerations.

Most literature utilising player positional data derived using GNSS reports number of satellites and HDOP. However, future research within sports science should look to better understand the consequences that multipathing may have upon the quality of wearable derived GNSS data. The emergence of real-time kinematics within the context of athlete tracking may provide substantially more accurate positional based GNSS tracking data (Waqar et al., 2020), however whether this technology is able to mitigate the effects of multipathing remains unknown and should be the topic of future investigation.

Finally, rugby league appears to review and modify rules on a regular (i.e., annual) basis therefore specific findings may appear outdated for practitioners once new rules are implemented. Evaluating the trends following rule changes helps policymakers understand the potential impact of new rules and may inform future decision making therefore ongoing research into their effects is recommended.

7.6 Conclusions

This thesis contributes a deeper understanding of the locomotor and collision characteristics of international and Super League rugby league and their associated variability, as well reporting the methodological quality of research investigating the effects of rule changes within football-code teams sports. This thesis built upon previous research by investigating and describing the variability specifically of tackles, ball carries and tackler involvements using over 1,000,000 tackle events over a seven-year period.

Data collected and analysed from the 2017 RLWC revealed that forwards and backs displayed significantly lower average speed during attacking phases when compared to defensive phases, however the inverse was shown for high-speed running distance per minute. Analysis from the RLWC also revealed that forwards completed more collisions per minute when defending whereas backs completed more collisions per minute when attacking. There are distinct differences in locomotor and collision characteristics when attacking and defending during international rugby league match-play, and these findings may be useful to plan or evaluate training practices.

Previous research has demonstrated different competitions within professional rugby league to exhibit different match characteristics (Twist et al., 2014), therefore understanding the physical match-play characteristics of Super League competition specifically is important. Moreover, the generalisability of single team studies is limited and therefore league-wide data analysis may provide a more general overview of match characteristics. Using league-wide data collected from eleven participating teams over a three-year period in Super League competition, the evolution and changes in match characteristics were presented. Significant reductions in match duration and BIP duration

were observed for adjustables and backs in season 2019 when compared to 2018. Although duration reduced, adjustables reported increased average speed suggesting that recovery time between bouts reduced. This phenomenon may have contributed to the increase in missed tackles also reported by this positional group. When comparing season 2020_a and 2020_b, all positional groups experienced reduced average speed and average acceleration. Forwards experienced an increased number of tackles and carries, adjustables experienced an increased number of carries, and backs experienced an increased number of missed tackles when comparing these variables between season 2020_a and 2020_b. When analysing specific match events, props reported the greatest number of tackle events whilst wingers and fullbacks reported the least. There is large between-position variability in peak tackle events, ball carrier events, and tackler involvements which suggests that coaches should separate players into positional groups and prescribe training accordingly. Total number of tackle events, ball carrier events, and tackler involvements were significantly greater in season 2020_b when compared to season 2014 to 2019 (inclusive). Rule changes introduced between seasons and more recently in response to COVID-19 restrictions may have contributed to changes in match-play characteristics.

Rule changes are introduced within football-code team sports with the objective of improving performance, enhancing player welfare, and making contests more appealing to spectators. The volume of research in the area of rule changes within football codes is increasing with 2022 producing the most publications in a single calendar year, yet the pool of evidence appears to be at high risk of bias. Ongoing evaluation of rule changes within football-code team sports is important since they may result in unintended consequences. It is imperative that future studies analysing rule changes within football codes account for confounding factors by implementing suitable study designs and statistical analysis techniques.

Overall, this thesis provides coaches, researchers and players with locomotor and collision match-play characteristics specifically related to international rugby league and Super League competition. This thesis also provides these stakeholders with novel insights into the frequency and variability of contact specific events (i.e., tackle events, ball carry events, and tackler involvements) during Super League matches. Additionally, it provides research-practitioners with guidance on enhancing the impact of research in applied sport science settings, most specifically in relation to future research related to rule changes within football codes.

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APPENDICES

Appendix 1: Project Super League - Catapult: RLWC Ethics Research Application.

Research Ethics Online

Ben Jones
Email: B.Jones@leedsbeckett.ac.uk

LREC: Barlow, Matthew
SCHOOL: ,

Movement Demands of the Rugby League World Cup

WILL YOUR RESEARCH STUDY.....?

Please answer the following:

- 1 Involve direct and/or indirect contact with human participants? No
- 2 Involve analysis of pre-existing data which contains personal or sensitive information not in the public domain? Yes
- 3 Require permission or consent to conduct? No
- 4 Require permission or consent to publish? Yes
- 5 Have a risk of compromising confidentiality? No
- 6 Have a risk of compromising anonymity? No
- 7 Collect / contain sensitive personal data? No
- 8 Contain elements which you OR your supervisor are NOT trained to conduct? No
- 9 Use any information OTHER than that which is freely available in the public domain? No
- 10 Involve respondents to the internet or other visual/vocal methods where participants may be identified? No
- 11 Include a financial incentive to participate in the research? No
- 12 Involve your own students, colleagues or employees? No
- 13 Take place outside of the country where you are enrolled as a student, or for staff, outside of the UK? No
- 14 Involve participants who are particularly vulnerable or at risk? No
- 15 Involve participants who are unable to give informed consent? No
- 16 Involve data collection taking place BEFORE informed consent is given? No
- 17 Involve any deliberate deception or covert data collection? No
- 18 Involve a risk to the researcher or participants beyond that experienced in everyday life? No
- 19 Cause (or could cause) physical or psychological harm or negative consequences? No
- 20 Use intrusive or invasive procedures? No
- 21 Involve a clinical trial? No
- 22 Involve the possibility of incidental findings related to health status? No
- 23 Fit into any of the following security-sensitive categories: concerns terrorist or extreme groups; commissioned by the military; commissioned under an EU security call; involve the acquisition of security clearances?
If you believe you may need to answer yes to this question, please check [here](#) for further guidance before finalising your decision.
No

RISK CATEGORY 2

Staff Applicants

Your study has been provisionally classified as Risk Category 2. This means that your project will normally be considered by your Local Research Ethics Coordinator (LREC).

