PHD

THE PHYSICAL AND PHYSIOLOGICAL DEMANDS OF REFEREEING RUGBY UNION

Tannhauser Sant'Anna, Ricardo

Award date:
2022

Awarding institution:
University of Bath

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A thesis submitted for the degree of Doctor of Philosophy

University of Bath

Department for Health

October 2021

Signature of author……………………………………………………………………..…….

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Declaration of any previous submission of the work

The material presented here for examination for the award of a higher degree by research has / has not been incorporated into a submission for another degree.

Candidate's Signature:

Declaration of authorship

I am the author of this thesis, and the work described therein was carried out by myself personally.

Candidate's Signature:

TABLE OF CONTENTS

THE PHYSICAL AND PHYSIOLOGICAL DEMANDS OF REFEREEING RUGBY UNION 1

DEDICATION...8

ACKNOWLEDGEMENTS...9

EPIGRAPH..11

ABSTRACT 12

PUBLICATIONS 14

LIST OF TABLES 16

LIST OF FIGURES 18

ABREVIATIONS...19

CHAPTER 1: INTRODUCTION...21

1.1 Match demands of refereeing rugby union...28

1.2 Thesis aims and objectives 29

CHAPTER 2: LITERATURE REVIEW...31

2.1 Overview..31

2.2 Demands of team sports officials 31

2.3 Demands of 15-a-side rugby 33

2.3.1 Rugby 15-a-side referees match demands 33

2.3.2 Rugby 15-a-side referees match physical demands (external) 36

2.3.3 Rugby 15-a-side referees match physiological demands (internal)..........38

2.4 Rugby sevens 40

2.4.1 Rugby sevens referees match demands 41

2.5 Field testing..43

2.5.1 Purpose of testing...43

2.5.2 Testing rugby referees using field tests 45

2.5.2.1 The Yo-Yo intermittent recovery test 45

2.5.2.1 – The 1.2 km shuttle run test..47

2.6 Refereeing Decision-making 47

2.7 Time-motion analysis in team field sports..51

2.8 Satellite positioning technology 54

2.8.1 Validity and reliability of tracking satellite systems 55

CHAPTER 3: GENERAL METHODS...58

3.1 Participants 58

3.2 Ethics...59

3.3 Study design and equipment..59

3.3 Match physical demands analysis 63

3.4 Match physiological demands analysis...64

3.5 Field test assessment 65

3.5.1 Yo-Yo Intermittent Recovery Test 65

3.5.2 1200-m shuttle (The Bronco) Test...67

3.6 Video coding...68

3.7 Data analysis...72

CHAPTER 4: PHYSICAL DEMANDS OF REFEREEING RUGBY SEVENS MATCHES AT DIFFERENT COMPETITIVE LEVELS 73

4.1 Introduction...73

4.2 Methods 74

4.2.1 Experimental Approach 74

4.2.2 Subjects and Experimental Procedures...75

4.2.3 Physical Demands Analysis...75

4.2.4 Statistical Analysis...76

4.3 Results 77

4.3.1 Total Distance and relative distance 77

4.3.2 Speed zones..77

4.3.3 Sprints 78

4.3.4 Repeated high-intensity efforts........78

4.3.5 Worst case scenario........81

4.4 Discussion........84

4.5 Conclusions and practical implications........87

CHAPTER FIVE: 15-A-SIDE RUGBY UNION REFEREES' PHYSICAL AND PHYSIOLOGICAL DEMANDS ACROSS DIFFERENT COMPETITIVE LEVELS........88

5.1 Introduction........88

5.2 Materials and methods........90

5.2.1 Participants and study design........90

5.2.2 Physical demands........92

5.2.3 Physiological demands........92

5.2.4 Statistical analysis........93

5.3 Results........94

5.3.1 Referees characteristics........94

5.3.2 Total distance and relative distance........94

5.3.3 Speed zones........95

5.3.4 Accelerations and decelerations........95

5.3.5 Sprints........95

5.3.6 Repeated high-intensity efforts (RHIEs)........96

5.3.7 Worst case scenario (WCS)........100

5.3.8 Heart rate (HR) and internal load........100

5.3.8 External and internal load relationships........102

5.4 Discussion........102

5.5 Conclusions and practical implications........105

CHAPTER SIX: COMPARING THE YO-YO INTERMITTENT AND BRONCO TESTS AND THEIR ASSOCIATIONS WITH MATCH DEMANDS AMONG RUGBY UNION REFEREES........107

6.1 Introduction........107

6.2 Methods *109*

6.2.1 Participants..109

6.2.3 Study protocol..110

6.2.3 Testing procedures..111

6.2.4 Statistical Analysis..113

6.3 Results *115*

6.3.1 Field tests results..115

6.3.2 Relationships between $YYIR_1$ and Bronco test data..115

6.3.2 Comparisons between HR zone data during the $YYIR_1$ and Bronco tests 116

6.3.3 Relationships between field tests results and match demands..........................117

6.3.4 Relationships between field test physiological demands and match demands..118

6.3.5 Field-test results regression analysis 121

6.3.6 $YYIR_1$ final distance and match total distance regression analysis 122

6.4 Discussion *123*

6.5 Conclusion and practical implications..*127*

CHAPTER SEVEN: REFEREE POSITIONING, BUT NOT MATCH DEMANDS, SCORE DIFFERENCE, OR FIELD LOCATION, ARE ASSOCIATED WITH BREAKDOWN DECISION-MAKING ACCURACY IN ELITE RUGBY SEVENS REFEREES..129

7.1. Introduction..*129*

7.2. Methods *131*

7.2.1 Participants..131

7.2.2 Decision-making accuracy...132

7.2.3 Field location, score difference, and referee positioning..................................133

7.2.4 Match demands..134

7.2.5 Procedure 135

7.2.6 Statistical analysis...135

7.3 Results *136*

7.3.1 Decision-making accuracy...136

7.3.2 Changes in decision-making accuracy over time 136

7.3.3 Differences in match demands between correct and incorrect decisions 137

7.3.4 Associations between match demands and decision-making accuracy 137

7.3.5 Associations between score difference, field location, referee positioning and decision-making accuracy...138

7.4. Discussion 138

7.5. Conclusion and practical implications...142

CHAPTER 8: GENERAL DISCUSSION..143

8.1 Introduction..143

8.1.1 Summary of the findings...143

8.2 Significance of the findings 145

8.2.1 Officiating rugby sevens..145

8.2.3 Officiating 15-a-side rugby..148

8.3 Original contribution to the literature and implications of findings.......................150

8.4 Limitations, future directions and practical applications 152

8.5 Conclusion...157

REFERENCES...158

APENDIX A...175

APPENDIX B 177

APENDIX C...192

DEDICATION

I truly believe that God works in mysterious ways, and sometimes you must lose first to win later. Therefore, this PhD thesis is dedicated to someone who is no longer here. Aunt Lúcia: you always encouraged me to look beyond and to step outside of my comfort zone. I know that you would have told me to take this opportunity with both hands, and I hope that from up above, you are proud of your nephew.

ACKNOWLEDGEMENTS

Firstly, I would like to thank my supervisors, Professor Keith Stokes, Dr Simon Roberts, and Dr Lee Moore. Keith, thank you for your lead guidance on this project, always looking at the big picture and pointing at the right direction. Si, thank you for your support during this journey, always being positive and available to help (and keen to travel when needed). Lee, thank you for your guidance (i.e., encouraged support) and for always being available to offer an advice (e.g., critical, and good feedback).

Also, I would like to thank the many collaborators and organizations whom I have worked with during my PhD: all the referees who took part, the Rugby Football Union, and in particular to Alex Reid for her valuable support, and to STATSports for providing the GNSS units. Additionally, I would like to thank the Santander Mobility Award for the financial support which allowed me to spend part of my PhD journey in South Africa. In this regard, my most sincere thanks to Dr Wilbur Kraak who received me with open arms, always smiling, and invested a lot of time and energy to make me feel more than welcome, as well as all the master's students at Stellenbosch University for your massive help during my busy days over there.

To the first Drs I had met: my grandpa Mario and my grandma Semiramis (*in memoriam*). A seed was planted during lunch on Saturdays at your house while I listened to the conversations about working at the University. Also, to my grandpa Luiz Carlos (*in memoriam*) and my grandma Dora (*in memoriam*) who taught me how to always be positive, to have faith, and to enjoy the simple things in life. To all my family for their support.

To my mum Elizabeth, to teach me how to have passion for life and always dream about good things for the future. To my dad Luiz Ricardo, who always encouraged me to keep learning, and whose support was invaluable to achieve this milestone. I know this is also your dream, so thank you so much for your support throughout this journey. To my sister Ana Luiza, to show me how to find happiness in all the small things. I hope I have made you guys proud.

Last but definitely not least, to my beloved wife Pamela. You are the truly example that good things come in small packages, and I don't know a stronger and more supportive person than you. Thank you for being by my side, to dream the same dream, to hold my hand

and guided me when I needed, to support me at my best and at my worst. I would not be half the person I am today without you. Love you.

In life you must be willing to take risks, and as Nelson Mandela once said, “there is no passion to be found playing small-in settling for a life that is less than the one you are capable of living”.

EPIGRAPH

"*The best thing in life is to go ahead with all your plans and your dreams, to embrace life and to live everyday with passion, to lose and still keep the faith and to win while being grateful. All of this because the world belongs to those who dare to go after what they want. And because life is really too short to be insignificant*."

Charlie Chaplin

ABSTRACT

The identification of specific movement patterns and associated physical and physiological demands during match play is important for optimising the training and preparation of rugby union referees. Therefore, using Global Navigation Satellite System (GNSS) units and heart rate (HR) recordings, the first aim of this PhD thesis was to provide a better understanding of the physical and physiological demands that rugby union referees encounter when officiating at different competitive levels (i.e., amateur to professional) during sevens (Chapter Four) and 15-a-side (Chapter Five) matches. The results showed that refereeing rugby sevens and 15-a-side is more physically demanding at higher competitive levels (e.g., elite), particularly in terms of high-intensity efforts. For example, compared with referees officiating at the amateur level, international, professional, and semi-professional level, referees completed more sprints during rugby sevens matches. Moreover, during 15-a-side rugby matches, professional level referees sprinted for longer durations and covered more distance sprinting than semi-professional and amateur level referees.

The fitness tests used to assess rugby referees' readiness to officiate have been based on general tests for team sport players, and therefore may not accurately reflect the physical and physiological demands placed upon rugby referees. Thus, using GNSS and HR data, a second aim of this PhD thesis was to compare commonly used fitness tests among rugby referees (i.e., Yo-Yo Intermittent Recovery level 1 vs. Bronco), and to examine whether the results of these tests were associated with the physical and physiological demands of 15-a-side rugby matches at amateur competitive level (Chapter Six). The results suggested that the Yo-Yo Intermittent Recovery level 1 and Bronco tests were significantly correlated. Additionally, the Yo-Yo Intermittent Recovery Test level 1 showed more significant correlations with match demands (e.g., total distance, sprints) than the Bronco test, and therefore could be regarded as the more valuable test to assess the match fitness of 15-a-side rugby referees.

It is vital that the decision-making of rugby referees during match play is accurate, and that the various factors that influence the decision-making accuracy of rugby referees are better understood. Accordingly, using GNSS and HR data along with video coding of matches, the third aim of this PhD thesis was to examine if the decision-making accuracy of rugby referees was associated with physical and physiological match demands prior to each decision, as well as score difference, field location, and referee positioning during an elite

rugby sevens tournament (Chapter Seven). The results suggested that referee decision-making accuracy at the breakdown (a match event comprising the tackle and ruck) remained relatively consistent across matches (e.g., first vs. second halves) and stages (e.g., group vs. knockout) of the elite rugby sevens tournament and was unaffected by match demands 30 seconds prior to the decision, as well as score difference and field location. However, better decision-making accuracy was associated with more optimal referee positioning.

Overall, this PhD thesis advances our understanding of rugby union refereeing, specifically in terms of the physical and physiological match demands when officiating at different competitive levels (e.g., amateur to professional), the adequacy of commonly used fitness tests (i.e., Yo-Yo Intermittent Recovery level 1 and Bronco), and the factors impacting decision-making (e.g., field location, referee positioning). In doing so, this PhD thesis provides important information that can be used by applied practitioners (e.g., strength and conditioning coaches) to improve the fitness and performance of rugby union referees.

PUBLICATIONS

The following is a list of published manuscripts and presentations that have arisen from the work reported in this thesis.

Articles

Sant'Anna Ricardo T., Roberts Simon P., Moore Lee J., Kraak Wilbur J., Stokes Keith A. (2022) Comparing the Yo-Yo intermittent and Bronco tests and their associations with match demands among rugby union referees. *International Journal of Sports Science & Coaching* (accepted). doi: 10.1177/17479541221078280.

Sant'Anna Ricardo T., Roberts Simon P., Moore Lee J., Stokes Keith A. (2021) Referee positioning, but not match demands, score difference, or field location, are associated with breakdown decision-making accuracy in elite rugby sevens referees. *International Journal of Performance Analysis in Sport*. Sep;21(6):1127-1139. doi: 10.1080/24748668.2021.1979824.

Sant'Anna Ricardo T., Roberts Simon P., Moore Lee J., Reid Alex, Stokes Keith A. (2021) Rugby union referees' physical and physiological demands across different competitive levels. *The Journal of Sports Medicine and Physical Fitness*. Jun;61(6):788-796. doi: 10.23736/S0022-4707.20.11447-6. Epub 2020 Nov 4. PMID: 33146494.

Sant'Anna Ricardo T., Roberts Simon P., Moore Lee J., Stokes Keith A. (2021) Physical Demands of Refereeing Rugby Sevens Matches at Different Competitive Levels, *Journal of Strength and Conditioning Research*. Nov 1;35(11):3164-3169. doi: 10.1519/JSC.0000000000003246.

Conference presentations

Sant’Anna Ricardo T., Physical demands of refereeing rugby sevens matches at different competitive levels. *Rugby Science Network Conference*. March 2019. Bath, UK. [Oral presentation].

Sant'Anna Ricardo T., Moore Lee J., Roberts Simon P., Stokes Keith A. (2019). Rugby union referees' external and internal load and heart rate responses during a national sevens tournament - BASES Conference- Leicester, UK, November 2019 [Poster presentation] – Programme and Abstracts. *Journal of Sports Sciences*. 2019;37(sup1):87. (Appendix A)

LIST OF TABLES

Table 1. RFU match officials' level of operation and experience (adapted from Webb, Rayner and Thelwell, 2019)...26

Table 2. Match demands that will be investigated throughout the current thesis. 29

Table 3. Mechanisms of peripheral and central fatigue (Schmidt et al., 2019)..................35

Table 4. Yo-Yo intermittent recovery test level 1 protocol, adapted from Souhail et al. (2010)...66

Table 5. Performance indicators and operational definitions used in Study 4...................69

Table 6. Data related to the physical demands of officiating at different competitive levels, Mean ± SD, (CI95%). 82

Table 7. Referees' characteristics according to the different competitive levels, Mean ± SD. 94

Table 8. Data related to the physical demands of officiating at different competitive levels, Mean ± SD, (CI95%). 97

Table 9. Data related to the physiological demands of officiating at different competitive levels, Mean ± SD, (CI95%)...100

Table 10. Correlation coefficients (r) between external (i.e., total distance covered) and internal load...102

Table 11. Mean ± SD (CI95%) results of the $YYIR_1$ (n = 48) and Bronco (n = 35) tests, and HR, and internal load data comparison during the $YYIR_1$ and Bronco (n = 27) tests. 115

Table 12. Correlations coefficients between performance (n = 32), HR (n = 27), and internal load (n = 27) from the $YYIR_1$ and Bronco tests. 116

Table 13. Internal load relative to time descriptive data for the YYIR1 and Bronco tests (n = 27). 116

Table 14. Mean ± SD (CI95%) match (i.e., physical and physiological) demand data per match [16 referees over 27 matches (1.7 ± 1.5 matches per referee)]. 118

Table 15. Correlation coefficients between $YYIR_1$ (n = 16) and Bronco (n = 11) test results and physical and physiological demands during actual match play. 119

Table 16. Correlation coefficients between physiological response data during the $YYIR_1$ (n = 16) and Bronco (n = 11) tests and physical and physiological demands during actual match play...120

Table 17. Summary of breakdown decision-making accuracy between the first and second halves during the two stages of the tournament (i.e., group and knock-out stages). 137

Table 18. Median (IQR) high-intensity distance, average HR, number of high-intensity accelerations and sprints, and sprint distance, in the 30 seconds before correct and incorrect breakdown decisions. 137
Table 19. Major finding and future directions from each empirical chapter....................155
Table 20. Example field training week schedule for an amateur or semi-professional 15-a-side rugby union referee. 156
Table 21. Example field training week schedule for a professional 15-a-side rugby union referee...156

LIST OF FIGURES

Figure 1. PubMed search of the number of rugby sevens publications from the earliest records (1999) to the last complete year (2020).....41
Figure 2. Participant using STATSports Apex unit and harness.....61
Figure 3. STATSports Apex unit and harness, and Polar heart rate strap used in all studies. 61
Figure 4. Example of individualized HR zones using the STATSports APEX software. ..64
Figure 5. Diagram for the YYIR level 1. 67
Figure 6. Diagram of the Bronco Test. 67
Figure 7. Example of NacSport software buttons template (coding window) used in Study 4.....72
Figure 8. Differences between the different competitive levels in terms of each speed zone showed in the percentage of distance covered. 79
Figure 9. Percentage of distance covered in each speed zone at each competition. 80
Figure 10. Differences between the competitive levels in terms of each speed zone showed in the percentage of distance covered. 99
Figure 11. Percentage of playing time spent in each heart rate zone at different competitive levels. 101
Figure 12. Percentage of time spent in each HR zone during the $YYIR_1$ and Bronco tests. 117
Figure 13. Bland-Altmann plot analysis. 95% of limits of agreement: -386.74 to 386.52-m. 122
Figure 14. Bland-Altmann plot analysis. 95% of limits of agreement: -587.56 to 588.42-m. 123
Figure 15. The schematic used to code the area of the field where the breakdown occurred. 133
Figure 16. The “clock definition” used to code referee positioning as optimal or suboptimal.....134

ABREVIATIONS

ANOVA	analysis of variance
au	Arbitrary Units
BMI	Body Mass Index
bpm	Beats per Minute
Cm	Centimetres
CNS	Computerised Notational Systems
CV	Coefficient of Variance
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HML	High Metabolic Load
HR	Heart Rate
HR_{max}	Maximum Heart Rate
HSD	Honestly Significant Difference
Hz	Hertz
IBM	International Business Machine Corporation
ICC	Intra-Class Correlation Coefficient
IL	Internal Load
IQR	Interquartile Range
Kg	Kilograms
$km \cdot h^{-1}$	Kilometres per Hour
m	Meters
$m.min^{-1}$	Meters per Minute
$m.s^{-2}$	Meters per Second (acceleration/deceleration)
min	Minutes
n	Number
PGMOT	Profession Group Match Official Team
PIs	Performance Indicators
REACH	Research Ethics Approval Committee for Health
RFU	Rugby Football Union
RHIE	Repeated High-Intensity Efforts
RMSE	Root Mean Square Error
s	Seconds
SD	Standard Deviation

SME	Scaled Mean Error
SPSS	Statistical Package for the Social Sciences
TEM	Technical Error of Measurement
TMO	Television Match Official
WCS	Worst Case Scenario
y	Years
YYIR$_1$	Yo-Yo Intermittent Recovery Test Level 1

CHAPTER 1: INTRODUCTION

Rugby union (rugby) is a team field-based intermittent contact sport including high-intensity movements (e.g., sprinting, tackling), combined with low-intensity actions (e.g., walking) (Deutsch, Kearney and Rehrer, 2007; Roberts et al., 2008; Read et al., 2017). Rugby is played throughout the world, with a total of 9.6 million male players and 2.7 million female players at different competitive levels (e.g., amateur, semi-professional and professional) (World Rugby, 2019b). It is played in two different codes on the same field dimensions: 15-a-side and sevens. Fifteen-a-side rugby is contested by two teams consisting of 15 players divided into two groups (i.e., eight forwards and seven backs) according to their role during the match (Roberts et al., 2008). It is played over two halves of 40 minutes, separated by a half-time interval of no more than 15 minutes (World Rugby, 2020). In contrast, rugby sevens is played with seven players (i.e., three forwards, four backs) and matches last 14 minutes, divided in to two seven minute halves with a half-time interval of no longer than two minutes (Ross et al., 2015). Regardless of code, the aim of a rugby match is to score more points than the opposition in accordance with the laws of the game, and there are five methods of scoring points: (1) try (5 points); (2) conversion (2 points); (3) penalty try (7 points); (4) penalty goal (3 points); and (5) drop goal (3 points) (World Rugby, 2020).

Fifteen-a-side rugby became a professional sport in August 1995, and since then has experienced a number of law changes to ensure the game remains attractive to spectators (Austin, Gabbett and Jenkins, 2011a). For example, since 2009, the offside line for backs moved five meters from the scrum, creating more space to play (World Rugby, 2020). Such law changes have contributed to a faster pace of play, increased ball-in-play time, and the game is more physically demanding as a result (Quarrie and Hopkins, 2007; Austin, Gabbett and Jenkins, 2011a; Blair et al., 2018b). Indeed, this has been supported by match statistics over the last decade or two (World Rugby, 2019a). For instance, comparisons over the 20-year period from 1995 to 2015 demonstrated that ball-in-play time during international 15-a-side rugby matches had increased by 33%, and the number of passes had increased by ~60% (World Rugby, 2019b).

The origin of the sevens code dates back to 1883 in Melrose, Scotland, but it was only during 1999-2000 that World Rugby (formally known as International Rugby Board), launched the annual Sevens World Series (Carreras et al., 2013), involving international teams. Since 2016, this series consists of 10 tournaments for the men and six tournaments for the women played over the course of eight months, often paired across consecutive weeks, and is widely considered the highest standard of rugby sevens in the world (Schuster et al., 2018). In this international competition, teams accumulate points based on their finishing ranking in each of the tournaments that comprise the World Series. Following the completion of all tournaments, the team with the highest accumulated points total are crowned the series champions (Henderson et al., 2018). Due to the impacts of the COVID-19 pandemic, the 2021 series will consist of two tournaments instead of the usual ten, while the final number of tournaments for the 2022 series is yet to be confirmed (World Rugby, 2021b). Further standalone pinnacle events such as the Rugby Sevens World Cup, Commonwealth Games, and Olympic Games operate in four-year cycles and take place outside of the Sevens World Series season, requiring additional preparation and careful load management across the annual calendar (Schuster et al., 2018). In contrast to 15-a-side rugby, where matches are typically separated by a week, rugby sevens competitions are often played over two- or three-day tournaments (Higham et al., 2012). Teams play three group stage matches on day one and/or two, typically with ∼3 hours between matches and then, depending on their results, they play up to three matches on the last day (Higham et al., 2012). However, at lower competitive levels (e.g., regional), the format can differ, with tournaments played over one or two days, but still with multiple matches per day.

The multiple daily performances and consecutive days of sevens competition, represents a physical and psychological challenge for both players and officials (Henderson et al., 2018). For example, the ball-in-play time during the 2016 Olympics in Rio de Janeiro was ~50% for both men and women (World Rugby, 2019b), imposing a faster running tempo compared to 15-a-side rugby where the ball-in-play time is typically 45% (Suarez-Arrones et al., 2013b; World Rugby, 2019b). However, the per-match average contact loads and distances covered for backs and forwards in international rugby sevens are relatively low when compared to international 15-a-side rugby (Ross, Gill and Cronin, 2015a). Thus, it would seem important to consider total tournament match demands when comparing rugby sevens and 15-a-side. For example, compared to an 80 minute 15-a-side rugby match, over the course of a tournament, rugby sevens backs and forwards cover ~51% and ~82% more total distance, respectively. Furthermore, rugby sevens backs are involved in ~40% more total contacts than 15-a-side backs, which could lead to post-tournament fatigue being higher in rugby sevens players than some 15-a-side rugby positions (Ross, Gill and Cronin, 2015a)**.** As a result of the greater ball-in-play time in rugby sevens, modern rugby referees need to be physically fit to keep up with the intensity of the play and to apply the laws of the game accurately. Indeed, inaccurate decision-making by rugby referees, regardless of code, can change the course of the game (Kraak, Malan and Van den Berg, 2011a).

Until 1875, the referee was not part of the rugby match (Rugby Football History, 2007), and the application of the laws and decisions were made jointly by the captains of the two teams, who agreed before on which laws would be accepted and, together, made the decisions during the match (De Klerk, 2009). The law 23 in 1846 simply stated that: "The Captains of the respective sides shall be the sole arbiters of all disputes" (Rugby Football History, 2007). There was no mechanism for further appeals in the event that an agreement could not be reached (World Rugby Museum, 2014). However, often the two captains were unable to agree on a specific situation and two umpires were introduced into matches in 1866 (World Rugby Museum, 2014), whose function was to decide only contentious issues. Inevitably, these two umpires could not reach an agreement in certain situations and were often accused of being biased towards one team (De Klerk, 2009). To resolve these issues, a "central" umpire was introduced in 1875 to decide the disagreements that the two captains could not resolve, and when the other two umpires could not reach a consensus (World Rugby Museum, 2014). This confusing system was solved in 1885 when the "central" umpire was given the right to make their own decisions (De Klerk, 2009), and the term "referee" was used for the first time (World Rugby Museum, 2014). The roles of the referee and umpires were distinct and their appointment was mandatory (World Rugby Museum, 2014), with the two original umpires being transformed into touch judges. This name was later changed to "line judges" and today they are called "assistant referees" (De Klerk, 2009).

When the first international match was played, in 1871, the two captains were still in control of the match (De Klerk, 2009). From 1891 to 1906, referees gained more authority to command international matches, and started to use whistles for the first time in 1885, while the line judges used sticks, which were later replaced by flags. Unlike sticks, which were raised to indicate that they agreed with an appeal, the flags were held up only when and where the ball went into touch (World Rugby Museum, 2014). The match between England and Scotland in 1882 was the first to have a neutral referee, who was of a different nationality from the countries involved (De Klerk, 2009). Coincidentally, it was in this match that the first victory of a visiting country took place, with Scotland winning in England. From that date on, neutral referees led international matches in the northern hemisphere, which was not repeated in the southern hemisphere, most likely due to the difficulties of traveling between countries (De Klerk, 2009). However, complaints about biased refereeing began to happen more often in the southern hemisphere. For example, in 1965, South Africa visited Australia and Australian referees Kevin Crowe and Craig Ferguson were accused of being biased (De Klerk, 2009). These disputes and grievances continued until 1975, when the Scottish referee Scot Norman Sanson was the first neutral referee to conduct a match in the southern hemisphere, refereeing South Africa against France in Bloemfontein (De Klerk, 2009). From that date on, neutral referees became a tradition in international matches, until in 2007, the South African Jonathan Kaplan broke this trend, refereeing the match between South Africa and Namibia in Cape Town (De Klerk, 2009).

Nowadays, the referee and assistant referees are known as match officials, and those responsible to enforce the laws during a rugby match at a national and international level are known as the “Team of three” (i.e., a referee and two assistant referees). With the development of technology, and to ensure referees are accurate in their decisions, a fourth official, named the Television Match Official (TMO), was introduced in elite rugby in 2001 (Stoney and Fletcher, 2020). A TMO can use technology to clarify situations relating to: (1) the grounding of the ball in the in-goal area, (2) touch or touch-in-goal in the act of grounding the ball or the ball being made dead, (3) where there is doubt as to whether a kick at goal has been successful or not, (4) where officials believe an infringement may have occurred in the playing area leading to a try or preventing a try, and (5) foul play, including sanctions (e.g., yellow or red card). Any of the acting officials, including the TMO, may recommend a review by the TMO (Stoney and Fletcher, 2020). However, at lower competitive levels (e.g., amateur), it is unlikely that a “Team of three” or a TMO is appointed. Therefore, at lower levels, a sole referee is responsible for maintaining flow and control, and ensuring fair play in accordance with the laws and spirit of the game (World Rugby, 2020). As sports have developed, evolved, and professionalised over time, the role of officials has become more important. This focus on the match official in elite sport has also brought greater attention to officials at lower competitive levels, with outrage over decision-making evident even at amateur levels (Webb, Rayner and Thelwell, 2019). Thus, the performance of rugby referees is critical. Not only are referees responsible for maintaining a safe environment, but they are also expected to ensure that the result of each match is just (Mascarenhas et al., 2005).

In England the national governing body, the Rugby Football Union (RFU), oversees the almost the entire sport (i.e., schools rugby are independent, although typically aligned with RFU guidelines), from community (or grassroots) to elite-level rugby. The RFU has specific development officers who oversee refereeing at national and regional levels, and at the elite-level, the RFU has a National Panel of Match Officials which comprises the best 180 match officials from a total of ~6000 match officials in the country. These referees primarily operate in the national leagues (i.e., from Level 5 upwards) at the top of the league structure (Webb, Rayner and Thelwell, 2019). Rugby referees societies exist to support match officials and are evident at county level throughout England, although some county societies also operate together under a Federation (e.g., Gloucestershire Federation of Rugby Union Referees provides the development pathway for aspiring referees from both Bristol and Gloucester & District Referees' Societies; Webb, Rayner and Thelwell, 2019). The categorisation of match officials on the development and promotion pathway used by the RFU for English competitions is outlined in Table 1.

Table 1. RFU match officials' level of operation and experience (adapted from Webb, Rayner and Thelwell, 2019).

Category	Level	Experience Required
Elite	• Level 1 (Premiership) • Level 2 Championship)	• Member of the Professional Game Match Official Team (PGMOT)
National Panel	• Level 3 (National 1) • Level 4 (National 2)	• Hold the Development Award • Be a member of a Group Scheme • Taken the Level 1 Touch Judge Course • Complete the Advanced Match Official Award (AMOA) Course • Completed the appropriate fitness assessment
National Panel/Regional Group	• Level 5	• Complete the Development Award • Nominated by Society or Federation • Accepted by Group Committee
Federation	• Up to Level 6 (referees join the Federation usually when they are graded at Level 7)	• Complete the Society Match Official Award • Nominated by Society • Accepted by the Federation
Society	• From Level 12 up to Level 6	• Complete the Entry Level Referee Award Stage 1, 2 and 3 • Registered with and observed by a local Society

Despite some research being conducted at an elite-level (Blair et al., 2018b; Bester et al., 2019; Elsworthy, Blair and Lastella, 2020), to date, there is still a lack of published data on the match demands of refereeing community-level rugby (i.e., levels 6 and 7 in the RFU structure), and no study has compared the match demands of rugby referees officiating across competitive levels (i.e., amateur to professional) in one country. Knowing how match demands differ across competitive levels is vital as can inform the fitness requirements for referees when transitioning between levels. Additionally, the continued changes in match characteristics require well-developed fitness qualities for rugby referees to cope with the demands of the match and consequently keep up with play (Suarez-Arrones et al., 2013a). To excel and progress through the levels, a referee must have good fitness, including endurance, power, agility, and speed (Blair et al., 2018a). To ensure that these fitness standards are met, field tests are used to assess the physical and physiological capacity of referees (e.g., Yo-Yo Intermittent Recovery level 1 and Bronco). Indeed, minimum requirements are set by the governing bodies, with an arbitrary minimum score required to officiate at a given competitive level. For example, for a male referee at elite-level rugby, it is deemed acceptable to achieve a level of 18 on the Yo-Yo Intermittent Recovery level 1 (Blair et al., 2018a). However, the use of these arbitrary test scores is not based on empirical evidence, and it is unclear how they relate to match demands. Thus, it is important that the relationship between field test scores and the match demands of rugby refereeing is examined. Additionally, developing a sport-specific conditioning programme requires an understanding of the match demands experienced by rugby referees (Deutsch et al., 1998). Thus, training programmes aiming to improve referees' fitness must target the aforementioned characteristics (e.g., endurance, speed), and be based on field test results, as this information is key to develop the aims of a training programme, plan short- and long-term goals, provide feedback, and motivate referees (Svensson and Drust, 2005).

Beyond exceptional physiological abilities (e.g., endurance, speed), officiating field-based invasion team sports such as rugby requires fast and accurate processing of gameplay information to guide appropriate infringement-based decision-making (Ollis, Macpherson and Collins, 2006). Accordingly, rugby referees must be able to maintain attention and cognitive performance throughout the match to correctly implement the laws of the game (Ahmed et al., 2020). This perceptual-cognitive skill and the ability to make correct decisions could be compromised as physical demands and fatigue increase, particularly during the latter stages of a match or in subsequent matches if officiating multiple matches on the same day (e.g., rugby sevens tournaments; Krustrup and Bangsbo, 2001; Ahmed et al., 2020). Indeed, it has been reported that physical activities (e.g., running) significantly impact information processing and cognition (Tomporowski and Ellis, 1986; Ahmed et al., 2020), and the acute effects on cognitive performance are influenced by the nature, duration, and intensity of exercise (Tomporowski and Ellis, 1986; Del Giorno et al., 2010; Ahmed et al., 2020). For instance, a moderate-intensity exercise could improve performance whereas high-intensity exercise would lead to a decrease in cognitive performance (Brisswalter, Collardeau and René, 2002). It is therefore vital that referees' decision-making is effective, and that the various factors (e.g., ability to meet physical and physiological demands) that influence the decision-making accuracy of referees are better understood (Bloß et al., 2020). Indeed, such information could aid the development of interventions aimed at improving the decision-making accuracy of rugby referees (MacMahon, Starkes and Deakin, 2007; Kittel et al., 2021).

1.1 Match demands of refereeing rugby union

While officiating, rugby referees are required to undertake extensive external and internal loads ensuring they are in an optimal position around play for accurate decision-making (Blair et al., 2018a). External loads refer to the physical work performed during a match (e.g., total, and high intensity distance covered), while internal loads represent the physiological responses to the external loads (e.g., heart rate; McLaren et al., 2018; Elsworthy, Blair and Lastella, 2020). It is understood that greater external loads increase metabolic energy costs and soft tissue force absorption and production, thereby increasing internal loads (McLaren et al., 2018). Therefore, better knowledge of the external and internal loads encountered by referees during a match has the potential to enhance training prescription, periodization, and management through a detailed assessment of training fidelity and efficacy (McLaren et al., 2018).

The physical (i.e., external load) and physiological (i.e., internal load) demands encountered by the referee during a match might impair the perceptual and cognitive process of decision-making (Bloß et al., 2020). For example, high physical and physiological match demands can cause a reduction in attention and executive function, which may impair referees' attentional control and, consequently, their decision-making (Bloß et al., 2020). Additionally, high physical and physiological match demands could cause a reduction in referees' running performance across the course of a match, which is indicative of fatigue (Waldron and Highton, 2014). Indeed, a significant reduction in the distance covered by referees has been found in the last 30-minutes of a match compared to the first 10-minutes

(Suarez-Arrones et al., 2013c). Additionally, fewer sprints were performed, and more time elapsed between consecutive sprints during the second half compared with the first half (Suarez-Arrones et al., 2013c). However, it was not clear whether the reduction in running performance during the second half was because of the referee's fatigue or changes in the pattern of play, as both are likely to influence referees' movement pattern (Suarez-Arrones et al., 2013c). While the detailed examination and discussion of referees' fatigue is beyond the scope of this thesis, the topic of "fatigue" in team sports is an growing research area (Waldron and Highton, 2014; Habay et al., 2021). Table 2 outlines the match demands of interest that will be examined in the following chapters of this thesis.

Table 2. Match demands that will be investigated throughout the current thesis.

Match Demands	
External Load	Internal Load
Physical	Physiological
• Total distance • Relative distance • High-intensity distance • Speed zones • Accelerations/decelerations • Sprinting • Repeated high-intensity efforts • Worst case scenario	• Heart rate • Heart rate zones • Edwards training impulse (TRIMP)

1.2 Thesis aims and objectives

The primary focus of this PhD thesis was to analyse the physical and physiological demands encountered by rugby referees during sevens and 15-a-side matches, using Global Navigation Satellite System (GNSS) technology and heart rate (HR) recordings, and to examine how these match demands differ across competitive levels and relate to field test results (e.g., Yo-Yo Intermittent Recovery level 1 and Bronco) and on-field decision-making accuracy. In doing so, this PhD thesis will provide vital information that can be used by applied practitioners (e.g., strength and conditioning coaches) to optimise the design and content of training programmes for rugby referees. Accordingly, this PhD thesis aimed to:

- Examine how the physical and physiological demands encountered by rugby referees during sevens matches differs across different competitive levels (i.e., amateur to elite).

- Investigate how the physical and physiological demands encountered by rugby referees during 15-a-side matches varies across different competitive levels (i.e., amateur to elite).
- Compare two field tests commonly used to assess the fitness of rugby referees (i.e., Yo-Yo Intermittent Recovery level 1 and Bronco) and examine whether the results of these tests correlate with the physical and physiological demands encountered by amateur rugby referees during 15-a-side matches.
- Investigate if physical and physiological match demands, score difference, field location, or referee positioning are associated with the decision-making accuracy of rugby referees during an elite rugby sevens tournament.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

This chapter will provide an overview of the literature regarding match demands, including theory of movement demands tracking technologies, referees' fitness assessments and decision-making among sport officials. Specifically, the aim is to provide context and justify the importance of academic research among rugby referees.

2.2 Demands of team sports officials

The physical and physiological responses of athletes, and the energetic demands of participation in a range of team sports have been widely described (Martin et al., 2005). Typically, this research has involved the recording of the movement patterns, types of activities, and direct measurements of physical and physiological demands during match play (Martin et al., 2005). For example, in team sports, physical demands can be described by measures of total distance covered (or in specific speed zones), while physiological demands incorporates the physiological response (e.g., HR) that the body initiates to cope with the requirements elicited by the physical demand (Impellizzeri, Marcora and Coutts, 2019). Such information is useful in characterising the physical and physiological requirements of athletes during match play and in designing appropriate training programmes to optimise performance (Martin et al., 2005). However, to date, little attention has been focused on the officials who enforce the laws in these team sports (Martin et al., 2001). This is surprising given that referees have the responsibility to ensure that teams and players always abide by the sport-specific laws, their decisions can have an impact on match outcomes and that fatigue accompanying exercise can affect the accuracy and speed of decision-making (Martin et al., 2001; Bloß et al., 2020).

Increased professionalism in team sports has changed the fitness level of players, reflecting in an increasing competitiveness as teams seek to gain advantage over their opponents (Kraak, Malan and Van den Berg, 2011a; Blair et al., 2018a). Consequently, these changes have produced an increase in the requirements placed on sport officials from a range of sports, including Association Football ("soccer") (Krustrup and Bangsbo, 2001), Australian Football (Kittel, Elsworthy and Spittle, 2019), Rugby League (Emmonds et al., 2015), and Rugby Union ("rugby") (Suarez-Arrones et al., 2013a; Blair et al., 2018b; Bester et al., 2019). Most of these requirements placed on sport officials are best described as high-intensity intermittent exercise, and it is recognized that the ability to maintain repeated bouts of high-intensity exercise, often over extended periods, is crucial to succeed in elite sport (Austin, Gabbett and Jenkins, 2011c). For example, soccer referees perform 161 high-intensity running activities during a match, covering a distance of ~1600m (Krustrup and Bangsbo, 2001). In contrast, rugby union referees spend between 4% and 10% (Suarez-Arrones et al., 2013a) of the time in the high-speed zone and perform ~12 high-intensity accelerations during a match (Bester et al., 2019), while rugby league referees cover ~9000 m a match, consisting of ~500m of high-intensity activities (Emmonds et al., 2015). Finally, Australian Football umpires run between 10500 and 12000 m per match, of which ~20% is considered high speed running (Kittel, Elsworthy and Spittle, 2019). Even though researchers used different methodologies to assess high-intensity activities (e.g., minimum speed reached to be consider a high-intensity effort varies from 18.1 $km \cdot h^{-1}$ to 18.4 $km \cdot h^{-1}$; Suarez-Arrones et al., 2013a; Blair et al., 2018b) for rugby union referees, the physical demands reported highlight the intermittent nature of such team sports and, consequently, the importance of high-intensity intermittent efforts performed by officials. Nevertheless, their ability to repeat and recover from these high-intensity bouts seems likely to be an important influence on referees' officiating performance (Martin et al., 2001).

In terms of physiological responses, heart rate has been commonly used to report and analyse the physiological demands among officials of intermittent team sports and research has revealed that most of the match is performed in zones above 80% of the maximum (Krustrup and Bangsbo, 2001; Martin et al., 2005; Blair et al., 2018a). For example, the mean heart rate during match-play corresponded to 85% of the maximum for soccer referees (Krustrup and Bangsbo, 2001), and ranged between 82% and 85% for rugby union referees (Martin et al., 2005; Suarez-Arrones et al., 2013a; Blair et al., 2018b). Although heart rate can be influenced by external factors (e.g., state anxiety), it is a relatively reliable, practical, and cost-effective method to assess physiological responses among sports officials (Krustrup and Bangsbo, 2001; Blair et al., 2018a). Additionally, the energy cost of an activity can be estimated if the relationship between heart rate and oxygen uptake is known (Martin et al., 2001). Finally, heart rate can be used to assess, monitor, and adjust a targeted training intensity to ensure the effectiveness and safety of an activity (Boudet et al., 2002). Thus, heart rate is an important measure to be used with sport officials as it can be a psychophysiological indicator of one's ability to cope with the demands and requirements elicited by the match (Impellizzeri, Marcora and Coutts, 2019).

2.3 Demands of 15-a-side rugby

Fifteen a side rugby is classified as an intermittent high-intensity sport which involves maximum strength and power outputs, static efforts, collisions and impacts, and high-speed running interspersed with low-intensity efforts and rest periods (Cunniffe et al., 2009; Cunningham et al., 2018). The widespread use of microtechnology such as Global Positioning System (GPS; West et al., 2019) has allowed sports scientists and coaches to assess physical demands during both training and matches (Aughey, 2011; Cummins et al., 2013), with the most common metrics in the English Premiership reported to be distance covered in speed zones followed by high-speed running and total distance covered (West et al., 2019). Typically, players cover distances of between 5000 and 7000 m during matches, with backs covering greater high-speed running distances and forwards getting involved in more impacts (Ziv and Lidor, 2016), collisions, and static work (e.g. mauls and scrums; Roberts et al., 2008).