You must complete the remainder of this application, which will automatically be sent to your LREC upon submission, who will review your project and decide whether to grant ethical approval, request revisions or refer it to the appropriate School level group for review. For security-sensitive research, see the Research Ethics Procedures for details of the approval process.

You will be notified of the outcome by email. You can also view the outcome on the 'My Applications' page of this system.

PROJECT SUMMARY

Start date of project

13th February 2018

Expected completion date of project

31st December 2018

Externally Funding

Is this project externally funded? No

Project Summary

Please give a brief summary of your study (maximum 100 words).

The aim of this study is to report the movement (GPS) demands of the Rugby League World Cup. To date, no study has reported the movements demands of a World Cup competition via GPS.

Project Group Members

Is this a group project? No

PROJECT DETAILS

1) Project Overview

Please give a brief overview of your study, including a summary of your aims and objectives:

The reporting of the movement demands of competition is common (Sykes et al., 2010), and is used by researchers and practitioners to understand the requirements of sport. These data are typically collected as part of normal professional club practices. While the demands of rugby league have been reported for NRL and ESL (Twist et al, 2014), data on the international competition, specifically during a World Cup are limited.

The aim of this study is to report the movement demands and match-to-match variability of the 2017 rugby league world cup (RLWC), from an international team. Variables will include; distance covered at various speed thresholds and also relative to time.

2) Methodology

Please give a description of your methodology, including any data collection and analysis methods:

Anonymised data that were collected as part of normal monitoring procedures via GPS devices will be obtained from a national governing body. GPS data from 17 players who competed in 4 matches from the RLWC will be used in the study

The data will be analysed using magnitude-based inferences to quantify the differences between positional groups and matches.

3) Main Ethical Considerations

Please give a description of the main ethical considerations involved in the study:

The main ethical considerations for this study are the use of secondary data. Given the data are anonymised when received and an approval letter has been provided by a senior representative from the RFL, these considerations are mitigated.

Also, the sharing of these data may be seen as providing an advantage to other nations. Given these data are only physical, and an approval letter has been provided by a senior representative from the RFL, again these considerations are mitigated.

4) Human Participants

If your study includes Human Participants (or their data), please give a description of who will be included:

n/a

5) Recruitment and Participation

If your study includes Human Participants, please give a brief description of the recruitment process, how you will ensure voluntary participation, if (and how) informed consent will be obtained prior to participants taking part in the study, and the right of withdrawal from the research process:

N/A

6) Risks and Benefits

Please give a brief description of how, when and where the research will take place and whether there are any risks and/or benefits involved:

There are no risks to anyone in this study

Benefits include furthering the understanding of rugby league, to allow researchers and practitioners to better understand the demands of the sport for future studies and practice.

7) Personal Data, Anonymity and Confidentiality

Please specify what type of information/data will be collected/analysed and the source(s). In addition, specify if and how you will ensure the anonymity of participants and keep information confidential:

All received data have been anonymised, and the nation the data will come from will remain anonymous.

8) Reporting and Dissemination

Please give details of the planned dissemination and specify if the findings from the research will be published and whether any permission is required for this:

Data will be used in conferences, teaching, and peer-review publications

9) Location of research

Will the research take place outside of the country where you are enrolled as a student, or for staff, outside of the UK?
No

10) Collaborative Projects

Is the research is a collaborative project (ie, it involves more than one institution): No

11) Any other permission or external ethical approval required to undertake the project

Please specify if the project requires any other ethical approval or permissions not mentioned previously in this application and how and when these will be obtained:

Approval email attached

RISK CATEGORY 2: DECLARATION

Comply with Policy and Procedures

Yes : I confirm that I have read the Research Ethics Policy and relevant sections of the Research Ethics Procedures and will adhere to these in the conduct of this project.

Confirmation

Yes : I confirm that I will undertake this project as detailed in the application. I understand that I must abide by the terms of this approval and that I may not make any substantial amendments to the project without further approval. I understand that research with human participants must not commence without ethical approval.

Benefits

Yes : The results of the research should benefit society directly or by generally improving knowledge and understanding. Please tick this box to confirm that your study has a potential benefit.

Learned Societies

I have read an appropriate professional or learned society code of ethical practice: No

SUBMISSION CHECKLIST

Please indicate the supporting documents submitted by ticking the appropriate boxes below:

For projects involving human participants, you must submit, where appropriate, the Participant Information Sheet/consent form. You must also submit every communication a participant will see or receive. Failure to do so will cause delays to the application.

Yes : Participant Information Sheet(s)

Yes : Consent Form(s)

Yes : Assent Form (usually for children participants)

Yes : Recruitment documents eg, posters, flyers, advertisements, email invitations, letters, web pages if online research

Yes : Measures to be used eg, questionnaires, surveys, interview schedules, psychological tests

Yes : Screening questionnaire

Yes : Letters/communications to and from gatekeepers/third parties

Yes : Evidence of any other approvals or permissions eg, NHS research ethics approval, in-country approval

Yes : Research proposal/protocol (no more than 2-3 A4 pages): It is not a requirement that this is included, however, if this would help the understanding of a complex project by the reviewer(s), please include

Yes : Risk assessment form: Some projects may require a risk assessment form: see the Procedures document for details (eg, projects involving a physical intervention, collecting data off-campus)

Yes : Approval documentation for projects involving ionising radiation

Yes : Confirmation of insurance and indemnity cover: Some projects need to be referred to the Insurance & Risk Officer: see the Procedures document for details

Yes : Other document/s

File uploads

Please upload your files here:

[Download All \(zip\)](#)

Name	File Size	Date Uploaded
Research Request.pdf - preview download	47.19 KB	13-FEB-18

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Appendix 2: Project Super League - Catapult: Group Ethics Research Application.

Research Ethics Online

NICHOLAS DALTON

ID: 77187145

Course: Sport and Exercise Physiology (Doctor of Philosophy)

Email: N.Dalton2258@student.leedsbeckett.ac.uk

Supervisor: Jones, Ben

LREC: Barlow, Matthew

SCHOOL: Prentice, Clare

Contextual influences on running and collision match demands in the European Super League

WILL YOUR RESEARCH STUDY.....?

Please answer the following:

- 1 Involve direct and/or indirect contact with human participants? Yes
- 2 Involve analysis of pre-existing data which contains personal or sensitive information not in the public domain? No
- 3 Require permission or consent to conduct? No
- 4 Require permission or consent to publish? Yes
- 5 Have a risk of compromising confidentiality? No
- 6 Have a risk of compromising anonymity? No
- 7 Collect / contain sensitive personal data? No
- 8 Contain elements which you OR your supervisor are NOT trained to conduct? No
- 9 Use any information OTHER than that which is freely available in the public domain? Yes
- 10 Involve respondents to the internet or other visual/vocal methods where participants may be identified? No
- 11 Include a financial incentive to participate in the research? No
- 12 Involve your own students, colleagues or employees? No
- 13 Take place outside of the country where you are enrolled as a student, or for staff, outside of the UK? No
- 14 Involve participants who are particularly vulnerable or at risk? No
- 15 Involve participants who are unable to give informed consent? No
- 16 Involve data collection taking place BEFORE informed consent is given? No
- 17 Involve any deliberate deception or covert data collection? No
- 18 Involve a risk to the researcher or participants beyond that experienced in everyday life? No
- 19 Cause (or could cause) physical or psychological harm or negative consequences? No
- 20 Use intrusive or invasive procedures? No
- 21 Involve a clinical trial? No
- 22 Involve the possibility of incidental findings related to health status? No
- 23 Fit into any of the following security-sensitive categories: concerns terrorist or extreme groups; commissioned by the military; commissioned under an EU security call; involve the acquisition of security clearances? If yes, see Help for guidance.
No

RISK CATEGORY 2

Student Applicants

Your study has been provisionally classified as Risk Category 2.

You must complete the remainder of this application, which will automatically be sent to your Research Supervisor upon submission, who will review your application and decide whether to recommend ethical approval, request revisions or reject the application.

If your Supervisor recommends approval of your project they will refer it to the Local Research Ethics Coordinator (LREC) who will review your project and decide whether to grant ethical approval, request revisions, reject the application or refer it to the appropriate School level group for review. For security-sensitive research, see the Research Ethics Procedures for details of the approval process.

You will be notified of the outcome by email. You can also view the outcome on the 'My Applications' page of this system.

PROJECT SUMMARY

Start date of project

18th April 2018

Expected completion date of project

1st October 2020

Externally Funding

Is this project externally funded? Yes

Project Summary

Please give a brief summary of your study (maximum 100 words).

The aim of this project is to understand how the context surrounding a match influences both the magnitude and structure (i.e. running or collisions) of the external load that players encounter during professional rugby league competition. This project will analyse raw anonymised global-positioning-systems match data, acquired from every first team within the European Super League over the 2018, 2019, and 2020 seasons. Situational and performance-related variables, available in the public domain, will be modelled to explain fluctuations in external load using various statistical learning methods. Such information would allow coaches to precisely alter training between-matches according to upcoming matches.

Project Group Members

Is this a group project? No

PROJECT DETAILS

1) Project Overview

Please give a brief overview of your study, including a summary of your aims and objectives:

The use of global positioning systems (GPS), with embedded micro-electrical-mechanical-systems (MEMS), to quantify the physical match demands encountered within rugby league is now commonplace (Cummins et al., 2013). This is an important process so that coaches can prescribe the appropriate volume and intensity of training throughout the training microcycle (Impellizzeri et al., 2005). However, the match demands encountered in rugby league are inherently multifaceted and stochastic in nature, and are the likely result of a myriad of interacting situational, physical, technical, and tactical factors (Gabbett et al., 2008).

Within the Australasian National Rugby League (NRL), Kempton et al. (2015) observed large match-to-match variability in high-speed running distance (HSR; coefficient of variation [CV]; $\pm 90\%$ confidence limit [CL] = 14.6%; $\pm 2.2\%$) and very high-speed running distance (VHSR; 37.9%; $\pm 6.1\%$), whereas total distance remained relatively stable (CV \pm CL = 3.6%; $\pm 0.5\%$). Even larger variability was observed when matches were analysed relative to pre-defined 10-min segments for both HSR (CV range = 32.7–50.2%) and VHSR (CV range = 91.1–158.2%). The variability of shorter time windows is unknown, which is important given that typical high-intensity interval conditioning programmes may use much shorter bout durations (<5 mins, Buchheit & Laursen, 2013). Since only one team was used from the NRL during this analysis (Kempton et al., 2015), it is unclear whether these findings are generalisable to the ESL. Moreover, no study to date has analysed the variability in collision demands, which constitute a large proportion of the biomechanical external load (i.e. mechanical stresses to the musculoskeletal system, Vanrenterghem et al., 2017) imposed on players during match-play (Johnston et al., 2014). Therefore, the first aim of this project is to quantify the between-match, -player, and -team variability in running and collision match demands. Such information is vital in calculating substantial thresholds for monitoring meaningful within-player changes in external load.