As well as allowing coaches and researchers to assess match demands during rugby match-play, the use of satellite technology such as GPS has allowed for a better understanding of the physical load players experience, and the use of this data could be used to design training sessions that replicate or indeed even exceed match-play demands in order to enhance performance, and also to analyse differences between competitions (i.e., amateur vs. elite; Cummins et al., 2013; Read et al., 2017; Bridgeman and Gill, 2021). Such investigations have been widely conducted among rugby players, but there is still little research that has been done to investigate referee demands during actual match-play.

2.3.1 Rugby 15-a-side referees match demands

Although the match demands of rugby players have been studied in recent years (Bridgeman and Gill, 2021), there is still a lack of literature regarding the specific demands required for a rugby referee. Indeed, relatively few studies described the physical demands placed on rugby referees during match play, with the total distance covered ranging from 6000 to 8500 m (Martin et al., 2001; Kraak, Malan and Van den Berg, 2011b; Suarez-Arrones et al., 2013c; Blair et al., 2018b; Bester et al., 2019), and relative distance ranging from 74 to 83 $m.min^{-1}$, with most distance covered walking or jogging (< 12 $km.h^{-1}$) (Suarez-Arrones et al., 2013c; Blair et al., 2018b). Although two studies found no difference in the distance covered by rugby referees over consecutive 10-minute periods (Martin et al., 2001; Bester et al., 2019), one study found a 20% reduction in the last 30-minute compared with the first 10 minutes (Suarez-Arrones et al., 2013c). However, it was unclear if this reduction was due to fatigue or changes in the pattern of play, with both likely to impact referee movement (Suarez-Arrones et al., 2013c). Additionally, Suarez-Arrones et al. (2013c) reported small to moderate decreases in high-intensity running demands (>18.1 $km \cdot h^{-1}$) during the middle of a match (30–70 min), with no differences reported between 0 to 10 and 70 to 80 minutes. Teams are afforded the opportunity to substitute players, should coaching staff identify a decline in the physical performance of a player. As such, this may explain the maintenance of higher speed running in players, as those who can not maintain the required standard are able to be removed from play (Blair et al., 2018b). Therefore, the higher-intensity movement profiles of elite rugby union players are typically 'flat' across matches (Waldron and Highton, 2014). It is likely that the continual performance of so-called 'static-exertions' (i.e., non-running energy expenditure), such as tackling, rucking, and mauling is responsible for this finding (Waldron and Highton, 2014). Referees, on the other hand, must demonstrate the ability to maintain their physical performance throughout the a match (Blair et al., 2018a; Blair et al., 2018b). Thus, reduced time spent in higher running speeds towards the end of matches may be a result of physical fatigue (Blair et al., 2018b). In such cases, it is imperative that referees are suitably prepared for the physically demanding aspects of the final stages of a match (Blair et al., 2018b).

Fatigue is indicated by a reduction in maximal force or power that is associated with sustained exercise and is reflected in a decline in performance (Waldron and Highton, 2014). In this instance, "performance" can be identified by the self-regulated movement distance or intensity of the refeeree during a match (Waldron and Highton, 2014). It would appear that both progressive declines in match-running intensity between the first and final stages of matches, and temporary reductions in movement determined by motion-tracking systems (e.g., GPS), have been accepted as valid indications of fatigue (Waldron and Highton, 2014). The potential causes of fatigue during matches are multifaceted and are likely to act in combination to reduce performance (Waldron and Highton, 2014). For example, acute fatigue may occur as a result of either, or a combination of, peripheral and central factors. Peripheral fatigue relates to a biochemical change (distal of the central nervous system) that limits the muscle's capacity to produce work, while central fatigue relates to the reduced central motor 'drive' of the central nervous system (occurring at a spinal or supraspinal level) to recruit available motor units (Waldron and Highton, 2014). Therefore, a decline in running performance at the end of a match may not necessarily be caused by the same mechanism that induces transient fatigue over a given period (Waldron and Highton, 2014).

Refereeing is a task that superimposes a high-intensity exercise demand onto a high perceptual-cognitive demand (e.g., number of decisions that a referee makes during a match), which may cause mental exertion (Schmidt et al., 2019). In this regard, it has been proposed that prolonged mental exertion decreases visual attention and executive functions (e.g., attentional control; Schmidt et al., 2019). Besides the impact of mental exertion on cognitive performance, it should be noted that the concept of fatigue includes the effects of exercise on the muscles and brain. The manifestations of peripheral fatigue in the brain include altered decision-making and decreased attention performance (Schmidt et al., 2019). Therefore, most fatigue associated with exercise involves both peripheral and central nervous system fatigue (Schmidt et al., 2019). A brief review of these mechanisms is provided in Table 3.

Table 3. Mechanisms of peripheral and central fatigue (Schmidt et al., 2019).

Sources of Peripheral Fatigue	**Central Fatigue**
• Accumulation of inorganic phosphate, reducing muscular force	• Changes in body homeostasis
• Accumulation of potassium in the muscle	
• Glycogen depletion	
• Dehydration	
• Environment conditions (i.e., heat or altitude exposure)	

It has been suggested that players regulate their efforts during matches by, for example, down-regulating energy output to preserve energy for later match periods (Waldron and Highton, 2014). However, referees may not have this option as it could compromise their positioning and thus decision-making (Elsworthy, Burke and Dascombe, 2014; Blair et al., 2018a). Although it is known that player exercise varies within matches, there are no investigations that have linked player demands to referee physical performance (Blair et al., 2018a). Therefore, further research is needed to reveal whether or not a referee's lower running performance towards the end of a match is due to reduced demands of play or referee fatigue (Suarez-Arrones et al., 2013c; Blair et al., 2018a).

2.3.2 Rugby 15-a-side referees match physical demands (external)

One study investigated elite International Spanish and Portuguese referees over a nine month period during the national 15-a-side season (Suarez-Arrones et al., 2013c). The findings showed that the total distance covered by the referees was 6322 ± 564 m, with a range of 5459 to 7426 m. As a percentage of total distance, 37% (2356 ± 291 m) was spent walking, 24% (1524 ± 229 m) jogging, 10% (656 ± 130m) running at low intensity, 17% (1110 ± 212 m) at medium intensity, 5% (347 ± 27m) at high intensity, and 5% (328 ± 230m) sprinting. A significant decrease in running performance was observed between the first and second halves in the three highest intensities. These distances were lower than in a previous study with English Premiership referees (Martin et al., 2001), that estimated an average total distance of 8581 m covered by the referee. The explanation for these differences could be the differing playing patterns in the Spanish top division compared with that in the English Premiership, and the different data collection method used (i.e., notational analysis vs. GPS; Suarez-Arrones et al., 2013a). In the study by Martin et al. (2001), which evaluated nine referees who were ranked in the top 20 referees in England over a total of 19 matches, the average total distance per match was 8581 ± 668 m and the mean percentage of total playing time spent in each activity was: (1) standing still = 37 ± 11%; (2) walking forward = 29 ± 7%; (3) walking backward = 9 ± 3%; (4) jogging = 12 ± 3%; (5) running = 9 ± 2%; and (6) sprinting = 1%. The results suggest that refereeing top English rugby union matches is physically demanding due to short-duration sprint bouts, and the associated accelerations and decelerations, which places additional metabolic demands on referees. Additionally, their ability to repeat and recover from these high-intensity bouts seems likely to be an important influence on their refereeing performance (Martin et al., 2001).

Another study evaluated eight referees who participated in the 2007 National Club Rugby Championship held in Stellenbosch, South Africa (Kraak, Malan and Van den Berg, 2011b). The referees were monitored during a total of 16 matches using one video camera for each match. Since no GPS was used in this study, the distance covered by the referee was not measured, but running intensities were subjectively determined from the video footage. Thus, the relevant finding of this study was that the rugby union referees performed less sprinting activities and more standing still, walking, jogging, and lateral movement activities in the second half of the match compared to the first half (Kraak, Malan and Van den Berg, 2011b). Due to the limitations of this study, the reasons for this decrease in movement patterns was not established, although it could be due to referee's fatigue or changes in the pattern of match play, as both can influence the referee's movement patterns. However, is worth nothing that direct comparisons between studies need to be done cautiously, due to different methodologies applied (e.g., GPS vs. video analysis). Additionally, although the same population has been studied (i.e., rugby referees), they have been assessed at different time points (e.g., different period in a season) and in various countries at different competitive levels (e.g., elite vs amateur), likely resulting in different match demands placed on referees.

Due to the highly intermittent and varied nature of play in a rugby match, the ability to repeat high intensity efforts with short recovery time is considered as a major determinant of performance (Deutsch, Kearney and Rehrer, 2007; Vachon et al., 2021). To date, only three studies have described the percentage of time spent by rugby referees performing highly energetic activities and sprinting (Martin et al., 2001; Kraak , Malan and Van den Berg, 2011a; Blair et al., 2018b), with a further two studies reporting the number of sprints (i.e., ~20 sprints per match at > 20.1 $km.h^{-1}$; Suarez-Arrones et al., 2013c; Bester et al., 2019). Although the average number of sprints reported may provide valuable information on the overall physical match demands, it provides limited insight into the referee's ability to perform short-duration sprints (i.e., high-intensity effort) over a brief period (Spencer et al., 2004). To date, no study has investigated repeated high-intensity efforts among rugby referees. Since the ability to perform and recover from repeated high-intensity efforts has been suggested to be an important fitness component of team sports (Spencer et al., 2004), the specific nature and composition of this activity (i.e., frequency, duration, time between bouts, etc.) among rugby referees is still unclear. Spencer et al. (2004) investigated the repeated sprint demands of elite field hockey players and found the number of sprints completed within a repeated sprint bout ranged between 3 and 7. Additionally, ~25% of the recovery periods between sprints were less than 21 s in duration (Spencer et al., 2004). Therefore, a minimum of three high-intensity activities with less than 21 s of recovery seems an appropriate definition to analyse repeated high-intensity bouts, as this may represent a typical period of intense repeated high-intensity activity (Spencer et al., 2004).

While more detailed information relating to the distance covered by rugby referees in high-speed running is lacking, some studies suggested that reporting match average activities can have limited relevance in athlete preparation, as applying such values towards training may not expose players (or referees) to the most intense periods which occur intermittently during matches (Delaney et al., 2015; Novak et al., 2021). Thus, to capture those periods – often referred to as the “worst case scenario” (WCS) – is important, as it can be used as benchmarks for exercise replication (Delaney et al., 2015; Novak et al., 2021). Although different methods to capture the WCS have been used (e.g., analysing periods of repeated high-intensity efforts; Johnston, Gabbett and Jenkins, 2014), the intent appears the same, which is to capture the most intense activity experienced during match-play, so that the same stimulus can be reproduced in training (Novak et al., 2021). One study used the maximum ball-in-play time as the most physically demanding period a referee could face (WCS; Igoe and Browne, 2019b). In this study, less than 2% of time in the WCS was spent in high-speed running, and so it seems inappropriate to define the most extended passage of play as the most demanding part of the match. Thus, a definition of WCS which uses the single longest bout of repeated high-intensity efforts performed by the referee, is likely to provide a more valid estimate of the WCS (Johnston, Gabbett and Jenkins, 2014), as it is likely to be much longer and incorporate more high intensity efforts, than the average reported for repeated high intensity efforts bouts and the maximum ball-in-play time (Austin, Gabbett and Jenkins, 2011b; Reardon et al., 2017). However, the WCS appears to be highly individual (i.e., two referees completing the same scenario are unlikely to respond the same physiologically; Novak et al., 2021). Therefore, caution is advised on the use of WCS for training and setting targets, and the concept of the WCS has not been well defined to date, thus requiring further investigation (Novak et al., 2021).

2.3.3 Rugby 15-a-side referees match physiological demands (internal)

The concept of internal load incorporates all the psychophysiological responses occurring during the execution of the exercise, and HR has been shown to be a valid measure of internal load (Impellizzeri, Marcora and Coutts, 2019). HR is widely used to prescribe training programmes to athletic populations. However, it is important to be able to differentiate between percentage of maximum HR and percentage of HR reserve, due to the fact that HR does not have absolute zeros, and maximum values vary depending on the individual (Solheim, Keller and Fountaine, 2014). HR reserve is defined as the maximal HR minus the resting HR, and has been reported a more accurate measure of training prescription for moderate exercise (Weltman et al., 1990; Solheim, Keller and Fountaine, 2014). However, for high-intensity intermittent activities, such as rugby refereeing, the use of HR reserve for training prescription might lose accuracy, especially for intensities near or above the lactate threshold (Weltman et al., 1990; Solheim, Keller and Fountaine, 2014). Additionally, the measure of resting HR has some limitations, especially if collected without a HR monitor (i.e., collected using radial pulse), leading to an inaccurate calculation of the real HR reserve and consequently the percentages of HR reserve to be used in training (Solheim, Keller and Fountaine, 2014). Therefore, the use of percentage of maximum HR is a simpler and more convenient method to control training intensities and has been recorded and analysed in sports officials from several high-intensity intermittent team sports (Blair et al., 2018a).

Mean HR values for rugby referees are, overall, consistent in the literature, with an average of approximately 150 beats per minute (bpm) (Martin et al., 2005a), although an investigation with club level matches in South Africa revealed surprisingly low mean HR responses between 122 and 141 bpm (Kraak, Malan and Van der Berg, 2011a). However, the mean HR values reported for rugby union referees are similar to those reported for soccer (Krustrup and Bangsbo, 2001) and rugby league (Emmonds et al., 2015) referees. Although mean HR data are useful, a better understanding about physiological response is gained when this value is converted to a percentage of maximum HR (%HR_{max}), and times spent above and below specified zones at percentages of HR_{max} are examined. Time spent in various HR zones provides an indication of the anaerobic nature of officiating rugby, revealing that for most of the match, HR is spent in the zones above 80% HRmax (Martin et al., 2005; Suarez-Arrones et al., 2013a; Blair et al., 2018b). Indeed, Martin et al. (2005) reported ~50% of game time in this zone for English Premiership rugby referees, which is similar with the ~53% reported for elite international referees (Bester et al., 2019), ~40% for Spanish and Portuguese elite referees (Suarez-Arrones et al., 2013c), and ~60% for Super Rugby referees (Blair et al., 2018b). Such differences in the amount of time spent in different HR zones provides further evidence of the contrasting demands or requirements when officiating matches at different competitive levels in various parts of the world.

Although one study has examined how match demands differ between referees of varying experience, revealing that inexperienced referees jogged and sprinted more than experienced referees (Kraak, Malan and Van den Berg, 2011b), most research has only described the match demands of refereeing rugby at an elite level (Blair et al., 2018b; Bester et al., 2019). Indeed, to date, no study has investigated whether match demands differ across rugby referees officiating at different competitive levels (e.g., elite vs. amateur). Such information is vital as would add to the knowledge of the match demands at different competitive levels and would contribute to the preparation of the referee to officiate at a given competitive level.

2.4 Rugby sevens

The multiple daily performances and consecutive days of a rugby sevens competition represents a physical and psychological challenge that are not commonly encountered at the elite-level of 15-a-side rugby. In addition to the intra-tournament recovery challenges, rugby sevens tournaments are often scheduled on two consecutive weekends, followed by a three to seven week break from competition (Henderson et al., 2018). As such, teams are required to undertake significant travel to the tournaments, varying from as little as one hour to more than 24 hours of accumulated flight time and, this has been suggested to influence the performance of elite-level team-sport athletes such as rugby sevens players (Mitchell, Pumpa and Pyne, 2017). However, at lower competitive levels, the format of rugby sevens tournaments can differ, with competitions being played and officiated over one or two days, but still with multiple matches being played and officiated per day.

Once viewed as a novelty variation of 15-a-side rugby union, rugby sevens now exists as an Olympic sport. Players at the professional level are more commonly becoming contracted as full-time sevens players and train to the specific demands of rugby sevens (Henderson et al., 2018). The inclusion of rugby sevens in 2016 Rio Olympics resulted in a growth in popularity from spectators and researchers, and as a result, the number of research studies into rugby sevens has increased substantially in recent years (Suarez-Arrones et al., 2016; Tucker, 2016) (Figure 1).

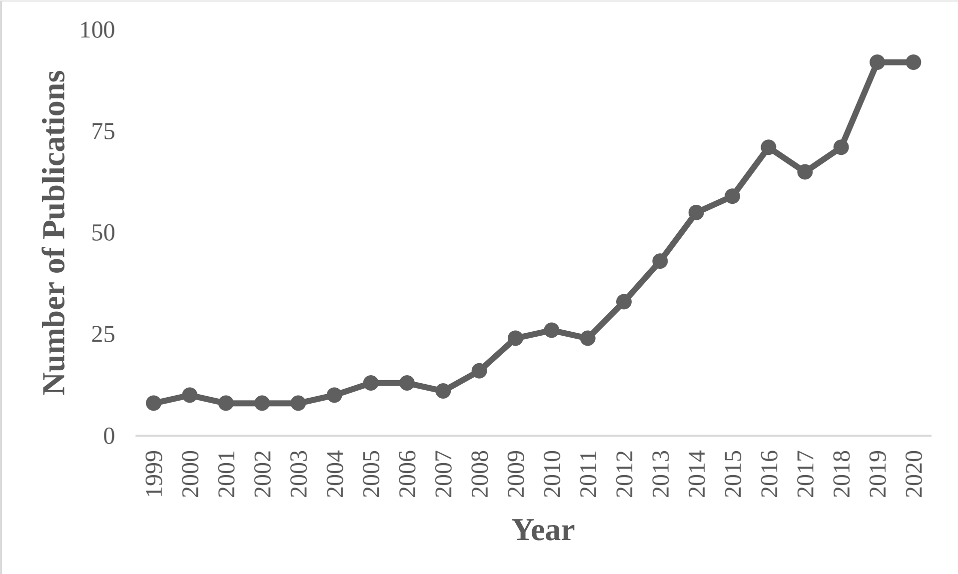


Figure 1. PubMed search of the number of rugby sevens publications from the earliest records (1999) to the last complete year (2020).

2.4.1 Rugby sevens referees match demands

The ability of the referee in rugby sevens to keep up with play and to be in good position is critical in enabling correct decisions to be made. Thus, the ability of the rugby sevens referee to meet the physical and physiological demands imposed during match play is believed to be a necessary prerequisite for optimal positioning and successful refereeing (Suarez-Arrones et al., 2013a), and, as a result, contributes to a better, safer, and more enjoyable match. The unique features of rugby sevens, including the lower number of players, the same pitch dimensions and the shorter game duration, likely impose distinct physical and physiological demands for referees compared to 15-a-side rugby (Suarez-Arrones et al., 2013a), namely, higher running demands interspersed with short periods of recovery in between high-intensity efforts (Higham et al., 201b; Suarez-Arrones et al., 2012a; Suarez-Arrones et al., 2012b). However, to date only a few studies have examined the physiological demands of refereeing rugby sevens matches (Suarez-Arrones et al., 2013a; Suarez-Arrones et al., 2013b; Nazarudin et al., 2017). These studies have shown that officiating rugby sevens matches is characterized by relatively higher running demands (e.g., maximal speed), and suggesting that the physiological demands of officiating rugby sevens are greater relative to the playing time than those for 15-a-side rugby union. The lower frequency of game-related non-locomotive activities, such as rucks or scrums, are believed to be partly responsible for the increased running demands in rugby sevens (Luis Suarez-Arrones et al., 2013a).

The first study to characterize the match demands and associated physiological strain of referees during rugby sevens competition was conducted by Suarez Arrones and colleagues (2013a). In this study, twelve referees were monitored during 38 matches in two international rugby sevens tournaments. All the referees monitored in this study were refereeing at the top level in Spain or Portugal and some of them also at the top level in Europe. All referees had a minimum of four years of refereeing experience. The referees were asked to carry a GPS unit (SPI Pro X; GPSports Systems, Canberra, Australia) during the game and GPS data were recorded at 15 Hz frequency and accelerometer data to 100Hz. Time-motion data from all referees were retained and coded into the following categories and speed thresholds: standing and walking (0.1 – 6.0 km.h^{-1}), jogging (6.1 – 12.0 km.h^{-1}), cruising (12.1 – 14.0 km.h^{-1}), striding (14.1 – 18.0 km.h^{-1}), high-intensity running (18.1 – 20.0 km.h^{-1}), and sprinting (> 20.1 km.h^{-1}). Exercise intensity was quantified by monitoring HR during each match. Heart rate was continuously measured with short-range telemetry (SPI Pro X; GPSports, Canberra, Australia), and was expressed in relation to individual maximal heart rate (HR_{max}) estimated through the equation: 208 – 0.7 x age (Tanaka, Monahan and Seals, 2001).

The average total distance covered by the referees per match was 1665 ± 203 m with a range of 1332 to 2002 m. As a percentage of total distance, 22% (372 ± 49 m) was covered standing or walking, 25.9% (431 ± 93 m) jogging, 12.4% (206 ± 53 m) cruising, 23.8% (395 ± 694 m) striding, 8% (133 ± 62 m) at high intensity, and 7.6% (127 ± 87 m.) sprinting. The average speed was 6.6 ± 0.8 km.h^{-1}, and the referees' work-to- rest ratio was 3.5:1 (i.e., for every 3.5 m covered at moderate- and high-intensity speed [> 6.1 km.h^{-1}], 1 m was covered at low intensity [0.1–6.0 km.h^{-1}]). There were few significant differences between the first and the second halves apart from average HR, which was lower in the first half (154 ± 11 b.min^{-1}; 83 ± 6% of the estimated HR_{max}) than the second half (160 ± 9 b.min^{-1}; 86 ± 5% HR_{max} of the estimated). Moreover, a higher HR_{max} was recorded in the first half than the second half (177 ± 10 vs. 171 ± 12 b.min^{-1}), with referees attained average values of HR_{max} of 174 ± 11 b.min^{-1} (94 ± 6% of the estimated HR_{max}). Finally, differences were observed between halves in some HR zones, with the second half being lower in zone 1 (> 60% HR_{max}) and 3 (71 - 80% HR_{max}) and higher in zone 5 (91 - 95% HR_{max}) compared to the first half. On average, referees spent most of the time in zone 4 (81 – 90% HR_{max}). A limitation of this study was that the referees were only evaluated at one competitive level, and therefore no comparison could be made between different competitive levels (e.g., elite to amateur). Such comparisons can provide vital information that can be used to optimize the training and preparation of referees for rugby sevens tournaments, and ensure such training is suitable for the competitive level.

The unique aspect of a sevens tournament (i.e., several matches in a day, consecutive days of competition) is a physical challenge for rugby sevens referees, as successive matches may compromise their physical performance (Suarez-Arrones et al., 2013b). Indeed, to date, only one study examined the effect of several matches within a day on the running performance and HR of referees during a National Rugby Sevens Championship (Suarez-Arrones et al., 2013b). The results showed that consecutive match play within a day resulted in a progressive (from match 1 to match 3) deterioration in running performance (Suarez-Arrones et al., 2013b). Although this reduction in performance could be due to tactical demands or other match-related factors (e.g., players fatigue), it is worth noting that a previous study on international Rugby Sevens players showed a preservation of running performance between the first and last match of a multiday tournament, suggesting that the potential fatigue accumulated during matches in players was transient, with minimal impact on running performance (Higham et al., 2012). Thus, it seemed that residual fatigue from match to match was evident in rugby sevens referees. While experience in tactical positioning may allow referees to keep up with the tempo of the match, that such reductions in physical performance could adversely affect decision-making accuracy (Suarez-Arrones et al., 2013b). Additionally, in parallel with the observed reductions in running, the referees' HR was lower in the second and third matches, which may be associated with decrements in running performance and muscular fatigue (Suarez-Arrones et al., 2013b). Overall, the results suggested that rugby sevens referees' fitness training should aim at maintaining the capacity to perform high-intensity running actions to promote fatigue resistance in the latter matches of the day. Moreover, recovery strategies (e.g., hydration, food intake) would be advisable for referees to maintain running performance over a rugby sevens tournament (Suarez-Arrones et al., 2013b).

2.5 Field testing

2.5.1 Purpose of testing

Performance in most sports is the result of several factors, including genetic attributes as well as training and health status of the athlete (Svensson and Drust, 2005). The sports scientist can, through fitness testing, analyse these factors and use the information to provide individual profiles of their respective strengths and weaknesses (e.g., aerobic fitness). If individuals have weaknesses in any particular fitness component relative to their sport, they can be detected during the completion of fitness tests and subsequently remedied by employing appropriate training (Svensson and Drust, 2005). Further tests enable practitioners to monitor individual development and can then be used to evaluate the impact of training interventions on the individual's fitness profile, thereby evaluating the effectiveness of the programme (Gabbett, 2005; Dobbin et al., 2018).

Fitness testing of athletes participating in team sports has become more common because of the increased awareness of the benefits attained from a scientific approach to training (Boddington et al., 2001). Fitness tests that are conducted outside of the laboratory offer the sports scientist, coach, and athlete an accessible method of determining specific fitness components relevant to their sport (Boddington et al., 2001). The results from a fitness test provide valuable feedback both on the usefulness of the intervention programme and on the responses of each athlete (Svensson and Drust, 2005). It is also important that performance on the test mimics the physical performance in the real event (Hopkings, Hawley and Burke, 1999). These issues are addressed by determining the reliability and the validity of the test (Boddington et al., 2001; Svensson and Drust, 2005). Reliability is defined as a characteristic of a measurement or experimental procedure, which produces similar results on two or more separate occasions without any change in fitness (Boddington et al., 2001). The test will only be reliable if the intrinsic variation of the test is less than the variation in the athlete's fitness between test sessions. Hopkins Hawley and Burke (1999) noted that the most reliable tests with the best athletes have a coefficient of variation in performance of about 3%. Clearly, the reliability of a fitness test is crucial when deciding on its ability to detect subtle changes in physical performance after a period of physiological, psychological or nutritional intervention (Boddington et al., 2001). The validity of a test is defined as the extent to which a component of fitness is accurately measured (Heale and Twycross, 2015), and has been commonly determined by assessing the relationship using correlation analysis between performances on the test and physical performance in the actual event. If the correlation is high, the usual perception is that the test is valid (Svensson and Drust, 2005). Additionally, the specificity of the test (i.e., the ability of a test to correctly assess the athlete fitness for the sport in question) should also include an assessment of the relevant energy system(s) that predominate in the support of the specific activity (Svensson and Drust, 2005).

2.5.2 Testing rugby referees using field tests

While laboratory tests are used to evaluate fitness in standardized conditions (e.g., VO_{2max}) the performance of intermittent sports demands is very difficult to replicate in this laboratory environment. Therefore, it is essential to consider the use of field-based tests, which transfer the assessment to a more realistic setting (Bouzas-Rico et al., 2021), and are more time-efficient and cheaper to implement. As a result, refereeing international governing bodies, such as World Rugby, as well as several of the main national federations (e.g., Rugby Football Union), systematically evaluate the physical fitness of their affiliated referees through field-based tests (Weston et al., 2012; Blair et al., 2018a; Bouzas-Rico et al., 2021).

Fitness tests that are performed in the field enhance the specificity of the evaluation, which, in turn, increases the validity of these tests (Svensson and Drust, 2005). The fitter the rugby referee is, the more likely they are to be in optimal positions to make accurate decisions (Mallo et al., 2012). Therefore, minimum mandatory fitness requirements for referees using field tests (e.g., Yo-Yo intermittent recovery test level 1 [$YYIR_1$]; Blair et al., 2018a) are set by rugby governing bodies, whereby referees who achieve these standards are deemed to have appropriate fitness to cope with the match demands for a given competitive level. However, how the results of these tests relate to rugby referees' match demands (i.e., direct validity), is unclear. Indeed, studies with soccer referees have reported poor correlations between field test measures (e.g., mean HR during the high-intensity 150 m interval test) and match demands (e.g., total distance covered and time spent running at high speed; (Mallo et al., 2009). Therefore, given the nonspecific nature of the field tests used to assess the fitness of rugby referees (e.g., $YYIR_1$), it is important that the relation between field test results and actual match demands are examined. Indeed, if the current tests being utilised are found to have little relation to match demands, then alternative fitness tests may be needed.

2.5.2.1 The Yo-Yo intermittent recovery test

The development of the YYIR test was inspired by the Legér multistage fitness test (Leger and Lambert, 1982). As in the Legér test, the participants in the YYIR test run 20 m shuttles. However, each shuttle is interspersed with a recovery period (Bangsbo, Iaia and Krustrup, 2008) to make it more specific to the phases of recovery in a team sport match.

Thus, the YYIR test consists of 2 × 20 m shuttle runs at increasing speeds, interspersed with a 10 second period of active recovery (controlled by audio signals). An athlete runs until they are not able to maintain the speed, and the distance covered at that point is noted as the test result (Bangsbo, Iaia and Krustrup, 2008). There are two levels to the test: level 1 starts at a lower speed than level 2, and the increases in speed in level 1 are more moderate than for the level 2 test. Both levels of the test have rapidly become some of the most extensively studied fitness tests in sports science (Bangsbo, Iaia and Krustrup, 2008). Due to their specificity and practicality, the tests have also been widely applied in many team sports to assess players' abilities to repeatedly perform high-intensity exercise (Bangsbo, Iaia and Krustrup, 2008; Schmitz et al., 2018).

The validity and reliability of the YYIR test were established by Krustrup et al. (2003) among elite Danish soccer players. They reported no difference in performance (i.e., 1867 ± 72 vs. 1880 ± 89 m) between a first and second YYIR test conducted within a week of each other. The authors found significant correlations ($r = 0.71$) between performance on the YYIR test, and the amount of high-intensity running performed during a soccer match. Additionally, a significant improvement (i.e., 25%) in test performance was reported just before the season started compared with before the pre-season fitness training phase (Svensson and Drust, 2005). Moreover, the test simulates both aerobic and anaerobic glycolysis, as the players' heart rates and blood lactate concentrations are elevated at the end of the test (Svensson and Drust, 2005). Finally, there was a high breakdown of phosphocreatine at test end (i.e., 51% lower compared with rest), which suggests that the phosphagen energy system was also taxed during the test (Svensson and Drust, 2005).

The Yo-Yo intermittent recovery level 1 ($YYIR_1$) test (Bangsbo, Iaia and Krustrup, 2008) is regularly used to estimate aerobic power (i.e., oxygen uptake during dynamic exercise), providing an indirect indication of the physical capacity of intermittent team sport athletes (Krustrup et al., 2003; Blair et al., 2018a). When the standards for the $YYIR_1$ test were established, they were used globally to evaluate the capacity to repeatedly perform and recover from intense activity (Krustrup et al., 2003; Bangsbo, Iaia and Krustrup, 2008; Blair et al., 2018a). It is within this context that this test is used for rugby referees. For instance, for a male referee at an elite competitive level, the ability to repeatedly perform and recover from intense activity, is deemed acceptable if they achieve a $YYIR_1$ test level around 18 (Blair et al., 2018a). This standard is similar to the results obtained for elite male soccer referees with studies revealing $YYIR_1$ test levels of 18.7 (Krustrup et al., 2003), and 18.2

(Castagna, Abt and D'Ottavio, 2005). Although acceptable $YYIR_1$ test levels have been suggested for elite male and female rugby referees (i.e., levels 18 and 15, respectively; Blair et al., 2018a), to date, no empirical research has supported these standards.

2.5.2.1 – The 1.2 km shuttle run test

The 1.2 km shuttle run test (1.2_{SRT}), also known as the Bronco test, was originally described by Kelly and Wood (2013), and is gaining popularity in applied rugby contexts (Deuchrass et al., 2019). Whilst research on the Bronco test is still emerging, the test protocol itself, which consists of continuous 20 m, 40 m, and 60 m straight shuttle runs, completed five times at a maximal intensity (i.e., 20 m and back, 40 m and back, 60 m and back), consists of similar variables to other tests (e.g., $YYIR_1$), such as accelerations, decelerations, changes of direction, and aerobic and anaerobic capacity, despite being continuous and removing the inter-shuttle recovery aspects which are characteristics of intermittent sports (Kelly and Wood, 2013; Brew and Kelly, 2014). Recently, this test has been used to assess rugby referees' fitness levels, as it requires only basic equipment (e.g., stopwatch and cones), and can be run on marked rugby fields, improving the test's usability. Moreover, it takes only 5 to 6 minutes to complete, compared with ~20 minutes for the $YYIR_1$ (Kelly, Jackson and Wood, 2014; Deuchrass et al., 2019). Additionally, the Bronco test can be used to determine maximal aerobic running speed (Kelly, Jackson and Wood, 2014; Deuchrass, 2019). However, the Bronco test is often performed outdoors as it requires at least 60-m of ground, thereby increasing the influence of weather conditions (e.g., wind and rain) and reducing its reliability across repeated tests (Deuchrass et al., 2019). In contrast, the $YYIR_1$ test can be completed indoors as it requires less space (i.e., 25-m), which enhances its reliability due to the less variable surface and weather conditions (Deuchrass et al., 2019). That said, the Bronco is a highly practical test, and it has been shown to strongly correlate with the $YYIR_1$ test (r = -0.87) among elite youth rugby players as well as with maximal running speed (r = 0.88) attained using the 30 – 15 Intermittent Fitness Test Deuchrass et al., 2019). However, the relationship between these field tests and the actual match demands placed on rugby referees (i.e., direct validity) has not yet been investigated. This information is important because direct validity is considered an essential pre-requisite of an accurate sport-specific field test (Boddington, Lambert and Waldeck, 2004).

2.6 Refereeing Decision-making

In the domain of sport, officials are required to oversee the competitive environment to ensure athletes are competing in a fair and safe manner. Officials such as Australian football (AF) umpires, soccer referees, and rugby referees are classed as "interactor officials", where they experience a high combined physical and perceptual-cognitive (i.e., decision-making) demand during match play (Kittel, Elsworthy and Spittle, 2019). Officiating field-based invasion team sports such as Australian football, soccer, and rugby is a demanding task that requires fast accurate processing of match-play information to guide infringement-based decision-making (Larkin et al., 2014). Sports officials are responsible for ensuring that teams and players always abide by the sport-specific laws and intervene when a team or player infringes a law (Bloß et al., 2020). Therefore, a central task in sports officiating is to make decisions about technical, offensive, and defensive infringements (Bloß et al., 2020). As referees' decisions can ultimately impact match outcome (Larkin et al., 2014; Bloß et al., 2020), it is vital that referees' decision-making is optimal (Bloß et al., 2020). This includes that referees are able to apply the sport-specific laws during the entire match; that is, they need to have a well-developed physical fitness to keep up with the match dynamics when officiating (Bloß et al., 2020). Additionally, higher anxiety results when officials perceive themselves to have made a mistake, reinforcing the importance of highly developed decision-making skill (Kittel, Elsworthy and Spittle, 2019).

To provide a true representation of a referee's decision-making performance, investigations need to consider the relationship between decision-making and physical and physiological demands during actual match play (Larkin et al., 2014). To date, only a limited number of studies have been carried out during actual match play among rugby league (Emmonds et al., 2015) and soccer (Riiser et al., 2019) referees, as well as Australian football umpires (Elsworthy, Burke and Dascombe, 2014). For instance, Emmonds et al. (2015), observed no significant relationships between distance covered, high-intensity running efforts, mean heart rate, and decision-making accuracy among rugby league referees. Additionally, Riiser et al. (2019) found that running performance was not related to decision-making accuracy in soccer referees, concluding that the referees had the fitness required to keep up with play and maintain their decision-making accuracy. However, Elsworthy, Burke and Dascombe (2014) found that the running speed recorded for Australian football umpires immediately prior to a free kick being awarded was significantly higher for incorrect decisions than correct decisions, suggesting that increased physiological loads may impede decision-making accuracy (Elsworthy, Burke and Dascombe, 2014). Given these mixed findings and the fact that they are limited to rugby league, Soccer, and Australian football, further investigations are required, particularly in other sports such as rugby union. Furthermore, most studies have examined the relationship between external load and decision-making, rather than internal load (Bloß et al., 2020). This may be problematic because external load is more of a description of a physical task (e.g., distance) (Bloß et al., 2020). Internal load, however, is an individual's psychophysiological response to external load (Impellizzeri, Marcora and Coutts, 2019; Bloß et al., 2020). Thus, different referees can experience the same external load (e.g., operationalized by match period) differently (Impellizzeri, Marcora and Coutts, 2019; Bloß et al., 2020).

Beyond match demands, some studies have investigated the associations between match period and decision-making accuracy in soccer (Mascarenhas et al., 2009; Mallo et al., 2012; Riiser et al., 2019) and futsal (Ahmed, Davison and Dixon, 2017) referees, as well as Australian football umpires (Elsworthy et al., 2014; Larkin et al., 2014). However, to date, the findings have been inconsistent. For example, Mallo et al. (2012) observed that decision-making accuracy was lowest for soccer referees in the last 15 minutes of a match, suggesting that fatigue during the final stages of a match might influence decision-making. Moreover, Ahmed, Davison and Dixon (2017) found more incorrect decisions and missed fouls during the second half of matches by futsal referees. However, the reasons for the results are unclear, with the authors suggesting that they could be due to changes in the intensity of the match (i.e., player fatigue) or referee fatigue (Ahmed, Davison and Dixon, 2017). Conversely, Mascarenhas et al. (2009) reported that the lowest accuracy of New Zealand soccer referees occurred in the opening 15 minutes of each half, attributing poorer decision-making to a lack of mental warm-up techniques immediately prior to each half. In contrast, Elsworthy et al. (2014) reported that Australian football umpires' accuracy was consistent across all four quarters of a match, while Larkin et al. (2014) found that Australian football umpires' decision-making accuracy improved during the fourth quarter, possibly due to the key time and context of the matches. Since rugby sevens is a unique sport to officiate because of the combined fitness and decision-making requirements during multiple days of competition, the application of evidence from other sports may be incongruent for the decision-making of rugby sevens referees. Therefore, further investigations are required to explore the possible relationship between match period (i.e., first and second halves), days of competition (i.e., group and knock-out stage), and the decision-making accuracy for rugby sevens referees.

Some studies have examined the associations between the difference in score between teams and referees' decision-making accuracy among Australian football umpires

(Corrigan et al., 2019) and soccer referees (Lago-Peñas and Gómez-López, 2016). Specifically, Corrigan et al. (2019) found that score differential between two teams did not affect the number of correct (i.e., accurate decisions), missed (i.e., decisions that should have been made, but were not), or unwarranted (i.e., decisions that were made, but should not have been made) decisions, but it did affect the error rate of Australian football umpires. Specifically, as the score differential increased, umpire's decision-making accuracy improved, and the umpires were less likely to miss decisions or make unwarranted decisions (Corrigan et al., 2019). Additionally, Lago-Peñas and Gómez-López (2016) indirectly implied that score difference might influence soccer referee decision-making. Specifically, they found that the greater the score difference, the less extra time was added. However, when the score difference was small between teams, referees tended to add more extra time if a higher level team were losing, and less time if they were winning (Lago-Peñas and Gómez-López, 2016). No study has yet investigated if the score difference could have some influence on the decision-making of rugby referees. Thus, more work to enhance understanding of such association would be worthwhile.

Another factor to consider is the influence of field location on decision-making accuracy, which has been assessed among Australian Football umpires (Elsworthy et al., 2014; Corrigan et al., 2019) and soccer referees (Gómez Carmona and Pino Ortega, 2016; Castillo et al., 2019b). Specifically, Australian football umpires were found to make a larger number of decisions in the midfield of play, when compared to the two end zones (Elsworthy et al., 2014; Corrigan et al., 2019). Additionally, incorrect decisions made in the end zones favoured the defending team, due to fewer than expected missed decisions and more than expected unwarranted decisions (Corrigan et al., 2019), suggesting that umpires may prevent a team from scoring by avoiding making decisions that could impact the scoreboard (Corrigan et al., 2019). Moreover, Gómez Carmona and Pino Ortega (2016) found that soccer referees were more likely to make incorrect decisions on the right side of the field versus the central area, probably due to the diagonal running lines of the referees. In contrast, Castillo et al. (2019b) found that field locations did not impact the decision-making of soccer referees, possibly due to the extensive experience of the referees in their study (i.e., mean age = 40 years), helping them to achieve better positioning on the field (Castillo et al., 2019b). Collectively, these results suggest that the decision-making accuracy of referees could be influenced by field location, but little work exists among rugby referees.

To effectively apply the laws of the game and make accurate decisions, it is imperative that referees position themselves optimally to provide an unobstructed view of the play, while also maintaining an appropriate distance as to not interfere (Mallo et al., 2012; Elsworthy, Burke and Dascombe, 2014; Riiser et al., 2019). Given the dynamic environment of rugby, the referee's position and movement are likely to be critical in enabling a correct judgement. Therefore, referees should aim to be positioned in a way that allows them to obtain relevant visual information for making correct decisions (Johansen and Erikstad, 2020). For example, one study with soccer referees found that the further the referee was positioned from the ball at an infringement, the more likely they were to make an incorrect decision (Mallo et al., 2012). On the other hand, the distance from play when a free kick was awarded did not affect the accuracy of decisions by Australian football umpires (Elsworthy, Burke and Dascombe, 2014). Thus, the findings relating to referee positioning and decision-making accuracy are mixed to date and may be specific to the particular sport, and so further research is needed. Indeed, to the author's knowledge, the association between positioning and decision-making accuracy has not been assessed in rugby referees.

Despite the key involvement of the referee in a rugby match, little is known about their match demands in relation to decision-making during match play. In the context of performance optimisation, knowing the variables that affect the interaction between physical, physiological, and cognitive processes may provide a better insight into the true relationship between those demands and the decision-making accuracy of rugby referees.