An understanding of the most important contextual factors that may explain fluctuations in external load is an important consideration for practitioners. As such, an evaluation of the pure effect of a given covariate within a multivariate analysis is warranted. In doing so, the between-match training microcycle can be tailored according to the context of

the upcoming match. However, few studies have considered the complex interplay between these variables and have adopted a univariate approach within their models. This problem is compounded by the difficulty in quantifying each of the aforementioned latent constructs (i.e. situation, physical, technical, or tactical) which have the potential to influence match demands. Previous studies in rugby league have used a mixed models approach to investigate the influence of context on match demands (Delaney et al., 2016; Kempton & Coutts, 2016). Mixed models have the advantage of assessing the pure effect of a covariate whilst holding all others within the model constant (i.e. fixed effects), as well as accounting for dependency between observations (i.e. random effects) (West, Welch & Galecki, 2014). Kempton & Coutts (2016) found that factors such as player fitness (effect size [ES]; $\pm 90\%$ CL = 0.51; ± 0.08), season phase (ES; $\pm 90\%$ CL = 0.36; ± 0.08), and location (ES; $\pm 90\%$ CL = 0.31; ± 0.08) all influenced total distance during competition in a single NRL team. However, previous studies have not accounted for the high-dimensionality, and possible multicollinearity, within complex datasets which may lead to spurious relationships (effects) between explanatory and dependent variables (Wonsuck et al., 2014). Therefore, the use of dimension reduction techniques such as principal component analysis or singular value decomposition within this type of analysis is warranted. Therefore, the second aim of this project is to identify the most important contextual variables that may influence and explain variability in the match-running and -collision demands in the ESL, by use of a multivariate approach.

In summary, the aims of this project are:

1. To evaluate the between-match, -player, and -team variability in whole-match and peak running and collision demands within the ESL.
2. To understand the most parsimonious combination of situational-, physical- and performance- (i.e. technical, and/or tactical) related factors that influence the running and collision demands experienced by ESL players during competition.

2) Methodology

Please give a description of your methodology, including any data collection and analysis methods:

RESEARCH DESIGN

This study will consist of a longitudinal observational research design, and will be conducted during the 2018, 2019, and 2020 ESL seasons, analysing anonymised player data. The project will analyse anonymised data that are collected by a representative member of every ESL club's strength and conditioning/sports science support staff during every competitive ESL match as part of normal practices. The running and collision match demands will be quantified via GPS and embedded MEMs. Following each match, as part of normal practices, each club will upload their raw data to Catapult Sports' online servers. Catapult will then ensure that the data are anonymised before being sent to the research team for subsequent analyses. Catapult Sports are a GPS manufacturing company and will provide the microtechnology devices for each ESL team.

MATCH DEMANDS

None of the research team will have any part in the data collection procedures. However, during every competitive ESL match, the representative member selected from each club will ensure that all players within their team are fitted with an Optimeye S5 10 Hz GPS unit, embedded with 100 Hz accelerometer, magnetometer, and gyroscope (Catapult Sports, Melbourne, Australia). The device will be housed within a customised pouch in each player's jersey and located at the scapulae. All data collected is part of the club's regular monitoring practices. As such, all players and staff are fully familiarised with the equipment and have used the microtechnology devices for at least a preseason period. Players will wear the same unit throughout the data collection period to minimise inter-unit error. This will be ensured via training provided by Catapult, as part of the rugby clubs practices. The data will then be downloaded by the club and subsequently uploaded to Catapult's secure online servers via Catapult's proprietary software (Openfield, Catapult Sports, Melbourne, Australia).

DATA ANALYSIS

Once the data have been uploaded to the online servers by each club (identified as the club accounts), the anonymised raw 100 Hz files will be downloaded by Catapult via a single parent account. Following this, the raw anonymous GPS data will be sent to the research team by Catapult (see section 3; Sharing of Data). Using the raw data, dependent variables relating to external load will be outputted by the lead researcher via an open-source software environment (R Studio). Metrics will include raw doppler-derived speed, PlayerLoadTM, and frequency of collisions. From this, both peak demands and summary data will be calculated and exported to a database, which will also include all other contextual explanatory variables. All situational and performance contextual variables will be available within the public domain.

3) Main Ethical Considerations

Please give a description of the main ethical considerations involved in the study:

This research will not involve any direct data collection by the research team and is reliant upon sharing of data from each ESL club. Therefore, due to the observational nature of the research, the main ethical considerations are regarding sharing of data, data protection, maintenance of anonymity and confidentiality.

SHARING OF DATA

A representative member of each ESL club's strength and conditioning or sport science staff will be responsible for the collection and sharing of all GPS data. Following each ESL match, each of the club accounts (i.e. clubs) will have a deadline to upload their data to Catapult's secure online servers. This is done via a "Full Sync" and "Cloud Archive" on the Openfield software. Catapult will then be able to download all raw files from each match to a single password-protected laptop. This parent account will only be accessible by Catapult. The sharing of all data with Catapult has already been contractually agreed by representatives of the RFL, the ESL, and signed by the chief executive officers from all current ESL clubs. This is outlined in sub-clause 4.1 in the "Wearable Services Agreement" which states:

"4.1 The Club agrees to grant the RL Parties use of Data and shall actively secure the agreement of the users of the Equipment to the use and processing of the Data by the RL Parties and Catapult."