2.7 Time-motion analysis in team field sports

Time-motion analysis has been used by many researchers to provide an insight into the physical and physiological demands of athletes (Dogramaci and Watsford, 2006). This information can be used to provide direct feedback to athletes and by practitioners to improve the specificity of conditioning programmes (Roberts, Trewartha and Stokes, 2007). Initially, time-motion analysis in team field sports involved direct observations of live match-play coupled with pen and paper notational analysis (Cunneen, Borges and Smith, 2020). Although this methodology provided valuable information on match demands, the accuracy of this technique was subject to many limitations (e.g., subjectivity). For example, analysis relied on the investigators ability to keep up with the speed of real-time match-play, with no option to correct errors or re-analyse particular segments of play (Cunneen, Borges and Smith, 2020). Nevertheless, the introduction of modern technology, such as video cameras, provided a practical solution to overcome previous limitations, and thus, create a more valid record of events (Cunneen, Borges and Smith, 2020).

Manual video-based analysis often required the use of several video-cameras positioned at different locations and elevations around the playing field, where each camera focused on an individual player for a specific time during the match (Dobson and Keogh, 2007; Cunneen, Borges and Smith, 2020). This enabled the observers to have a closer view of the relevant player, thus increasing the precision of their measure (i.e., improving the ability to code each movement pattern accurately; Dobson and Keogh, 2007). Additionally, this methodology allowed movements to be recorded throughout real-time match-play, therefore, allowing the calculation of movement variables (i.e., distance, sprints) and the measure of work-to rest ratios (Cunneen, Borges and Smith, 2020). However, manual video-based analysis has its limitations. For example, it is restricted to the analysis of a single player, potentially limiting the sample size (Dobson and Keogh, 2007; Cunneen, Borges and Smith, 2020). Furthermore, parallax and perspective error must be taken into consideration when positioning cameras (Dobson and Keogh, 2007; Cunneen, Borges and Smith, 2020), and the majority of manual video-based analysis studies require the use of some form of subjective judgment regarding the categorization of each individual movement, placing the decision of accurately coding each movement solely on the interpretation of the observer(s), potentially affecting the reliability of the interobserver results (Dobson and Keogh, 2007).

Advances in technology have allowed the development of more progressive video-based analysis techniques (i.e., computerised analysis systems), as well as the application of Global Positioning Systems (GPS) devices within team field sports (Cunneen, Borges and Smith, 2020). Computerised analysis systems and tools, which are used to generate match data, are called computerised notational systems (CNS). CNS are computer-based programmes, which allows coaches, analysts, or researchers to log match events to produce quantitative data, and to categorise the match actions that have occurred to create an objective statistical analysis of the match (Painczyk, Hendricks and Kraak, 2018). Briefly, the GPS system is based on the emission of radio signals in a synchronized way by satellites in orbit around the earth, equipped with an atomic clock which emits, at the speed of light, the exact time and its position (Schutz and Chambaz, 1997). The GPS receiver (worn on the player) compares the time emitted by each satellites signal. This time is identical for all satellites but, to be recognized, each satellite has a different `signature'. The lag time-measured by the receiver between two satellites emissions is translated into distance by trigonometry (Schutz and Chambaz, 1997). A computer then calculates the distance to each satellite from the measured time delay and the known velocity of the travelling signal. In order to identify one single point by triangulation, this method requires measurements from three satellites simultaneously in two-dimensional plane and four satellites simultaneously in three-dimensions (Schutz and Chambaz, 1997).

GPS technology has rapidly advanced in recent years and has become a common method for assessing the physical demands of training and competition in field-based team sports (Aughey, 2011; Rampinini et al., 2015). GPS allows the accurate tracking of the change in position of an object (e.g., an athlete) in real-time; consequently, portable GPS devices are utilised to objectively quantify the external load of individual athletes throughout both match-play and training (Dobson and Keogh, 2007; Cummins et al., 2013; Cunneen, Borges and Smith, 2020). Initially, GPS permitted the quantitative measurement of player position, distance, velocity, and frequency of accelerations and decelerations (Cummins et al., 2013; Cunneen, Borges and Smith, 2020). However, the inclusion of inertial microsensors (i.e., accelerometers, gyroscopes, and magnetometers) enabled further assessment of physical demands such as the number of impacts and collisions, metabolic load, and accumulative mechanical stress occurred throughout team field sports (Cunneen, Borges and Smith, 2020). GPS provides an alternate data acquisition method with the potential to overcome the limitations associated with previous time-motion-analysis methodologies (e.g., analysis limited to few players, labour-intensive nature of analysis, inability to operate in real-time, etc.) (Cunneen, Borges and Smith, 2020).

Understanding the physical load athletes experience during match play through GPS may allow training sessions to be designed that replicate or exceed the demands of match-play to enhance performance (Cummins et al., 2013; Read et al., 2017; Bridgeman and Gill, 2021). It has also been suggested that this information could be used to identify athletes with the potential to progress to higher-level competition, understand the differences between different age-grade competitions, and to analyse the differences between competitions (Read et al., 2017; Bridgeman and Gill, 2021). In addition, the use of GPS data could be used to reduce the risk of injury through the monitoring of athletes' training and match loads, and identifying athlete's readiness to return to play post-injury (West et al., 2019; Bridgeman and Gill, 2021).

2.8 Satellite positioning technology

The global positioning system (GPS) that is now regularly applied in the sporting sphere is only possible through the work of the 1944 Nobel laureate in physics Isidor Rabi (Aughey, 2011). Rabi and his students invented the magnetic resonance method through their precise measures on the hydrogen atom (Rabi et al., 1938). The development of the nuclear magnetic resonance method lead directly to the creation of atomic clocks, the precise timepieces that form the basis of satellite navigation (Aughey, 2011). The precise measurement of time from the atomic clock allows for the calculation of the length of time it takes a radio signal to travel from the satellite to the GPS receiver on earth (Aughey, 2011). The GPS is a satellite-based navigation system consisting of a network of operational satellites in orbit around the earth. The U.S. Department of Defence funds this system for navigation, originally developed for military use, but it is increasingly used for aviation, marine and recreational outdoor purposes (Schutz and Herren, 2000; Larsson, 2003). It consists of 27 satellites equipped with atomic clocks in orbit around the earth. These satellites continually send information to GPS receivers and, using these signals, the receivers calculate the distance to the satellite (Larsson, 2003).

In most commercially available GPS systems, speed of displacement is determined by measuring the rate of change in the satellites' signal frequency attributable to movement of the receiver (i.e., Doppler shift; Schutz and Herren, 2000; Townshend, Worringham and Stewart, 2008). GPS receivers used in team sports, also calculate speed using Doppler shift. This is attained by examining the frequency of the satellite signal, which changes because of the movement of the receiver (Larsson, 2003). However, GPS has both technological and practical limitations. Satellite signals can be obstructed by the atmosphere and local environmental objects (e.g., stadiums and tall buildings) which can lead to measurement error (Larsson, 2003; Scott, Scott and Kelly, 2016). Likewise, the number of satellites interacting with the GPS receiver plays an important role in determining the accuracy of position estimates (Scott, Scott and Kelly, 2016). Although four satellites are the theoretical minimum number needed to triangulate a GPS receiver's position, there is a moderate negative correlation between the total distance error (i.e., the difference between the recorded distance and actual distance) recorded by a GPS receiver and the number of satellites signalling the receiver (Gray et al., 2010). Similarly, velocity measurements can be susceptible to an increase in error as the number of satellites interacting with the receiver decreases. Additionally, the positioning of satellites interacting with the receiver is also vital in determining the accuracy of measurements recorded by the receiver (Witte and Wilson, 2004; Scott, Scott and Kelly, 2016).

With recent technological developments, nowadays most devices feature a Global Navigation Satellite System (GNSS) receiver (Garzia et al., 2016) which is capable of acquiring and tracking multiple satellite systems concurrently, and thus providing a more accurate positional information (Beato et al., 2018). GNSS positioning is a more general term that encompasses all global satellite-based positioning systems, each one developed and operated by different countries, such as GPS (United States), GLONASS (Russia), Galileo (European Union), and BeiDou (China) (Zimbelman and Keefe, 2018). Commonly, GNSS units sampling rates are at 10 Hz and 18 Hz, with both reported to have a small bias (i.e., < 5%) for distance measures (e.g., 400 m trial, 128.5 m circuit, and 20 m trial) and peak velocity (e.g., 20 m sprint; Beato et al., 2018).

First utilized for athlete tracking in 1997 (Schutz and Chambaz, 1997; Cummins et al., 2013), GPS technology is now increasingly used in team sport settings to provide sports scientists, coaches, and trainers with comprehensive and real-time analysis of on-field player performance during competition or training (Cummins et al., 2013). GPS technology has rapidly advanced in recent years, with extensive validation and reliability testing being completed, and the devices applied heavily across many team sports (Aughey, 2011). Owing to the increased application of such technology and volume of data it can produce, sport scientists now have a deeper understanding of the activity profiles of a range of sports and positions within those sports, and it has enabled researchers to investigate relationships between physical capacity and match performance (Aughey, 2011). The integration of this and other data, such as decision-making analysis, will continuously expand the body of knowledge of activity in field sports in the future (Aughey, 2011).

2.8.1 Validity and reliability of tracking satellite systems

The validity of an instrument reflects the ability of that instrument to accurately measure what it intends to measure (Scott, Scott and Kelly, 2016). Reliability relates to the consistency of a measure using an instrument with repeated testing (Heale and Twycross, 2015). In a real-world application, this is vital to all facets of GPS use (Scott, Scott and Kelly, 2016). GPS devices are currently manufactured with sampling rates (i.e., the speed at which the unit gathers data) ranging from 1 Hz to 20-Hz (i.e., 1-, 5-, 10-, 15-, 18- and 20-

Hz) sampling rates (Cummins et al., 2013; Hausler, Halaki and Orr, 2016; Beato et al., 2018; Hoppe et al., 2018). Research suggests that GPS units with higher frequency sampling rates provide greater validity for the measurement of distance (Jennings et al., 2010). Overall, 1 Hz to 15 Hz devices all permit a valid and reliable determination of the total distance covered, however, devices with low sample rates (i.e., 1 Hz to 5 Hz) have limitations for assessing the distance covered during high speed runs, accelerations over short distances, and velocity measures, especially when changes of direction are performed (Hoppe et al., 2018). While 10 Hz devices overcome most of these limitations, 15 Hz devices show no superior validity and reliability (Scott, Scott and Kelly, 2016).

The first attempt to validate a commercially available GPS device (GPS 45, Garmin) for the measurement of human locomotion was published in 1997 (Schutz and Chambaz, 1997). One participant undertook 76 trials at 19 different walking and 22 different running velocities with GPS data compared with a Swiss chronometer. The participant was paced with a metronome and the correlation between GPS and chronometer speed of displacement was high (r = 99), with a 5% coefficient of variation for the regression slope line (Schutz and Chambaz, 1997). While promising, this early research was hardly a gold-standard confirmation of the validity of GPS for velocity measurement (Aughey, 2011). After this first trial, GPS have rapidly advanced, extensive validation and reliability have been completed, and the devices have been used heavily across many team sports (Coutts and Duffield, 2010; Aughey, 2011; Varley, Fairweather and Aughey, 2012; Johnston et al., 2014).

GPS sampling at 1 Hz were the original units commercially available and were the initial GPS units used in team sport research (Scott, Scott and Kelly, 2016). One study performed 59 trials of a 1 Hz GPS after marked circuits of varying distances and found that the GPS measures of total distance differed significantly from criterion measures (Edgecomb and Norton, 2006). However, 1 Hz GPS units were found to be capable of providing accurate information on distance for straight-line walking and low-speed running over a moderate distance. Additionally, the 1 Hz GPS devices were effective at producing accurate curvilinear distances at varying velocities (Petersen et al., 2009; Portas et al., 2010). On the other hand, reducing the linear distance of tests seems to impair the accuracy of the distance measurement recorded by the 1 Hz GPS units. Walking, jogging, medium-intensity running and sprinting across shorter straight-line distances all failed to have acceptable validity (Jennings et al., 2010). This finding highlights a potentially limitation of using 1 Hz GPS devices in team sports, as these devices are unlikely to report accurate distances covered during high-speed efforts (Scott, Scott and Kelly, 2016).

Similar to 1 Hz GPS devices, 5 Hz GPS devices have been used widely for athlete tracking (Scott, Scott and Kelly, 2016). The evidence largely suggests that 5 Hz GPS units are able to accurately quantify player distances during team sports, with good validity when reporting straight-line distance during walking and low-speed running over a moderate distance (Portas et al., 2010; Scott, Scott and Kelly, 2016). Additionally, 5 Hz GPS devices have good validity when measuring curvilinear distances at varying velocities, from walking to running, suggesting that these devices are able to accurately report distances during different speeds and during moderate to long distances (Petersen et al., 2009; Scott, Scott and Kelly, 2016). However, there have been concerns over the accuracy of moderate distance measures during high-intensity and maximal speed running, and when change of direction is required (Jennings et al., 2010; Rampinini et al., 2015). Previous studies have reported that GPS units with higher sampling rates (e.g., 10 Hz) offer several advantages in terms of validity and reliability when compared to less powerful devices (e.g., 1 to 5 Hz; Scott, Scott and Kelly, 2016). Higher accuracy in total distance covered during both linear activities (e.g., forward running), sports-specific circuits, and peak velocity have been reported for 10 Hz than 1 to 5 Hz devices (Scott, Scott and Kelly, 2016). Nevertheless, it has been shown that sampling rate, speed, duration, and nature of the exercise, all affect the validity and the reliability of GPS units (Rampinini et al., 2015). Specifically, it appears that validity improves with higher sampling rate, while reliability decreases in tasks requiring regular changes of direction and short accelerations (Coutts and Duffield, 2010; Gray et al., 2010; Jennings et al., 2010; Rampinini et al., 2015).

CHAPTER 3: GENERAL METHODS

3.1 Participants

For studies 1 (Chapter 4), 2 (Chapter 5), and 4 (Chapter 7), amateur, semi-professional, and professional rugby union referees participating in levels 1 to 7 in RFU competitions were recruited (Table 1). Specifically, professional referees are those who are a member the RFU PGMOT and officiate at Premiership (Level 1) and Championship (level 2) leagues in England. These referees are made up of a combination of full-time salaried officials and contracted part-time officials who receive a retainer and match fee. Semi-professional referees are those usually officiating at Levels 3 and 4 and receive a match fee, but they were not contracted officials. Finally, amateur referees are those officiating up to Level 5, who are not contracted officials and do not receive a match fee but do get travel expenses. Professional referees receive medical, sports science, and strength and conditioning support provided by the RFU, while semi-professional and amateur referees do not receive this support. For study 1, full-time professional referees who were involved in Rugby Europe and World Rugby Tournaments, were also included.

For study 3 (Chapter 6), all referees were actively officiating in South Africa at either the residence "Koshuis" tournament at Stellenbosch University, or the Western Province Rugby Union Super League competition, played across the Western Cape Province. The "Koshuis" tournament includes ~200 matches over seven months, divided into first-, second-, third-, and fourth- league matches, played on weeknights. Except for one "private-residence" team, all teams comprised Stellenbosch University students and could be described as recreational, with a few semi-professional players. The total match duration was 60 minutes for leagues one to three, and 50 minutes for the fourth league (Brown et al., 2019). The Western Province Super League is organised by the Western Province Rugby Union (i.e., one of the fourteen provincial unions in South Africa), and is played by amateur clubs, sub-divided into A, B, C and Under-20 teams. It follows a single round format where each team plays every other team in their league once a season (between April and September), and total match duration was 80 minutes for league A, 70 minutes for leagues B and Under-20, and 60 minutes for league C (Painczyk, Hendricks and Kraak, 2018).

In all studies, formal requests were sent to Referee Managers of the International and National Societies who then forwarded the information to the Referees. Those referees who had less than two years of refereeing experience, who officiated above RFU level 7 (i.e., from level 8 to 12), and those who had sustained an injury in the previous six months, were not included in any of the studies. Over the four studies, 121 referees (117 male, 4 females) volunteered to participate. Each study provides specific detail regarding the participants who took part.

3.2 Ethics

Ethics approval for all studies was submitted to and granted by the University of Bath's Research Ethics Approval Committee for Health (REACH). Data collection for studies 1 (Chapter 4) and 2 (Chapter 5) were included in the same ethics application - REACH code, EP 17/18 112. For studies 3 (Chapter 6) and 4 (Chapter 7), amendments were included in the same ethics application. Specifically, for study 3 (Chapter 6), an amendment request was approved to include referees involved in the following South African competitions: South Africa WP Super League A and/or "Koshuis" Rugby Championship 1st, 2nd, 3rd and 4th League. In addition, for study 4 (Chapter 7) an amendment was asked to include a third research question (i.e., What are the most common referees' decisions and non-decisions in the breakdown during a rugby sevens tournament, and does the match demands have any impact on decision making accuracy?). Each study was approved by REACH prior to any data collection taking place. Additionally, prior to volunteering in any of the studies, all participants were provided with verbal and written information regarding the study procedures and were given face-to-face explanations before the start of the data collection process. Participants were given the right to withdraw and data were stored securely and in an anonymous format to aid confidentiality. Finally, all participants signed a written statement of consent. The latest approved document containing the ethics application, amendments, participant information sheet, and the consent form is included (Appendix B).

3.3 Study design and equipment

An observational study design was used across the four studies. The data for study 1 (Chapter 4) was collected during the sevens season in the summer of 2018 (i.e., May to July), and the data for study 2 (Chapter 5) was collected during the 15-a-side season between September 2018 and May 2019. Moreover, data for study 3 (Chapter 6) was collected in

South Africa, during the end of the competitive season (i.e., August 2019), and the data for study 4 (Chapter 7) was collected during a National Sevens Tournament in September 2019.

For all studies, referees wore a multi-GNSS augmented (Apex, 10 Hz, 44 mm width, 84 mm height, 20 mm depth, 952 Hz accelerometer and gyroscope, 10 Hz magnetometer, STATSports, Belfast, UK), which was worn between the shoulder blades using an adjustable neoprene harness (Figure 2) located beneath their normal refereeing clothing. The STATSports Apex unit is an athlete-tracking system released in August 2017, and it is widely used in professional clubs (e.g., soccer clubs in the English Premier League) (M. Beato et al., 2018a). The same set of unit was used over the four studies, and each referee was allocated a specific GNSS unit for the entire duration of studies 1 (Chapter 4), 2 (Chapter 5), and 4 (Chapter 7). For the duration of study 3 (Chapter 6), as the referees attended the tests and matches in a random order based on their availability, this was not possible to achieve for all the referees. Many of the referees were familiar with units, having worn similar units when officiating previously.

For studies 2 to 4 (Chapters 5 to 7), HR data were collected through a HR sensor (Polar T31, Polar Electro, Kempele, Finland) worn around the referee's chest (Figure 3), which transmitted real-time data via Bluetooth to the GNSS unit where it was recorded. As noted in the STATSports Apex user manual, to allow the unit to locate the satellites, for each referee, the GNSS unit was switched on outdoors ~15 minutes before each match or field test, and immediately turned off at the end of each match or field test. The data were then stored on the GNSS unit until it was downloaded to dedicated software for analysis (STATSposts Apex software, v. 3.0.04101 and v. 3.0.02011).

Figure 2. Participant using STATSports Apex unit and harness.

Figure 3. STATSports Apex unit and harness, and Polar heart rate strap used in all studies.

A 10 Hz multi-GNSS augmented unit can acquire and track multiple satellite systems [e.g., global positioning system (GPS), GLONASS, Galileo, and BeiDou] concurrently, thus providing more accurate positional information, and has shown good levels of accuracy (bias < 5%) in sport specific metrics (Beato et al., 2018). For example, Apex 10 Hz units have shown small bias in distance measures during 400-m, 128.5-m, and 20-m trials, compared with ground truth reference (i.e., radar gun). The distance biases for the Apex 10 Hz in the 400 m trial, 128.5 m circuit, and 20 m trial were 1.05 ± 0.87%, 2.3 ± 1.1%, and 1.11 ± 0.99%, respectively (Beato et al., 2018). The STATSports Apex 10 Hz device utilizes a multi-band GNSS receiver in combination with corrected signal information from space-based augmentation systems to achieve enhanced data quality. These technological improvements could explain the lower bias reported compared to previous STATSports units (Beato et al., 2018). Additionally, Apex intra and inter-unit reliability was excellent (i.e., intra-class correlation coefficient = 0.99; 95% confidence interval = 0.98-0.99; technical error of measurement = 0.12; coefficient of variation = 1.85%) for sprint distances (ranging from 5 to 30 m), showing that the Apex unit can be used to monitor peak velocity (Beato and de Keijzer, 2019). Moreover, the validity of Apex vs. a gold standard criterion device (i.e., radar gun) reported a nearly perfect correlation ($r = 0.96$) during a 20 m sprint, with no significant difference between the two tools ($p = 0.32$), and good inter-unit reliability for 20 m sprints expressed as CV = 2.3% (Beato et al., 2018; Beato and de Keijzer, 2019).

Several studies have highlighted that sampling rate is a crucial factor associated with the validity and reliability of GPS units (Coutts and Duffield, 2010; Beato et al., 2018; Hoppe et al., 2018)**,** as well as data accuracy (Scott, Scott and Kelly, 2016). Indeed, units with higher sampling frequencies (i.e., 10 Hz to 15 Hz) have been shown to be more accurate and reliable than units with lower frequencies (i.e., 1 Hz to 5 Hz; Scott, Scott and Kelly, 2016). However, research has compared 10 Hz versus 15 Hz devices, and concluded that the 10 Hz units were more accurate for measuring total distance and had greater inter-unit reliability (Johnston et al., 2014). Specifically, the 10 Hz units displayed lower levels of error (< 14%) and stronger ICC scores (> 0.8) for all movement demands when compared with the 15 Hz units (%TEM ≤ 20%, ICC ≥ 0.75; Johnston et al., 2014). Furthermore, 10 Hz units have demonstrated superior accuracy when quantifying distance covered at higher speeds (Rampinini et al., 2015). Taken together, it appears that higher sampling frequencies of GPS units, up to 10 Hz, show greater validity and reliability, and the additional sampling frequency units (e.g., 15 Hz to 18 Hz) do not seem to provide additional benefits (Johnston et al., 2014; Beato et al., 2018). An explanation might be that 10 Hz sampling frequency results in theoretically more precise identification of motion (Nikolaidis et al., 2018). For instance, a 10 Hz unit can analyse a motion with a precision of 0.1 s, whereas a 5 Hz unit has a precision of 0.2 s (Nikolaidis et al., 2018). However, it is unclear why 10 Hz units are often found to be more reliable than 15 Hz units, although it should be noted that the 15 Hz units possess a true GPS sampling frequency of 5 Hz, which is interpolated to 15 Hz using a tri-axial accelerometer embedded within the microtechnology unit (Weaving et al., 2014; Read et al., 2017).

3.3 Match physical demands analysis

For all studies, data from sevens and 15-a-side rugby matches, as well as field tests (e.g., $YYIR_1$, Bronco), included: (1) total distance (m), (2) relative distance ($m.min^{-1}$) (3) high-intensity (> 18. 4 $km.h^{-1}$) distance covered (m), (4) percentage of time spent within six speed zones: zone 1 (< 5.4 $km.h^{-1}$); zone 2 (5.41 – 10.8 $km.h^{-1}$); zone 3 (10.81 – 14.4 $km.h^{-1}$); zone 4 (14.41 – 18.4 $km.h^{-1}$); zone 5: (18.41 – 25.2 $km.h^{-1}$), and zone 6 (> 25.2 $km.h^{-1}$), (5) high-intensity accelerations and deceleration (> 2.79 $m.s^{-2}$) (n), (6) average number of sprints (n), (7) average maximal speed of a sprint ($km.h^{-1}$), (8) average maximal distance of a sprint (m), (9) average sprint distance (m), and (10) average duration of a sprint (s). Accelerations and decelerations were calculated from a single derivation of the speed during a period of 0.5 seconds (Couderc et al., 2019), and a sprint was defined as when the referee reached 20 $km \cdot h^{-1}$ and sustained this speed for at least 1 second (Suarez-Arrones et al., 2013b; Suarez-Arrones et al., 2013c). STATSports APEX software offer six customisable speed zones, with each having a minimum and maximum speed. Accordingly, the abovementioned speed zones were manually incorporated into the software, and selected as they have been used in previous research with rugby players and referees (Roberts et al., 2008; Suarez-Arrones et al., 2013a).

To investigate high intensity activities, a bout of repeated high-intensity efforts (RHIE) was defined as a minimum of three high-intensity activities (i.e., sprints or high-intensity acceleration) with less than 21 seconds of recovery between efforts (Spencer et al., 2004; Austin, Gabbett and Jenkins, 2011b; Gabbett, Jenkins and Abernethy, 2012; Jones et al., 2015). The definition of a bout duration was from the time the referee first performed a high-intensity activity (i.e., sprint or high-intensity acceleration) and repeated a minimum of two other efforts, with less than 21 seconds between those activities. This definition was adapted from previous research with rugby players (Austin, Gabbett and Jenkins, 2011b; Suarez-Arrones et al., 2016) because no study has analysed RHIE for rugby referees. Accordingly, each RHIE bout included data for: (1) frequency (n), (2) duration (s), (3) time between RHIE (s), (4) distance (m), and (5) maximal speed during RHIE. The single longest period of a RHIE bout from each match was identified and analysed as the "worst case scenario" (WCS) (Reardon et al., 2017). Thus, the WCS is likely to be the most intense period of the match in which a referee could be involved. For each WCS, data included: (1) total duration (s), (2) total distance (m), (3) maximum speed ($km.h^{-1}$), (4) total distance relative to the bout duration ($m.min^{-1}$), (5) the number of sprints (n), and (6) the number of accelerations (n).

3.4 Match physiological demands analysis

Maximal heart rate (HR_{max}) was determined as the highest of either: (1) HR_{max} estimated through the formula: 208 – (0.7 x age) (Tanaka, Monahan and Seals, 2001), or (2) HR_{max} values obtained during the field tests or match (Boudet et al., 2002; Suarez-Arrones et al., 2013a). The data were classified based on the percentage of total playing time spent in six HR zones: zone 1 (< 60% HR_{max}), zone 2 (61 – 70% HR_{max}), zone 3 (71 – 80% HR_{max}), zone 4 (81 – 90% HR_{max}), zone 5 (91 – 95% HR_{max}), and zone 6 (> 96% HR_{max}). The HR zones were adapted from previous studies with rugby referees (Suarez-Arrones et al., 2013a; Suarez-Arrones et al., 2013c; Blair et al., 2018b). In addition, internal load (i.e., Edwards TRIMP) was calculated by multiplying the time spent (in minutes) in five pre-defined HR zones by a coefficient assigned to each zone (i.e., 50 - 60% HR_{max} = 1, 60 - 70% HR_{max} = 2, 70 - 80% HR_{max} = 3, 80 - 90% HR_{max} = 4, and 90 - 100 HR_{max} = 5) (Edwards, 1993). STATSports APEX software offer six customisable HR zones, with each having a minimum and maximum percentage range based on the HRmax. Once the referee's HRmax had been identified based on the abovementioned methods, the value was manually incorporated in the software and relative HR zones were calculated for each referee (Figure 4).

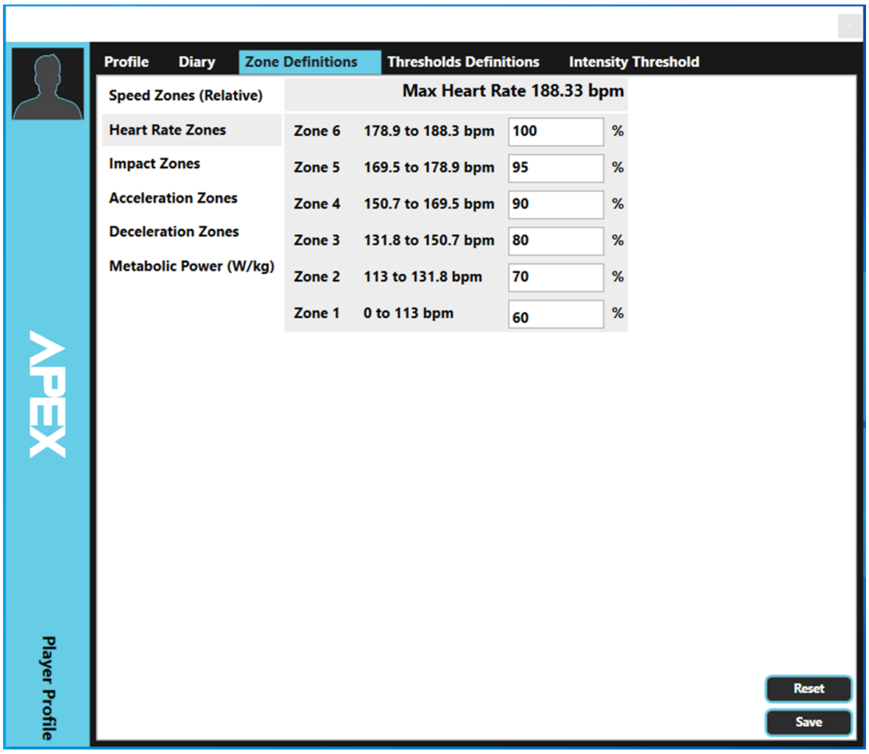


Figure 4. Example of individualized HR zones using the STATSports APEX software.

3.5 Field test assessment

For study 3 (Chapter 6), two field test were used, $YYIR_1$ and the Bronco test. Both field tests were performed on a rugby field (i.e., Stellenbosch University) on dry and firm conditions, reducing the influence of weather. A minimum of 48 hours, and a maximum of six days, of rest was enforced between tests to limiting the effects of fatigue (Deuchrass et al., 2019). The field tests were scheduled by the research team, and the referees attended the tests in a random order based on their availability. All referees were familiar with both testing protocols as they complete them regularly throughout the season. The referees were instructed to maintain normal dietary intake, training, and sleeping patterns in the two days prior to each test, avoid heavy exercise and the consumption of alcohol in the preceding 24 hours, and avoid consuming a heavy meal and caffeinated beverages in the preceding two hours. Finally, referees were allowed to do their own specific warm-up for 10 minutes before each test, with activation exercises and one high-intensity running shuttle (i.e., 20 m and back) advised before the $YYIR_1$ test, and one practice repetition (i.e., 20-40-60 m) recommended before the Bronco test, and verbal encouragement was provided by the testers during both tests. The paragraphs below provide a description of each test protocol.

3.5.1 Yo-Yo Intermittent Recovery Test

The YYIR comprises repeated 2×20 m runs back and forth between the starting, turning, and finishing line (marked by cones) at a progressively increasing speed controlled by audio signals (Figure 5). The participants have an active 10 second rest between each running bout, which consists of a 2×5 m jog. Another cone, placed 5 m behind the finishing line, marks the running distance during the active recovery. One researcher was standing beside the finishing line to guarantee that the referee reached the line in time with the audio signal. When the referee failed once, they received a warning. When the referee failed twice, the distance and the level of the test of their last successful shuttle was recorded as the final test result. The YYIR may be performed at two different levels with differing speed profiles (level 1 and 2). The YYIR level 1 ($YYIR_1$) test starts at a lower speed (i.e., 10 $km.h^{-1}$) and increases in speed are more moderate than in level two, which starts at a higher speed (i.e., 13 $km.h^{-1}$; Bangsbo, Iaia and Krustrup, 2008; Schmitz et al., 2018). Based on this difference, the $YYIR_1$ test has been preferred to test endurance capacity, whereas the YYIR level 2 ($YYIR_2$) test is preferred to determine the ability to repeatedly perform intense exercise with a high anaerobic energy contribution (Bangsbo, Iaia and Krustrup, 2008; Schmitz et al., 2018). Additionally, $YYIR_1$ provides an indirect indication of the physical capacity of intermittent team sport athletes (Krustrup et al., 2003; Blair et al., 2018a). When the standards for the $YYIR_1$ test were established, they were used globally to assess the ability of team sport athletes to repeatedly perform and recover from intense activity. It is within this context that this test is used for referees (Blair et al., 2018a).

Thus, in study 3 (Chapter 6), $YYIR_1$ was used, which includes four running bouts at 10-13 km/h (0-160 m) and seven running bouts at 13.5-14 $km{\cdot}h^{-1}$ (160-440 m). After that, it continues with stepwise 0.5 $km{\cdot}h^{-1}$ speed increments after eight running bouts (i.e., 760, 1080, 1400, 1720 m, etc.) until exhaustion (Table 4). The test lasted ~20 minutes.

Table 4. Yo-Yo intermittent recovery test level 1 protocol, adapted from Souhail et al. (2010).

Level	Speed ($km.h^{-1}$)	Shuttle bouts (2 x 20 m)	Split distance (m)	Accumulated distance (m)
5	10	1	40	40
9	12	1	40	80
11	13	2	80	160
12	13.5	3	120	280
13	14	4	160	440
14	14.5	8	320	760
15	15	8	320	1080
16	15.5	8	320	1400
17	16	8	320	1720
18	16.5	8	320	2040
19	17	8	320	2360
20	17.5	8	320	2680
21	18	8	320	3000
22	18.5	8	320	3320
23	19	8	320	3640

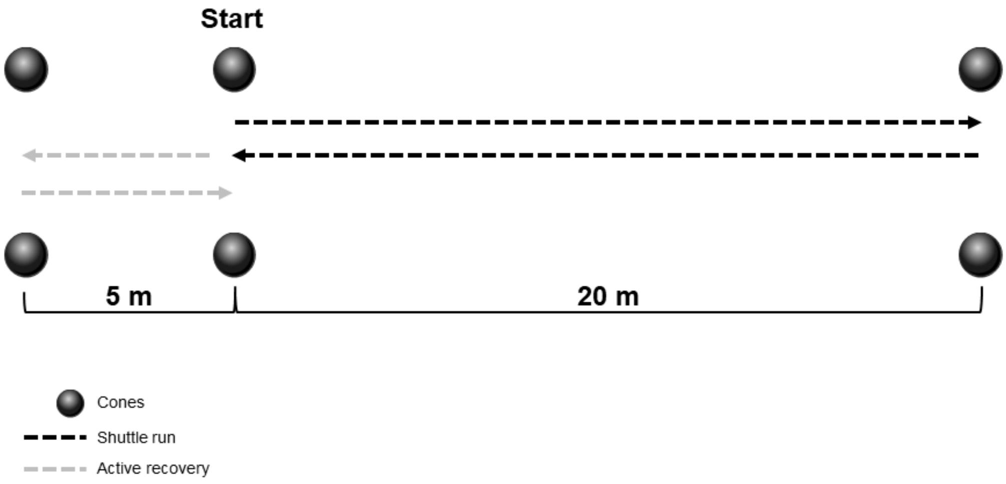


Figure 5. Diagram for the YYIR level 1.

3.5.2 1200-m shuttle (The Bronco) Test

The Bronco Test is widely used in rugby environments and consists of running 1200 m in a shuttle-type manner (Mayo et al., 2018; Deuchrass et al., 2019). For study 3 (Chapter 6), cones were marked out in 0 m, 20 m, 40 m, and 60 m lines. Referees were required to run from 0 to 20 m and back, then 40 m and back to the 0 m line, and then run again to the 60 m and return to the 0 m line. Completion of the 20-40-60 m shuttles was considered one repetition. The aim of the test was to perform five repetitions without rest as quickly as possible (Teece et al., 2021) (Figure 6). Hand-held stopwatches were used to record the finishing time for each participant in seconds. The test lasted ~6 minutes.

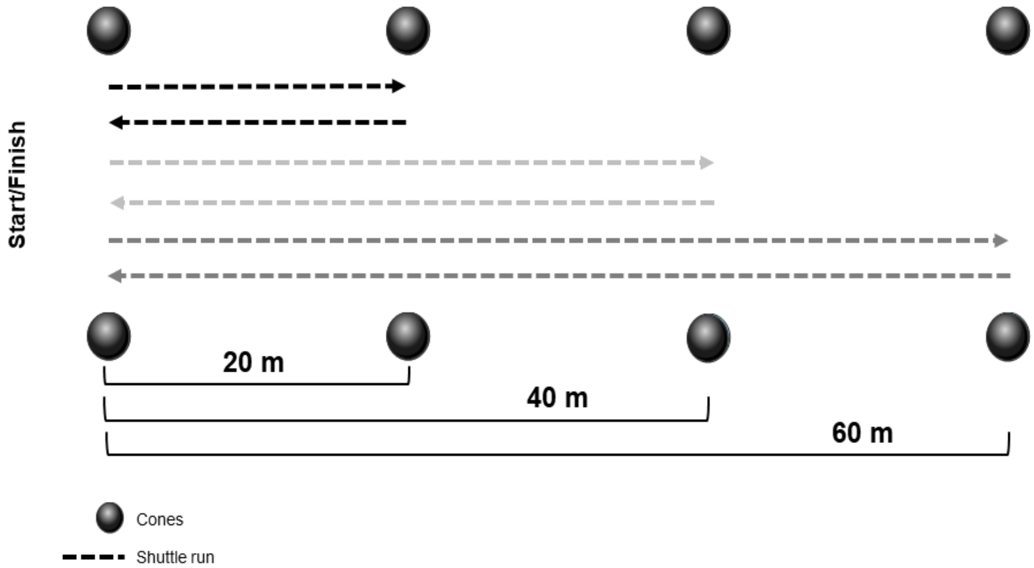


Figure 6. Diagram of the Bronco Test.

3.6 Video coding

Video analysis is a subdiscipline of performance analysis, that incorporates biomechanical methods and notational analysis, using systematic observation through the interpretation of videos, providing additional information to improve future sports performance (Hughes and Bartlett, 2002; Glazier, 2010; Vilar et al., 2012). The video is analysed according to a set of predefined performance indicators (PIs) to identify and describe actions and patterns of play in relation to specific performance outcomes (Hughes and Bartlett, 2002; Mellalieu, Trewartha and Stokes, 2008; Vilar et al., 2012). A PI is a selection, or combination, of action variables that aim to define some or all aspects of a performance and should relate to outcomes (Hughes and Bartlett, 2002; Vilar et al., 2012). Computerised software is required to code specific PIs according to their operational definitions.

For study 4 (Chapter 7), 22 matches during a professional National Sevens Tournament were broadcast live on television by a commercial broadcasting company, the recordings of which were used for analysis using sports performance analysis coding software (NacSports Pro Plus V.5.0.1). The use of the software allowed for a specific match event (i.e., breakdown) to be coded by the lead researcher according to the PIs previously identified (Table 5). NacSports allows customised templates (coding window) to be created to track the actions and data to explore and review the PIs. Buttons are created for each event (Figure 7), where the coder clicks the corresponding buttons for each event as they occur. Each click generates a tag within the software marking the time when they happened. When the match analyses end, NacSports software displays all the tracked events grouped into category rows and/or chronologically on a timeline. For study 4 (Chapter 7), the lead researcher coded the referees' decisions at each of the 602 breakdowns in all 22 matches and then recoded all matches two weeks later for intra-coder reliability. Inter-coder reliability was also assessed via an experienced rugby referee reviewer coding all the matches once (Chapter 7).

Table 5. Performance indicators and operational definitions used in Study 4.

Performance indicator	Operational definition
Breakdown	Breakdown is a rugby term for the short period of play just after the tackle and before and during the ruck (Mitchell and Tierney, 2020). It covers laws 14 and 15 (World Rugby, 2020). In terms of analysis, it will include all the tackle and ruck situations.
Tackle	A tackle occurs when the ball-carrier (i.e., player carrying the ball) is held and brought to the ground by one or more opponents (Law 14.1) (World Rugby, 2020). Being brought to the ground means that the ball-carrier is lying, sitting or has at least one knee on the ground or on another player who is on the ground (Law 14.2) (World Rugby, 2020).
Ruck	A ruck is formed when at least one player from each team are in contact, on their feet and over the ball which is on the ground (Law 15.2) (World Rugby, 2020).
Penalty	Penalties are awarded to restart play after infringements (Law 20) (World Rugby, 2020).
Time period (World Rugby, 2020)	Half 1: 0-7> minutes Half 2: 7-14> minutes
Decision-making (Emmonds et al., 2015; Riiser et al., 2019).	(1) correct (i.e., penalty was awarded against a player who had infringed) (2) incorrect (i.e., penalty was awarded but no infringement was committed, or a penalty was awarded against a player who had not infringed) (3) missed (i.e., penalty was not awarded against a player who had infringed) (4) play on (i.e., no infringement or a infringement with no clear effect or impact).
Field location (in relation to the team who had possession of the ball) (van Rooyen, Diedrick and Noakes, 2010).	Zone A: Attacking area between 22-m area and the try line. Zone B: Attacking area between 22-m area and halfway line.

	Zone C: Defence area between 22-m area and the halfway line. Zone D: Defence area between 22-m area and the try line.
Referee positioning (RFU, 2018)	Optimal Sub-optimal
Score differential (Corrigan et al., 2019)	The difference in the score between the two teams at the time of the decision, categorised as small < 07, medium 08-14, or large > 15 points.
Tackle infringements (World Rugby, 2020)	Tackler not rolling away: tacklers must immediately move away from the tackled player and from the ball or get up (Law 14.5b). Holding on: Tackled players must immediately make the ball available so that play can continue by releasing, passing or pushing the ball in any direction except forward. They may place the ball in any direction (Law 14.7a). They must ensure that they do not lie on, over or near the ball to prevent opposition players from gaining possession of it (Law 14.7c). Assistant tackler not clear release: Assistant tacklers must remain on their feet and release the ball and the ball-carrier immediately (Law 14.8a). Tackle-side entry: Any player must arrive at the tackle from the direction of their own goal line before playing the ball (Law14.8c). Off feet: Any player must remain on their feet when they play the ball (Law 14.8b). Dangerous tackle: A player must not tackle an opponent early, late or dangerously (Law 9.13). High tackle: An illegal tackle causing head contact, where head contact is identified by clear, direct contact to ball-carrier's head/neck or the head visibly moves backwards from the contact point or the ball-carrier requires an head injury assessment (HIA). A

	player must not tackle or attempting to tackle an opponent above the line of the shoulders even if the tackle starts below the line of the shoulders (Law 9.13). Tip tackle: A player must not lift an opponent off the ground and drop or drive that player so that their head and/or upper body make contact with the ground (Law 9.18). Shoulder charge: Arm of the shoulder making contact with the ball-carrier is behind the tackler's body or tucked in 'sling' position at contact.
Ruck infringements (World Rugby, 2020)	Neck roll: A player must not make contact with an opponent above the line of the shoulders (Law 9.20b). Not supporting own body weight ("off feet"): A player to join a ruck must be on his feet (Law 15.5). Joining the ruck while in an offside position: A player joining the ruck may not do so while in an offside position. Non-participants at the breakdown must be behind the hindmost foot of the last player in their side of the ruck (Law 15.5). Shoulder charge: A player must not charge into a ruck. Charging includes any contact made without use of the arms, or without grasping a player (Law 9.20a). Side entry: Any player must join alongside the ruck but not in front of the hindmost player (Law 15.6). Not grasping on teammate: A player joining a ruck must bind on a teammate or an opponent, using the whole arm. The bind must either precede, or be simultaneous with, contact with any other part of the body of the player joining the ruck (Law 15.7). Cleaning a player not involved in the ruck: A player must not take out opposition players who are not part of the ruck (Law 9.15).