Once the raw data has been uploaded, Catapult will then download and associate each raw GPS file with a new unique, randomly generated player ID code which will be solely used for this project. This subsequent sharing of data with Leeds Beckett University, for the purposes of research, has also been agreed by the RFL, the ESL, and all ESL clubs within the "Wearable Services Agreement", as stated in sub-clause 4.3:

"4.3 The club also agrees that anonymised Club and player Data may also be shared with academic research partners for research purposes. If a research project is commissioned, the RL Parties will provide the club with a brief of the project, and also ongoing updates of the findings. Any research project undertaken will follow strict ethical guidelines, which clearly stipulate how the Data can be handled, with anonymity a key priority.

All data relating to performance and situational contextual variables will be available within the public domain. All situational variables, such as home or away, score-line, match turnaround or time in season are readily available on websites (e.g. "www.flashscore.com/rugby-league/england/super-league/"). Variables relating to performance statistics, such as linebreaks, tackles, interceptions, or handling errors will be acquired from a data feed available provided by Opta Sports and made available to Catapult. Catapult will subsequently anonymise all data and create a spreadsheet relating all situational and performance metrics to the participant ID code before sharing with the lead researcher. Opta Sports is a sports analytics company and code all ESL matches in real time via a live video stream. Data is then made available to the public for purchase. Although a charge is incurred, this data is still considered as reasonably accessible to the applicant, and so complies with the Freedom of Information Act (2000) (Section 21; Sub-sections 1, 2) which states:

"21.

- (1) Information which is reasonably accessible to the applicant otherwise than under section 1 is exempt information.
- (2) For the purposes of subsection (1)—
 - (a) information may be reasonably accessible to the applicant even though it is accessible only on payment, and
 - (b) information is to be taken to be reasonably accessible to the applicant if it is information which the public authority or any other person is obliged by or under any enactment to communicate (otherwise than by making the information available for inspection) to members of the public on request, whether free of charge or on payment."

ANONYMITY AND CONFIDENTIALITY

As stated above, the research team will be blinded to all names and will receive raw anonymous GPS data from Catapult with the associated player ID code, created by Catapult. The research team will also receive all situational and performance related variables from Catapult in an anonymised spreadsheet containing the same player ID code. Within a separate sheet in the same spreadsheet, Catapult will also include a relational table indicating the player ID code, their primary playing position, and the club ID that the player represents. Therefore, anonymity and confidentiality will be maintained at all times. The actual relational table linking the player ID codes to the names will be stored by Catapult within a password-protected spreadsheet on a password-protected laptop. The only party that will be able to access this table will be Catapult.

DATA PROTECTION

Since the research team will be blinded to all names, it will be impossible to identify any data stored by the research team by name. All raw anonymous GPS data will be stored on a password-protected hard drive, which will be stored in a safe and secure locked filing cabinet at Leeds Beckett University – only accessible by the lead researcher. The spreadsheet containing the performance and situational variables, the player ID codes, their positions, and their clubs, as well the database of summary and peak demands will be password-protected and stored on a password-protected laptop. If published, the player ID codes will be removed, and only their position reported.

4) Human Participants

If your study includes Human Participants (or their data), please give a description of who will be included:

Thirty GPS devices have been provided to all twelve clubs within the ESL, all of whom will participate in this study. Therefore, a minimum of 360 elite adult male rugby league players registered to the first team squads within the ESL will take part in this study. However, GPS units may be swapped between players if, for example, a player is injured and they are replaced by an academy player. Therefore, it is envisaged the sample size may increase to around 450 by the end of the 2020 season, although the exact figure is impossible to know.

5) Recruitment and Participation

If your study includes Human Participants, please give a brief description of the recruitment process, how you will ensure voluntary participation, if (and how) informed consent will be obtained prior to participants taking part in the study, and the right of withdrawal from the research process:

All clubs have agreed to share data with Catapult and Leeds Beckett University prior to the commencement of the 2018 season through a contractual agreement between the RFL, the ESL, and the chief executive officers of every ESL club (see clause 4; "Wearable Services Agreement"). The lead researcher will periodically travel to each ESL club to update all players and sport science support staff of the research project, in accordance with the "Wearable Services Agreement" (sub-clause 4.3).

6) Risks and Benefits

Please give a brief description of how, when and where the research will take place and whether there are any risks and/or benefits involved:

This research will involve no direct data collection by the research team and will only deal with anonymous secondary data, meaning there will be no risk to any players. Nevertheless, all data collected is part of the ESL club's usual monitoring practices. As the sample consists of multiple teams and identities removed it will also be highly unlikely that players can be identified if the data are published and in the public domain.

There may be a risk to the lead researcher for handling such a large amount of data. For example, there may be concerns raised by relevant stakeholders (e.g. strength & conditioning or sport science staff from ESL teams) relating to sharing of their data with rival parties, such as other ESL teams or other governing bodies (e.g. Australasian National Rugby League). In the event that this happens, it will be communicated that the lead researcher will only be dealing with anonymised data and at no point will this data be shared with any other parties.

This study will benefit the body of sport science literature, since a study of this magnitude has never been done before in rugby league and will provide new insights into the contextual factors influencing match demands. Such information will allow technical/tactical coaches and strength and conditioning/sports scientists to improve their training practices.

7) Personal Data, Anonymity and Confidentiality

Please specify what type of information/data will be collected/analysed and the source(s). In addition, specify if and how you will ensure the anonymity of participants and keep information confidential:

The research team will be blinded to all names and will only receive raw GPS files from Catapult Sports with a unique player ID, their playing position, and the club they represent (see section 3; Anonymity and Confidentiality).