	Hands in the ruck: Once a ruck is formed, no player may handle the ball unless they were able to get their hands on the ball before the ruck formed and stay on their feet (Law 15.11). Collapse a ruck: Players must not collapse a ruck or jump on the top of it (Law 15.16b). Fall over: A player must not fall over the ball as it is coming out of a ruck (Law 15.16d).

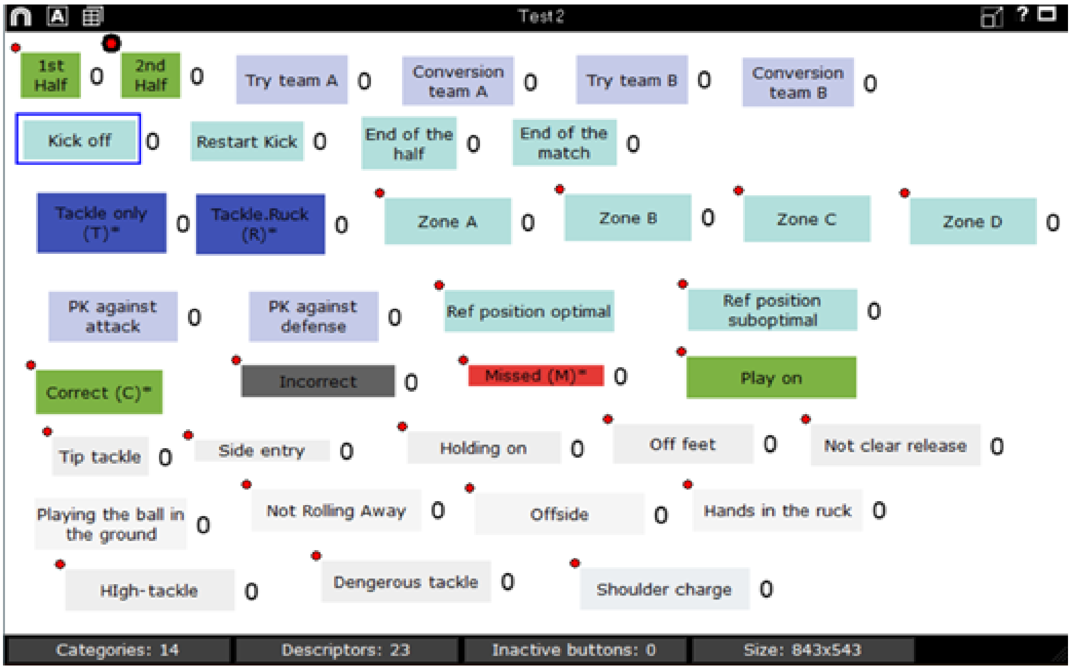


Figure 7. Example of NacSport software buttons template (coding window) used in Study 4.

3.7 Data analysis

Throughout all studies, a range of statistical analyses were used via the IBM Statistical Package for the Social Sciences (SPSS) (version 27.0; IBM Corporation., Armonk, New York, USA). Additionally, data were analysed and handled using specific software, such as video analysis software Nacsport (Pro PLUS version 5.0.1), and GNSS analysis software (STATSports Apex software, version 3.0.02011), and imported to a spreadsheet software, Microsoft Excel (Microsoft Corporation, Redmond, WA), prior to the main analysis. Given the different statistical approaches adopted for each study, each study chapter provides specific details regarding the statistical analyses employed.

CHAPTER 4: PHYSICAL DEMANDS OF REFEREEING RUGBY SEVENS MATCHES AT DIFFERENT COMPETITIVE LEVELS

(Citation: Sant'Anna R.T., Roberts S.P., Moore L.J., Stokes K. A. (2021) Physical Demands of Refereeing Rugby Sevens Matches at Different Competitive Levels, Journal of Strength and Conditioning Research. Nov 1;35(11):3164-3169- doi: 10.1519/JSC.0000000000003246.)

4.1 Introduction

Rugby sevens is an intermittent contact sport played across different ages and competitive levels (e.g., youth to adult, amateur to international) (Higham et al., 2012; Ross, Gill and Cronin, 2015b). Although it is played under the same laws and on the same size field as 15-a-side rugby union, rugby sevens teams comprise fewer players, and matches are 14 minutes in duration (i.e. two halves of 7 minutes) (Ross, Gill and Cronin, 2015b). At all levels of rugby sevens, multiple daily performances and consecutive days of competition present a physical and psychological challenge, whereby players and referees must manage physical readiness and psychological arousal throughout the day, ensuring they peak in time for matches (Henderson et al., 2018). Rugby sevens matches are under the control of a referee and two touch judges or assistant referees (Suarez-Arrones et al., 2013a). Two in-goal judges also officiate in elite level matches but are usually only incorporated in the knockout stages of lower competitive levels. The referee is the sole judge of fact and is required to apply the Laws of the Game in every match (World Rugby, 2020). The ability of the rugby sevens referee to meet the physical demands imposed during match play is likely to be crucial for optimal positioning and thus decision-making (Suarez-Arrones et al., 2013a).

Studies have described the match demands of refereeing 15-a-side rugby union (Martin et al., 2001; Suarez-Arrones et al., 2013c; Blair et al., 2018b) and league (Kay and Gill, 2004; O'Hara et al., 2013; Emmonds et al., 2015), but only a few have examined the physical demands of refereeing rugby sevens matches (Suarez-Arrones et al., 2013a; Suarez-Arrones et al., 2013b; Nazarudin et al., 2017). In sum, these studies have shown that officiating rugby sevens is characterized by higher running and physiological demands per minute (Suarez-Arrones et al., 2013a). Also, these studies have shown that the running demands of refereeing rugby sevens is typically higher than the demands encountered when refereeing other rugby codes, and the demands are comparable to those experienced by rugby sevens players (Suarez-Arrones et al., 2013a). However, a limitation of this research is that the referees were only evaluated at one competitive level, and thus no comparison was made between different competitive levels. To the author's knowledge, there is only one study that has compared the movement demands of rugby referees across different levels (Kraak, Malan and Van den Berg, 2011a) . This study, found that less experienced referees spent more time in jogging and sprinting activities when compared to more experienced referees (Kraak, Malan and Van den Berg, 2011a). However, this study was conducted during 15-a-side matches and compared the referees according to their level of experience at the same tournament, and thus no comparisons were made across tournaments of different competitive levels. This is an important limitation as such comparisons would provide vital information that can be used by practitioners to optimize the training and preparation of referees for rugby sevens tournaments, and ensure this training is suitable for the competitive level they will officiate.

Thus, this study investigated the physical demands of officiating at different competitive levels in rugby sevens (i.e., amateur to international). Additionally, our study aimed to determine the specific physical demands of the most intense period of the match that the referee could be involved in (i.e., "worst case scenario") (Reardon et al., 2017). Given that international rugby players have been shown to perform a greater quantity of very high speed running than provincial rugby players (Ross, Gill and Cronin, 2015b), it was hypothesised that officiating lower level matches (i.e., amateur) would be characterized by more low and moderate-intensity activities, while refereeing higher level matches (i.e., semi-professional, professional and international) would be characterized by more time spent in high-intensity activities.

4.2 Methods

4.2.1 Experimental Approach

An observational design was used and referees wore an augmented concurrent multi-GNSS receiver (GNSS) Unit (Apex, 10 Hz, STATSports, Belfast, UK), between their shoulder blades using an elasticated vest, worn beneath their normal kit. The validity and reliability of this unit has been reported previously. For example, intra and inter-unit reliability was excellent (i.e., intra-class correlation coefficient = 0.99; 95% confidence interval = 0.98-0.99; technical error of measurement = 0.12; coefficient of variation = 1.85%) for sprint distances (ranging from 5 to 30 m, Beato and de Keijzer, 2019). Moreover, the validity of Apex vs. a gold standard criterion device (i.e., radar gun) reported a nearly perfect correlation ($r = 0.96$) during a 20 m sprint, with no significant difference between the two tools ($p = 0.32$), and good inter-unit reliability for 20 m sprints expressed as CV = 2.3% (Beato et al., 2018; Beato and de Keijzer, 2019). The GNSS unit was switched on 5 minutes before, and immediately turned off at the end of each match. Data from all referees who completed the entire first and second halves were included in the final analysis. Data was excluded for one referee in the amateur level who sustained an injury and was replaced at half time. In two matches during the knock-out stage at the professional tournament, extra time was played. However, data from this extra time was not included in the final analysis, and only data from the two “standard” halves were used.

4.2.2 Subjects and Experimental Procedures

This study received institutional ethics approval and informed consent was obtained from each referee. In total, data were obtained from 27 referees (26 male, 1 female), with at least two years refereeing experience (6 ± 3 years), and 24 were amateur and three were professional. Three referees provided data for two different competitive levels. Data were recorded for between one and six matches for each referee, culminating in a total of 114 matches across five rugby sevens tournaments between May and July 2018. These tournaments were categorised into four competitive levels: (1) International (34 matches, 6 referees, age: 27 ± 3 years, body mass: 74.8 ± 4.7 kg, height: 177 ± 5 cm, refereeing experience: 8 ± 3 years), (2) professional (22 matches, 6 referees, age: 28 ± 5 years, body mass: 83.8 ± 9.2 kg, height: 181 ± 2 cm, refereeing experience: 5 ± 2 years), (3) semi-professional (26 matches, 8 referees, age: 27 ± 4 years, body mass: 79.3 ± 11.5kg, height: 179 ± 8 cm, refereeing experience: 4 ± 1 years) , and (4) amateur (32 matches, 10 referees, age: 27 ± 8 years, body mass: 79.4 ± 10.3 kg, height: 180 ± 6 cm, refereeing experience: 6 ± 2 years). The total match time analysed was made up by the periods of match play activities as well as stoppages in play (excluding the half-time interval), which led to total match time exceeding 14 minutes (15 min 57 s ± 1 min 08 s).

4.2.3 Physical Demands Analysis

Data collected included: total distance (m), relative distance (m.min^{-1}), percentage of time spent walking (<5.40 km.h^{-1}), jogging (5.41 – 10.80 km.h^{-1}), and in low intensity (10.81 – 14.40 km.h^{-1}), medium intensity (14.41 – 18.40 km.h^{-1}), high intensity (18.41 –

25.20 $km.h^{-1}$), and maximal speed (> 25.20 $km.h^{-1}$) running, average number of sprints (n), average maximal speed of a sprint ($km.h^{-1}$), average maximal distance of a sprint (m), average sprint distance (m), and average duration of a sprint (s). The speed zones have been used previously to analyse the physical demands of rugby players and referees (Roberts et al., 2008; Suarez-Arrones et al., 2013a). A sprint was defined as when the referee reached 20 $km{\cdot}h^{-1}$ and sustained this speed for at least 1 second. This was classified based on previous research with rugby sevens referees (Suarez-Arrones et al., 2013a; Suarez-Arrones et al., 2013b).

To further investigate high intensity activities, the frequency (n), duration (s), time between repeated high-intensity efforts (RHIE) (s), distance (m) and maximal speed ($km{\cdot}h^{-1}$) of RHIE bouts was analysed. A bout was defined as a minimum of three sprints and/or high acceleration efforts (> 2.79 $m.s^{-2}$) with less than 21 seconds of recovery between efforts (Austin, Gabbett and Jenkins, 2011b; Jones et al., 2015). The single longest period of a RHIE bout from each match was identified and analysed as the "Worst Case Scenario" (WCS) (Cillian Reardon et al., 2017b). The definition of a bout duration was from the time the referee first performed a high-intensity activity (i.e., sprint or high-intensity acceleration) and repeated a minimum of two other efforts with less than 21 seconds between those activities. For each WCS, the total duration (s), total distance (m), maximal speed ($km{\cdot}h^{-1}$), total distance relative to the bout duration ($m.min^{-1}$), number of sprints (n), and number of accelerations (n) was analysed.

4.2.4 Statistical Analysis

After collection, data from each GNSS unit was downloaded to analysis software (i.e., STATSports Apex software, v. 3.0.04101). Data were then exported to Microsoft Excel and statistical analysis software (IBM Corp., Armonk, NY, USA; IBM SPSS v. 22.0). Data distributions were tested using Kolmogorov-Smirnov tests. Next, means, standard deviations, and confidence intervals of the mean (95%) were calculated. To examine any differences between the competitive levels a series of one-way analyses of variance (ANOVAs) were used, with homogeneity of variances tested using the Levene's test and post-hoc analyses conducted using Tukey HSD when homogeneous and T2 Tamhane when nonhomogeneous. Effect sizes were calculated as partial eta squared (η_p^2), but are only presented for significant differences. Partial eta squared values of ≥ 0.01, ≥ 0.06, and ≥ 0.14

were interpreted as small, medium, and large effect sizes, respectively (Cohen, 1988), and α was set at 0.05.

4.3 Results

4.3.1 Total Distance and relative distance

Compared with all other competitive levels, referees who officiated at the amateur level covered significantly less total, $F(3, 110) = 13.68$, $p < 0.001$, $\eta_p^2 = 0.27$, and relative, $F(3, 110) = 17.56$, $p < 0.001$, $\eta_p^2 = 0.32$, distance (Table 6). However, there were no significant differences between the other competitive levels ($p > 0.05$).

4.3.2 Speed zones

For referees who officiated at the amateur level, a greater percentage of the total distance was covered walking, $F(3, 110) = 10.42$, $p < 0.001$, $\eta_p^2 = 0.22$, and jogging, $F(3, 110) = 24.72$, $p < 0.001$, $\eta_p^2 = 0.40$, compared with the other competitive levels (Figure 8). In addition, the referees involved in the international and professional levels covered a significantly greater percentage of the total distance in the high-intensity, $F(3, 110) = 47.92$, $p < 0.001$, $\eta_p^2 = 0.56$, and maximal, $F(3, 110) = 8.50$, $p < 0.001$, $\eta_p^2 = 0.18$, speed zones. Furthermore, the referees who officiated at the semi-professional level covered a significantly greater percentage of the total distance in the medium-intensity speed zone, $F(3, 110) = 18.55$, $p < 0.001$, $\eta_p^2 = 0.33$. Finally, the referees who officiated at the semi-professional and amateur levels covered a significantly greater percentage of the total distance in the low-intensity speed zone, $F(3, 110) = 19.25$, $p < 0.001$, $\eta_p^2 = 0.34$.

At the international competitive level, referees covered a significantly greater percentage of the total distance in the medium and high-intensity speed zones compared with all of the other zones, $F(2.1, 71.0) = 78.35$, $p < 0.001$, $\eta_p^2 = 0.70$ (Figure 9). At the professional level, the referees covered a significantly greater percentage of the total distance jogging, and in the medium and high-intensity speed zones, in comparison with walking, low-intensity, and maximal speed zones, $F(1.7, 37.6) = 29.72$, $p < 0.001$, $\eta_p^2 = 0.58$. There were no significant differences in the professional level between the distance covered jogging and in the medium ($p = 0.538$) and high-intensity ($p = 0.360$) speed zones. At the semi-professional level, referees covered a significantly greater percentage of the total distance in the medium-intensity speed zone in comparison to the other zones, $F(3.0, 77.1) = 178.20$, $p < 0.001$; $\eta_p^2 = 0.87$. Finally, at the amateur level, referees covered a significantly greater percentage of the total distance jogging in comparison to the other speed zones, $F(2.4, 76.1) = 112.79$, $p < 0.001$, $\eta_p^2 = 0.78$.

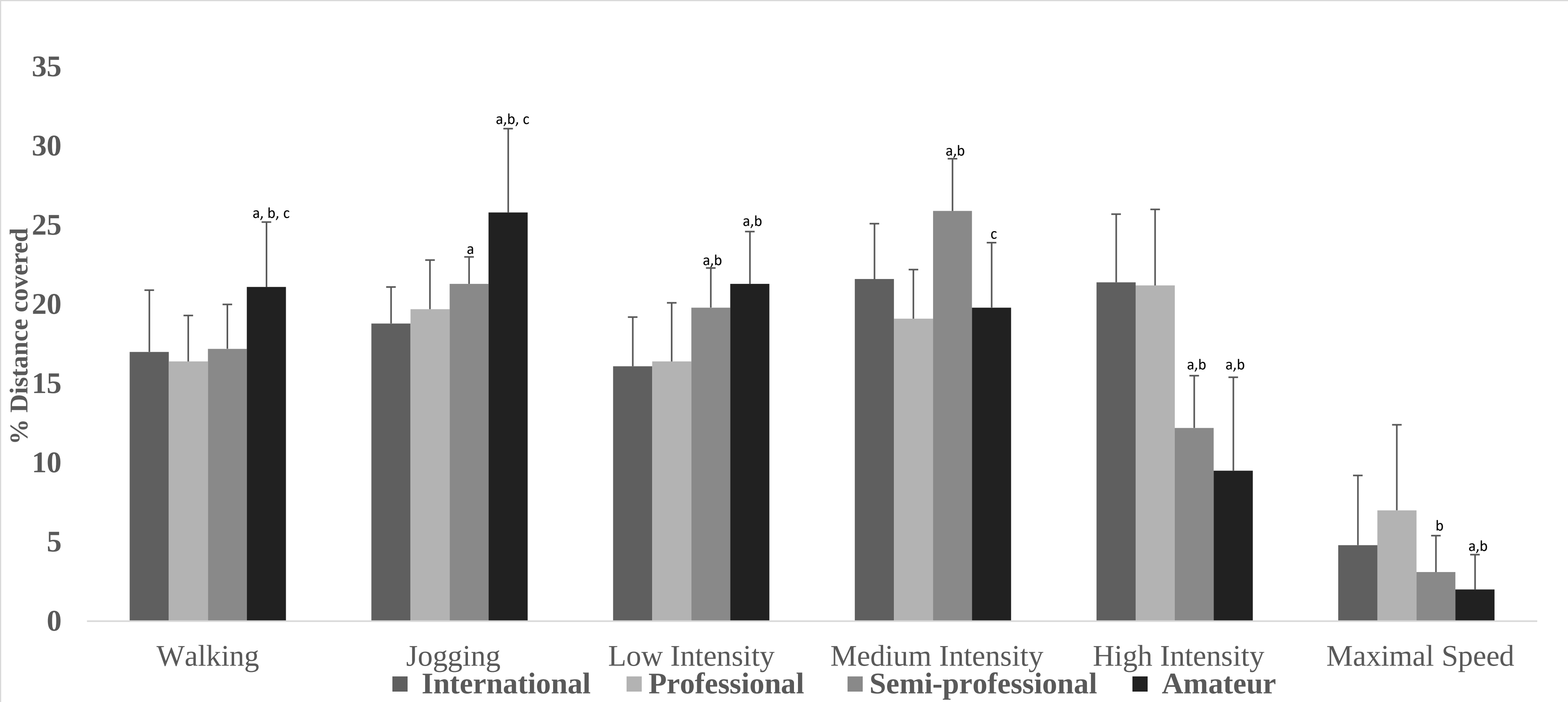
4.3.3 Sprints

Overall, there were significant differences in the number of sprints performed by the referees, $F(3, 108) = 33.47$, $p < 0.001$, $\eta_p^2 = 0.48$ (Table 6). Notably, the referees who officiated at the professional level performed more sprints compared with the referees who officiated at the semi-professional level, ($p = 0.001$) and the referees who officiated at the amateur level performed less sprints compared with the referees who officiated at all the other levels (all $p < 0.001$). Moreover, for referees at the amateur level, a lower maximal sprint speed was recorded compared with referees at the professional competitive level, $F(3, 108) = 4.43$, $p = 0.006$, $\eta_p^2= 0.11$. Finally, there were no significant differences between the levels for maximal distance, average distance, or average duration of sprints (all $p > 0.05$).

4.3.4 Repeated high-intensity efforts

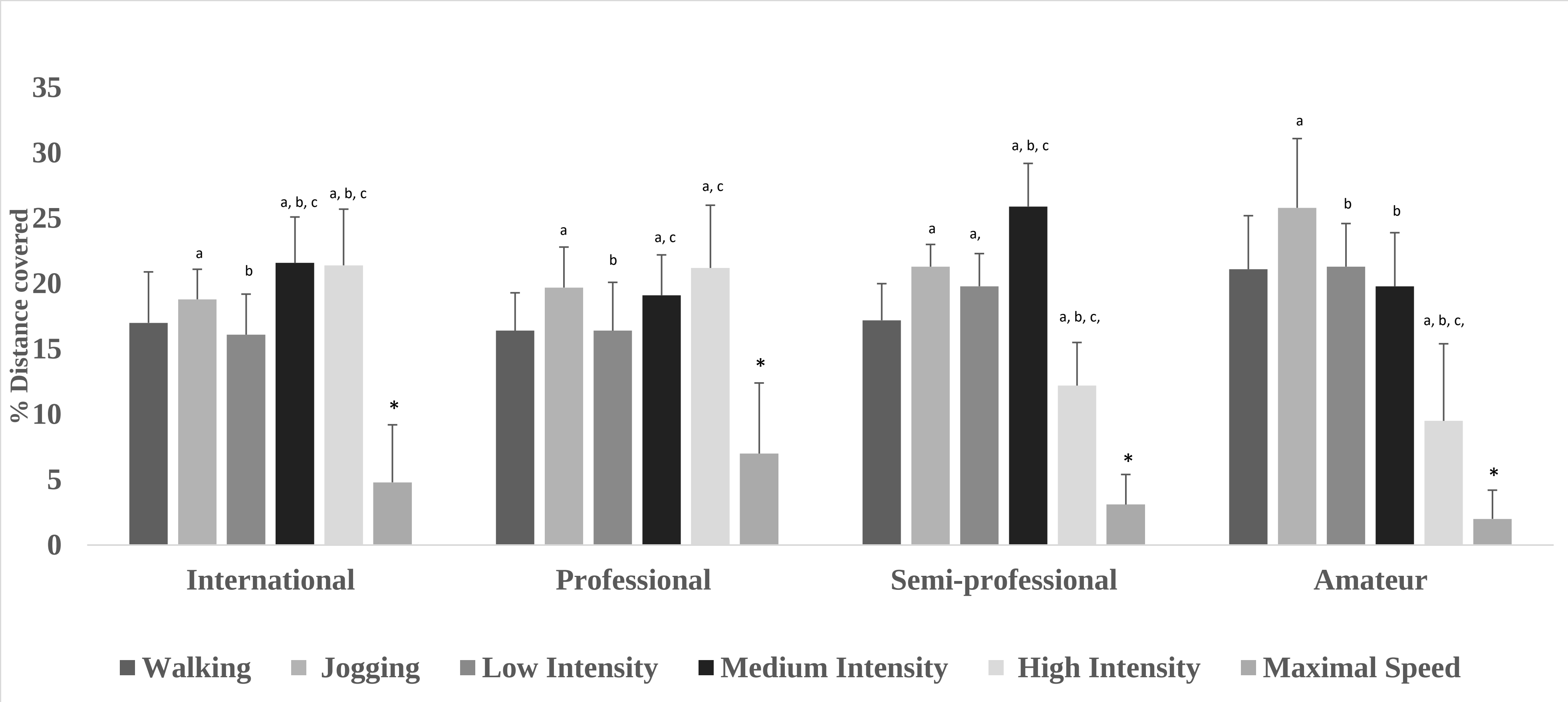
There were significant differences in the frequency of RHIE per game, $F(3, 100) = 25.96$, $p < 0.001$, $\eta_p^2 = 0.43$. Specifically, there were fewer RHIEs at the amateur level compared with all other competitive levels (all $p < 0.005$,), and fewer at the semi-professional level compared with the international ($p < .001$) and professional ($p = 0.002$) levels. In addition, at the amateur level, there was a longer time between RHIEs, $F(3, 657) = 3.95$, $p = 0.008$, $\eta_p^2 = 0.01$, in comparison with all other levels (all $p < 0.05$). Moreover, at the amateur level, RHIEs had a lower duration, $F(3, 847) = 4.40$, $p = 0.004$, $\eta_p^2 = 0.01$, compared with the professional ($p = 0.005$) and semi-professional ($p = 0.034$) levels. Furthermore, referees at the amateur level covered less distance, $F(3, 847) = 5.74$, $p = 0.001$, $\eta_p^2 = 0.02$, compared with the professional ($p = 0.003$) and semi-professional ($p = 0.002$) levels. Finally, referees at the amateur level achieved a lower maximal speed in RHIEs, $F(3, 847) =4.76$, $p = 0.003$; $\eta_p^2 = 0.01$, compared with the professional ($p = 0.003$) and semi-professional ($p = 0.018$) levels.

Figure 8. Differences between the different competitive levels in terms of each speed zone showed in the percentage of distance covered.



[a] = significantly different to International tournament 1; [b] = significantly different to Professional tournament; [c] = significantly different to Semi-professional tournament.

Figure 9. Percentage of distance covered in each speed zone at each competition.



[a] = significantly different to Zone 1; [b] = significantly different to Zone 2; [c] = significantly different to Zone 3; [d] = significantly different to Zone 4; * = significantly different to Zones 1, 2, 3, 4 and 5.

4.3.5 Worst case scenario

There were significant differences in the duration of the longest period of high-intensity activities (i.e., WCS), F (3, 98) = 11.44, $p < 0.001$, $\eta_p^2 = 0.25$, with the amateur level being shorter than all of the other competitive levels, and the semi-professional level being shorter than the professional level (Table 6). Also, within the WCS, the referees officiating at the amateur level covered significantly less distance than the referees who officiated at the other levels, F(3, 99) = 19.33, $p < 0.001$, $\eta_p^2 = 0.36$, and reached lower maximal speeds in comparison with the referees at the semi-professional and professional levels, F(3, 102) = 4.53, $p = 0.005$, $\eta_p^2 = 0.11$. Moreover, within the WCS, the referees who officiated at the amateur and semi-professional levels, performed fewer sprints than the referees who officiated at the professional level, F(3, 87) = 4.32; $p = 0.007$, $\eta_p^2 = 0.13$. In addition, the referees who officiated at the amateur level performed fewer high-intensity accelerations than the referees who officiated at the other levels, F(3, 96) = 11.83, $p < 0.001$, $\eta_p^2 = 0.27$. Finally, within the WCS, there were no significant differences in the relative distance, and no significant differences between the international and professional levels for any variable ($p > 0.05$).

Table 6. Data related to the physical demands of officiating at different competitive levels, Mean ± SD, (CI95%).

	International	Professional	Semi-professional	Amateur
Distance				
Total distance (m)	1865 ± 187 (1800-1930)	1922 ± 182 (1842-2003)	1819 ± 129 (1768-1872)	1653 ± 165 (1594-1843) [a, b, c]
Relative distance ($m.min^{-1}$)	114.3 ± 10.1 (110.7-117.8)	118.4 ± 9.3 (114.2-122.4)	118.7 ± 8.8 (115.1-122.2)	103.5 ± 8.0 (100.6-106.4) [a, b, c]
Sprints				
Number per match (n)	13.7 ± 3.6 (12.4-14.9)	15.7 ± 3.3 (14.2-17.2)	11.9 ± 3.1 (10.7-13.2) [b]	7.1 ± 3.0 (6.0-8.3) [a, b, c]
Maximal speed ($km \cdot h^{-1}$)	27.0 ± 1.6 (26.4-27.6)	28.1 ± 1.9 (27.3-29.0)	27.9 ± 1.7 (27.2-28.6)	26.2 ± 3.0 (25.1-27.3) [b]
Maximal distance (m)	58.5 ± 15.4 (53.1-63.9)	56.9 ± 11.7 (51.7-62.2)	57.1 ± 13.4 (51.7-62.5)	49.2 ± 16.8 (43.0-55.6)
Average distance (m)	25.6 ± 5.4 (23.7-27.5)	24.2 ± 4.3 (22.3-26.1)	26.3 ± 5.9 (24.0-28.7)	27.3 ± 8.3 (24.2-30.4)
Average duration (s)	4.4 ± 0.9 (4.1-4.7)	4.1 ± 0.6 (3.8-4.4)	4.4 ± 0.9 (4.1-4.8)	4.6 ± 1.2 (4.2-5.1)
RHIE				
Number per match (n)	9.6 ± 1.9 (8.9-10.2)	9.2 ± 1.4 (8.6-9.9)	7.4 ± 1.6 (6.7-8.1) [a, b]	5.3 ± 2.6 (4.3-6.4) [a, b, c]
Duration (s)	32.2 ± 18.9 (30.1-34.2)	36.5 ± 22.2 (33.4-39.7)	38.3 ± 40.6 (32.6-44.1)	29.4 ± 16.3 (26.6-32.2) [b, c]
Time between RHIE (s)	65.7 ± 38.5 (61.0-70.3)	62.9 ± 38.6 (56.7-69.1)	62.6 ± 39.3 (56.3-68.8)	79.9 ± 60.0 (67.6-92.3) [a, b, c]

Distance (m)	102.0 ± 57.6 (95.8-108.3)	114.4 ± 62.5 (105.6-123.3)	115.1 ± 87.9 (102.7-127.4)	89.0 ± 44.2 (81.5-96.7) [b, c]
Maximal speed ($km \cdot h^{-1}$)	23.5 ± 3.2 (23.2-23.9)	24.1 ± 3.3 (23.6-24.5)	23.9 ± 3.5 (23.4-24.4)	22.7 ± 3.4 (22.2-23.3) [b, c]
WCS				
Duration (s)	67.9 ± 20.4 (60.8-75.0)	77.1 ± 22.3 (66.2-87.2)	61.0 ± 10.7(56.2-65.7) [b]	44.8 ± 22.3 (35.6-54.0) [a, b, c]
Distance (m)	205.3 ± 53.9 (186.5-224.1)	221.0 ± 61.9 (192.8-249.2)	170.7 ± 38.5 (154.5-187.0) [a, b]	122.1 ± 37.0 (106.5-137.7) [a, b, c]
Maximal speed ($km \cdot h^{-1}$)	24.6 ± 2.5 (23.7-25.6)	24.9 ± 2.5 (23.7-26.0)	25.3 ± 2.4 (24.4-26.3)	22.9 ± 2.7 (21.7-24.0) [b, c]
Sprints (n)	2.1 ± 1.2 (1.7-2.6)	2.5 ± 1.0 (2.0-3.0)	1.7 ± 0.8 (1.4-2.0) [b]	1.5 ± 0.7 (1.2-1.8) [b]
Accelerations (n)	4.7 ± 1.4 (4.2-5.1)	3.8 ± 1.4 (3.1-4.4)	3.8 ± 1.2 (3.3-4.3)	2.5 ± 1.3 (2.0-3.1) [a, b, c]
Relative distance ($m.min^{-1}$)	184.3 ± 30.4 (173.7-194.9)	172.8 ± 16.0 (165.5-180.1)	172.1 ± 27.1 (161.2-183.1)	181.6 ± 40.2 (165.0-198.2)

[a] = significantly different to International tournament; [b] = significantly different to Professional tournament; [c] = significantly different to Semi-professional tournament. RHIE: Repeated High-Intensity Efforts; WCS: Worst Case Scenario.

4.4 Discussion

This study compared the physical demands of refereeing at different competitive levels in rugby sevens, from amateur to international. In summary, the results revealed that relative to the other competitive levels, referees who officiated at the amateur level ran less distance, covered a higher percentage of total distance walking and jogging, completed fewer sprints, and repeated high-intensity efforts, and spent more time between RHIE. Finally, compared with the other competitive levels, the WCS for the referees involved at the amateur level consisted of a shorter duration, less distance, and fewer accelerations.

The referees involved in the amateur competitive level covered a similar total distance to the distance reported in Suarez-Arrones et al. (2013a) (i.e., 1653 ± 165 m and 1665 ± 203 m, respectively). The results from this previous study by Suarez-Arrones et al. (2013a) showed that the relative distance covered by rugby sevens referees was 110 $m.min^{-1}$. This result was greater than the relative distance found in the present study at the amateur level, which might be due to different total match durations (including stoppages in play) in each study. However this finding from both studies was lower than the relative distance covered at the international, professional, and semi-professional levels (Table 6). Although comparisons with previous research should be made cautiously, one possible explanation for these differences is the higher level of rugby sevens played at the tournaments accessed in the present study (i.e., professional and international). For instance, professional players likely possess greater tactical awareness, and limit handling errors, which would reduce match stoppages (Ross, Gill and Cronin, 2015b). Consequently, the ball in play time is often higher at the professional level, requiring the referees to cover a greater distance per minute.

Overall, the results show that at higher competitive levels, the referees were required to cover greater distance at high-intensity running and maximal speed. The results previously reported by Suarez-Arrones et al. (2013a) were similar to the findings for the semi-professional level in the present study, with the referees covering nearly 60% of total distance in low-intensity running, jogging, and walking, and approximately 15% in high-intensity running and at maximal speed. In the present study, there were differences between the lower (i.e., amateur) and higher (i.e., international and professional) levels. Specifically, in the latter, the referees covered approximately 50% of the total distance in speed zones below 14 $km \cdot h^{-1}$, whereas in the former, the referees covered approximately 70% of the total distance within these zones. Moreover, differences were observed between these levels for high-intensity and maximal speed running. Indeed, the referees who officiated at the higher levels (i.e., international and professional) covered approximately 30% of the total distance within these speed zones, whereas referees at the lower level (i.e., amateur) covered only 11%. These results might be partly explained by the greater speed characteristics of the international and professional players, who cover larger distances at higher speeds than amateur players, and also because professional matches involve greater ball-in-play time (Ross, Gill and Cronin, 2015b). Thus, a referee officiating at a higher competitive level must have the capacity to cover more distance at higher speed than referees officiating at lower competitive levels.

There will be passages of play in rugby sevens, where the transition of the ball from one side of the pitch to the other is quick, with less phases and stoppages (e.g., rucks, scrums) (Suarez-Arrones et al., 2012a), and the referee is therefore required to cover greater distance in a shorter period of time. Thus, sprinting is a necessary demand for officiating rugby sevens matches. The findings of the present study show that referees involved at the professional level sprinted approximately 15 times per match, which was significantly higher than at the semi-professional and amateur levels (approximately 11 and 7 sprints per match, respectively), and similar to the number of sprints previously reported for rugby sevens players (Suarez-Arrones et al., 2012b; Suarez-Arrones et al., 2016). Moreover, the referees were required to sprint over an average distance of 25 meters and occasionally over 60 metres.

To our knowledge, this was the first study to analyse RHIE for rugby sevens referees. The findings show that the number of RHIE was highest at the professional and international competitive levels, which is unsurprising due to the greater percentage of total distance covered in high-intensity speed zones. The mean duration of a RHIE was shorter and the time between RHIE was longer at the amateur level compared with the professional and semi-professional levels. These findings could be explained by the superior skill level of the international and professional players, resulting in fewer stoppages and more ball-in-play time (Roberts et al., 2008). However, it should be noted that there were no significant differences between the amateur and international levels. This comparison was also similar for the results related to the distance covered during RHIE. These findings were surprising due to the fact that international matches encompass a greater frequency of long-duration activity cycles (Ross, Gill and Cronin, 2015b). Despite a direct comparison being difficult due to the different roles, the results show a similar number of RHIEs per match to those reported for rugby sevens players (Suarez-Arrones et al., 2016) and a similar average duration of RHIE to players (backs positional group) during rugby union matches (Austin, Gabbett and Jenkins, 2011b). However, this comparison should be made cautiously, because players will also be involved in collisions, which are characterized as high-intensity efforts (Austin, Gabbett and Jenkins, 2011b), and this does not typically apply to referees.

The analysis of the WCS, showed that the amateur competitive level had a lower duration, lower distance covered, and a lower number of accelerations performed by the referee during the most intense period of match, when compared with the other levels. Additionally, referees officiating at the amateur level also performed fewer sprints than those at the professional level. Interestingly, at the semi-professional level, the duration of the WCS, and the number of sprints performed within this period, was lower than at the professional level. Likewise, at the semi-professional level, the referees covered less distance than during the professional and international levels. These might be explained by the fact that at the professional level, the players are athletically superior to players at the lower levels (i.e., semi-professional and amateur), resulting in higher physical demands during the matches involving higher quality players (Argus, Gill and Keogh, 2012; Fontana et al., 2015). These findings also suggest that at higher competitive levels, referees' ability to sustain high-intensity activity is more significant. Although the comparison between different studies should be made with caution, because of the different roles performed in a rugby match, within the WCS, the referees in this study covered a higher distance per minute, and performed more sprints, than previously reported for professionals rugby union players (Reardon et al., 2017).

This study adds to the literature regarding the physical demands of refereeing rugby sevens. However, there are some limitations that should be noted. First, rugby sevens referees are often required to officiate in more than one match per day and on consecutive days. Unfortunately, due to logistical challenges, this study did not investigate variation between matches (i.e., exercise-induced fatigue), and thus researchers should aim to examine such variation in the future. Second, the outcomes of this study are specific to referees within tournaments in the northern hemisphere, potentially limiting the generalisability of the findings. Future research is therefore encouraged to investigate the physical demands of officiating rugby sevens in other nations and at international tournaments involving both northern and southern hemisphere teams (e.g., World Sevens Series). Finally, the data for this study was collected during one season, and so, future research should aim to examine longitudinal data and investigate match-to-match and within season variations in physical demands.

4.5 Conclusions and practical implications

In summary, this study examined the physical demands of refereeing rugby sevens matches at different competitive levels. The findings showed that rugby sevens refereeing is characterised by high intermittent running demands that are greater at higher levels of competition. This study provides rugby sevens referees and practitioners with an understanding of the physical demands of officiating at different competitive levels. The findings can help practitioners optimise the training of rugby sevens referees to ensure that they have the capacity to perform the repeated high-intensity efforts needed on a match day. More specifically, the high intensity intermittent nature of officiating rugby sevens matches, requires the development of training programmes that include high intensity efforts (i.e., > 18.1 km·h^{-1}) interspersed with short periods of recovery at low intensity running (i.e., 1 minute between 10.8 and 14.4 km·h^{-1}). Additionally the analysis of the WCS provides useful information for the prescription of training aimed at improving rugby referees' fitness to cope and overlap with the most demanding periods of the match. In particular, to induce overload in training for rugby sevens referees, practitioners may wish to design training programmes which include sessions exceeding the WCS identified in the current study. For example, repeated high-intensity efforts (i.e., > 3 sprints) for a longer period (i.e., > 80 seconds) replicating the movement demands of the match, which should include change of directions exercises. Furthermore, sprint training should be designed for rugby sevens referees that reflects and replicates the physical demands encountered in this research. As rugby sevens referees are subjected to a high physical demand during matches, they should follow structured weekly training plans that have an emphasis on intensive and intermittent exercise sessions.

CHAPTER FIVE: 15-A-SIDE RUGBY UNION REFEREES' PHYSICAL AND PHYSIOLOGICAL DEMANDS ACROSS DIFFERENT COMPETITIVE LEVELS

(Citation: Sant'Anna R.T., Roberts S.P., Moore L.J., Reid A., Stokes K.A. (2021) Rugby union referees' physical and physiological demands across different competitive levels. The Journal of Sports Medicine and Physical Fitness. Jun;61(6):788-796. doi: 10.23736/S0022-4707.20.11447-6. Epub 2020 Nov 4. PMID: 33146494.)

5.1 Introduction

Fifteen-a-side rugby union (hereafter referred to as rugby) is an intermittent sport involving periods of high-intensity (e.g., sprinting) and static (e.g., scrums) exercise, interspersed with low-intensity activity (e.g., walking) (Roberts et al., 2008; Cunningham et al., 2016; Blair et al., 2018b). Rugby is played across different ages, genders, and competitive levels (e.g., amateur to professional) (Argus, Gill and Keogh, 2012), and over the years, there have been changes to the laws and preparation of players that have contributed to a faster pace of play, increased ball-in-play time, and more physical contact (Austin, Gabbett and Jenkins, 2011a; Blair et al., 2018b). These changes have also increased the requirements of rugby referees (Blair et al., 2018b), with the ability to meet the physical and physiological demands of a match being vital for optimal positioning and decision-making (Suarez-Arrones et al., 2013a). This study will explore if the demands placed upon rugby referees differ across competitive levels (e.g., amateur, semi-professional, and professional).

The physical demands placed on rugby referees during match play has been described previously, with the total distance covered ranging from 6000 to 8500 m (Martin et al., 2001; Kraak, Malan and Berg, 2011b; Suarez-Arrones et al., 2013c; Blair et al., 2018b; Bester et al., 2019), and relative distance ranging from 74 to 83 m.min-1, with most distance covered walking or jogging (< 12 $km \cdot h^{-1}$) (Suarez-Arrones et al., 2013c; Blair et al., 2018b). Although two studies found no difference in the distance covered by rugby referees over consecutive 10-minute periods (Martin et al., 2001; Bester et al., 2019), one study found a 20% reduction in the last 30-minutes compared with the first 10 minutes (Suarez-Arrones et al., 2013c). However, it was unclear if this reduction was due to fatigue or changes in the pattern of play, with both likely to impact referee movement (Suarez-Arrones et al., 2013c).

To date, only two studies have described the percentage of time spent by rugby referees performing highly energetic activities and “sprinting” (Martin et al., 2001; Kraak, Malan and Van den Berg, 2011a), with another two studies reporting the number (~20 per match) of sprints (> 20.1 $km \cdot h^{-1}$) (Suarez-Arrones et al., 2013c; Bester et al., 2019). However, more detailed information relating to the distance covered by rugby referees in high-speed running and, particularly, the most demanding periods of running, is lacking. One study used the maximum ball-in-play time as the most physically demanding period a referee could face, termed the “worst case scenario” (WCS) (Igoe and Browne, 2019b). In this study, less than 2% of time in the WCS was spent in high-speed running, and so it seems inappropriate to define the most extended passage of play as the most demanding part of the match. Thus, a definition of WCS which uses the single longest bout of repeated high-intensity efforts performed by the referee, is likely to provide a more valid estimate of the WCS, as it could be longer in duration, and incorporate more high intensity efforts than the average reported for repeated high-intensity efforts and the maximum ball-in-play time (Austin, Gabbett and Jenkins, 2011b; Reardon et al., 2017), and has been used in a recent study with rugby sevens referees (Chapter 4). This more advanced insight into the high-intensity efforts performed by rugby referees will aid the development of more specific training programmes and fitness tests.

Rugby match demands can be expressed in terms of external (physical demands; e.g., total distance covered) and internal (physiological demands; e.g. heart rate) loads, and greater knowledge of the relationship between external and internal loads enables a better understanding of the dose-response nature of training and competition (Castillo et al., 2017). HR responses of rugby referees have been studied, and results have shown that most of the time is spent in higher HR zones (e.g., > 80% HR_{max}) (Martin et al., 2005; Suarez-Arrones et al., 2013c; Blair et al., 2018b). Despite one study of rugby sevens referees analysing HR responses as a measure of internal load (Appendix A), to date, no studies have analysed the internal load measures for rugby referees during 15-a-side matches or examined the external-internal load relationship. However, previous research with soccer referees has found a moderate correlation between external (i.e., total distance) and internal (i.e., HR responses) load (Castillo et al., 2017). Information regarding external and internal load will provide novel insights into the specific match demands placed on rugby referees during competitive matches, enabling practitioners to improve conditioning programmes and fitness testing protocols.

Although one study has examined how match demands differ between referees of varying experience, revealing that inexperienced referees jogged and sprinted more than experienced referees (Kraak, Malan and Van den Berg, 2011a), most available research has only described the match demands of refereeing rugby at an elite level (Blair et al., 2018b; Bester et al., 2019). Indeed, to date, no study has investigated whether match demands differ as a function of expertise, across rugby referees officiating at different competitive levels (e.g., elite vs. amateur). Thus, in order to provide important information for applied practitioners working with rugby referees, the primary aim of this study was to compare the match (physical and physiological) demands of officiating 15-a-side rugby at amateur, semi-professional, and professional levels, focusing particularly on high-intensity efforts (i.e., sprints), and WCS. A secondary aim was to investigate the relationship between external (e.g., total distance) and internal load (e.g., HR) at each competitive level (i.e., amateur, semi-professional, and professional). It was predicted that officiating professional and semi-professional rugby would involve more time in high-intensity activities (e.g., sprinting) and a longer WCS than refereeing amateur rugby.

5.2 Materials and methods

5.2.1 Participants and study design

This study received institutional ethics approval and used an observational design. Referees who were officiating at levels 1 to 7 in the Rugby Football Union competitions (Rugby Football Union, 2019) were invited to participate in the study via an advert sent out by Referee Managers of the National Societies. There are no fitness criteria which must be met to start refereeing; those referees who had less than two years of refereeing experience, and those who had sustained an injury in the previous six months, were not included in the study. The referees who accepted the invitation to take part in the study, were contacted by the lead researcher and asked to provide their contact details, if they were taking any medication, as well as their age, refereeing experience, body mass, and height. Body mass index (BMI; body mass divided by square height) was calculated for all referees. Data were collected from 21 referees (20 male, 1 female, age: 27 ± 6 years [range: 18-39 years], body mass: 83.3 ± 10.2 kg, height: 179 ± 5 cm), with at least two years' experience (6 ± 3 years). Seven referees were professional, three were semi-professional, and 11 were amateur. Data were recorded for between one and 11 matches per referee, with a total of 82 matches between September and May during the 2018/19 season, across seven competitive levels in

England (Level 1 [English Premiership] to Level 7 [Community Rugby] - according to the RFU (Rugby Football Union, 2019). These levels were further categorised into three competitive levels: (1) Professional (Levels 1 and 2, 30 matches, 7 referees), (2) Semi-professional (Levels 3, 4 and 5, 22 matches, 6 referees), and (3) Amateur (Levels 6 and 7, 30 matches, 9 referees). One referee officiated at levels 2 and 3, thus providing data for two competitive levels (professional and semi-professional). The number of referees at each competitive level was determined by those who volunteered to take part in the study and the number of matches per referee was determined by the logistics of getting the GNSS units to the referees (e.g., number of units available, and geographical location of the referee). The GNSS units were used in a rotation system according to the referees' appointments at the semi-professional and amateur competitive levels, resulting in a different number of recordings per referee. The total match time recorded included ball-in-play time and stoppages (excluding the half-time interval), which led to an average total match time exceeding 80 minutes (90 minutes 32 seconds ± 4 minutes 51 seconds).

Referees were advised to maintain their normal daily routine (i.e., nutrition and sleep) prior to the matches, and no referees were taking any medication that could have influenced their heart rate. On match day, they were advised to keep their normal preparation, including their normal ingestion of fluids before and during the matches, and their own warm-up routine before the matches (e.g., stretching, jogging, and accelerations). During matches, the full rest period was used during half-time, consisting of an interval between halves not exceeding 15 minutes, and this was consistent across all competitive levels. Although no specific information was collected, the travel time to the matches would typically range from one to four hours either by public or private transport. The referees who officiated at levels 1 and 2 (i.e., professional competitive level) within this study were made up of a combination of full-time salaried officials and contracted part-time officials who received a retainer and match fee. Referees officiating at levels 3 and 4 (i.e., semi-professional competitive level) received a match fee, but they were not contracted officials. Referees officiated at levels 5 (i.e., semi-professional competitive level), 6, and 7 (i.e., amateur competitive level) were not contracted officials, and did not receive a match fee, but did receive travel expenses. Informed consent was obtained from each referee.

5.2.2 Physical demands

Beneath their normal kit, referees wore an elasticated vest with an augmented concurrent multi-GNSS receiver unit (Apex, 10 Hz, STATSports, Belfast, UK), located between their shoulder blades. The validity and reliability of this unit has been reported previously (Beato et al., 2018). The unit was switched on 15 minutes before, and turned off immediately after, each match. The physical demands accessed in this study were: total distance (m), relative distance ($m.min^{-1}$), and the percentage of time spent walking (< 5.40 $km{\cdot}h^{-1}$), jogging (5.41 – 10.80 $km{\cdot}h^{-1}$), and in low (10.81 – 14.40 $km{\cdot}h^{-1}$), medium (14.41 – 18.40 $km{\cdot}h^{-1}$)' and high (18.41 – 25.20 $km{\cdot}h^{-1}$) intensity, and maximal speed (> 25.20 $km{\cdot}h^{-1}$), running (Chapter 4) Furthermore, data collected also included the average number of high-intensity (> 2.79 $m.s^{-2}$) accelerations and decelerations (n), average number of sprints (n), average maximal speed of a sprint ($km{\cdot}h^{-1}$), average maximal distance of a sprint (m), average sprint distance (m), average duration of a sprint (s), total sprint distance (m), and percentage of total match distance spent sprinting (%). Accelerations and decelerations were calculated from a single derivation of the speed during a period of 0.5 seconds (Couderc et al., 2019), and the definition of high-intensity efforts (> 2.79 $m.s^{-2}$) has been used previously (Chapter 4). Finally, a sprint was defined as when the referee reached 20 $km{\cdot}h^{-1}$ and sustained this speed for at least one second (Chapter 4).

To further investigate high intensity activity, the frequency (n), average duration (s), average time between repeated high-intensity efforts (RHIE) (s), distance covered during RHIE bouts (m), and maximal speed of RHIE bouts ($km{\cdot}h^{-1}$), were analysed. An RHIE bout was defined as a minimum of three sprints or high acceleration efforts (> 2.79 $m.s^{-2}$) with less than 21 seconds of recovery between efforts (Austin, Gabbett and Jenkins, 2011b; Jones et al., 2015). Bout duration was defined as the time from the first to the final high-intensity activity. The single longest RHIE from each match was identified as the WCS (Reardon et al., 2017), for which, the total duration (s), total distance (m), maximal speed ($km{\cdot}h^{-1}$), total distance relative to the bout duration ($m.min^{-1}$), number of sprints (n), and number of accelerations (n) were analysed.

5.2.3 Physiological demands

HR data were collected from 57 matches from the professional (22 matches, five referees, age: 33 ± 4 years, body mass: 78.4 ± 4.1 kg, height: 178 ± 4 cm), semi-professional

(18 matches, five referees, age: 26 ± 7 years, body mass: 82.7 ± 8.3 kg, height: 177 ± 4 cm), and amateur (17 matches, seven referees, age: 24 ± 3 years, body mass: 81.8 ± 5.2 kg, height: 183 ± 4 cm) levels. HR data were collected for between one and eight matches from each referee through a HR sensor (Polar T31, Polar Electro, Kempele, Finland) worn around each referee's chest, which transmitted real-time data via Bluetooth to the GNSS unit. Maximal HR (HR_{max}) was determined as the highest of either: (1) HR_{max} estimated thorough the formula: 208 – (0.7 x age) (Tanaka, Monahan and Seals, 2001), or (2) HR_{max} values obtained during the match (Suarez-Arrones et al., 2013c). HR data were classified based on the percentage of total playing time spent in six HR zones (Suarez-Arrones et al., 2013c): zone 1 (< 60% HR_{max}), zone 2 (61 – 70% HR_{max}), zone 3 (71 – 80% HR_{max}), zone 4 (81 – 90% HR_{max}), zone 5 (91 – 95% HR_{max}), and zone 6 (>96% HR_{max}). Consistent with published guidance (Edwards, 1993), internal load was calculated by multiplying the time spent (in minutes) in five pre-defined HR zones by a coefficient assigned to each zone (i.e., 50 - 60% HR_{max} = 1, 60 - 70% HR_{max} = 2, 70 -80% HR_{max} = 3, 80 - 90% HR_{max} = 4, and 90 - 100 HR_{max} = 5).

5.2.4 Statistical analysis

After collection, data from each GNSS unit was downloaded to analysis software (STATSports Apex software, v. 3.0.02011). Data were then exported to statistical analysis software (IBM SPSS v. 26.0; IBM Corp., Armonk, NY, USA). Data distributions were tested using Kolmogorov-Smirnov tests. Next, means, standard deviations, and 95% confidence intervals were calculated. To examine any differences between the different competitive levels (i.e., professional, semi-professional, and amateur), a series of one-way analysis of variances (ANOVAs) were conducted, with homogeneity of variances tested using the Levene's test and post-hoc analyses conducted using Tukey's HSD when homogeneous and T2 Tamhane when non-homogeneous. Effect sizes were calculated as partial eta squared (ηp^2), and values of ≥ 0 .01, ≥ 0.06, and ≥ 0.14 were interpreted as small, medium, and large, respectively (Cohen, 1988). Pearson's correlations were used to examine the relationship between external (e.g., total distance) and internal (e.g., HR) load, conducted separately for each competitive level. Correlation coefficients (*r*) of 0.1-0.3, 0.3-0.5, and > 0.5 were interpreted as small, moderate, and large, respectively (Hopkins et al., 2009). For all analyses, α was set at 0.05.

5.3 Results

5.3.1 Referees characteristics

There were significant differences between the competitive levels for age $F(2,21) = 3.76$, $p = 0.042$, $\eta p2 = 0.28$, and refereeing experience $F(2,21) = 6.09$, $p = 0.009$, $\eta p2 = 0.39$. Specifically, referees officiating at the professional level were older than referees officiating at the semi-professional level ($p = 0.035$), and more experienced than referees officiating at the amateur level ($p = 0.007$). However, there were no significant differences between the competitive levels in terms of height ($p = 0.660$), weight ($p = 0.297$), or body mass index ($p = 0.139$) (Table 7). The final analysis reported below were repeated with age and experience added as covariates, but the pattern of results was unchanged.

Table 7. Referees' characteristics according to the different competitive levels, Mean ± SD.

	Professional	**Semi-professional**	**Amateur**
Age (y)	32 ± 5	25 ± 3[a]	25 ± 7
Referee experience (y)	10 ± 3	6 ± 3	4 ± 2[a]
Height (cm)	178 ± 4	182 ± 5	179 ± 5
Body mass (kg)	79.7 ± 6.2	79.8 ± 6.9	86.9 ± 13.7
Body mass index (au)	25.2 ± 2.0	24.1 ± 1.5	27.0 ± 3.6

[a] = significantly different to professional level

5.3.2 Total distance and relative distance

There were significant differences between the competitive levels for total, $F(2, 81) = 15.91$, $p < 0.001$, $\eta_p^2 = 0.28$, and relative, $F(2, 81) = 5.77$, $p = 0.005$, $\eta_p^2 = 0.12$, distance. Amateur level referees covered less total distance than the professional ($p < 0.001$) and semi-professional ($p = 0.006$) level referees, and less relative distance than the professional level referees ($p = 0.003$) (Table 8).

5.3.3 Speed zones

There were significant differences between the competitive levels for the distance covered walking, $F(2, 76) = 6.33$, $p = 0.003$, $\eta_p^2 = 0.14$, jogging, $F(2, 75) = 23.56$, $p < 0.001$, $\eta_p^2 = 0.38$, and at low intensity, $F(2, 76) = 6.80$, $p = 0.002$, $\eta_p^2 = 0.15$, medium intensity, $F(2, 77) = 5.43$, $p = 0.006$, $\eta_p^2 = 0.12$, and maximum speed, $F(2, 76) = 6.79$, $p = 0.002$, $\eta_p^2 = 0.15$. Compared with the professional level referees, amateur level referees covered less distance walking ($p < 0.001$), jogging ($p < 0.001$), and at low ($p = 0.004$) and medium ($p = 0.014$) intensity, and maximum speed ($p = 0.001$). Moreover, amateur level referees covered less distance jogging ($p < 0.001$), and at low ($p = 0.023$) and medium ($p = 0.006$) intensity compared with the semi-professional level referees. Finally, semi-professional level referees covered less distance jogging ($p = 0.015$) than professional level referees (Figure 10).

5.3.4 Accelerations and decelerations

There were significant differences between the competitive levels for high-intensity accelerations, $F(2, 77) = 3.23$, $p = 0.045$, $\eta_p^2 = 0.08$, with amateur level referees making fewer accelerations than professional level referees ($p = 0.040$). However, there were no significant differences for decelerations, $F(2,78) = 1.39$, $p = 0.256$, $\eta_p^2 = 0.03$ (Table 8).

5.3.5 Sprints

There were significant differences between the competitive levels for the maximal speed reached during a sprint, $F(2, 80) = 4.49$, $p = 0.014$, $\eta_p^2 = 0.10$, maximum sprint distance, $F(2, 81) = 3.88$, $p = 0.024$, $\eta_p^2 = 0.09$, average sprint distance, $F(2, 79) = 6.35$, $p = 0.003$, $\eta_p^2 = 0.14$, and average sprint duration, $F(2, 79) = 5.82$, $p = 0.004$, $\eta_p^2 = 0.13$. Compared with professional level referees, amateur level referees recorded a lower maximal speed ($p = 0.011$) and maximum sprint distance ($p = 0.022$). Moreover, professional level referees covered a higher average sprint distance than semi-professional ($p = 0.013$) and amateur ($p = 0.006$) level referees. A longer average sprint duration was also observed for professional level referees compared with semi-professional ($p = 0.018$) and amateur ($p = 0.010$) level referees (Table 8).

5.3.6 Repeated high-intensity efforts (RHIEs)

There were significant differences between the competitive levels in the time between RHIEs, $F(2, 427) = 9.31$, $p < 0.001$, $\eta_p^2 = 0.04$, with amateur level referees spending less time between RHIEs than professional ($p = 0.016$) and semi-professional ($p < 0.001$) level referees (Table 8). There were no significant differences between the competitive levels for the number of RHIEs per match, $F(2,78) = 2.46$, $p = 0.092$, $\eta_p^2 = 0.61$, average duration of RHIEs, $F(2, 556) = 1.23$, $p = 0.293$, $\eta_p^2 = 0.00$, distance covered at RHIEs, $F(2, 556) = 0.709$, $p = 0.492$, $\eta_p^2 = 0.00$, or maximal speed reached during RHIEs, $F(2, 546) = 1.12$, $p = 0.327$, $\eta_p^2 = 0.00$ (Table 8).

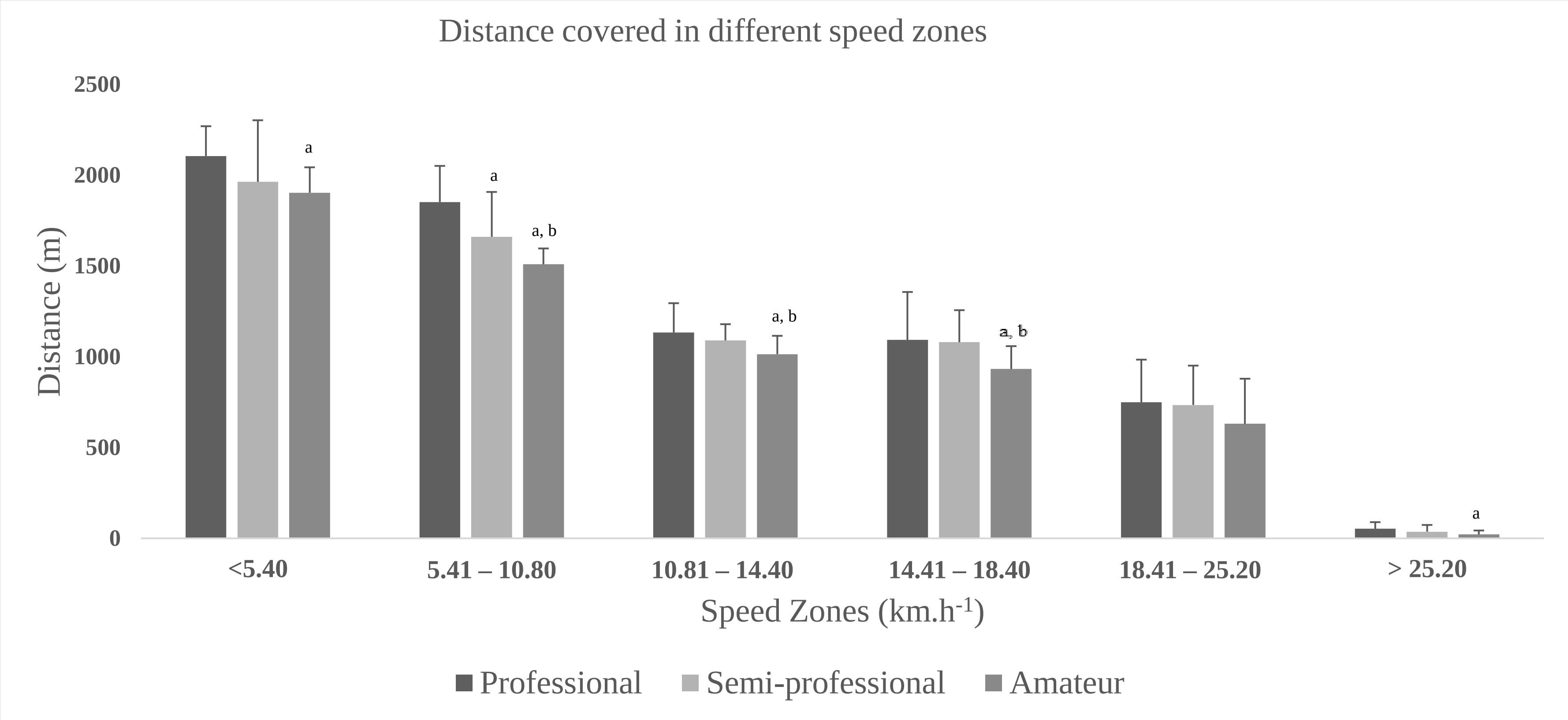
Table 8. Data related to the physical demands of officiating at different competitive levels, Mean ± SD, (CI95%).

	Professional	Semi-professional	Amateur
Distance			
Total distance (m)	6994 ± 757 (6711-7276)	6611 ± 644 (6326-6896)	6059 ± 508[a, b] (5869-6249)
Relative distance ($m.min^{-1}$)	75.2 ± 7.5 (72.4-78.0)	72.8 ± 6.3 (70.0-75.6)	69.5 ± 5.5[a] (67.4-71.5)
High-Intensity (> 2.79 $m.s^{-2}$) accelerations (n)	55 ± 20 (48-63)	51 ± 13 (45-58)	40 ± 30[a] (29-52)
High-Intensity (> 2.79 $m.s^{-2}$) decelerations (n)	39 ± 14 (33-44)	32 ± 9 (27-36)	31 ± 25 (22-41)
Sprints			
Number per match (n)	27 ± 8 (24-30)	27 ± 7 (24-30)	26 ± 11 (22-30)
Maximal speed ($km{\cdot}h^{-1}$)	27.2 ± 1.4 (26.6-27.7)	26.5 ± 1.4 (25.8-27.1)	26.0 ± 1.6[a] (25.4-26.6)
Maximal distance (m)	60 ± 15 (54-66)	57 ± 10 (53-62)	50 ± 16[a] (44-56)
Average distance (m)	23 ± 3 (22-24)	21 ± 3[a] (20-22)	21 ± 3[a] (19-22)
Average duration (s)	4.1 ± 0.4 (3.9-4.2)	3.7 ± 0.5[a] (3.5-4.0)	3.7 ± 0.5[a] (3.5-3.9)
Total sprint distance (m)	630 ± 204 (554-706)	561 ± 158 (489-634)	541 ± 255 (446-636)
Percentage of total game distance (%)	8.9 ± 2.3 (8.0-9.8)	8.8 ± 2.4 (7.7-9.9)	8.8 ± 3.8 (7.4-10.2)
RHIEs			

Number of RHIEs per match (n)	8.4 ± 4.9 (6.5-10.3)	6.3 ± 4.5 (4.2-8.3)	5.4 ± 6.0 (3.1-7.6)
Average RHIE duration (s)	26.4 ± 11 (25-27.8)	25.6 ± 11.8 (23-27.6)	27.6 ± 11.4 (26-29.2)
Time between RHIEs (s)	314 ± 250 (278-349)	387 ± 298 (325-447)	243 ± 203[a, b] (209-278)
RHIE distance (m)	79.3 ± 34.9 (75-84.7)	76.3 ± 34.7 (70.3-82.4)	81 ± 31.5 (76.3-82)
RHIE maximal speed (km·h^{-1})	22.9 ± 2.7 (22.6-23.3)	22.7 ± 2.4 (22.2-23.1)	23.1 ± 2.1 (22.7-23.1)
WCS			
WCS duration (s)	45.6 ± 15.5 (39.7-51.5)	39.3 ± 10.0 (34.4-44.1)	35.6 ± 13.3[a] (29.8-41.3)
WCS distance (m)	130.6 ± 41.1 (115.0-146.2)	115.3 ± 29.9 (101.3-129.3)	104.2 ± 33.2[a] (89.9-118.6)
WCS maximal speed (km·h^{-1})	24.5 ± 2.5 (23.5-25.4)	22.4 ± 2.4[a] (21.3-23.5)	22.8 ± 1.4[a] (22.2-23.4)
WCS sprints (n)	1.6 ± 0.7 (1.3-1.9)	1.4 ± 0.9 (0.9-1.8)	1.6 ± 0.9 (1.2-1.9)
WCS accelerations (n)	3.0 ± 1.2 (2.5-3.7)	2.5 ± 0.9 (2.1-2.9)	2.4 ± 1.4 (1.8-3.0)
WCS relative distance (m.min^{-1})	172.5 ± 28.4 (161.5-183.5)	175.6 ± 38.8 (158.0-193.3)	183.4 ± 45.9 (164.0-202.7)

[a] = significantly different to professional level; [b] = significantly different to semi-professional level. RHIE: Repeated High-Intensity Efforts; WCS: Worst Case Scenario.

Figure 10. Differences between the competitive levels in terms of each speed zone showed in the percentage of distance covered.



[a] Significantly different to professional level. [b] Significantly different to semi-professional level.

5.3.7 Worst case scenario (WCS)

There were significant differences between the competitive levels in the duration, $F(2, 70) = 3.68$, $p = 0.030$, $\eta_p^2 = 0.10$, distance covered, $F(2, 71) = 3.54$, $p = 0.034$, $\eta_p^2 = 0.09$, and maximal speed reached, $F(2, 71) = 5.98$, $p = 0.004$, $\eta_p^2 = 0.14$, during the WCS. Compared with professional level referees, amateur level referees had a lower WCS duration ($p = 0.026$) and covered less distance in the WCS ($p = 0.028$). Professional level referees also had a higher maximal speed during the WCS than semi-professional ($p = 0.020$) and amateur ($p = 0.015$) level referees (Table 8).

5.3.8 Heart rate (HR) and internal load

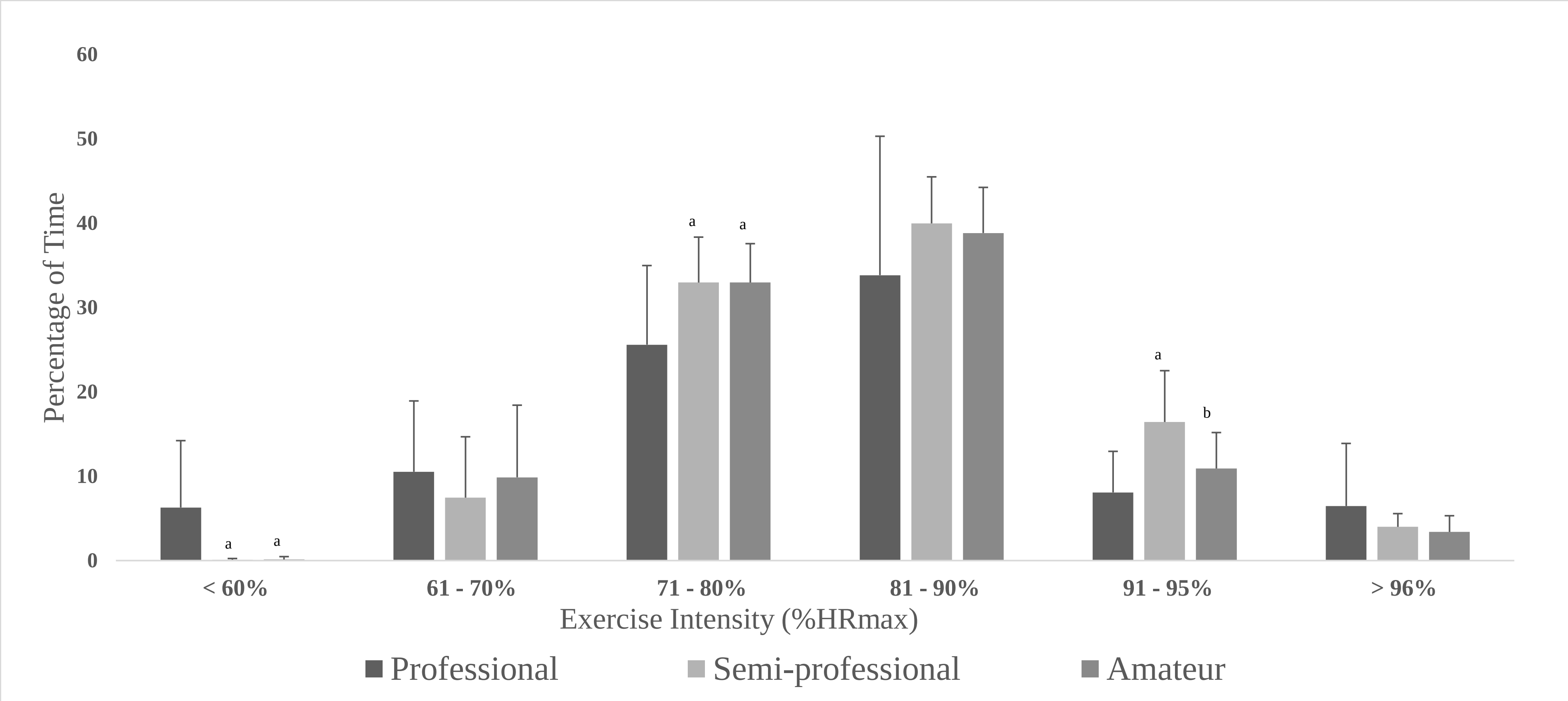
There were significant differences in average HR (beats.min^{-1}) between the competitive levels, $F(2, 53) = 11.08$, $p < 0.001$, $\eta_p^2 = 0.30$. Professional level referees showed a lower average HR compared with semi-professional ($p < 0.001$) and amateur ($p = 0.013$) level referees (Table 9). There were no significant differences between the competitive levels for maximum HR per match, $F(2, 54) = 0.981$, $p = 0.382$, $\eta_p^2 = 0.04$, average percentage HR_{max}, $F(2, 52) = 2.50$, $p = 0.092$, $\eta_p^2 = 0.09$, or internal load, $F(2, 49) = 1.44$, $p = 0.248$, $\eta_p^2 = 0.06$. However, there were significant differences in HR between the competitive levels in zone 1 (< 60% HR_{max}), $F(2, 42) = 7.75$, $p < 0.001$, $\eta_p^2 = 0.27$, zone 3 (71-80% HR_{max}), $F(2, 51) = 6.08$, $p = 0.004$, $\eta_p^2 = 0.19$, and zone 5 (91-95% HR_{max}), $F(2, 50) = 12.19$, $p < 0.001$, $\eta_p^2 = 0.33$. Professional level referees spent more time in zone 1 compared with semi-professional ($p = 0.010$) and amateur ($p = 0.010$) level referees. Moreover, professional level referees spent less time in zone 3 compared with semi-professional ($p = 0.013$) and amateur ($p = 0.022$) level referees. Finally, semi-professional level referees spent more time in zone 5 than professional ($p < 0.001$) and amateur ($p = 0.013$) level referees (Figure 11).

Table 9. Data related to the physiological demands of officiating at different competitive levels, Mean ± SD, (CI95%).

	Professional	**Semi-professional**	**Amateur**
Max HR (bpm)	190 ± 17 (182-198)	195 ± 6 (192-198)	191 ± 4 (188-194)
Mean HR (bpm)	147 ± 11 (142-152)	160 ± 7 (157-164) [a]	156 ± 7 (152-160) [a]
Mean HR (%max)	78 ± 8 (75-82)	82 ± 2 (81-83)	82 ± 2 (81-83)
Internal Load (au)	312 ± 80 (277-348)	332 ± 27 (318-345)	296 ± 11 (300-332)

[a] = significantly different to professional level.

Figure 11. Percentage of playing time spent in each heart rate zone at different competitive levels.



[a] Significantly different to professional level, [b] Significantly different to professional level. Data are mean ± SD.

5.3.8 External and internal load relationships

A large significant correlation was found between external and internal load for semi-professional level referees ($r = 0.75$, $p < 0.001$). However, no significant correlations were found for the professional and amateur level referees (all $p > 0.05$; Table 10).

Table 10. Correlation coefficients (r) between external (i.e., total distance covered) and internal load.

	Professional	Semi-professional	Amateur
r	0.98	0.75*	0.20
p	0.666	< 0.001	0.432

Note: *correlation significant at 0.01 level.

5.4 Discussion

This study was the first to compare the match (physical and physiological) demands of 15-a-side rugby refereeing at different competitive levels, from amateur to professional. Overall, the results revealed that compared with officiating at the amateur level, referees officiating at the professional level covered more total and relative distance, and referees officiating at the semi-professional level covered more total distance. In addition, relative to officiating at other competitive levels, referees officiating at the professional level covered a higher average sprint distance, and had a longer average sprint duration. Additionally, compared with refereeing at the amateur level, referees officiating at the professional level completed more high-intensity accelerations, achieved higher maximum speeds, and covered more average and maximum distance during each sprint. Finally, the WCS for referees officiating at the professional level was longer in duration, involved covering more distance, and achieving a higher maximal speed, than refereeing at the amateur level.

Previous research with Super Rugby (Blair et al., 2018b), International (Bester et al., 2019), and Spanish and Portuguese (Suarez-Arrones et al., 2013c) referees, reported a mean total distance covered per match of 8030 m, 6825 m, and 6322 m, respectively. Although our findings from referees officiating at amateur (6059 m), semi-professional (6611 m), and professional (6994 m) competitive levels are similar to the distances reported in Internationals referees, and Spanish and Portuguese referees (Suarez-Arrones et al., 2013c; Bester et al., 2019), a higher mean distance was reported in Super Rugby (Blair et al., 2018b), which could be attributed to the different nature of the game played in Super Rugby competition compared to the matches assessed in this study during competitions in England. However, Blair et al. (2018b) found that Super Rugby referees spent a low percentage of each match (< 0.1%) in speeds above 25 $km \cdot h^{-1}$, which is lower than the percentage of time referees spent at those speeds in this study, at professional (~ 0.7%), semi-professional (~ 0.5%), and amateur (~ 0.3%) levels. This could also be explained by the different playing style in the southern (e.g., greater intensity of ball contest and more collisions), compared to the northern (e.g., more expansive running game), hemisphere (Reardon et al., 2017). It appears that as the competitive level of the match increased, the pace of the match also increased. Therefore, this may explain why the referees officiating at amateur level covered less total distance than the referees at the semi-professional and professional level. Additionally, referees officiating at the professional competitive level accessed in this study received medical, sports science, and strength and conditioning support, and they were training within an elite professional group of officials on a regular basis. As such, they would have been exposed to training, including high-intensity intermittent intervals, speed, speed endurance, and multi-directional sessions. This greater exposure to strength and conditioning and medical support, as well as more regular training sessions, could therefore have potentially differentiated the physical capacities between officials at the different competitive levels (Kraak, Malan and Van den Berg, 2011a).

The present study also examined the physical demands at different speed zones to see if any differences existed across the competitive levels. While referees at the professional level covered more distance walking and jogging compared with referees at the semi-professional and amateur levels, most of the match (~56%), regardless of competitive level, was spent at speeds below 10.8 $km \cdot h^{-1}$, interspersed with periods of high-speed running (i.e., sprinting). Despite a lack of statistically significant differences in the number of sprints, the average sprint duration and distance covered per sprint was significantly higher for referees at the professional level, compared with the other competitive levels. Additionally, referees at the professional level performed significantly more high-intensity accelerations than referees at the amateur level. Consistent with previous research with rugby players (Reardon et al., 2017), the findings suggest that officiating 15-a-side rugby at higher competitive levels (e.g., professional or elite) in rugby is more physically demanding than officiating at lower levels (e.g., semi-professional and amateur).

In relation to HR responses, regardless of competitive level, the referees spent most of the match in the 81 to 90% HRmax zone, which is consistent with previous research (Blair et al., 2018b). The findings revealed that referees officiating at the semi-professional level spent more time in the 91 to 95% HRmax zone than referees at the professional and amateur level. Furthermore, referees at the professional level spent less time in the 71 to 80% HRmax zone, and more time below 60% HRmax compared to referees at the semi-professional and amateur level. The mean HRmax in this study for referees at the semi-professional and amateur level (~82%) were similar to previous research with sub elite referees (~85%), which was likely due to the sub-elite level and inferior physical condition of the referees assessed in previous research (Anon., 2003). Additionally, the lower mean HR for referees at the professional level (~78%) in this study, could be explained by the professional status and higher physical condition of the referees evaluated, allowing them to better cope with the match demands.

This study was the first to quantify the internal load of referees during match play and demonstrated no differences between the competitive levels, possibly due to the relatively small sample size and limited number of matches analysed. However, the large correlation between external and internal match load for referees at the semi-professional level, suggests that the internal responses to match-play are strongly associated with the amount of running completed (McLaren et al., 2018). However, it is likely that these associations could be moderated by factors such as referee fitness levels, and acute physiological stress incurred as a result of physical (e.g., recent training, nutrition), and social (e.g., travel, sleep) factors (Castillo et al., 2017). This might explain why no correlation was found between external (i.e., total distance) and internal (i.e., Edwards training load) load for referees officiating at the professional and amateur levels. Nevertheless, knowing the relationship between external and internal match load may help practitioners working with rugby referees decide whether both match loads methods are necessary, or if only using one method is enough to organise appropriate training sessions.

This study addresses a significant gap and adds to the literature regarding the match demands of refereeing 15-a-side rugby at different competitive levels (i.e., professional to amateur). However, there are some limitations that should be noted. First, as alluded to above, the outcomes of this study are specific to referees within England Rugby competitions, thus potentially limiting the generalizability of the findings. Future research is therefore encouraged to investigate the match demands of officiating rugby in other nations to determine whether different competitions impose different match demands on referees. Second, future research could investigate the influence of the number of match events (e.g., tackles, scrums, mauls) on the match demands placed on rugby referees. Third, as previous research (Emmonds et al., 2015) with rugby league referees reported that decision-making accuracy is reduced in the final 10 minutes of the match, future studies could investigate whether the match demands placed on rugby referees has an impact on their decision-making accuracy. Additionally, the data collection was exclusively during matches, hence no laboratory-based tests were performed (e.g., anthropometric). Supplementary research is therefore encouraged to also include laboratory-based tests (i.e., VO2max) to further investigate the differences between rugby referees according to the competitive level they are officiating, allowing referees and practitioners to use this more specific information (i.e., threshold zones) to improve training programmes for rugby referees. Finally, the heart rate data in this study was only collected during matches, therefore, future research should incorporate the monitoring of resting heart rate and heart rate variability to investigate the effect of training on these measures in rugby referees, and the associated impact of this training on match performance (Williams et al., 2018).

5.5 Conclusions and practical implications

In summary, this study examined the match demands of refereeing 15-a-side rugby union matches at different competitive levels. The findings showed that refereeing professional or elite rugby was associated with greater high-intensity demands compared with lower levels of competition (e.g., amateur). Based on the findings of this study, rugby union referees' training programmes should therefore include endurance sessions and intermittent sessions at heart rates above 80% of maximum. In addition, sprint training should be designed that replicates the physical demands reported in this study. Specifically, repeated sprint and maximal sprint sessions could be used to develop anaerobic capacity and anaerobic power, respectively (Blair et al., 2018a). Therefore, repeated sprint training sessions should have a total volume of 20 to 30 sprints, varying from 20 to 25 meters. Additionally, the sprint distance during maximal sprint training sessions should vary according to the competitive level. For instance, for referees officiating at an amateur level, sprint training sessions should include 45 to 55 metre sprints, while 55 to 65 metre sprints are more appropriate for referees officiating at semi-professional and professional levels.

Moreover, to induce overload in training, practitioners may wish to design programmes which include sessions exceeding the WCS identified in this study. For example, for referees officiating at an amateur level, RHIEs (> 3 sprints) for longer periods (> 50 s) covering sprint distances from 15 to 60 metres, while sprint distances from 20 to 70 metres may be more appropriate for referees officiating at semi-professional and professional levels. These recommendations may be particularly important for rugby referees to be ready for tournaments, given that the COVID-19 pandemic has created unprecedented challenges in rugby, restricting competition and physical training among rugby referees at all competitive levels (Stokes et al., 2020).

CHAPTER SIX: COMPARING THE YO-YO INTERMITTENT AND BRONCO TESTS AND THEIR ASSOCIATIONS WITH MATCH DEMANDS AMONG RUGBY UNION REFEREES

6.1 Introduction

Rugby union ("rugby") is a highly demanding intermittent contact sport, consisting of high-intensity efforts interspersed with low-intensity activity played over two 40-minute halves (Roberts et al., 2008). During match play, rugby referees combine high-intensity running actions, with low-intensity activity, covering six to eight kilometres per match, with a corresponding mean heart rate of 80% of their maximum (Suarez-Arrones et al., 2013c; Blair et al., 2018b; Bester et al., 2019, Chapter 5). On average, during semi-professional and professional matches, a referee covers 11% of the total match distance in high intensity (> 18. 4 km·h^{-1}) running (Suarez-Arrones et al., 2013c, Chapter 5) and it has been reported that there is a small to moderate decrease in high-intensity running during the middle of a match (i.e., 30-70 min), with no differences reported between 0-10 and 70-80 minutes (Suarez-Arrones et al., 2013c). It is important that rugby referees can maintain their physical performance throughout a match, and their ability to meet the physical (i.e., high-intensity running) and physiological (i.e., heart rate) demands imposed on them during match play is crucial for optimal positioning and thus decision-making (Mallo et al., 2012; Suarez-Arrones et al., 2013c; Blair et al., 2018b; Elsworthy, Blair and Lastella, 2020).

The fitter the rugby referee is, the more likely they are to be in optimal positions to make accurate decisions (Mallo et al., 2012). Therefore, minimum mandatory fitness requirements have been established for rugby referees by governing bodies using field tests, with referees who achieve these standards deemed fit enough to cope with the match demands of officiating. However, how the results of these fitness tests relate to the demands placed on rugby referees during actual match play (i.e., direct validity) is unclear. Indeed, studies with soccer referees have reported poor correlations between field tests measures (e.g., mean heart rate during the high-intensity 150 m interval test) and match demands (e.g., total distance covered and high speed running; Mallo et al., 2009). Therefore, given the nonspecific nature of the field tests used to assess the fitness of rugby referees, it is important that the relation between field test results and actual match demands are examined.

The Yo-Yo intermittent recovery level 1 ($YYIR_1$; Bangsbo, Iaia and Krustrup, 2008) is regularly used to provide an indirect indication of the physical capacity of intermittent team sport athletes (Krustrup et al., 2003; Blair et al., 2018a). When the standards for the $YYIR_1$ test were established, they were used globally to evaluate the capacity to repeatedly perform and recover from intense activity (Krustrup et al., 2003; Bangsbo, Iaia and Krustrup, 2008; Blair et al., 2018a). It is within this context that this test is used for rugby referees. Specifically, adding to the fact that the test stimulates both aerobic and anaerobic systems, it has been shown to elevate heart rate and blood lactate concentration as well as a high breakdown of phosphocreatine, at the end (i.e., 51% lower compared with rest), suggesting that the phosphagen energy system is also taxed during the test (Svensson and Drust, 2005). Therefore, it appears that the better the referee can perform during the $YYIR_1$ test, the better their ability may be to delay fatigue and recover during the active recovery phases of the test (Vachon et al., 2021), potentially helping to avoid a significant reduction in high-intensity running towards the end of a match (Suarez-Arrones et al., 2013c).