8) Reporting and Dissemination

Please give details of the planned dissemination and specify if the findings from the research will be published and whether any permission is required for this:

The intended outputs of this projects will be the production of a PhD thesis, publication in peer-reviewed journals and presentation at appropriate conferences. Data collected may also be used for undergraduate and masters dissertation projects at Leeds Beckett University.

9) Location of research

Will the research take place outside of the country where you are enrolled as a student, or for staff, outside of the UK?
No

10) Collaborative Projects

Is the research is a collaborative project (ie, it involves more than one institution): No

11) Any other permission or external ethical approval required to undertake the project

Please specify if the project requires any other ethical approval or permissions not mentioned previously in this application and how and when these will be obtained:

Although this is not a collaborative project with any other institution, the project will be externally funded by Catapult Sports.

All permissions relating to the sharing of data with Leeds Beckett University are outlined within the "Wearable Services Agreement".

RISK CATEGORY 2: DECLARATION

Comply with Policy and Procedures

Yes : I confirm that I have read the Research Ethics Policy and relevant sections of the Research Ethics Procedures and will adhere to these in the conduct of this project.

Confirmation

Yes : I confirm that I will undertake this project as detailed in the application. I understand that I must abide by the terms of this approval and that I may not make any substantial amendments to the project without further approval. I understand that research with human participants must not commence without ethical approval.

Benefits

Yes : The results of the research should benefit society directly or by generally improving knowledge and understanding. Please tick this box to confirm that your study has a potential benefit.

Note: If you cannot identify a benefit you must discuss your project with your Research Supervisor to help identify one or adapt your proposal so the study will have an identifiable benefit.

Learned Societies

I have read an appropriate professional or learned society code of ethical practice: Yes

SUBMISSION CHECKLIST

Please indicate the supporting documents submitted by ticking the appropriate boxes below:

For projects involving human participants, you must submit, where appropriate, the Participant Information Sheet/consent form. You must also submit every communication a participant will see or receive. Failure to do so will cause delays to the application.

No : Participant Information Sheet(s)

No : Consent Form(s)

No : Assent Form (usually for children participants)

No : Recruitment documents eg, posters, flyers, advertisements, email invitations, letters, web pages if online research

No : Measures to be used eg, questionnaires, surveys, interview schedules, psychological tests

No : Screening questionnaire

No : Letters/communications to and from gatekeepers/third parties

Yes : Evidence of any other approvals or permissions eg, NHS research ethics approval, in-country approval

No : Research proposal/protocol (no more than 2-3 A4 pages): It is not a requirement that this is included, however, if this would help the understanding of a complex project by the reviewer(s), please include

No : Risk assessment form: Some projects may require a risk assessment form: see the Procedures document for details (eg, projects involving a physical intervention, collecting data off-campus)

No : Approval documentation for projects involving ionising radiation

No : Confirmation of insurance and indemnity cover: Some projects need to be referred to the Insurance & Risk Officer: see the Procedures document for details

No : Other document/s

File uploads

Please upload your files here:

Name	File Size	Date Uploaded
<input type="checkbox"/> RFL ESL Catapult club contract.pdf	134.66 KB	18-APR-18

Appendix 3a: Project Super League - Catapult: Individual Ethics Research Application.

Research Ethics Online

GORDON RENNIE

ID: 77196787

Course: Sport and Exercise Physiology (Doctor of Philosophy)

Email: G.Rennie4852@student.leedsbeckett.ac.uk

Supervisor: Weaving, Dan

LREC: Dinsdale, Alex

SCHOOL: Prentice, Clare

Tackle demands of rugby league: A seven-year league-wide study including over 1,000,000 tackles

Amendments to this application

Attached letter / email of consent from organisation (RFL / Super League) to analyse data.

WILL YOUR RESEARCH STUDY.....?

Please answer the following:

- 1 Involve direct and/or indirect contact with human participants? No
- 2 Involve analysis of pre-existing data which contains personal or sensitive information not in the public domain? No
- 3 Require permission or consent to conduct? No
- 4 Require permission or consent to publish? No
- 5 Have a risk of compromising confidentiality? Yes
- 6 Have a risk of compromising anonymity? Yes
- 7 Collect / contain sensitive personal data? No
- 8 Contain elements which you OR your supervisor are NOT trained to conduct? No
- 9 Use any information OTHER than that which is freely available in the public domain? No
- 10 Involve respondents to the internet or other visual/vocal methods where participants may be identified? No
- 11 Include a financial incentive to participate in the research? No
- 12 Involve your own students, colleagues or employees? No
- 13 Take place outside of the country where you are enrolled as a student, or for staff, outside of the UK? No
- 14 Involve participants who are particularly vulnerable or at risk? No
- 15 Involve participants who are unable to give informed consent? No
- 16 Involve data collection taking place BEFORE informed consent is given? No
- 17 Involve any deliberate deception or covert data collection? No
- 18 Involve a risk to the researcher or participants beyond that experienced in everyday life? No
- 19 Cause (or could cause) physical or psychological harm or negative consequences? No
- 20 Use intrusive or invasive procedures? No
- 21 Involve a clinical trial? No
- 22 Involve the possibility of incidental findings related to health status? No
- 23 Fit into any of the following security-sensitive categories: concerns terrorist or extreme groups; commissioned by the military; commissioned under an EU security call; involve the acquisition of security clearances?
If you believe you may need to answer yes to this question, please check here for further guidance before finalising your decision.
No

RISK CATEGORY 2

Student Applicants

Your study has been provisionally classified as Risk Category 2.

You must complete the remainder of this application, which will automatically be sent to your Research Supervisor upon submission, who will review your application and decide whether to recommend ethical approval, request revisions or reject the application.