Acceptable $YYIR_1$ test levels have been suggested for elite male and female rugby referees (i.e., levels 18 and 15, respectively) (Blair et al., 2018a). However, to date, no empirical research has supported these fitness standards, and applied practitioners have started to use other more expedient test with referees. Indeed, recently, the 1.2 km shuttle run test (1.2_{SRT}) (Kelly and Wood, 2013), also known as the Bronco test, is gaining popularity in applied rugby contexts (Kelly, Jackson and Wood, 2014; Deuchrass et al., 2019). It has been used to assess rugby referees' fitness levels and has been shown to strongly correlate with the $YYIR_1$ (r = -0.87) among elite youth rugby players (Deuchrass et al., 2019). Both tests (i.e., $YYIR_1$ and Bronco) are currently used with rugby referees as they incorporate repeated high-intensity sprints as well as periods of acceleration, deceleration and change in direction, which are characteristics of intermittent activities (Brew and Kelly., 2014). Additionally, the $YYIR_1$ is regularly used to assess aerobic power (i.e., oxygen uptake during dynamic exercise), providing an indirect indication of the physical capacity of intermittent team sport athletes (Krustrup et al., 2003; Blair et al., 2018a), and the Bronco test can be used to determine maximal aerobic running speed $YYIR_1$ (Kelly, Jackson and Wood, 2014; Deuchrass et al., 2019). The information provided from these tests enables practitioners to monitor individual development and can be used for training prescription and to evaluate the impact of training interventions (Gabbett, 2005; Dobbin et al., 2018). However, the relationship between the results of these field tests and the actual match demands placed on rugby referees has not yet been investigated. This information is important because direct validity is considered an essential pre-requisite of an accurate sport-specific field test (Boddington, Lambert and Waldeck, 2004).

To extend previous research, this study aimed to: (1) directly compare the $YYIR_1$ and Bronco tests, by correlating the final results of (e.g., distance, completion time), and physiological responses during (e.g., heart rate [HR] and internal load), the two tests; (2) verify the direct validity of the $YYIR_1$ and Bronco tests by examining how the results of these tests relate to the physical (e.g., high-intensity distance) and physiological (e.g., internal load) demands placed on rugby referees during actual match play; and (3) propose reference values for the $YYIR_1$ and Bronco tests by generating estimating equations to determine the minimum fitness requirements need to officiate at different competitive levels (e.g., amateur to elite rugby).

6.2 Methods

6.2.1 Participants

Overall, 67 referees (65 male, 2 female; age: 30 ± 11 years [range: 18-57 years]; body mass: 77.4 ± 13.1 kg; height: 175 ± 8 cm), with at least two years' officiating experience (7 ± 5 years), participated in the study. Referees could not participate if they had not been refereeing in the previous six months or more due to injury. This study received institutional ethics approval and informed consent was obtained from each referee.

Field test analysis: $YYIR_1$ test data were collected from 48 referees (46 male, 2 female; age: 27 ± 8 years; body mass: 76.6 ± 13.9 kg, height: 175 ± 8 cm; experience: 6 ± 4 years), and Bronco test data were collected from 35 referees (34 male, 1 female; age: 29 ± 11 years; body mass: 75.7 ± 12.5 kg; height: 174 ± 9 cm; experience: 7 ± 6 years). Of these referees, 32 completed both field tests (31 male, 1 female; age: 27 ± 8 years; body mass: 74.3 ± 11.9 kg; height: 174 ± 9 cm; experience: 6 ± 4 years).

Match demands analysis: Match demand data were collected from 16 referees (15 male, 1 female; age: 24 ± 5 years; body mass: 76.6 ± 10.3 kg; height: 177 ± 8 cm; experience: 6 ± 4 years) over 27 matches, ranging from two to six matches per referee (1.7 ± 1.5 matches per referee). While all 16 of these referees completed the $YYIR_1$ test, only 11 performed the Bronco test (11 male, age: 23 ± 5 years; body mass: 79.3 ± 7.3 kg; height: 180 ± 7 cm; experience: 6 ± 3 years).

The sample size justification was resource constraint based (Lakens, 2021) in that we were constrained by the referees' availability to voluntary attend both tests and matches. All referees were actively officiating in South Africa at either the residence "Koshuis" tournament at Stellenbosch University, or the Western Province Rugby Union Super League competition, played across the Western Cape Province. The "Koshuis" tournament includes ~200 matches over seven months, divided into first-, second-, third-, and fourth- league matches, played on weeknights. Except for one "private-residence" team, all teams comprised Stellenbosch University students and could be described as recreational, with some semi-professional players. The total match duration was 60 minutes for leagues one to three, and 50 minutes for the fourth league (Brown et al., 2019). The Western Province Super League is organised by the Western Province Rugby Union (i.e., one of the fourteen provincial unions in South Africa), and is played by amateur clubs, sub-divided into A, B, C, and Under 20 teams. It follows a single round format where each team plays every other team in their league once a season (April to September), and total match duration was 80 minutes for league A, 70 minutes for leagues B and Under-20, and 60 minutes for league C (Painczyk, Hendricks and Kraak, 2018).

6.2.3 Study protocol

An observational research design was used. During the field tests and rugby matches, referees wore an elasticated vest with an augmented concurrent multi-GNSS receiver unit (Apex, 10 Hz, STATSports, Belfast, UK), located between their shoulder blades. The validity and reliability of this GNSS unit has been reported previously (Beato et al., 2018). The GNSS unit was switched on ~15 minutes before, and turned off immediately after, each field test and match. HR data were collected during the field tests and matches through a HR sensor (Polar T31, Polar Electro, Kempele, Finland) worn around each referee's chest, which transmitted real-time data via Bluetooth to the GNSS unit. All measurements were obtained at the end of the competitive season, and field testing was performed by the same assessors.

6.2.3 Testing procedures

Both field tests were performed on a rugby field on dry and firm conditions, and a minimum of 48 hours and a maximum of six days rest between tests. The field tests were scheduled by the research team, and the referees attended the tests in a random order based on their availability. All referees were familiar with both testing protocols as they complete them regularly throughout the season. The referees were requested not to undertake vigorous physical activity and to maintain normal dietary intake and sleeping patterns in the preceding 24 hours, and avoid consuming a heavy meal and caffeinated beverages in the preceding two hours. Finally, referees were allowed to do their own warm-up for 10 min before each test, with activation exercises and one high-intensity running shuttle (i.e., 20-m and back) advised before the $YYIR_1$ test, and one practice repetition (i.e., 20-m-40-m-60-m) recommended before the Bronco test.

The $YYIR_1$ test was performed according to standard procedures (Krustrup et al., 2003; Bangsbo, Iaia and Krustrup, 2008), comprising repeated 2 × 20-m shuttles at a progressively increasing speed controlled by audio signals with an active 10-s rest between each shuttle, which consisted of jogging 2 x 5-m. When the referees failed twice to reach the finish line before the audio signal, the test was ended and the final distance (m) and level were recorded (Krustrup et al., 2003; Bangsbo, Iaia and Krustrup, 2008). The peak velocity reached during the $YYIR_1$ test was calculated from the equation $V_{YYIR1} = V + 0.5 \times (n/8)$, where *V* represents the velocity during the next to last stage, the *0.5* represents the increment in velocity after each stage (in $km \cdot h^{-1}$), *n* represents the number of runs completed in the last stage, and *8* represents the number of runs in each stage from 14.5 $km \cdot h^{-1}$ (Dupont et al., 2009). The test lasted ~20 min.

For the Bronco test, cones were placed at the 0 m, 20 m, 40 m, and 60 m lines and marked using a 50 m measuring tape (Richer 50-meter steel). Referees were asked to run from the 0 m line to the 20 m line and back, then run from the 0 m line to the 40 m line and back, and finally run from the 0 m line to the 60 m line and back. Completion of these 20-40-60 m shuttles was considered one repetition, with referees completing five repetitions to achieve a distance of 1200 m as quickly as possible (Kelly and Wood, 2013; Kelly, Jackson and Wood, 2014; Mayo et al., 2018). A hand-held stop watch (Casio HS-80TW-1EF) was used to record completion time in seconds (Kelly, Jackson and Wood, 2014). The maximal aerobic speed was then calculated by dividing the 1200 m distance by the recorded time and adjusted to $km \cdot h^{-1}$ by multiplying the result by 3.6 (Silva et al., 2021). The test lasted ~6 min.

In line with previous research (Weston et al., 2009), the physical demands assessed during both field tests and actual match play included: total, relative ($m.min^{-1}$), and high-intensity (> 18. 4 $km \cdot h^{-1}$) distance covered (m), maximal speed ($km \cdot h^{-1}$), and number of high-intensity (> 2.79 $m.s^{-2}$) accelerations (n) and sprints (20 $km \cdot h^{-1}$ or greater sustained for at least one second) (n) (Chapter 4 and 5) and the frequency (n) of repeated high-intensity efforts (RHIE) bouts was analysed. A RHIE bout was defined as a minimum of three high-intensity efforts (i.e., sprints or high-intensity accelerations) with less than 21 seconds of recovery between efforts (Austin, Gabbett and Jenkins, 2011b). The single longest period of a RHIE bout from each match was identified and analysed as the "Worst Case Scenario" (WCS) (Reardon et al., 2017). A bout duration was defined as the time the referee first performed a high-intensity activity (i.e., sprint or acceleration) and repeated a minimum of two other efforts with less than 21 seconds between those efforts (Chapter 4 and 5). For each WCS, the total duration (s), total distance (m), and total distance relative to the bout duration ($m.min^{-1}$) was analysed. Additionally, high metabolic load (HML) distance (m) (i.e., distance covered > 18.1 $km \cdot h^{-1}$ and accelerating and decelerating over 2 $m.s^{-2}$), and HML efforts (n) (i.e., number of separate efforts undertaken in producing HML distance) were analysed (Cunningham et al., 2016). Accelerations and decelerations were calculated from a single derivation of the speed during a period of 0.5 seconds (Couderc et al., 2019).

HR data were assessed during both field tests and actual match play, with maximal HR (HR_{max}) determined as the highest of either: (1) HR_{max} estimated thorough the formula: 208 – (0.7 x age) (Tanaka, Monahan and Seals, 2001), or (2) HR_{max} values obtained during the field tests (Boudet et al., 2002) or match (Suarez-Arrones et al., 2013a). HR data were classified based on the percentage of total time spent in six HR zones (Suarez-Arrones et al., 2013c): zone 1 (< 60% HR_{max}), zone 2 (61-70% HR_{max}), zone 3 (71-80% HR_{max}), zone 4 (81-90% HR_{max}), zone 5 (91-95% HR_{max}), and zone 6 (> 96% HR_{max}). Internal load was calculated by multiplying the time spent (in mins) in the five HR zones by a coefficient assigned to each zone (i.e., 50-60% HR_{max} = 1, 60-70% HR_{max} = 2, 70-80% HR_{max} = 3, 80-90% HR_{max} = 4, and 90-100 % HR_{max} = 5) (Edwards, 1993).

6.2.4 Statistical Analysis

After collection, data from each GNSS unit was downloaded to analysis software (STATSports Apex software, v. 3.0.02011), and then exported to statistical analysis software (IBM SPSS v. 26.0; IBM Corp., Armonk, NY, USA). Kolmogorov-Smirnov tests revealed that data were normally distributed. Next, means, standard deviations, and 95% confidence intervals were calculated. Subsequently, a series of Pearson's product-moment tests were conducted to assess the correlations between: (1) the $YYIR_1$ final level and distance vs. the Bronco test final time, (2) HR and internal load from the $YYIR_1$ test vs. HR and internal load from the Bronco test, and (3) the aforementioned field test data and physical (i.e., total, relative and high-intensity distance, maximal speed, high-intensity accelerations, sprints, RHIE, WCS distance, WCS duration, and WCS relative distance, and HML efforts and distance) and physiological (i.e., HR and internal load) demands during actual match play. Given the different number of matches officiated by each referee, the average match demands were calculated for each referee and used throughout the third step. Correlation coefficients (*r*) of 0.1-0.3, 0.3-0.5, and > 0.5 were interpreted as small, medium, and large, respectively (Hopkins et al., 2009).

Next, a single two-way repeated measure analysis of variance (ANOVA) with follow-up paired samples t-tests was used to determine the differences between the six HR zones for the $YYIR_1$ and Bronco tests. Effect sizes were calculated as partial eta squared (η_p^2), and values of ≥ 0 .01, ≥ 0.06, and ≥ 0.14 were interpreted as small, medium, and large, respectively (Cohen, 1988). Additionally, differences in HR and internal load between the $YYIR_1$ and Bronco tests were assessed via a dependent t-test, with Cohen's *d* effect sizes of 0.2, 0.5, and 0.8 interpreted as small, medium, and large, respectively (Cohen, 1988).

Finally, since the $YYIR_1$ test final distance was significantly correlated with the time taken to complete the Bronco test, and with the total distance covered in actual match play, two separate linear regression equations were generated to estimate the $YYIR_1$ test final distance. The $YYIR_1$ test final distance was entered as the dependent variable, and the time taken to complete the Bronco test and total distance covered in a match were entered as independent variables. The adequacy of the results generated by the equations was investigated through Bland-Altman's graphical analysis between true and estimated values, and concomitant analysis of result significance through: (1) simple Student's t-test between

“0” and the difference in results between true and estimated values of $YYIR_1$ test final distance, and (2) linear regression analysis of agreement values (Bland and Altman, 1986). The bias (mean difference between true and estimated values), accuracy (overall distance between true and estimated values), and precision (statistical variance) of the equations were calculated by the scaled mean error (SME), the root mean square error (RMSE), and the coefficient of variance (CV), respectively (Walther and Moore, 2005):

$$SME = MEAN$$

where SME is the bias and MEAN is the mean of all differences between the true and estimated values,

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{n}}$$

where RMSE is the accuracy, $X_{obs,i}$ are the observational true values and $X_{model,i}$ are the estimated values obtained by the equation, and

$$CV = (SD_{diff})/(MEAN_{diff}) \text{ x } 100$$

where CV is the coefficient of variation (precision indicator), SD_{diff} is the standard deviation from the difference between true and estimated values, and $MEAN_{diff}$ is the average difference obtained from true and estimated values. The limits of agreement (LoA) between methods were also evaluated (random error = SD of the differences x 1.96) and represents the 95% likely range for the difference between the true values and those estimated by Equations 1 and 2 (Bland and Altman, 1986).

The reliability between true and estimated values ($YYIR_1$ test final distance) generated by Equations 1 and 2 was also analysed using an absolute-agreement, two-way mixed model, intraclass correlation coefficient (ICC), and values of < 0.5, 0.5-0.75, 0.75-0.9, and > 0.90 were interpreted as poor, moderate, good, and excellent reliability, respectively (Koo and Li, 2016). An α of 0.05 was used in all analyses.

6.3 Results

6.3.1 Field tests results

Compared to the Bronco test, HR_{max} was significantly higher in the $YYIR_1$ test both in terms of bpm, $t_{(26)} = 5.16$, $p < 0.001$, $d = 0.74$, and percentage, $t_{(27)} = 5.35$, $p < 0.001$, $d = 1.27$. Additionally, internal load was significantly greater in the $YYIR_1$ test compared to the Bronco test, $t_{(26)} = 6.72$, $p < 0.001$, $d = 1.89$. Average HR did not differ significantly ($p = 0.764$) (Table 11).

Table 11. Mean ± SD (CI95%) results of the $YYIR_1$ (n = 48) and Bronco (n = 35) tests, and HR, and internal load data comparison during the $YYIR_1$ and Bronco (n = 27) tests.

	$YYIR_1$	Bronco
$YYIR_1$ final level	16.4 ± 1.4 (16.1-16.8)	-
$YYIR_1$ final distance (m)	1243 ± 427 (1119-1367)	-
$YYIR_1$ peak velocity ($km \cdot h^{-1}$)	16.4 ± 0.3 (16.1-16.7)	-
$YYIR_1$ time to completion (s)	622 ± 208 (561-681)	-
Bronco time (s)	-	326 ± 34 (314-337)
Bronco MAS ($km \cdot h^{-1}$)	-	14.3 ± 1.4 (13.8-14.8)
HR_{max} (bpm)	197 ± 9 (194-200)	192 ± 6 (189-194) *
HR_{max} (%)	98.9 ± 1.9 (98.2-99.2)	96.2 ± 2.4 (95.3-97.2) *
Average HR (%max)	89.6 ± 3.5 (88.2-91.0)	89.2 ± 4.7 (87.3-91.1)
Internal load (au)	40.1 ± 14.9 (34.2-46.0)	19.2 ± 4.7 (17.4-21.1) *

Notes: $YYIR_1$ = Yo-Yo intermittent recovery level 1, MAS = Maximal Aerobic Speed, HR = Heart Rate, *Significant difference between tests at the $p < 0.05$ level.

6.3.2 Relationships between $YYIR_1$ and Bronco test data

There was a significant negative correlation between total distance covered in the $YYIR_1$ test and the time taken to complete the Bronco test ($p < 0.001$), and a significant positive correlation between average HR in the $YYIR_1$ and Bronco tests ($p = 0.034$). Finally, there was a significant negative correlation between internal load during the $YYIR_1$ test and the time taken to complete the Bronco test ($p < 0.001$) (Table 12).

Table 12. Correlations coefficients between performance (n = 32), HR (n = 27), and internal load (n = 27) from the $YYIR_1$ and Bronco tests.

	Bronco avg. HR	Bronco IL	Bronco final time
$YYIR_1$ total distance (m)	-0.12	-0.34	-0.88**
$YYIR_1$ avg. HR (%max)	0.67*	0.08	0.27
$YYIR_1$ IL (au)	-0.10	-0.12	-0.74**

Notes: $YYIR_1$ = Yo-Yo intermittent recovery level 1, HR = Heart Rate, IL = Internal Load *correlation is significant at the p < 0.05 level, **correlation is significant at the $p < 0.01$ level.

Table 13. Internal load data relative to time for the $YYIR_1$ and Bronco tests (n = 27).

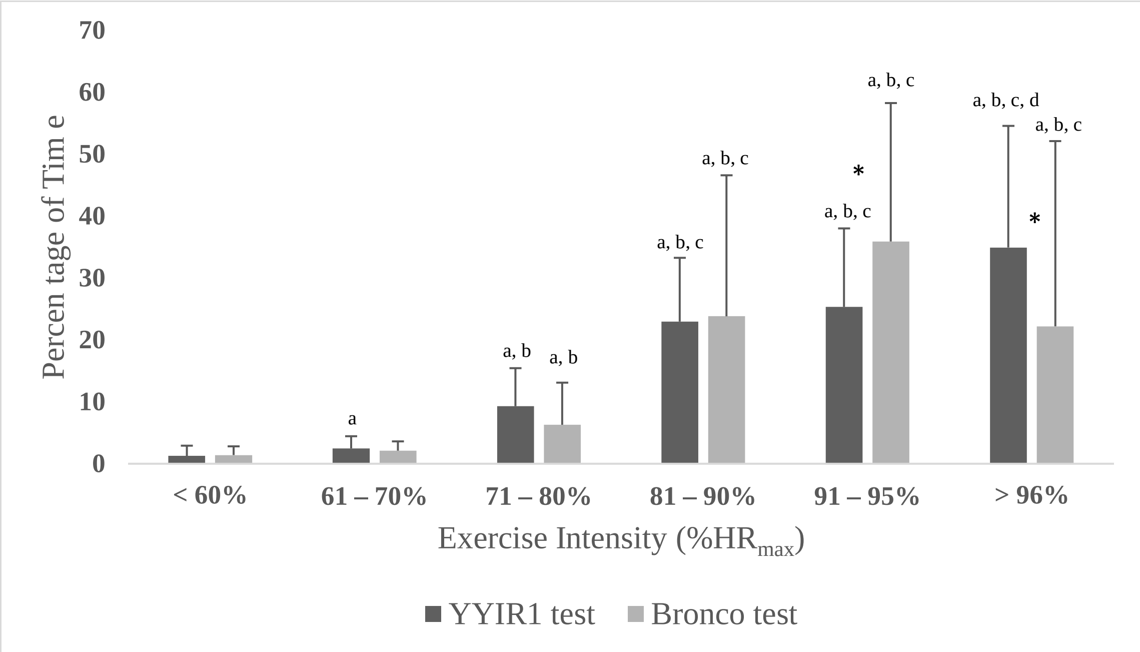
		$YYIR_1$		Bronco	
%HRmax	Coefficient	Time (min)	Internal load	Time (min)	Internal load
50-60	1	0.10 ± 0.11	0.10 ± 0.11	0.05 ± 0.05	0.05 ± 0.05
60-70	2	0.53 ± 0.83	1.07 ± 1.65	0.14 ± 0.22	0.28 ± 0.44
70-80	3	1.72 ± 2.05	5.15 ± 6.15	0.80 ± 0.97	2.40 ± 2.92
80-90	4	2.46 ± 1.57	9.83 ± 6.27	1.46 ± 1.27	5.84 ± 5.07
90-100	5	4.79 ± 3.28	23.97 ± 16.42	2.13 ± 1.97	10.64 ± 9.84

6.3.2 Comparisons between HR zone data during the $YYIR_1$ and Bronco tests

There was no significant main effect for Test, $F(1, 307) = 0.44$, $p = 0.509$, $\eta_p^2 = 0.00$. However, there was a significant main effect for HR Zone, $F(5, 307) = 40.90$, $p < 0.001$, $\eta_p^2 = 0.40$, and a significant interaction effect, $F(5, 307) = 3.24$, $p = 0.007$, $\eta_p^2 = 0.05$. Follow up t-tests revealed that referees spent significantly less time in HR zone 5 (91-95 HR_{max}, $p = 0.040$), and more time in HR zone 6 (> 96% HR_{max}, $p = 0.049$), during the $YYIR_1$ test compared to the Bronco test. Furthermore, during the $YYIR_1$ test, referees spent longer in HR zone 6 (> 96% HR_{max}) compared to HR zones 1 (< 60% HR_{max}, $p < 0.001$), 2 (61-70% HR_{max}, $p < 0.001$), 3 (71-80% HR_{max}, $p < 0.001$), and 4 (80-90% HR_{max}, $p = 0.021$). Finally, during the Bronco test, referees spent longer in HR zones 4 (81-90% HR_{max}), 5 (91-95% HR_{max}) and 6 (> 96% HR_{max}) compared to HR zones 1 (< 60% HR_{max}, ps < 0.001), 2 (61-70% HR_{max}, ps < 0.002), and 3 (71-80% HR_{max}, ps < 0.018), and longer in HR zone 3 (71-

80% HR_{max}) compared to HR zones 1 (< 60% HR_{max}, $p = 0.003$) and 2 (61-70% HR_{max}, $p = 0.008$) (Figure 12).

Figure 12. Percentage of time spent in each HR zone during the $YYIR_1$ and Bronco tests (n = 27).



Notes: *Significant difference between tests at the $p < 0.05$ level; [a]Significantly different from < 60% HR_{max}, [b]Significantly different from 61-70% HR_{max}, [c]Significantly different from 71-80% HR_{max}, and [d]Significantly different from 80-90% HR_{max}.

6.3.3 Relationships between field tests results and match demands

The descriptive match demand data are presented in Table 14. There were significant positive correlations between $YYIR_1$ test final distance and match demands including: total ($p = 0.023$) and high-intensity ($p = 0.002$) distance, maximal speed ($p = 0.001$), number of high-intensity accelerations ($p = 0.022$) and sprints (p = 0.004), and number of repeated high-intensity efforts ($p = 0.019$), WCS duration ($p = 0.035$), distance covered during the WCS ($p = 0.047$), number of HML efforts ($p = 0.002$) and HML distance ($p = 0.003$). Additionally, there were significant negative correlations between the final time taken to complete the Bronco test and match demands including: maximal speed ($p = 0.022$), number of high-intensity accelerations ($p = 0.048$), and relative distance covered during the WCS ($p = 0.030$) (Table 15).

6.3.4 Relationships between field test physiological demands and match demands

There was a significant negative correlation between $YYIR_1$ test HR_{max} and relative distance covered in match play (p = 0.038), and significant positive correlations between $YYIR_1$ test HR_{max} and HR_{max} (p = 0.004), average HR (p = 0.046), and internal load (p = 0.043) during match play. The average HR in the $YYIR_1$ test was significantly and positively correlated with the number of high-intensity accelerations per match (p = 0.013), and significantly and negatively correlated with the relative distance covered during the WCS (p = 0.010). Significant positive correlations were found between the $YYIR_1$ test internal load and high-intensity distance (p = 0.023), maximal speed (p = 0.022), number of high-intensity accelerations (p = 0.008) and sprints (p = 0.018), RHIE (p = 0.004), total (p = 0.016) and relative (p = 0.042) distance covered during the WCS, and number of HML efforts (p = 0.011) and distance (p = 0.014) during match play. Finally, there were significant positive correlations between the Bronco test HR_{max} and HR_{max} (p = 0.001) and average HR (p = 0.010) during match play, and there was a significant positive correlation between average HR during the Bronco test and average HR during match play (p = 0.025) (Table 16).

Table 14. Mean ± SD (CI95%) match (i.e., physical and physiological) demand data per match [16 referees over 27 matches (1.7 ± 1.5 matches per referee)].

Total Distance (m)	4828.8 ± 867.0 (4328.2-5329.4)
Relative Distance (m.min^{-1})	75.8 ± 5.0 (72.9-78.7)
High-intensity distance (>18.4 km·h^{-1})	561.3 ± 265.5 (408.0-714.6)
Maximal speed (km·h^{-1})	27.4 ± 2.1 (26.2-28.6)
High-intensity accelerations (n)	42 ± 15 (34-51)
Sprints (n)	21 ± 11(15-28)
RHIE (n)	6 ± 5 (3-9)
WCS duration (s)	38 ± 12 (31-45)
WCS distance (m)	88.7 ± 34.2 (69.0-108.5)
WCS relative distance (m.min^{-1})	140.2 ± 39.0 (117.7-162.7)
HML efforts (n)	110 ± 25 (96-125)
HML distance (m)	1173.0 ± 368.3 (960.3-1385.6)
HR_{max} (bpm)	196 ± 9 (191-200)
Average HR (%max)	82 ± 4 (80-84)
Internal load (au)	233 ± 48 (206-259)

Notes: RHIE = Repeated High-Intensity Efforts; WCS = Worst Case Scenario; HML = High Metabolic Load.

Table 15. Correlation coefficients between $YYIR_1$ (n = 16) and Bronco (n = 11) test results and physical and physiological demands during actual match play.

	$YYIR_1$ final distance	Bronco final time
Total distance (m)	0.56^{*}	-0.25
Relative distance ($m.min^{-1}$)	0.28	-0.34
High-intensity distance (>18.4 $km \cdot h^{-1}$)	0.70^{**}	-0.30
Maximal speed ($km \cdot h^{-1}$)	0.73^{**}	-0.68^{*}
High-intensity accelerations (n)	0.54^{*}	-0.61^{*}
Sprints (n)	0.68^{*}	-0.55
RHIE (n)	0.62^{*}	-0.40
WCS duration (s)	0.56^{*}	-0.44
WCS distance (m)	0.54^{*}	-0.53
WCS relative distance ($m.min^{-1}$)	0.10	-0.71^{*}
HML efforts (n)	0.70^{**}	-0.56
HML distance (m)	0.69^{**}	-0.55
Match HR_{max} (bpm)	-0.21	0.27
Match average HR (%max)	-0.06	0.31
Match internal load (au)	0.36	0.01

Notes: RHIE = Repeated High-Intensity Efforts; WCS = Worst Case Scenario; HML = High Metabolic Load. *correlation is significant at the $p < 0.05$ level, **correlation is significant at the $p < 0.01$ level.

Table 16. Correlation coefficients between physiological response data during the $YYIR_1$ (n = 16) and Bronco (n = 11) tests and physical and physiological demands during actual match play.

	$YYIR_1$ HR_{max}	Bronco HR_{max}	$YYIR_1$ avg.HR	Bronco avg.HR	$YYIR_1$ IL	Bronco test IL
Total distance (m)	0.03	-0.24	0.09	-0.27	0.41	-0.16
Relative distance ($m.min^{-1}$)	-0.54*	-0.26	0.00	-0.17	0.16	-0.11
High-intensity distance (>18.4 $km·h^{-1}$)	0.05	-0.14	0.18	-0.31	0.58*	-0.36
Maximal speed ($km·h^{-1}$)	0.18	0.17	0.12	-0.14	0.58*	-0.45
High-intensity accelerations (n)	0.15	0.16	0.60*	0.12	0.66**	-0.01
Sprints (n)	0.09	-0.09	0.21	-0.19	0.60**	-0.25
RHIE (n)	0.31	0.17	0.36	-0.16	0.74**	-0.42
WCS duration (s)	0.15	0.09	0.35	-0.06	0.55	-0.18
WCS distance (m)	0.12	0.01	-0.01	-0.22	0.65*	-0.41
WCS relative distance ($m.min^{-1}$)	0.04	-0.12	-0.66**	-0.30	0.57*	-0.63
HML efforts (n)	0.15	-0.15	0.47	-0.28	0.64*	-0.34
HML distance (m)	0.05	-0.15	0.47	-0.24	0.62*	-0.26
Match HR_{max} (bpm)	0.72**	0.84**	0.23	0.42	-0.18	-0.27
Match average HR (%max)	0.54*	0.73*	0.40	0.67*	0.15	0.39
Match IL (au)	0.55*	0.24	0.33	0.15	0.37	0.08

Notes: RHIE = Repeated High-Intensity Efforts; WCS = Worst Case Scenario; HML = High Metabolic Load; IL = Internal Load. *correlation is significant at the $p < 0.05$ level, **correlation is significant at the $p < 0.01$ level.

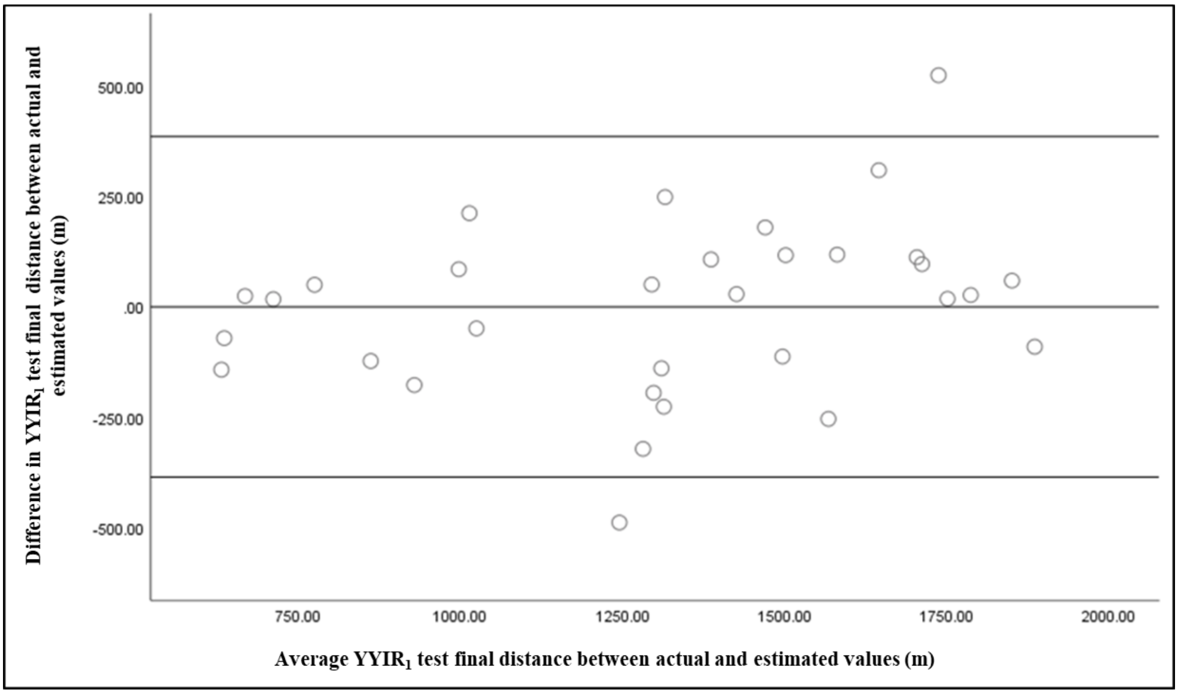
6.3.5 Field-test results regression analysis

A linear regression model was applied between the $YYIR_1$ test final distance and the time taken to complete the Bronco test, which was statistically significant (R^2 = 0.78, $F_{(1, 30)}$ = 104.46, p < 0.001), and had an explanatory power of 76.9% for $YYIR_1$ test distance. Hence, the following equation estimates the distance covered in the $YYIR_1$ test while taking into consideration the time taken in seconds to complete the Bronco test:

Equation 1: $\text{Yo-Yo}_{dist} = (-15.744 * \text{Bronco}_{time}) + 6323.282$

Where Yo-Yo_{dist} is the estimated distance in the $YYIR_1$ test (m) and Bronco_{time} is the time taken to complete the Bronco test (s). Equation 1 was created from the data of 32 rugby referees and has a bias of -0.11 m, an accuracy of 194.2 m, and a precision of 15.1%. Figure 13 shows Bland-Altman's graphical analysis between true and estimated values of the $YYIR_1$ distance from Equation 2, indicating acceptable agreement limits with all but two values falling within the 95% LoA (i.e., -386.7-m and 386.5-m). The average difference between true and estimated values of distance in the $YYIR_1$ test was similar to zero (t_{31}=-0.003, p = 0.998). By plotting a regression line between values identified in Bland-Altman's diagram, it was found that it was not statistically significant (R^2 = 0.07, $F(1,31)$ = 2.15, p = 0.153), and the unstandardized coeficient was similar to zero (β = 0.134), which means that no proportional bias in the data was obtained by Equation 1. Thus, the difference in values resulting from the two measures (true and estimated values) does not increase or decrease in proportion to the average values (Ludbrook, 2010), resulting in an accurate estimation of the result from Equation 1. The average ICC was 0.93, with 95% confidence intervals from 0.87 to 0.97 ($F(31,31)$ = 14.93, p < 0.001). Thus, excellent reliability was found between the true and estimated values generated by Equation 1.

Figure 13. Bland-Altmann plot analysis (n = 32). 95% of limits of agreement: -386.74 to 386.52-m.



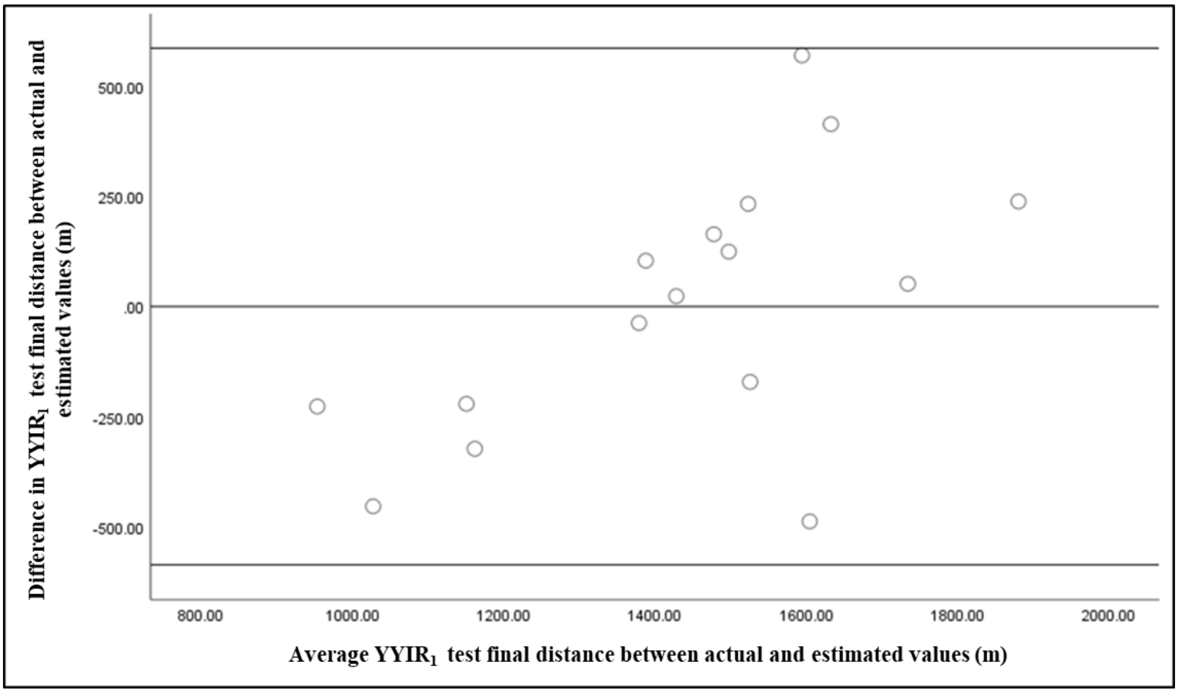
6.3.6 $YYIR_1$ final distance and match total distance regression analysis

A linear regression model was applied between the $YYIR_1$ test final distance and the total distance covered in match play, which was statistically significant (R^2 = 0.32, $F_{(1, 14)}$ = 6.47, p = 0.023), and had an explanatory power of 26.7% for Yo-Yo IRL1 test distance. Hence, the following equation estimates the distance covered in the $YYIR_1$ test while taking into consideration the total distance covered in a match:

$$\text{Equation 2: Yo-Yo}_{dist} = (0.246 * \text{MATCH}_{dist}) + 259.027$$

Where Yo-Yo_{dist} is the estimated distance in the $YYIR_1$ test (m) and MATCH_{dist} is the total distance covered in a match (m). Equation 1 was created from the data of 16 rugby referees and has a bias of 0.43 m, an accuracy of 290.5 m, and a precision of 21%. Figure 14 shows Bland-Altman's graphical analysis between actual and estimated values of the $YYIR_1$ test distance from Equation 1, indicating acceptable agreement limits with all values falling within the 95% LoA (-587.6-m and 588.4-m). The average difference between true and estimated values of distance in the $YYIR_1$ test was similar to zero (t_{15}= 0.01, p = 0.995). However, by plotting a regression line between values identified in Bland-Altman's diagram it was found that it was statistically significant (R^2 = 0.35, F(1,14) = 7.58, p = 0.016), meaning that there was a proportional bias. Thus, the difference in values resulting from the two measures (true and estimated values) concentrate either above or below the mean of differences, resulting in an overestimation or underestimation of the result from Equation 2. The average ICC was 0.66, with 95% confidence intervals from -0.01 to 0.88 (F(15,15) = 2.85, p = 0.026). Therefore, moderate reliability was found between the true and estimated values generated by Equation 2.

Figure 14. Bland-Altmann plot analysis (n = 16). 95% of limits of agreement: -587.56 to 588.42-m.



6.4 Discussion

This study aimed to compare the $YYIR_1$ and Bronco tests in amateur rugby referees and verify the direct validity of these tests in relation to the physical and physiological demands placed on referees during actual match play. Additionally, reference values were generated for the $YYIR_1$ and Bronco tests that allow one to determine the fitness levels required to officiate at different competitive levels. The results revealed a strong correlation between the $YYIR_1$ and Bronco test results. Furthermore, strong correlations were found between the $YYIR_1$ test result and physical and physiological demands during actual match play, including total and high-intensity distance covered, maximal speed, number of high-intensity accelerations and sprints, number of RHIEs, WCS duration, distance covered during the WCS, number of HML efforts, and match HML distance. Additionally, the time taken to complete the Bronco test was strongly correlated with physical match demands including maximal speed, number of high-intensity accelerations, and relative distance covered within the WCS. Finally, regression equations were generated that had acceptable reliability and could be used, when combined with field testing, to evaluate the effects of fitness training and to identify whether a referees' fitness level is acceptable to officiate at a given competitive level.

The correlation found in this study between the distance covered in the $YYIR_1$ test and time taken to complete the Bronco test is similar to the results found for elite youth rugby players (Deuchrass et al, 2019). Although the nature of the two field tests differ (e.g., continuous self-paced Bronco test and an intermittent externally-paced $YYIR_1$ Deuchrass et al., 2019), the average HR reported by rugby referees during both tests was around 90% of their maximum. Additionally, the strength of the correlation between the $YYIR_1$ and Bronco test results might indicate that the tests measure similar characteristics (e.g., ability to perform intermittent high-intensity exercise) and are therefore potentially interchangeable. However, the greatest percentage of time (~36%) was spent in the 91-95% HR_{max} zone during the Bronco test, whereas the largest percentage of time (~35%) was spent in the > 96% HR_{max} zone during the $YYIR_1$ test. This might be explained by the differences in pacing between the tests, with the externally paced nature of the $YYIR_1$ test allowing referees to perform at a greater percentage of their maximum HR. Moreover, compared with the Bronco test, the maximum HR reached during the $YYIR_1$ test was significantly higher. Thus, in comparison with the Bronco test, the $YYIR_1$ test might better determine the maximal HR of rugby referees (Mallo et al., 2009), information that is critical for training prescription.

A field test cannot be considered sufficiently sport-specific until a direct association has been observed between the field test result and the most relevant aspects of match performance (Boddington, Lambert and Waldeck, 2004). Taking that into consideration, the $YYIR_1$ test result and internal load was significantly correlated with referees' physical match demands. Furthermore, the $YYIR_1$ test maximum HR was significantly correlated with referees' physiological match demands, supporting the direct validity of the test. Collectively, the significant correlations found between the $YYIR_1$ test result and the high-intensity demands placed on referees in a match, implies that the test is a good tool to evaluate if the referee is fit enough to cope with match demands, since it is the amount of high-intensity exercise that best predicts the development of fatigue (Krustrup and Bangsbo, 2001). Additionally, the significant correlation found between the $YYIR_1$ test results and number of sprints and RHIEs performed per match is an interesting finding, suggesting that the physical and physiological attributes required to perform the $YYIR_1$ test are similar to those required to maintain RHIEs and sprinting during a match. Finally, the number of HML efforts performed by the referees was significantly correlated with $YYIR_1$ test result, which is in agreement with a study performed with elite soccer referees (Krustrup and Bangsbo, 2001), suggesting that the $YYIR_1$ test might provide a valid measure of physical performance in intermittent activities.

The significant correlation found between the $YYIR_1$ test results and the WCS, might suggest that the better the rugby referee performed in the $YYIR_1$ test, the better they coped with the most demanding period in a match. Since, the $YYIR_1$ test elicits maximal aerobic responses and is focused on evaluating the ability to perform and recover from high-intensity exercise, which are essential components during the most intense periods in a match (Krustrup et al., 2003; Bangsbo, Iaia and Krustrup, 2008), it seems logical to be performed by referees, because if a rugby referee can recover more quickly from maximal or near-maximal efforts, the referee would be most likely to complete more of these efforts during a match (Lockie et al., 2017). However, the constant changes of direction in a set distance (i.e., 20-m) does not accurately replicate the movements during rugby officiating and should be considered as a limitation of using the $YYIR_1$ test with rugby referees. In particular, during the test, referees have to turn frequently at 180°, which can be demanding to the joint musculature (Svensson and Drust, 2005), while rugby refereeing also incorporates lateral changes of direction movements (Blair et al., 2018a). Additionally, the $YYIR_1$ does nor replicate a sprint speed of match play and the longer sprint distances of ~70-m (Chapter 4, Chapter 5, Blair et al, 2018a). Thus, alternative tests might be needed that incorporate more valid movement patterns while evaluating the ability to perform high-intensity exercise.

The Bronco test appears to have ecological validity for rugby referees as it includes shuttles across a variety of distances rather than a single fixed distance, as well as periods of acceleration, deceleration, and changes in direction, thus partially replicating the demands placed on rugby referees during actual match play. Indeed, the referee's maximal speed and number of high-intensity accelerations per match were strongly correlated with the Bronco test result. Additionally, maximum and average HR during the Bronco test and actual match play were strongly correlated, which could provide an indicator of match fitness. However, the self-paced continuous nature of the Bronco test, unlike the intermittent nature of rugby refereeing, and the lack of correlations found between the Bronco test result and high-intensity match demands (e.g., high-intensity distance, number of sprints, and RHIEs), suggests that the Bronco test may not replicate the true metabolic demands placed on rugby referees during matches, which raises questions about the direct validity of the test, since the quantity of high-intensity exercise is a better indicator of match demands (Krustrup and Bangsbo, 2001). Based on that, it was not possible to establish the direct validity of the Bronco test for rugby referees in this study.

When analysing the results obtained by the Bland-Altman's graphical analysis, the findings demonstrate the possibility to use Equations 1 and 2 to estimate the $YYIR_1$ test final distance. From a practical viewpoint, Equation 1 provides an estimation of which $YYIR_1$ test final distance a referee would achieve considering the time taken to complete the Bronco test. Furthermore, Equation 2 can be used to estimate criterion-referenced standards for referees aiming to perform at a given competitive level (e.g., elite). More specifically, criterion-referenced standards are determined with reference to the physical requirements for the task (Payne and Harvey, 2010). In this regard, knowing the total distance covered in a match by a referee in a specific competitive level, it would be possible to estimate the appropriate $YYIR_1$ test final distance and, consequently, the $YYIR_1$ test level deemed necessary to cope with the match demands at that level. However, caution is advised when using both Equations to estimate the $YYIR_1$ test final distance. Although Equations 1 and 2 have excellent and moderate reliability, respectively (Koo and Li, 2016), it should be acknowledged that the outcome (i.e., $YYIR_1$ test final distance) can have a variance of ~15% (Equation 1) and ~20% (Equation 2) compared to the true value. Also, the results generated by the Equations may be considered a contrived variable when compared to the gold standard (i.e., $YYIR_1$ test directly). Thus, both Equations should only be used as an estimation of $YYIR_1$ test performance and should not replace the actual test result.

This study uniquely adds to the literature regarding the fitness testing of rugby referees. However, some limitations should be noted. First, the correlation analyses were performed with a relatively small sample size, and so, similar studies with a larger sample size should be conducted in order to replicate the results of this study and to generate even more accurate estimating equations. Second, this study was conducted with southern hemisphere rugby referees during a range of competitive 15-a-side matches of differing durations (i.e., 50 to 80 min), potentially limiting the generalizability of the findings. Future research is therefore encouraged to collect data from both northern and southern hemisphere referees and from rugby matches at different competitive levels (elite, semi-professional, amateur). Finally, only observational data were collected during this study, and no laboratory-based tests were performed (e.g., $VO2_{max}$), thus preventing a more detailed analysis against a "gold standard" and ventilatory threshold zones (Krustrup et al., 2003). Future research is therefore encouraged to include laboratory-based tests (e.g., $VO2_{max}$) and more physiological variables (e.g., blood lactate) to further investigate the relationships between field test results and actual match demands.

6.5 Conclusion and practical implications

In conclusion, this study has shown that the $YYIR_1$ and Bronco tests are strongly correlated, therefore both tests might be useful in prescribing individualised fitness training for rugby referees. Additionally, this study has shown that the results of the $YYIR_1$ test are significantly correlated with the physical and physiological demands placed on rugby referees during actual match play and may therefore be considered a valuable tool for assessing the fitness of rugby referees. Moreover, given the relevance of high-intensity running for a rugby referee's physical match performance (Krustrup and Bangsbo, 2001), this study offers empirical support for the direct validity (Boddington, Lambert and Waldeck, 2004) of the $YYIR_1$ test for the physical assessment of rugby referees. However, the direct validity of the Bronco test could not be confirmed by the findings of this study. Overall, the results imply that while the field tests assessed in this study could be useful in providing information on rugby referees' fitness, they should never be used to predict the referee's overall on-field performance because of the multitude of factors (e.g., positioning, psychological stress) impacting referee decision-making (Rampinini et al., 2007).

The findings indicate that the $YYIR_1$ test better correlates with actual match demands than the Bronco test. Thus, the use of the $YYIR_1$ test in high-intensity training sessions is recommended (Krustrup and Bangsbo, 2001). Additionally, for the purpose of evaluating if a referee is fit enough to cope with the match demands, the $YYIR_1$ test should be used over the Bronco test and Equation 2 outlined in this study could be used. For instance, if the average total match distance covered by a referee is 6 km, a level of ~17.1 on the $YYIR_1$ test is suggested, whereas for a match with average total distance of 8 km, a level of ~18.5 on the $YYIR_1$ test would be recommended. While accepting that the total distance covered in a match has limitations as a measure of the total physical strain placed on a referee (Krustrup and Bangsbo, 2001), recent technological advancements in smartwatches and GPS devices means that total distance can be measured relatively easily by practitioners and referees to be included in Equation 2. Moreover, this study showed that the $YYIR_1$ and Bronco tests are strongly correlated. Thus, the Bronco test might be a reasonable alternative to use in referees' training sessions under time-constraints.

CHAPTER SEVEN: REFEREE POSITIONING, BUT NOT MATCH DEMANDS, SCORE DIFFERENCE, OR FIELD LOCATION, ARE ASSOCIATED WITH BREAKDOWN DECISION-MAKING ACCURACY IN ELITE RUGBY SEVENS REFEREES.

(Citation: Sant'Anna R. T., Roberts S. P., Moore L. J., Stokes K.A. (2021) Referee positioning, but not match demands, score difference, or field location, are associated with breakdown decision-making accuracy in elite rugby sevens referees. International Journal of Performance Analysis in Sport Sep;21(6):1127-1139. doi: 10.1080/24748668.2021.1979824.)

7.1. Introduction

Rugby sevens is an intermittent contact sport played across different ages and competitive levels (e.g., youth to adult and amateur to international; Ross, Gill and Cronin, 2015b; Chapter 4). Although it is played under the same laws and on the same size field as 15-a-side rugby union, rugby sevens teams comprise fewer players, matches are 14 minutes in duration (i.e., 2 halves of 7 minutes), and is usually played in a tournament format, with teams playing multiple matches over one or consecutive days of competition (Ross, et al., 2015). Rugby sevens matches are under the control of a referee and two touch judges or assistant referees (Suarez-Arrones et al., 2013a). In elite-level matches, two in-goal judges are also incorporated (Chapter 4). Officiating field-based invasion team sports such as rugby sevens requires fast accurate processing of gameplay information to guide appropriate infringement-based decision-making (Ollis, Macpherson and Collins, 2006). The referee is the sole judge of fact and responsible for enforcing the laws of the game, ensuring matches are played in a fair and safe manner (World Rugby, 2020). Referees cover a total distance ranging from ~1600 m to 2000 m, of which ~550 m is covered at high-intensity (> 18.4 $km \cdot h^{-1}$) speed at an average of ~85% of maximum heart rate (Suarez-Arrones et al., 2013a; Suarez-Arrones et al., 2013b), and these match demands do not appear to differ between halves or days of competition (Suarez-Arrones et al., 2013a). However, to date, no study has investigated the associations between the match demands placed on rugby sevens referees and their decision-making accuracy. Indeed, only a relatively small number of studies have shed light on this issue in any sport, revealing mixed results. For example, Emmonds et al. (2015) observed no significant relationships between distance covered, high-intensity running efforts, mean heart rate, and decision-making accuracy among rugby league referees. However, Elsworthy et al. (2014) found that the running speed prior to an incorrect decision was significantly higher than for a correct decision, thus impeding the decision-making accuracy of Australian football umpires.

Beyond match demands, research has investigated the associations between decision-making accuracy of officials and time (Mascarenhas et al., 2009; Mallo et al., 2012; Elsworthy et al., 2014; Larkin et al., 2014; Ahmed, Davison and Dixon, 2017; Riiser et al., 2019), score difference (Lago-Peñas and Gómez-López, 2016; Corrigan et al., 2019), field location (Elsworthy et al., 2014; Gómez Carmona and Pino Ortega, 2016; Castillo et al., 2019b; Corrigan et al., 2019), and referee positioning (Mallo et al., 2012; Elsworthy, Burke and Dascombe, 2014). In terms of time, Mallo et al. (2012) found decision-making accuracy to be lowest among soccer referees in the last 15 minutes of a match, but Macarenhas et al. (2009) found the lowest accuracy to occur in the opening 15 minutes of each half during a soccer match. With regards to score difference, Lago-Peñas and Gómez-López (2016) found that a greater score difference between the teams resulted in less extra time being added by the referees, but as score difference increased, Australian football umpire's decision-making accuracy were found to improve (Corrigan et al., 2019). In terms of field location, Castillo et al. (2019b) found no differences in the decision-making accuracy of soccer referees, while Gómez Carmona and Pino Ortega (2016) found that they were more likely to make incorrect decisions on the right side of the field. Regarding referee positioning, Mallo et al. (2012) found that greater distances from the play were associated with poorer decision-making among soccer referees, while Elsworthy et al. (2014) found that distance from play did not affect the accuracy of free-kick decisions among Australian football umpires. Thus, overall, the findings from the literature have been inconsistent, and no study to date has been conducted with rugby sevens referees specifically.

During a rugby sevens match, the most frequent contact events, where opposing players physically engage with each other to contest for possession of the ball, occur during the tackle and ruck (Hendricks et al., 2020). A tackle occurs when the ball-carrier is held and brought to the ground by one or more opponents, and a ruck is formed when at least one player from each team are in contact, on their feet and over the ball which is on the ground (World Rugby, 2020). The short period of play including and immediately after the tackle, and before and during the ruck, is collectively known as the breakdown (Mitchell and Tierney, 2020), and is the event where most (52%) penalty kicks (or penalties) are awarded in a rugby sevens match (World Rugby, 2019a). Additionally, over 60% of all player injuries occur during the breakdown at an elite international level (Hendricks et al., 2020). Therefore, the breakdown is the most important and challenging event for a rugby sevens referee to officiate, hence the importance of accurate decision-making, ensuring a fair outcome at this phase of play in a match.

A previous study with Australian Football umpires suggested that the increased physiological loads observed when completing exercise above the ventilatory threshold immediately prior to a decision may facilitate a reduction in the cognitive processes due to changes in cerebral blood flow (Elsworthy, Burke and Dascombe, 2014), which could result in peripheral fatigue in the brain, and disruptions in attentional processes and subsequently suboptimal decision-making (Schmidt et al., 2019). Therefore, this study had two aims. First, the study aimed to assess referees' decision-making accuracy at the breakdown during an elite rugby sevens tournament, and to examine whether this changed over time (i.e., first vs. second half of a match, group [day one] vs. knockout [day two] stage of a tournament). Second, the study aimed to investigate whether the decision-making accuracy of referees was related to the match demands in the 30 seconds preceding the breakdown (e.g., high intensity running), as well as score difference, field position, or referee positioning. It was hypothesized that referee decision-making accuracy would not differ based on match period, tournament stage, and would not be related to score difference. However, it was predicted that decision-making accuracy would be related to match demands, field location, score difference, and referee positioning such that decision-making accuracy would be compromised after considerable high intensity running, for events located nearer the goal line, when score difference was small, and when the referee was sub-optimally positioned.

7.2. Methods

7.2.1 Participants

Six male referees (age: 26 ± 2 years; body mass: 77.6 ± 6.3 kg, height: 183 ± 5 cm) officiating at national level volunteered to participate in the study. All referees had at least two years' refereeing experience (6 ± 1 years). Data were collected during a professional National Rugby Sevens tournament in 2019, over 22 matches, resulting in 4 ± 2 matches per referee (range = 1 to 5 matches). The study received institutional ethics approval (University of Bath, REACH: EP 17/18 112) and permission to undertake the study was granted by the

RFU Referee Manager. Finally, written informed consent was obtained from each referee prior to data collection.

7.2.2 Decision-making accuracy

All matches were broadcast live on television by a commercial broadcasting company, the recordings of which were used for analysis using coding software (NacSports Pro Plus V.5.0.1). The total number and timing of each breakdown was coded by the primary researcher, who has more than 10 years of experience refereeing from amateur to elite level matches. The primary researcher coded the referees' decisions at each of the 602 breakdowns events in all 22 matches and then recoded all matches two weeks later with excellent intra-coder reliability (K = 0.81, $p < 0.001$, 95%CI [0.64-0.99]) (Cohen, 1988a). Inter-coder reliability was also assessed via an experienced rugby referee reviewer coding all the matches once, revealing excellent reliability (K = 0.86, $p < 0.001$, 95%CI [0.80-0.90]) (J Cohen, 1988a). Despite the excellent reliability, when an agreement could not be reached (n = 98), the "gold-standard" was set by the more experienced referee reviewer, who has officiated rugby at an elite-level and was actively reviewing elite rugby matches as their occupation at the time of the study.

Each of the 602 breakdowns were assessed in terms of whether a penalty offence was committed or not. Penalties were assessed according to the World Rugby law book (laws 14 and 15, tackle and ruck, respectively) (World Rugby, 2020). With the use of the video analysis, it was possible to play, replay, and pause all the situations before seeing the actual match referee's decision, to decide whether the decisions taken by the referees were correct or incorrect, and to identify any "missed" decisions by the referees. Coders were instructed not to watch or rely on the match referee's decision. Specifically, each breakdown decision was classified as either: (1) correct (i.e., penalty was awarded against a player who had infringed), (2) incorrect (i.e., penalty was awarded but no infringement was committed, or a penalty was awarded against a player who had not infringed), and (3) missed (i.e., a penalty was not awarded against a player who had infringed). These categories were used in previously research with rugby league (Emmonds et al., 2015), soccer (Riiser et al., 2019), and Australian football (Elsworthy et al., 2014) officials. In the case that no infringement had been committed, or the referee decided that the offence was not material (i.e., no clear effect or impact), the decision was placed into a fourth category (i.e., play on), provided none of the other categories applied. Incorrect and missed penalties (i.e., categories 2 and 3) were then combined to reflect "incorrect decisions", while correct and play on decisions (i.e., categories 1 and 4) were combined to reflect "correct decisions" (Emmonds et al., 2015; Riiser et al., 2019). Finally, decision-making accuracy was calculated as the number of correct decisions divided by the total number of decisions (i.e., correct, incorrect, missed, and play on) (Elsworthy et al., 2014).

7.2.3 Field location, score difference, and referee positioning

As well as examining the referees decisions, each breakdown was coded according to: (1) field location in relation to the team who had possession (i.e., zone A = attacking area between 22-m area and the try line, zone B = attacking area between 22-m area and the halfway line, zone C = defensive area between 22-m area and the halfway line, or zone D = defensive area between 22-m area and the try line (Van Rooyen, Diedrick and Noakes, 2010; see Figure 14); (2) score difference between the two teams at the time of the breakdown (i.e., small = ≤ 7 points, medium = 8 to14 points, or large = ≥ 15 points (Corrigan et al., 2019); and (3) referee positioning at the time of the breakdown, according to the "clock definition", with the breakdown at the centre of the "clock" (i.e., optimal = 4 to 8 o'clock, suboptimal = 8 to 4 o'clock (RFU, 2018; see Figure 16).

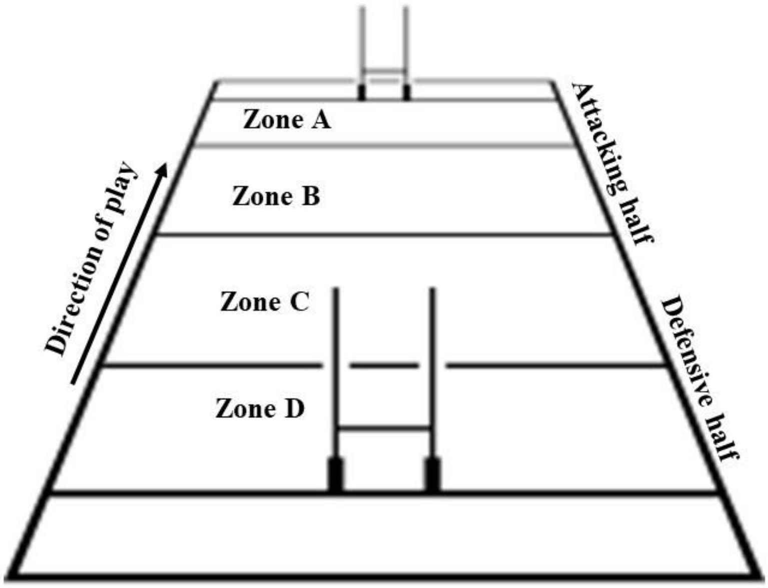


Figure 15. The schematic used to code the area of the field where the breakdown occurred.

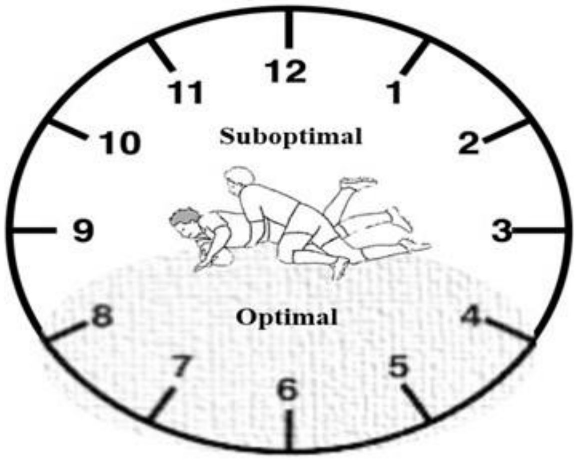


Figure 16. The "clock definition" used to code referee positioning as optimal or suboptimal.

7.2.4 Match demands

Beneath their normal kit, the referees wore an elasticated vest with an augmented concurrent multi-Global Navigation Satellite System (GNSS) receiver unit (Apex, 10 Hz, STATSports, Belfast, UK), located between their shoulder blades. The GNSS unit was switched on ~15 minutes before, and turned off immediately after, each match. The validity and reliability of this GNSS unit has been reported previously (Beato et al., 2018). Each referee was allocated a specific GNSS unit for the entire duration of the study and were familiar with wearing similar units. The data collected in each match included: total, and high-intensity (> 18.4 $km \cdot h^{-1}$) distance covered (m), the number of high-intensity (> 2.79 $m.s^{-2}$) accelerations (calculated from a single derivation of the speed during a period of 0.5 seconds (Couderc et al., 2019) and sprints (20 $km \cdot h^{-1}$ or greater sustained for at least one second (Chapter 4 and 5) (n), and total sprint distance (m) (Chapter 4).

Heart rate (HR) data were also collected during matches from each referee through a HR sensor (Polar T31, Polar Electro, Kempele, Finland) worn around each referee's chest, which transmitted real-time data via Bluetooth to the GNSS unit. Maximal HR (HR_{max}) was determined as the highest of either: (1) HR_{max} estimated thorough the formula: 208 – (0.7 x age) (Tanaka, Monahan and Seals, 2001), or (2) HR_{max} values obtained during the match (Suarez-Arrones et al., 2013a).

7.2.5 Procedure

After collection and before the analysis, match footage and GNSS data were manually synchronised by the primary researcher at the start of each half, and at the time of each breakdown. In line with previous research (Elsworthy, Burke and Dascombe, 2014; Riiser et al., 2019), the match demands 30 seconds prior to each breakdown event were determined for the total and high-intensity distance covered, number of high-intensity accelerations and sprints, sprint distance, and average HR. Unfortunately, due to GNSS signal loss in the last minute of two matches, the match demands prior to 10 breakdowns were not included in the final analysis. Thus, the analysis between match demands and decision-making accuracy were based on data from 592 breakdowns, while all other analyses were based on data from 602 breakdowns. Previous research has reported the validity and reliability of the GNSS during trials of approximately the same duration (i.e., 30 s), compared to a "gold standard" (i.e., radar gun), showing a small bias (i.e., 2.3 + 1.1%) during a specific circuit that replicated the movement demands of team sports, and a small effect size (i.e., 0.42) during a 20 m trial (Beato et al., 2018).

7.2.6 Statistical analysis

Video analysis data was exported from Nacsport software (Pro PLUS V.5.0.1) into Microsoft Excel. Data from each GNSS unit was downloaded to analysis software (STATSports Apex software, v. 3.0.02011). All data were then exported to statistical analysis software (IBM SPSS v.27.0; IBM Corp., Armonk, NY, USA). Data distributions were checked using Shapiro-Wilk tests and homogeneity of variances were investigated using Levene's tests where appropriate. Normally distributed data (i.e., total distance) are presented as mean plus standard deviation (SD), while non normally distributed data (i.e., high-intensity distance, average HR, number of high-intensity accelerations and sprints, and sprint distance) are presented as median with interquartile range (IQR). Differences in the number of correct and incorrect decisions between first and second halves of matches, group and knock-out stages of the tournament, score difference, field location, and referee positioning were analysed via chi-square tests. Furthermore, for normally distributed data, the differences in match demands between correct and incorrect decisions were analysed via paired samples t-tests, with effect sizes (Cohen's *d*) of 0.2, 0.5, and 0.8 interpreted as small, medium, and large, respectively (Cohen, 1988). In contrast, for non-normally distributed data, the differences in match demands between correct and incorrect decisions were examined by Wilcoxon signed rank tests, with effect sizes (*r*) of 0.1, 0.3, and 0.5 interpreted as small, medium, and large, respectively (Cohen, 1988). Finally, associations between match demands, field position, score difference, referee position and decision-making accuracy were analysed via a series of binary logistic regressions analyses, with decision-making accuracy (i.e., correct = 1 vs. incorrect = 2) entered as the dependent variable, and total and high-intensity distance, average HR, number of high-intensity accelerations and sprints, sprint distance, score difference, field position, and referee position entered as independent variables. For all statistical analyses, α was set at 0.05.

7.3 Results

7.3.1 Decision-making accuracy

During the tournament, there were a total of 602 breakdowns, with a mean of 27 ± 7 breakdowns per match, representing one breakdown every 35 ± 12 seconds. There was an average of 4 ± 2 breakdown penalties per match, which equates to one penalty every 9 ± 6 breakdowns. Overall, the referees made the correct decision in 531 breakdowns and incorrect decisions in 71 breakdowns (i.e., 52 missed and 19 incorrect decisions), which represents a decision-making accuracy of 88.2%.

7.3.2 Changes in decision-making accuracy over time

A total of 322 breakdowns occurred during the first half, with referees having a decision-making accuracy of 88.5% (285 breakdowns), and 280 breakdowns occurred during the second half, with referees having a decision-making accuracy of 87.8% (246 breakdowns). The frequency of correct and incorrect decisions did not differ significantly between the first and second halves of matches across the tournament ($X^2[1] = 1.06$, $p = 0.30$). In the group stage, there were a total of 341 breakdowns, with referees displaying a decision-making accuracy of 89.7% (306 breakdowns), whereas in the knockout stage there were a total of 261 breakdowns, with the referees having a decision-making accuracy of 86.2% (225 breakdowns). The frequency of correct and incorrect decisions did not differ significantly between the group and knockout stages of the tournament ($X^2[1] = 0.03$, $p = 0.87$). Finally, there were no significant differences in the decision-making accuracy of referees between the first and second halves during the group ($X^2[1] = 2.0$, $p = 0.16$) or knockout ($X^2[1] = 0.85$, $p = 0.35$) stages of the tournament (Table 17).

Table 17. Summary of breakdown decision-making accuracy between the first and second halves during the two stages of the tournament (i.e., group and knock-out stages).

		Group Stage		Knock-out Stage	
		First Half	Second Half	First Half	Second Half
	Accuracy	89.1%	90.5%	87.8%	84.4%
Decision	Correct	163 (89.1%)	143 (90.5%)	122 (87.8%)	103 (84.4%)
	Incorrect	20 (10.9%)	15 (9.5%)	17 (12.2%)	19 (15.6%)
	Totals	183 (100%)	158 (100%)	139 (100%)	122 (100%)

7.3.3 Differences in match demands between correct and incorrect decisions

In the 30 seconds prior to the breakdown, the total distance covered was not significantly different between correct and incorrect decisions (68 ± 6 m vs. 66 ± 8 m, respectively; $t(5) = 1.00$, $p = 0.36$, $d = 0.4$). Moreover, high-intensity distance covered ($Z = -0.73$, $p = 0.46$, $r = -0.21$), average HR ($Z = -0.52$, $p = 0.60$, $r = -0.15$), number of high-intensity accelerations ($Z = -0.105$, $p = 0.92$, $r = -0.03$), and sprints ($Z = -0.105$, $p = 0.92$, $r = -0.03$), and sprint distance ($Z = -0.73$, $p = 0.46$, $r = -0.21$), did not differ significantly between correct and incorrect decisions (Table 18).

Table 18. Median (IQR) high-intensity distance, average HR, number of high-intensity accelerations and sprints, and sprint distance, in the 30 seconds before correct and incorrect breakdown decisions.

	Correct decisions	Incorrect decisions
High-intensity distance (m)	16.4 (9.3)	16.4 (12.4)
Average HR (%)	87.4 (6.4)	86.9 (8.3)
High-intensity accelerations (n)	0.9 (0.4)	1.0 (0.5)
Sprints (n)	0.6 (0.3)	0.7 (0.6)
Sprint distance (m)	12.8 (7.8)	13.8 (12.6)

7.3.4 Associations between match demands and decision-making accuracy

Total ($\beta = -0.01$, $p = 0.63$) and high-intensity ($\beta = -0.01$, $p = 0.80$) distance, average HR ($\beta = -0.03$, $p = 0.12$), number of high-intensity accelerations ($\beta = 0.06$, $p = 0.69$) and sprints ($\beta = 0.16$, $p = 0.34$), and sprint distance ($\beta < 0.01$, $p = 0.58$), all failed to account for a significant proportion of variance in decision-making accuracy.

7.3.5 Associations between score difference, field location, referee positioning and decision-making accuracy

Neither score difference ($\beta = 0.09$, $p = 0.57$), nor field position ($\beta = 0.08$, $p = 0.56$), accounted for a significant proportion of variance in decision-making accuracy. However, referee positioning accounted for a significant proportion of variance in decision-making accuracy ($\beta = 1.21$, $p = 0.004$), with incorrect decisions more likely to occur when the referees were in a suboptimal (29.0%) compared to an optimal (10.9%) position.

7.4. Discussion

This study assessed rugby referees' decision-making accuracy at the breakdown during an elite rugby sevens tournament in relation to time (i.e., first vs. second halves, group vs. knock-out stages), match demands in the 30 seconds preceding the breakdown (e.g., high-intensity distance covered), score difference, field position, and referee positioning. The results showed no significant difference in the breakdown decision-making accuracy between the first and second halves of matches or the two stages of the tournament (i.e., group vs. knock-out), and no association between decision-making accuracy and the match demands 30 seconds prior to a breakdown decision. Furthermore, score difference and field position were unrelated to decision-making accuracy, but rugby referees were more likely to make an incorrect decision when officiating the breakdown from a suboptimal position, than an optimal position.

The decision-making accuracy of rugby sevens referees found in this study (i.e., 88.2%) is similar to that reported for Australian football umpires (Elsworthy, Burke and Dascombe, 2014), and higher than that reported for 15-a-side rugby (Mascarenhas et al., 2005) and rugby league (Emmonds et al., 2015) referees (i.e., ~50% and 74%, respectively). The contrast in referees' decision-making accuracy between rugby sevens and other rugby codes might be due to differences in the nature of the sports (i.e., less players involved in a contact situation in sevens), and the methods of quantifying decision-making accuracy (i.e., real-word match play vs. video-based test). Additionally, the results did not reveal any differences in decision-making accuracy between the first and second halves of matches, which corroborate the findings by Castillo et al. (2019b), that reported that soccer referees decision-making accuracy were not affected by match period. The relatively short duration (i.e., 14 minutes) and high-intensity nature of rugby sevens matches, may explain why no differences in decision-making accuracy was observed between halves. Indeed, the relatively short periods of rest (i.e., ball out-of-play time and half time interval) may protect rugby sevens referees from experiencing a dip in decision-making accuracy, with the referees better able to maintain their mental awareness throughout the entire match (Mascarenhas et al., 2009). Moreover, no differences in decision-making accuracy emerged between the group and knock-out stages of the tournament, which is in line with one study which found that soccer referees' decision-making accuracy was unaffected by tournament phase (Castillo et al., 2019b). Thus, the consecutive days of the tournament seemed to have no influence on decision-making accuracy, potentially because the referees maintained their optimal mental and physiological activation throughout both tournament stages.

This study showed that the quality of the referee officiating at the breakdown was not influenced by the match demands 30 seconds prior. Specifically, no significant effects emerged between correct and incorrect decisions, a finding that is consistent with the results of previous research conducted with soccer referees (Riiser et al., 2019) and Australian Football umpires (Elsworthy, Burke and Dascombe, 2014). However, Elsworthy et al. (2014) reported that higher relative running speeds 5 seconds before a decision increased the likelihood of a decisional error for Australian Football umpires, suggesting that the increased physiological loads immediately prior to a decision may facilitate a reduction in the cognitive processes which are involved in decision-making due to changes in cerebral blood flow. Additionally, no significant differences in average HR were observed between correct and incorrect decisions in the present study, which is consistent with the findings of previous research with soccer referees (Mascarenhas et al., 2009), but contradicts the findings from Gomez-Carmona and Pino Ortega (2016) who found an increase in errors among soccer referees when working above 85% of maximum HR. Thus, given the conflicting findings in the literature, and the lack of associations observed between decision-making accuracy and match demands 30 seconds prior to the breakdown in this study suggests that none of these variables (e.g., high-intensity distance covered) can be used in isolation to predict decision-making accuracy. Additionally, it is worth considering that all referees involved in this study were part of the RFU National Panel, routinely assessed in terms of physical fitness and match reviews. Therefore, their level of training (fitness and technical) is likely to be sufficient to enable their decision-making accuracy to be unaffected by stage of tournament or match demands.

The present study showed that decision-making was not associated with the score difference between the two teams. This result does not corroborate the findings of previous research conducted with Australian Football umpires (Corrigan et al., 2019), and contradicts the findings reported with soccer referees (Lago-Peñas and Gómez-López, 2016). Specifically, score differential appeared to affect soccer referees' decision-making in close matches as the amount of injury time they awarded depended on the score margin, with a greater score difference resulting in less extra time being added (Lago-Peñas and Gómez-López, 2016). Additionally, the present study analysed the association between decision-making accuracy and field position. In contrast to the findings reported with Australian Football umpires (Elsworthy et al., 2014; Corrigan et al., 2019), there was no association between field position and decision-making accuracy, which is in line with the result reported with soccer referees (Castillo et al., 2019b). Thus, our results might infer that the referees' decision-making accuracy did not seem to differ based on score differential or field position. One possible explanation for our findings, is that the tournament was held at a neutral venue with an impartial crowd, thus bias caused by "home advantage", where the surrounding crowd appears to influence (albeit subconsciously) the referees' decisions in favour the home team, were less likely to occur (Nevill et al., 2017).

The results of the present study indicated that rugby referees were more likely to make correct decisions in the breakdown when in an optimal position compared to a suboptimal position. This result is consistent with the findings of previous research with soccer referees (Johansen and Erikstad, 2020), and may indicate that optimal positioning (i.e., short distance, good angle of sight) allows referees to make better decisions based on more relevant and timely environmental cues, and that suboptimal positioning may lead to limited visual input and thus an increased risk of incorrect decisions (Johansen and Erikstad, 2020). In fact, to apply the laws of the game, referees are expected to follow the game closely irrespective of the intensity of their previous movements because good positioning is considered crucial for accurate decision-making (Helsen and Bultynck, 2004). Thus, the placement of the referee at an optimal angle and with good sight into the breakdown seems to be important for correct decision-making. Accordingly, for the practice of officiating, the findings suggest that referees should improve their awareness to achieve an optimal position at the breakdown (i.e., between 4 and 8 o'clock; RFU, 2018), which could result in more accurate decision-making.

This is the first study to examine the decision-making accuracy of rugby sevens referees, and to evaluate situations leading to both action and no action from the referee, giving a more representative and accurate assessment of decision-making accuracy. However, despite the novel findings of the present study, it is not without limitations. First, the analyses were performed during only one elite rugby sevens tournament, potentially limiting the generalizability of the findings to other rugby codes, tournaments, and competitive levels. Thus, similar studies in more sevens tournaments, and during 15-a-side rugby matches of different competitive levels (e.g., amateur vs. elite), should be conducted to either confirm or refute the findings from this study. Second, it is worth noting that the decision-making accuracy data presented in this study represents only a selection of incidents (i.e., breakdown events), and although breakdown decisions might represent a relatively large proportion of the total decisions a referee makes during a match (World Rugby, 2019a), rugby sevens refereeing also involves making decisions in other contact (e.g., scrums, lineouts) and game (e.g., forward passes, offsides) events. As such, future research should aim to establish methods to identify how the variables assessed in this study (e.g., score difference, referee positioning, etc.) influence the decision-making accuracy across all events during rugby sevens matches and tournaments. Third, this study focused only on-field referee's decision-making accuracy and did not consider inputs from assistant referees. Given that assistant referees monitor many elements of the game (e.g., foul play, offside lines) and frequently communicate with and support referees in their judgement of play (Mallo, et al., 2012; Pietraszewski et al., 2014), future research should examine the influence of assistant referees on the decision-making accuracy of on-field referees. Finally, this study only investigated whether internal match related factors (e.g., field location) influenced decision-making accuracy. Therefore, future research should investigate the influence of external factors (e.g., crowd noise) on the decision-making accuracy of rugby referees (Nevill et al., 2017).

7.5. Conclusion and practical implications

In conclusion, this study showed that the decision-making accuracy of rugby referees at the breakdown in an elite sevens tournament did not differ significantly over time (i.e., first vs. second halves of matches, group vs. knock-out stages of a tournament), and that the match demands 30 seconds prior to a breakdown event, score difference, and field position were not associated with decision-making accuracy. However, referees were more likely to make an incorrect decision when in a suboptimal position. Thus, positioning skills are worth reviewing and improving as part of referees' training programmes aimed at enhancing decision-making accuracy.

CHAPTER 8: GENERAL DISCUSSION

8.1 Introduction

The main objective of this PhD thesis was to describe the physical and physiological demands that rugby referees encounter when officiating at different competitive levels (i.e., amateur to international) during sevens and 15-a-side matches, and to investigate the associations between those match demands and field test results and on-field decision-making accuracy. In addition to match demands, it was investigated if score difference, field location, or referee positioning were related to decision-making accuracy. To address these aims, four studies were conducted which provide important knowledge regarding rugby refereeing that can be used to enhance the practices and training used within sports science and strength and conditioning departments with rugby referees. The paragraphs below highlight the main findings from the studies included in this PhD thesis:

8.1.1 Summary of the findings

To better understand the match demands encountered by the rugby referees when officiating, the first two studies of this PhD thesis examined the physical and physiological demands of refereeing. Specifically, Chapter 4 examined the physical demands of refereeing rugby sevens matches, while Chapter 5 investigated the physical and physiological demands of refereeing 15-a-side matches, with both Chapters comparing those demands across different competitive levels (i.e., amateur to international). The findings from Chapter 4 showed that rugby sevens refereeing is characterised by high intermittent running demands that are greater at higher competitive levels (i.e., international). Additionally, Chapter 5 showed that refereeing 15-a-side rugby matches at higher competitive levels (e.g., professional) was associated with greater high-intensity demands than officiating matches at lower competitive levels (e.g., amateur). For example, compared with referees officiating at the amateur level, the results revealed that semi-professional, professional and international level referees completed more sprints during rugby sevens matches. Also, at the international level in rugby sevens, referees covered significantly more distance in the medium and high-intensity speed zones compared with all other zones (e.g., low intensity, jogging, walking). Moreover, during 15-a-side matches, professional referees sprinted for longer durations, covered more distance sprinting, and had a higher maximum speed during the WCS than semi-professional and amateur level referees.

To investigate if the field-based fitness tests commonly used among rugby referees accurately reflect the physical and physiological demands of refereeing rugby matches, the third study (Chapter 6) of this PhD thesis compared the $YYIR_1$ and Bronco tests and examined whether the results of these tests were associated with the physical and physiological demands of officiating 15-a-side rugby matches at an amateur competitive level. This study showed that the $YYIR_1$ and Bronco tests were significantly correlated. Additionally, this chapter found that the results of the $YYIR_1$ test were significantly correlated with the physical and physiological demands encountered by rugby referees during actual match play (e.g., total and high-intensity distance, sprints). Moreover, this chapter offered empirical support for the direct validity of the $YYIR_1$ test for the physical assessment of rugby referees. However, the direct validity of the Bronco test could not be assured by the study findings, with the results from this test related to relatively few physical or physiological demands (e.g., high-intensity accelerations) during actual match play.

Finally, to examine what factors are related to rugby referees' decision-making accuracy, the fourth study (Chapter 7) of this PhD thesis examined if physical and physiological match demands, score difference, field location, or referee positioning were associated with referees' decision-making accuracy at the breakdown (i.e., tackle and ruck) during an elite rugby sevens tournament. This chapter showed that the decision-making accuracy of rugby sevens referees at the breakdown did not differ significantly over time (i.e., first vs. second halves of matches, group vs. knock-out stages of a tournament). Additionally, this chapter revealed that the match demands 30 seconds prior to a breakdown (e.g., high-intensity distance), score difference, and field position were not significantly associated with decision-making accuracy. However, decision-making accuracy was significantly related to referee positioning, with referees more likely to make an incorrect decision when in a suboptimal position. The findings of this PhD thesis make an original and significant contribution to the literature, as explained in the next subsection.

8.2 Significance of the findings

8.2.1 Officiating rugby sevens

With a robust annual international competition and the significance of Olympic inclusion, rugby sevens continues to grow, with countries receiving increased financial and administrative support from their respective Olympic committees and improving their development pathways to prepare players and referees (Ross, Gill and Cronin, 2014; Ross, Gill and Cronin, 2015b). Additionally, in an attempt to better understand the influence of situational and individual factors affecting performance (e.g., possession time, ball retention, restart contests won), rugby sevens has also grown in popularity among researchers, with the number of studies increasing in recent years (Henderson et al., 2018). Accordingly, this PhD thesis provided two studies aimed at understanding referees' performance during rugby sevens matches and tournaments.

Chapter 4 was the first study to investigate the physical demands of rugby sevens refereeing at different competitive levels, ranging from amateur to international. This fills a gap in the literature, as previous studies only evaluated referees at one competitive level (e.g., elite; Blair et al., 2018b), and no comparisons have been made between different competitive levels. Such comparisons are important as they inform the requirements for referees who are transitioning between competitive levels, and provide vital information that can be used by applied practitioners to optimize the training and preparation of referees for rugby sevens tournaments, ensuring such training is suitable for the competitive level to be officiated. Specifically, differences were observed at the international and professional competitive levels compared to the amateur level for high-intensity and maximal speed running. For example, the referees at the higher competitive levels (i.e., international and professional) covered nearly 30% of the total distance within these speed zones, whereas referees at the amateur competitive levels covered only 11%. These might be partly explained by the greater speed characteristics of the international and professional players, who cover larger distances at higher speeds than amateur players, and because professional matches involve more ball-in-play time than amateur matches (Ross et al., 2015). Thus, in rugby sevens, a referee officiating at a higher competitive level (i.e., international and professional) must be able to cover more distance at higher speed than referees officiating at lower competitive levels (i.e., amateur). This study reported for the first time the differences in physical demands of rugby sevens refereeing between amateur, semi-professional, professional, and international competitive levels. It is important to understand the match-specific activities performed by referees during a match at a given competitive level, both to quantify the total physical load and to understand the frequency at which tasks (e.g., sprints) are performed (Ross, Gill and Cronin, 2015b; Le Roux, Lombard and Green, 2021). This information is vital for referee physical development and match-specific training.