If your Supervisor recommends approval of your project they will refer it to the Local Research Ethics Coordinator (LREC) who will review your project and decide whether to grant ethical approval, request revisions, reject the application or refer it to the appropriate School level group for review. For security-sensitive research, see the Research Ethics Procedures for details of the approval process.

You will be notified of the outcome by email. You can also view the outcome on the 'My Applications' page of this system.

PROJECT SUMMARY

Start date of project

11th April 2022

Expected completion date of project

31st May 2022

Externally Funding

Is this project externally funded? No

Project Summary

Please give a brief summary of your study (maximum 100 words).

Through analysis of match event data, the primary aim of this study is to describe the highest frequency and the variability of tackle events, ball carries and tackler involvements per playing position during professional rugby league matches over a seven-year period using Opta Data. Opta data is a publicly available identifiable data source that is accessible via a pay wall. The data analysed within this study will be made available to the authors by the sports national governing body (RFL / Super League) (Appendix 1.0). The secondary aim is to investigate seasonal differences in tackle events, and tackle events as a ball carrier or tackler at a fixture level during rugby league matches between 2014 and 2020.

Project Group Members

Is this a group project? No

PROJECT DETAILS

1) Project Overview

Please give a brief overview of your study, including a summary of your aims and objectives:

During match-play, rugby league players undertake intermittent locomotor activities (e.g., accelerating and sprinting) and tackle events (i.e. tackler [defender] and ball carrier [attacker]). The tackle event is the most injurious activity during rugby league matches. The physical characteristics (e.g., frequency, intensity, and duration) of tackle events are typically reported using microtechnology or video-based notational analyses. The physical characteristics of locomotor activities are well documented yet the physical characteristics pertaining to tackle events are less understood, despite their importance from a performance and injury perspective.

The primary aim of this study was to describe the highest frequency and the variability of tackle events, ball carries and tackler involvements per playing position during professional rugby league matches over a seven-year period. The secondary aim was to investigate seasonal differences in tackle events, and tackle events as a ball carrier or tackler at a fixture level during rugby league matches between 2014 and 2020.

2) Methodology

Please give a description of your methodology, including any data collection and analysis methods:

This study will use a retrospective observational design in which tackle events, ball carries and tackler involvements will be analysed from 864 individual male professional rugby league players competing in 1,176 Super League fixtures from 2014 to 2020. Eight observational periods will be included: one for each season (2014 – 2019) and two for the

2020 season (2020a pre-COVID break and 2020b post-COVID break). Season 2020 will be separated into two sub-seasons due to the duration of the enforced break in fixtures and different rules (e.g., with and without scrums). Players will be categorised by their primary playing position during each match.

Event level match-play data will be provided by Opta (Stats Perform, London, United Kingdom) and extracted online (<https://www.optaprorugby.com/index.php>) as an extensible markup language (XML) file. Each XML file will be converted to a comma separated value (CSV) file that contained date, a unique fixture identification number (ID), player ID, position category, event ID, event timestamp, and collision event type (i.e. tackle events, ball carries or tackler involvements).

A CSV file containing the precise second of tackle event, tackle event as a ball carrier or tackler for each player and match will be imported into R (version 4.1.2) for analysis. The highest number of tackle events, ball carries and tackler involvements accumulated per individual within each match will be calculated for each defined time epoch (e.g., 1, 3, 5, 10, 20, 40-min and whole-match) using a rolling sum via the `roll_sum()` function, contained within the `RccpRoll` package. The highest value will be taken as the peak tackle event frequency for each time epoch characteristics. The total number of tackle events, ball carries and tackler involvements performed within each fixture (i.e. sum total of events during a fixture) will be determined by grouping and summing all defined events within a match.

For the peak 1-, 3-, 5-, 10-, 20-, 40-min and whole-match analysis, peak match-event data will be analysed through a series linear mixed effects models (LMM's) using the `lme4` package in R, with random effects for player ID (to estimate differences between-player means), position category (to estimate changes between-positions), fixture ID (to estimate changes between-matches) and season (to estimate changes between-seasons). The resultant estimates will be presented with 95% confidence intervals (CI). Within-player variation will then be attributed to that of otherwise unexplained variability (i.e. the residual). Variability will be expressed using the coefficient of variation (CV) and will be presented with 95% CIs as markers of uncertainly estimates; large changes will be interpreted as >10%.

For the total number of tackle events per fixture analysis, differences between the total number of events per fixture will be compared using a one-way analysis of variance (ANOVA) using the `aoV()` function in base R. Tukey's honestly significant difference (HSD) test will be used post-hoc using the `TukeyHSD()` function in base R to compare differences between seasons and adjusted p-values will be interpreted at an alpha-level of $p < 0.05$. The adjusted p-value identifies positional comparisons that are significantly different, whilst limiting the family error rate.

3) Main Ethical Considerations

Please give a description of the main ethical considerations involved in the study:

As a project using publicly available identifiable data accessible via a pay wall, there are relatively few ethical considerations. In order to protect the player's confidentiality, all data will be anonymised prior to analysis. Furthermore, the teams that each player plays for will be anonymised so that the identity of the players cannot be deduced from this information. Appendix 1.0 includes the letter / email of consent from the sports national governing body to analyse this data.

4) Human Participants

If your study includes Human Participants (or their data), please give a description of who will be included:

This study will use secondary data, available in the public domain behind a paywall. The match event level data is collated by the RFL EPU as part of a wider project surveying the Super League. All data will be anonymised prior to being analysed.

The match data includes details on the timing of different match actions (e.g., tackles and ball carries) being completed.

5) Recruitment and Participation

If your study includes Human Participants, please give a brief description of the recruitment process, how you will ensure voluntary participation, if (and how) informed consent will be obtained prior to participants taking part in the study, and the right of withdrawal from the research process:

As this study involves secondary data, there is no requirement to obtain individual participant's consent.

6) Risks and Benefits

Please give a brief description of how, when and where the research will take place and whether there are any risks and/or benefits involved:

As all data will be analysed in an anonymised manner, there is no risk to the participants. The project will significantly benefit the sports science and coaching community through improving the knowledge base of tackler involvement characteristics within rugby league.

7) Personal Data, Anonymity and Confidentiality

Please specify what type of information/data will be collected/analysed and the source(s). In addition, specify if and how you will ensure the anonymity of participants and keep information confidential:

Event level match-play data will be provided by Opta (Stats Perform, London, United Kingdom) and extracted online (<https://www.optaprorugby.com/index.php>) as an extensible markup language (XML) file. Each XML file will be

converted to a comma separated value (CSV) file that contained date, a unique fixture identification number (ID), player ID, position category, event ID, event timestamp, and collision event type (i.e. tackle events, ball carries or tackler involvements). A CSV file containing the precise second of tackle event, tackle event as a ball carrier or tackler for each player and match will be imported into R (version 4.1.2) for analysis. In order to protect the potential for breach of player's anonymity and confidentiality, all data will be anonymised prior to analysis. Each participant will receive a coded number linked to their ID. These coded numbers will be used for all the raw data and this data will therefore be made anonymous. The document that links the codes to the participants' names (the master list) will be held by the primary investigator on a password protected Microsoft OneDrive account requiring second factor authentication. In the handling and analysis of the data, only these coded numbers will be used, and it will not be possible to identify any of the presented results as coming from a particular players.

8) Reporting and Dissemination

Please give details of the planned dissemination and specify if the findings from the research will be published and whether any permission is required for this:

The intended output will be an academic journal, appropriate conferences in addition to PhD theses.

9) Location of research

Will the research take place outside of the country where you are enrolled as a student, or for staff, outside of the UK?
No

10) Collaborative Projects

Is the research is a collaborative project (ie, it involves more than one institution): No

11) Any other permission or external ethical approval required to undertake the project

Please specify if the project requires any other ethical approval or permissions not mentioned previously in this application and how and when these will be obtained:

Appendix 1.0 includes a letter / email of consent from the sports national governing body (RFL / Super League) to Director of Studies consenting to the analysis of this dataset and publish findings.

RISK CATEGORY 2: DECLARATION

Comply with Policy and Procedures

Yes : I confirm that I have read the Research Ethics Policy and relevant sections of the Research Ethics Procedures and will adhere to these in the conduct of this project.

Benefits

Yes : The results of the research should benefit society directly or by generally improving knowledge and understanding. Please tick this box to confirm that your study has a potential benefit.

Note: If you cannot identify a benefit you must discuss your project with your Research Supervisor to help identify one or adapt your proposal so the study will have an identifiable benefit.

Confirmation

Yes : I confirm that I will undertake this project as detailed in the application. I understand that I must abide by the terms of this approval and that I may not make any substantial amendments to the project without further approval. I understand that research with human participants must not commence without ethical approval.

Learned Societies

I have read an appropriate professional or learned society code of ethical practice: No

SUBMISSION CHECKLIST

Please indicate the supporting documents submitted by ticking the appropriate boxes below:

For projects involving human participants, you must submit, where appropriate, the Participant Information Sheet/consent form. You must also submit every communication a participant will see or receive. Failure to do so will cause delays to the application.

No : Participant Information Sheet(s)

No : Consent Form(s)

No : Assent Form (usually for children participants)

No : Recruitment documents eg, posters, flyers, advertisements, email invitations, letters, web pages if online research

No : Measures to be used eg, questionnaires, surveys, interview schedules, psychological tests

No : Screening questionnaire

Yes : Letters/communications to and from gatekeepers/third parties

No : Evidence of any other approvals or permissions eg, NHS research ethics approval, in-country approval

No : Research proposal/protocol (no more than 2-3 A4 pages): It is not a requirement that this is included, however, if this would help the understanding of a complex project by the reviewer(s), please include

No : Risk assessment form: Some projects may require a risk assessment form: see the Procedures document for details (eg, projects involving a physical intervention, collecting data off-campus)

No : Approval documentation for projects involving ionising radiation

No : Confirmation of insurance and indemnity cover: Some projects need to be referred to the Insurance & Risk Officer: see the Procedures document for details

No : Other document/s

File uploads

Please upload your files here:

[Download All \(zip\)](#)

Name	File Size	Date Uploaded
Screenshot 2022-05-12 at 09.13.14.png - preview download	296.47 KB	12-MAY-22

Appendix 3b: Project Super League - Catapult: Consent from National Governing Body.

From: [REDACTED]

Subject: Ethics

Date: 22 July 2020 at 10:04:23 BST

To: "Jones, Ben" [REDACTED]

Cc: [REDACTED]

Caution External Mail: Do not click any links or open any attachments unless you trust the sender and know that the content is safe.

Dear Ben

On behalf of the RFL, I am happy for you and PhD students at Leeds Beckett University to use the Opta data, which includes coding of player actions and outcomes from Super League and International matches to undertake studies which quantify player and team performance.

The RFL are happy for these studies to be published in journals and used in conferences, but player identify should remain anonymous.



[REDACTED]
Chief On-Field Officer
[REDACTED]
[REDACTED]

Appendix 4: Supplementary Materials

Chapter 3

Supplementary Material 3.1: [REDACTED]

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Supplementary Material 3.4: [REDACTED]

[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]

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Supplementary Material 3.5: [REDACTED]

[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]

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