Another novel and interesting finding highlighted in Chapter 4 was the relatively large number and short time between RHIE encountered by referees during rugby sevens matches. Indeed, regardless of competitive level, on average, a referee had 60 to 80 seconds to recover from six to 10 high-intensity bouts during a match, which exemplifies the highly intermittent nature of a rugby sevens match and the importance of being able to recover quickly between bouts when refereeing rugby sevens matches. Additionally, this study was the first to describe the most physically demanding period a referee could face during a match, termed the WCS, defined as the single longest RHIE bout (Reardon et al., 2017). This analysis provides more useful information for applied practitioners, as these periods are typically what referees should be physically prepared for, rather than simply relying on total distance, for example (Whitehead et al., 2019). Thus, the ability of the referee to meet the physical demands imposed during a rugby sevens match and tournament day (i.e., several matches in succession) is believed to be a prerequisite for optimal positioning, effective decision-making, and successful refereeing (Suarez-Arrones et al., 2013b).

Chapter 7 was the first study to assess rugby referees' decision-making accuracy at the breakdown during an elite rugby sevens tournament in relation to time (i.e., first vs. second halves, group vs. knock-out stages), match demands in the 30 seconds preceding the breakdown (e.g., high-intensity distance covered), score difference, field location, and referee positioning. The results did not reveal any differences in decision-making accuracy between the first and second halves of rugby sevens matches. Moreover, no differences in decision-making accuracy emerged between the group and knock-out stages of the tournament. Additionally, this study showed that the decision-making accuracy at the breakdown was not related to the match demands 30 seconds prior to the event (e.g., high-intensity distance covered). Furthermore, this chapter showed that decision-making accuracy was not associated with the score difference between the two teams or the location of the breakdown on the field.

Collectively, these findings might suggest that referees were able to maintain their decision-making accuracy over the course of sevens matches and stages of an elite sevens tournament, which could suggest resilience to the negative effects of physical and mental fatigue (Schapschröer et al., 2016; Habay et al., 2021). It could be that the actual physical demand was relatively low (i.e., their specific level of fitness was sufficient), so that the match was equivalent to moderate exercise, which is known to acutely enhance cognitive function (Brisswalter, Collardeau and René, 2002; Ahmed et al., 2020). It is also possible that the referees were well-trained and adapted to the demands of the matches (including the perceptual-cognitive demands), having on average six years of refereeing experience, and so the tournament did not represent a significant challenge for them. This might also be explained by referees' familiarity with exposure high physical and mental loads during an elite tournament, and the fact that moderate and high intensity physical exercise improves speed in perceptual-cognitive tasks and does not influence accuracy (Schapschröer et al., 2016). Indeed, it has been shown that cognitively demanding training and elite status are associated with resistance to physical and mental fatigue (Ahmed et al., 2020).

However, the findings of Chapter 7 indicated that rugby referees were more likely to make correct decisions at the breakdown when they were in an optimal position compared to a suboptimal position according to the "clock definition", with the breakdown at the centre of the "clock" (i.e., optimal = 4 to 8 o'clock, suboptimal = 8 to 4 o'clock; RFU, 2018); see Figure 16), revealing that referee positioning at the breakdown is important to improve decision-making accuracy. Thus, it is possible that the referees self-selected to reduce their work output (i.e., less distance covered) when approaching the breakdown. Yet, for the practice of officiating, the obtained results suggest that referees should work hard increasing their effort in achieving an optimal position at the breakdown (i.e., 4 to 8 o'clock), hence being more likely to make a correct decision. This was the first study to examine the decision-making accuracy of rugby union referees, investigating specific perceptual-cognitive performance under real-match situations during an elite rugby tournament. This fills the gap in the literature and adds to previous research among sport officials (Elsworthy, Burke and Dascombe, 2014; Riiser et al., 2019).

8.2.3 Officiating 15-a-side rugby

Like rugby sevens, 15-a-side rugby is an intermittent sport involving periods of high-intensity exercise (e.g., sprinting), interspersed with low-intensity activity (e.g., walking) (Roberts et al., 2008; Cunningham et al., 2016; Blair et al., 2018b). The ongoing evolution and improvement of the physical preparation of rugby players has resulted in an increase in their physical load during matches (Austin, Gabbett and Jenkins, 2011b), which has also impacted the requirements placed on the referees (Blair et al., 2018b; Bouzas-Rico et al., 2021). Although a few studies have described the match demands of officiating one competitive level (e.g., elite) (Martin et al., 2001;Blair et al., 2018b; Bester et al., 2019), no study has investigated whether the match demands encountered by rugby referees differs across different competitive levels (e.g., amateur vs. professional). To fill this gap in the literature, Chapter 5 was the first study to investigate the physical and physiological demands of refereeing 15-a-side rugby matches at different competitive levels (i.e., professional to amateur), and to quantify the internal load (i.e., Edwards training load) on referees and to examine the external-internal load relationship. The results revealed no differences between the competitive levels, possibly due to the small sample size and number of matches analysed. However, a large correlation was found between external and internal match load for semi-professional level referees, suggesting that the internal responses to matches were strongly associated with the amount of running completed at this level (McLaren et al., 2018). It is likely that the external-internal load relationship is moderated by factors such as referee fitness, and acute stress incurred as a result of physical (e.g., recent training, nutrition) and social (e.g., travel, sleep) factors (Castillo et al., 2017). This might partly explain why no correlation was found between external (i.e., total distance) and internal load for referees officiating at the professional and amateur levels. Still, these findings may help practitioners working with rugby referees decide whether both match loads methods are necessary, or if only using one method is enough to organise appropriate training sessions. Taken together, the results add to the literature surrounding the demands of rugby referees during competition. Additionally, an accurate and detailed understanding of competition demands can provide sport scientists and practitioners with an objective framework to prescribe the optimum training dose (Castillo et al., 2017).

Overall, the findings from Chapter 5 emphasise the importance that a 15-a-side rugby referee has the ability to perform high-intensity activities interspersed with less intense efforts, and applying the laws of the game while under the physical pressures of the intermittent nature of the game. Along with the knowledge of the laws, the referee's fitness is critical to their performance, allowing them to cope with the match demands, and being in the most ideal place to make the correct decisions (Igoe and Browne, 2019a; Bouzas-Rico et al., 2021). Consequently, there is a clear need to ensure the rugby referee has adequate levels of physical fitness to cope with the match demands to officiate at a given competitive level (Bouzas-Rico et al., 2021). Accordingly, to assess fitness, two field tests based on performance of repeated high-intensity activities are commonly used with rugby referees, namely the $YYIR_1$ and Bronco tests. Specifically, the $YYIR_1$ has been examined with other sport officials (e.g., soccer referees; Castillo et al., 2019a; Bouzas-Rico et al., 2021), while the Bronco test, has been under researched (Brew and Kelly., 2014). However, no research has examined the validity of these field-tests for rugby referees. Therefore, Chapter 6 was the first study to compare the $YYIR_1$ and Bronco tests in amateur 15-a-side rugby referees and to verify the direct validity of these tests in relation to the physical and physiological demands encountered by referees during actual match play. Additionally, Chapter 6 was the first study to propose reference values for the $YYIR_1$ and Bronco tests by generating estimating equations to determine the minimum fitness requirements needed to officiate at different competitive levels. Specifically, while Equation 1 (page 141) estimated which $YYIR_1$ test final distance a referee would achieve given the time taken to complete the Bronco test, Equation 2 (page 142) estimated which $YYIR_1$ test final distance a referee would achieve considering the total distance covered in a match.

In terms of the comparison between the two fitness tests, a large correlation was found between the distance covered in the $YYIR_1$ test and the time taken to complete the Bronco test. Although the two field tests are quite dissimilar in nature, with the Bronco test being a continuous, self-paced, and maximal effort shuttle run, over a set distance, and the $YYIR_1$ test being an intermittent, controlled-pace, and progressive maximal effort shuttle run over an unspecified total distance, the large correlation between test corroborates with previous research (Deuchrass et al., 2019). Additionally, the average HR reported by rugby referees during both tests was around 90% of their maximum, which suggests that both tests place similar physiological strain on the referees. However, the greatest percentage of time (~36%) was spent in the 91-95% HR_{max} zone during the Bronco test, whereas the largest percentage of time (~35%) was spent in the > 96% HR_{max} zone during the $YYIR_1$ test. Moreover, compared with the Bronco test, the maximum HR reached during the $YYIR_1$ test was higher (i.e., ~197 vs. ~192 bpm). While this was the first study to examined the HR during the Bronco test, preventing comparisons to previous research, the findings for the HR responses during the $YYIR_1$ agree with previous research and imply that the test can help determine the maximal HR of rugby referees (Bangsbo, Iaia and Krustrup, 2008).

Chapter 6 was the first study to investigate the relationships between the field test results and match demands. The findings shown that the $YYIR_1$ test result and internal load were correlated with referees' physical match demands (e.g., high-intensity distance), suggesting that the performance during the $YYIR_1$ test is associated with the running intensity that a referee sustain during match play as well as their ability to recover between high-intensity periods (Dobbin et al., 2018). Furthermore, the $YYIR_1$ test maximum HR was correlated with referees' physiological match demands (e.g., Match HR_{max}), supporting the direct validity of the test (Boddington, Lambert and Waldeck, 2004). In contrast, the Bronco test result was correlated with the referee's maximal speed and number of high-intensity accelerations during actual match play. Additionally, maximum and average HR during the Bronco test and actual match play were correlated. However, the lack of correlations between the Bronco test result and high-intensity match demands (e.g., high-intensity distance), and the self-paced continuous nature of the Bronco test, raise questions about the direct validity of the test, since the quantity of high-intensity exercise is a better indicator of match demands (Krustrup and Bangsbo, 2001). Based on that, it was not possible to establish the direct validity of the Bronco test for amateur 15-a-side rugby referees in Chapter 6.

8.3 Original contribution to the literature and implications of findings

This PhD thesis has made an original and meaningful contribution to the current literature. Specifically, this PhD thesis provided the first study to examine the match demands encountered by rugby union referees during sevens and 15-a-side matches across different competitive levels (i.e., amateur to international), while most of the previous research has only examined one competitive level (e.g., elite; Blair et al., 2018b; Bester et al., 2019). Additionally, this PhD thesis investigated in detail for the first time, the high-intensity efforts undertaken by rugby sevens and 15-a-side referees during actual match-play, specifically exploring the RHIEs and WCS a referee could be involved in during a match (Austin, Gabbett and Jenkins, 2011b; Jones et al., 2015). Moreover, this PhD thesis adds the first study to examine the direct validity of the $YYIR_1$ and Bronco tests for rugby referees, providing an extended analysis of the demands of the field-based tests currently being used among rugby referees (Bouzas-Rico et al., 2021). Therefore, the findings of this work are very useful for professionals who evaluate the fitness of rugby referees, as well as for the applied practitioners (e.g., strength and conditioning coaches) dedicated to their physical preparation. Finally, this PhD thesis provided the first study to quantify rugby sevens referee's decision-making accuracy during match play and investigate the factors that influence decision-making (i.e., match demands, score difference, field location, referee positioning). This information might inform the specific training methods and match day strategies used by rugby referees during a sevens tournament (Kittel et al., 2021).

In the strength and conditioning setting, it is imperative to utilise both applied experience as well as credible research to plan and prescribe training programmes that facilitate the best possible outcomes with the athletes (Bouzas-Rico et al., 2021). For rugby referees, access to the physical and physiological demands identified in this PhD thesis allows practitioners to plan and prescribe specific physical training sessions that more closely replicate the demands of the refereeing actual rugby matches. This ensures, for example, that rugby referees are prepared to cope with the WCS for rugby sevens and 15-a-side matches identified in Chapters 4 and 5, respectively, allowing them to better keep up with the pace of play and make more accurate decisions whilst under physical strain. Additionally, the findings from this PhD thesis will help not only rugby referees at the elite level, but they will also help up-and-coming referees make their training more efficient and specific to the demands of the competitive level they officiate. Indeed, the outcomes generated in this PhD thesis have been used by the RFU during educational referee courses, and specifically strength and conditioning modules (Appendix C), providing information to be used for training periodization, and to help refine fitness testing guidelines for rugby referees. Finally, the research produced in this PhD thesis helps the prescription and planning of conditioning programmes to cover all aspects of the game, creating robust and resilient referees ready to cope with the demands of rugby matches. Thus, because their physical capacity is well prepared, their mental capacity is likely to also improve, potentially enabling them to make better on-field decisions.

The findings from this PhD thesis provide an opportunity for the development of individualised strength and conditioning programmes for both aspiring and elite rugby referees. The data presented in Chapter 4 and 5 clearly demonstrate that refereeing rugby sevens and 15-a-side matches is a high-intensity intermittent effort, therefore the use of high-intermittent activities during training sessions is paramount. Specifically, practitioners working with rugby referees should consider designing training program activities using high-intensity speed (> 18.4 $km{\cdot}h^{-1}$), high-intensity accelerations and decelerations (> 2.79 $m.s^{-2}$), sprints (>20 $km{\cdot}h^{-1}$), and high-intensity HR (> 80% HR_{max}) (Suarez-Arrones et al., 2013a; Blair et al., 2018b; Bester et al., 2019). As highlighted in Chapter 6, the $YYIR_1$ test can also be used to determine the maximal HR, which is crucial information for training prescription (Bangsbo, Iaia and Krustrup, 2008). Additionally, at least one training session during a well-structured weekly plan should overload and mimic the demands of a match and include decision-making activities (Emmonds et al., 2015; Blair et al., 2018a). Although the findings from Chapter 7 showed that referee's decision-making accuracy remained constant throughout a rugby sevens match and unaffected by match demands, it was highlighted that it can be improved by optimising the referee's positioning. Therefore, referee's positioning skills should also be included in training programmes. For instance, during the breakdown, referees should be encouraged to be in an optimal position (see Figure 16). Specifically, incorporate positioning and decision-making activities in the physical fitness session, will stimulate referees to work hard to be in an optimal position with good angle and insight of a situation, and to improve the likelihood of making correct decisions, while also training their decision-making accuracy (Johansen and Erikstad, 2020).

8.4 Limitations, future directions and practical applications

The research among rugby referees is growing and is likely to continue to grow as the game of rugby is rapidly evolving and new law changes are frequently being introduced. For example, with the new law trials to be introduced (World Rugby, 2021a), it is reasonable to expect that more attacking space will be created (e.g., 50:22 law) and the number of scrums per match will be reduced (e.g., goal line drop-out law). While the primary aim of these new law trials is to improve player welfare and make the game safer, it is also expected that the ball-in-play time will increase, thereby increasing the demands encountered by referees. Since the studies in this PhD thesis were conducted over the course of one season, no between season variations of referee demands were examined, which could be viewed as potential limitation, as it was not possible to investigate if the match demands encountered by rugby referees differ over seasons. Future research is therefore encouraged to conduct a more longitudinal analysis of the match demands placed on rugby referees, allowing a comparison between seasons, and enabling a better understanding of the impact of the law changes on the demands encountered by referees (e.g., greater high-intensity activities). Additionally, a true WCS is likely to occur under multivariate conditions (e.g., a relatively high volume of sprinting), and numerous combinations of these conditions could induce a WCS (i.e., an extreme internal response to various external and contextual factors such as number of high-intensity activities and, the actual time of occurrence within the match half; Novak et al., 2021). Training periodization using average WCS (e.g., Chapter 5) may not provide adequate preparation, and a better understanding of how physical and contextual factors (e.g., the amount of activity completed in the period immediately preceding the WCS) combine to produce WCS responses might guide the development of more robust training programmes (Novak et al., 2021). Therefore, future studies must be conducted to develop our confidence that training to the WCS is a suitable approach to improve rugby referee performance (Novak et al., 2021).

Except for Chapter 6 which was conducted in South Africa, most studies in this PhD thesis were carried out with referees based in England, which could be seen as a potential limitation. In this sense, the teams' playing style and level are influenced by each country's specific context (e.g., more expansive running game vs. greater intensity of ball contest), which might have had an influence on the physical and physiological demands encountered by the referees (Bouzas-Rico et al., 2021). Therefore, the results obtained might not generalise to all rugby referees worldwide (e.g., Southern Hemisphere), and the equations suggested in Chapter 6 might perform worse in other settings, calling for further external validation studies in new settings and with other referee samples (e.g., elite). In this respect, as rugby referees' physical performance in matches are interrelated with those of the players (Weston et al., 2012), future research should determine the extent to which these activities are independently driven by the action of players or consciously by the referees themselves. Combining such work with attempts to relate the referees' physical performance to their own capabilities will provide better insight into the match demands and changes in the within-match activity profile (Weston et al., 2012).

Regarding fitness testing, this PhD thesis provided the first study assessing the direct validity of two field tests, the $YYIR_1$ and Bronco tests, for the assessment of rugby referees' physical fitness, giving empirical support to the direct validity of the $YYIR_1$ test as an indicator of match-related physical performance in rugby referees during amateur 15-a-side matches. However, the associations between both field tests and higher competitive level, as well as during and rugby sevens matches were not examined, potentially limiting the generalisability of the results. For that reason, future research should be conducted aiming to examine the validity of the $YYIR_1$ and Bronco tests as an indicator of referees' physical performance for elite and rugby sevens matches. Moreover, when considering the specific match demands imposed on rugby referees, both $YYIR_1$ and Bronco tests can be criticised in that referees do not perform consecutive runs (e.g., 2 x 20 m or 20-40-60 m). Besides, for any fitness test to be deemed relevant, it must measure components of fitness that are specific to the sport in question, and must also provide information that is valid, objective, and reliable (Boddington et al., 2001; Bouzas-Rico et al., 2021). Thus, future research should focus on developing and validating a specific field-based test for rugby referees that is based on the match demands and therefore more accurately evaluates referees' fitness. Indeed, such test is likely to combine maximal shuttle runs of varying distances with change of direction movements to assess intermittent work of short duration and high intensity (Thomas, Comfort and Jones, 2018). Additionally, minimum fitness standards should be determined by a field-based test that also incorporates a task analysis to clearly identify the critical and most physically arduous generic aspects of the role (Stevenson et al., 2016). Therefore, together with physical and physiological demands analysis, a field-based test should also involve a perceptual-cognitive element, such as concurrent cognitive tasks or video clips with match situations, so the referee could make decisions while under physical fatigue (Cunningham, Mergler and Wattie, 2022).

Although successful rugby refereeing is dependent on the ability to make decisions under psychological pressure, there is still limited research on the decision-making accuracy of rugby referees. Indeed, this PhD thesis provided the first study to examine the factors that are related to the decision-making accuracy of referees during an elite sevens tournament. However, the factors influencing decision-making accuracy were only analysed during elite rugby sevens matches and only observable decisions at the breakdown were examined, which could be considered a potential limitation, potentially limiting the generalisability of the findings to other rugby codes, and competitive levels. It is acknowledged that the referees are continuously making decisions throughout the match (Emmonds et al., 2015), therefore future research should aim to examine referees' decision-making accuracy in a broad selection of incidents during the match (e.g., scrums, line-outs), and during 15-a-side rugby matches of different competitive levels (e.g. amateur vs. elite). Additionally, this PhD thesis only investigated whether internal match-related factors (e.g., field location) were associated with decision-making accuracy. Thus, future studies should aim to analyse if external factors (e.g., crowd noise, pressure exerted by players and coaches), as well as referee's experience, and running profile influence rugby referees' decision-making accuracy (Burnett et al., 2017). Also, understanding how physical fitness training is involved in the acquisition and learning of perceptual-cognitive skills could be a question for future research (Cunningham, Mergler and Wattie, 2022).

Table 19 provides a summary of the major findings from each of the thesis empirical chapters and the related future research directions, while Tables 20 and 21 provide examples of how the findings from the empirical chapters in this thesis can be used in practice.

Table 19. Major finding and future directions from each empirical chapter.

	Major finding	Future directions
Chapter 4	Rugby sevens refereeing is characterized by high intermittent running demands that are greater at higher levels of competition.	To examine the efficacy of different recovery methods for restoring the physical and physiological attributes of referees between successive matches and days of competition.
Chapter 5	High standards of physical fitness, especially in terms of high-intensity efforts during 15-a-side matches, are expected of referees as the level of matches increases (i.e., amateur to professional).	Investigate if referee's physical performance in matches are interrelated with those of the players, providing a better insight into the demands of match play and changes in the within-match activity profile.
Chapter 6	The $YYIR_1$ test better correlates with actual match demands than the Bronco test.	To develop a specific rugby referee field-based test combining physical, physiological, and perceptual-cognitive evaluation, with a robust validation of minimum performance standards.
Chapter 7	Referee's decision-making accuracy at the breakdown is not associated with match demands, field location, or score difference, but is related to referee positioning.	Objective and reliable markers of decision-making should be established, with due consideration to the development of naturalistic test situations while maintaining experimental control. Also, process tracing measures, such as verbal and eye tracking recordings, should be used to identify the perceptual-cognitive processes involved in accurate decision making. Moreover, research is required to help understand the acquisition of superior decision-making and whether such expertise can be developed via bespoke training programmes.

Table 20. Example weekly training schedule for an amateur or semi-professional 15-a-side rugby union referee.

<table>
<tr><td>Monday</td><td>Tuesday</td><td>Wednesday</td><td>Thursday</td><td>Friday</td><td>Saturday</td><td>Sunday</td></tr>
<tr><td>Extensive aerobic training</td><td>HIIT#1</td><td>Rest</td><td>HIIT#2 or MSS</td><td>Rest</td><td>Match</td><td>Rest</td></tr>
<tr><td colspan="7">Extensive aerobic training: Running at low to medium intensity for 6 to 8 Km, for no more than 1 hour per session.</td></tr>
<tr><td colspan="7">HIIT#1: High-intensity interval training – running for 60 seconds at a HR of 80-95 %HRmax, with 60 seconds recovery at 55-70 %HRmax. Repeated 8 times. Target = 1500 m high-intensity running. Warm-up for 10 minutes before (e.g., running at low to medium intensity) and 10 minutes cool down after (e.g., 10 minutes low intensity running and stretching).</td></tr>
<tr><td colspan="7">HIIT#2: High-intensity interval training – 6 x 40 m sprints at maximum speed with 30 seconds rest between repeats. 5 minutes low intensity running recovery, repeated 2 twice.
RSS: Maximum sprints session: 10 x 45 to 55 m sprints at maximum speed. Target: 500 m total distance. Warm-up for 10 minutes before (e.g., running at low to medium intensity) and 10 minutes cool down after (e.g., 10 minutes low intensity running and static stretching).</td></tr>
</table>

Table 21. Example weekly training schedule for a professional 15-a-side rugby union referee.

<table>
<tr><td>Monday</td><td>Tuesday</td><td>Wednesday</td><td>Thursday</td><td>Friday</td><td>Saturday</td><td>Sunday</td></tr>
<tr><td>Extensive aerobic training</td><td>HIIT#1</td><td>Rest</td><td>HIIT#2 or MSS</td><td>AS and Match preparation</td><td>Match</td><td>Rest or RS</td></tr>
<tr><td colspan="7">Extensive aerobic training: Running at low to medium intensity for 7 to 9 Km, for no more than 1 hour per session.</td></tr>
<tr><td colspan="7">HIIT#1: High-intensity interval training – running for 120 seconds at a HR of 85-95 %HRmax, with 60 seconds recovery at 60-70 %HRmax. Repeated 8 times. Target = 1800 m high-intensity running. Warm-up for 10 minutes before (e.g., running at low to medium intensity) and 10 minutes cool down after (e.g., 10 minutes low intensity running and static stretching).</td></tr>
<tr><td colspan="7">HIIT#2: High-intensity interval training – 6 x 40 m runs at maximum speed with 20 seconds rest between repeats. 5 minutes low intensity running recovery, repeated twice.
RSS: Maximum sprints session: 10 x 55 to 65 m sprints at maximum speed. Target: 600 m total distance. Warm up for 10 minutes before (e.g., running at low to medium intensity) and 10 minutes cool down after (e.g., 10 minutes low intensity running and static stretching).</td></tr>
<tr><td colspan="7">AS: Activation session – high-intensity accelerations and decelerations – 4 x 5 seconds maximum speed and 10 seconds walk recovery. Repeat four times with 2 minutes low-intensity running between. Warm-up for 5 minutes before (e.g., running at low to medium intensity) and 5 minutes cool down after (e.g., 5 minutes low intensity running and static stretching).
Match preparation: mental activities (e.g., decision-making video analysis).</td></tr>
<tr><td colspan="7">RS: Recovery session – 20 to 30 minutes of low intensity running and static stretching.</td></tr>
</table>

8.5 Conclusion

This PhD thesis provides a better understanding of rugby refereeing, specifically in terms of physical and physiological match demands during sevens and 15-a-side matches, fitness testing, and the factors related to decision-making accuracy. The aims of this PhD thesis were to: (1) better understand the differences in the match demands encountered by rugby referees across different competitive levels (i.e., professional to amateur), (2) investigate the associations between the match demands (e.g., high-intensity running during matches) and the performance on current fitness tests to determine the efficacy of these tests in predicting the physical match performance of rugby referees, and (3) quantify referees' decision-making accuracy and examine if match demands, score difference, field location, or positioning were associated with decision-making accuracy. The results showed that refereeing rugby sevens and 15-a-side matches is more physically demanding at higher competitive levels (e.g., elite, international, or professional), particularly in terms of high-intensity efforts. Furthermore, the results suggested that the $YYIR_1$ and Bronco tests were highly correlated, but that the former should be regarded as the more valuable fitness test for rugby referees as it better predicts actual match demands (e.g., total and high-intensity distance). Finally, the results showed that decision-making accuracy was unaffected by match demands, score difference, or field position, but related to referee positioning, with more accurate decisions accompanying more optimal positioning.

Using a considerable sample size and covering all competitive levels of rugby (i.e., professional to amateur), this PhD thesis added to the literature and provided new information related to the physical and physiological demands of officiating rugby sevens and 15-a-side matches. Moreover, this PhD thesis contributed to the literature in terms of the field tests used to evaluate the fitness of rugby referees, investigating the direct validity of the $YYIR_1$ and Bronco tests, and suggesting minimum performance standards for rugby referees according to their competitive level. Finally, this PhD thesis provided novel information regarding the factors that may be related to rugby referees' decision-making, particularly highlighting the importance of referee positioning.

Overall, this PhD thesis represents the most complete investigation into rugby refereeing, adding to the literature and highlighting several key messages to referees and applied practitioners regarding how to improve referee training in preparation for matches.

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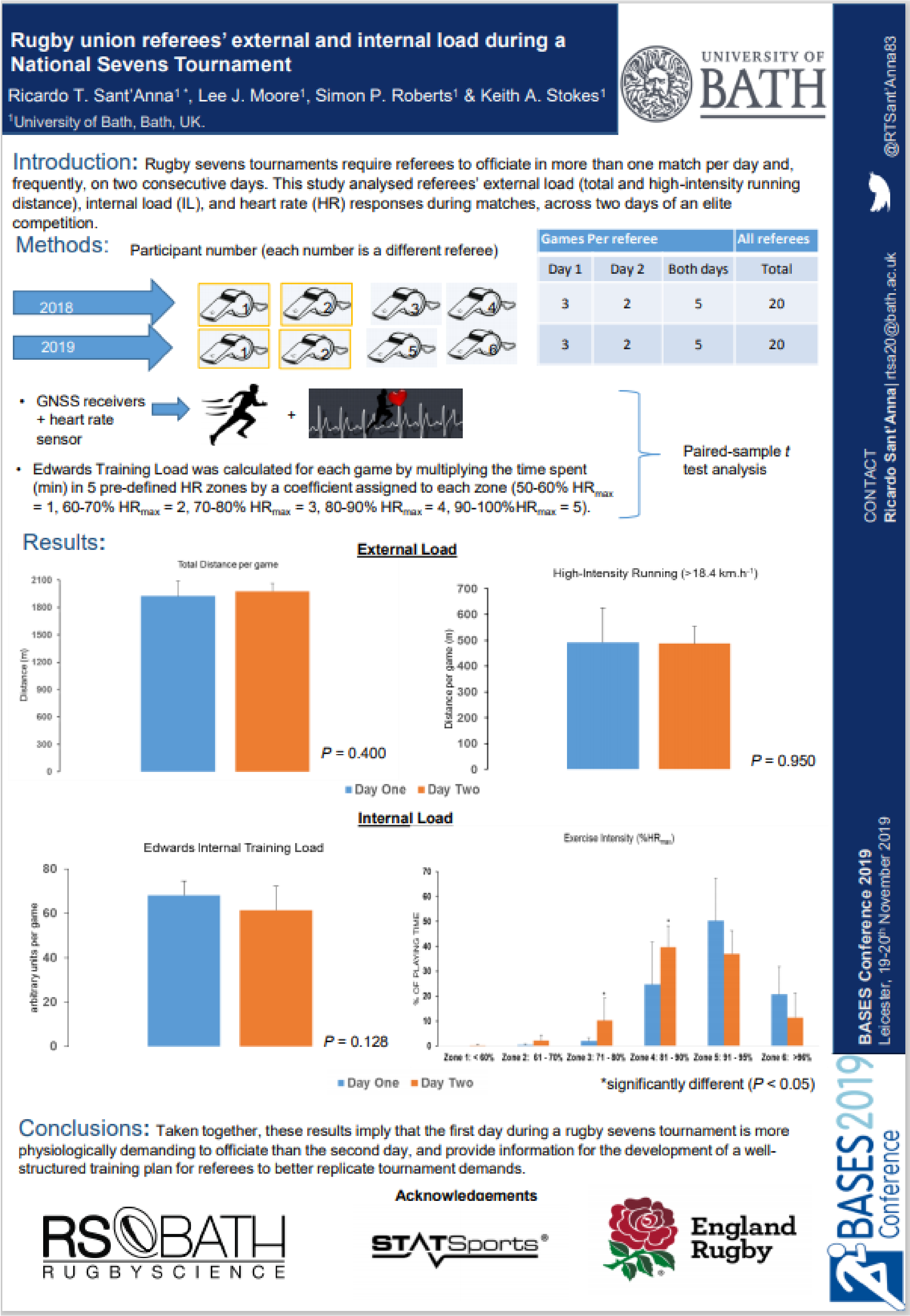
APENDIX A



Rugby union referees' external and internal load during a National Sevens Tournament
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Introduction: Rugby sevens tournaments require referees to officiate in more than one match per day and, frequently, on two consecutive days. This study analysed referees' external load (total and high-intensity running distance), internal load (IL), and heart rate (HR) responses during matches, across two days of an elite competition.
Methods: Participant number (each number is a different referee)
2018
2019
Games Per referee
All referees
Day 1
Day 2
Both days
Total
3
2
5
20
3
2
5
20
GNSS receivers + heart rate sensor
Edwards Training Load was calculated for each game by multiplying the time spent (min) in 5 pre-defined HR zones by a coefficient assigned to each zone (50-60% HRmax = 1, 60-70% HRmax = 2, 70-80% HRmax = 3, 80-90% HRmax = 4, 90-100%HRmax = 5).
Paired-sample t test analysis
Results:
External Load
Total Distance per game
Distance (m)
P = 0.400
High-Intensity Running (>18.4 km.h-1)
Distance per game (m)
P = 0.950
Day One
Day Two
Internal Load
Edwards Internal Training Load
arbitrary units per game
P = 0.128
Exercise Intensity (%HRmax)
% OF PLAYING TIME
Zone 1: <60%
Zone 2: 61 - 70%
Zone 3: 71 - 80%
Zone 4: 81 - 90%
Zone 5: 91 - 95%
Zone 6: >96%
Day One
Day Two
*significantly different (P < 0.05)
Conclusions: Taken together, these results imply that the first day during a rugby sevens tournament is more physiologically demanding to officiate than the second day, and provide information for the development of a well-structured training plan for referees to better replicate tournament demands.
Acknowledgements
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Rugby union referees' external and internal load during a National Sevens Tournament.

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Rugby sevens referees often officiate multiple matches per day over consecutive days. This study analysed referees' external load, internal load (IL) and heart rate (HR) responses across two days of competition. Following institutional ethics approval, six rugby referees (age: 26.1 ± 3.5 years), officiated matches during a two-day professional sevens tournament (day one = 3 matches, day two = 2 matches), in two subsequent years (i.e., 2018, 2019). Two referees officiated at both years. Referees wore Global Navigation Satellite Systems (GNSS) receivers (Apex, 10 Hz, STATSports), allowing total running distance (TRD) and high-intensity running (HIR; > 18.4 km.h -1) distance to be determined (m). HR data was also collected via a heart rate sensor (Polar T31, Finland), analysed in relation to maximal HR (HRmax) estimated via the formula: 208 – 0.7 x age (Tanaka et al., 2001, Journal of the American College of Cardiology, 37, 153-156) and the percentage of total playing time spent in six zones. IL calculation was performed as proposed by Edwards (1993, The Heart Rate Monitor Book. Sacramento: Fleet Feet Press). Paired-samples t tests revealed no differences between the two days of competition in terms of TRD (day one = 1925 ± 168 m, day two = 1977 ± 85 m; t(7) = -0.896 , P = 0.400, CI95% = -187.7-84.6, ES = - 0.31), HIR (day one = 492 ± 134 m, day two = 488 ± 67 m; t(6) = 0.066, P = 0.950, CI95% = -113.7- 120.0, ES = 0.02) or IL (day one = 68.2 ± 6.3 au, day two = 61.4 ± 10.6 au; t(7) = 1.725, P = 0.128, CI95% = -2.5-16.0, ES = 0.61). On the second day, relative to the first, referees spent more time at 71–80%HRmax (day one = 1.9 ± 1.3 %, day two = 10.2 ± 8.9 %; t(6) = -2.535, P = 0.044, CI95% = -16.4-[-0.3], ES = - 0.95) and 81–90%HRmax (day one = 24.7 ± 16.9 %, day two = 39.7 ± 8.4 %; t(7) = -2.735, P = 0.029, CI95% = -28.1-[-2.0], ES = -0.96). Taken together, these results imply that the first day during a rugby sevens tournament is more physiologically demanding to officiate than the second day. These findings provide information for the development of a well-structured training plan for referees to better replicate tournament demands

APPENDIX B

ANNEX FOUR – APPLICATION FORM FOR FULL SUBMISSION FOR RESEARCH ETHICS APPROVAL

PARTICIPANT INFORMATION SHEET

CONSENT FORM

ANNEX FOUR – Application form for full submission for research ethics approval

Department for Health

Research Ethics Approval Committee for Health

Title of study	The Physiological Demands of Refereeing Rugby Union
Chief investigator **(for research student projects, put research supervisors name here)** **(for undergraduate projects, put project supervisors name here)**	Name: Prof Keith Stokes e-mail: spsks@bath.ac.uk Telephone: 01225 384190 Name: Dr Simon Roberts e-mail: s.p.roberts@bath.ac.uk Telephone: 01225 384531 Name: Dr. Lee Moore Telephone: 01225 384205 e-mail: l.j.moore@bath.ac.uk
Other investigators	Name: Msc. Ricardo Tannhauser Sant'Anna

(for research student projects, put students name here) **(for undergraduate projects, put student(s) name here)**	e-mail:rtsa20@bath.ac.uk Telephone: 01225 385430 Mobile: 0[redacted]
Source of funding for the study	Self-funded
Proposed dates of study	February 2018- April 2020
Research question	The study aims to answer three main research questions: 1. What are the physiological demands of rugby referees according to the level of the game they are involved in and how the frequency of events (rucks, mauls, passes, tackles, scrums, etc) during a game impact on the referee movement demands? 2. Do the demands of the fitness tests reflect the referees' match demands and is there a relationship between how well a referee performs in the fitness tests and their match running performance? **3.** What are the most common referees' decisions and non-decisions in the breakdown during a rugby sevens tournament, and does the match demands have any impact on decision making accuracy
Background (less than 100 words)	The ability of the rugby referee to meet the physical and physiological demands imposed during match play is believed to be a necessary prerequisite for optimal positioning and successful refereeing. Identification of

	referee movement patterns and the associated physiological responses during match play, is important for optimizing training prescription and managing referee preparation for competition (Suarez-Arrones et al., 2013). To date, the fitness testing protocols used to assess referees' readiness to officiate have been based on general fitness tests for team sport players and therefore may not be the optimal test to evaluate the physiological demands for officials. Finally, little is known about how the physical demands placed on referees' influences their decision-making.
Methods (less than 300 words)	This will be done in three stages: • The first stage will investigate the physiological demands of rugby referees according to the level of the game they are involved in and how the frequency of events (rucks, mauls, passes, tackles, scrums, etc) during a game may impact on the referee movement demands. In this investigation, an observational design will be used to examine the match physical demands and exercise intensity of referees during competitive 15 and 7 a side rugby matches at different levels of competition. Time-motion analysis of running activity will be collected from referees involved in Rugby Europe competitions, World Rugby Tournaments, national competitions (Level 1 to 7) and South African competitions (South Africa WP Super League A and/or Koshuis Rugby Championship (university's internal champions) 1st, 2nd, 3rd and 4th League). The referees, during the games, will wear a

	Global Positioning System (GPS) and heart rate monitor. • For the second stage, associations between the physical demands of match play and the fitness tests presently used by rugby referees will be investigated to understand if the tests are valid for the match demands required by a referee. Participants will perform three fitness tests: Treadmill VO_{2Max}, Yo-Yo Intermittent Recovery Test Level 1 and the Bronco Test. The performance score in each test will be compared to the match performance of the referee. • For the third stage, the association between match demands (e.g., sprint distance) and referees' decisions during breakdown (i.e., tackle and ruck) events will be investigated in order to understand referees' decision-making accuracy during a professional rugby sevens tournament (i.e., Premiership Sevens 2019). This will be investigated using the GPS and HR data already collected, and a new analysis of the decision-making of referees via the tournament footage (available from the RFU Elite Hub), which was public and broadcasted live on TV. With the consent of the home club, matches will be filmed by members of the research team using a portable camcorder. In the case of teams who have recorded their own footage, or the match/tournament was broadcasted live on television, the research team will request access to that footage. For some tournaments, matches may involve school age players (under 18). Match footage from any such

	matches will only be used if it is made publicly available by the tournament organiser. All the tests (lab based and field test) will be conducted by a member of the research team, who are all experienced and trained to conduct the tests
Sample size (or equivalent qualitative approach)	For each playing level a minimum of 15 referees with two performances each resulting in 30 match performances for each level.
Proposed Analysis	Match running performance at different speeds at each playing level will be compared using a one-way analysis of variances (ANOVAs) with repeated measures. Correlations between match performance outcomes, fitness test results, and referees' decision-making will be determined using Pearson moment correlation test. In addition, one-way ANOVAs will be used to examine differences in match demands (e.g., sprint distance) immediately prior to correct, incorrect, and missed decisions.
Potential risks to volunteers	The first stage whereby physical demands are recorded, will be observational and, for that reason, the participants will not be asked to do anything that differs from their normal match preparation routine. For the fitness testing, participants will be asked to exercise to their maximum effort and therefore may feel some discomfort, such as nausea and dizziness. These effects will be temporary and subside during recovery. One test requires treadmill running for which a risk assessment is available (Woodway Treadmill risk assessment attached on this application). Researchers will refer to the Standard Operating Procedure for the Woodway Treadmill.
Potential for pain/discomfort	During the second phase, participants will be asked to take part in a laboratory-based fitness tests, for which they will be assessed for their readiness for such activity.
Benefits to participants	A detailed result of the match analysis and the fitness tests will be given to each referee and therefore provide them with

	relevant information for their training program and how their performances compare with the average of other referees.
Will the study involve deceiving the participants? If so, please justify why deception is necessary.	No, each participant (Referee) will understand the reason why they are involved in the research.
How will participants be recruited?	On a first stage, formal request by email will be sent to Referee Managers of the International and National Societies to explain the purpose of the study. On a second stage, with the approval of the Managers, the researcher will forward the Participant Information Sheet (included in this application) to the Referees.
Exclusion/inclusion criteria	Referees participating in levels 1 to 7 in English rugby union will be included. Only 1st XV matches will be used. Referees who are involved in Rugby Europe and World Rugby Tournaments will also be included. Additionally referees involved in the following South African competitions: South Africa WP Super League A and/or Koshuis Rugby Championship (university's internal champions) 1st, 2nd, 3rd and 4th League.
How will participants consent be taken?	Prior to the first match analysis, all referees will be provided with information about the study and given the opportunity to ask questions before providing informed consent by signing a participant consent form. Only referees over 18 years of age will be involved and will be assured their data will not be identifiable
How will confidentiality be ensured?	They will not be able to be identified in any follow-up publications. Data will be stored on a database located within the University X Drive for which access will only be available to the researchers of this investigation. In the

	match footage analysis, no identifiable information (e.g., referees' names) will be recorded.

Attach the following (where relevant):

1. Participant information sheet
2. Consent Form
3. Health history questionnaire
4. Poster/promotional material
5. Copy of questionnaire/ proposed data collection tool (questionnaire; interview schedule/ observation chart/ data record sheet/ participant record sheet)
6. Data Management plan

Signed by: Principal Investigator or Student Supervisor

Prof Keith Stokes

[redacted] Date: 15/12/2017

Signed by: Student or other researchers

MSc, Ricardo Tannhauser Sant'Anna

[redacted] Date: 18/12/2017

PARTICIPANT INFORMATION SHEET

The Physiological Demands of Refereeing Rugby Union

Name of Researcher: Msc. Ricardo Tannhauser Sant'Anna

Contact details of Researcher:

e-mail:rtsa20@bath.ac.uk

Telephone: 01225 385430

Mobile: [redacted]

Name of Supervisor: Prof Keith Stokes

Contact details of Supervisor:

e-mail: spsks@bath.ac.uk

Telephone: 01225 384190

Second Supervisor: Dr Simon Roberts

e-mail: s.p.roberts@bath.ac.uk

Telephone: 01225 384531

Third Supervisor: Dr Lee Moore

e-mail: l.j.moore@bath.ac.uk

Telephone: 01225 384205

This information sheet forms part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. Please read this information sheet carefully and ask one of the researchers named above if you are not clear about any details of the project.

1. What is the purpose of the project:

To understand the physical demands of rugby union referees across different variants of the game and at different playing levels to inform physical aspects of referee preparation.

2. Why have I been selected to take part?

You have been selected to take part in this study because have been involved in refereeing matches in one or more of the following competition: Level 1 to 7 in English rugby union, Rugby Europe, World Rugby Tournament, South Africa WP Super League A and/or Koshuis Rugby Championship (university's internal champions)1st, 2nd, 3rd and 4th League.

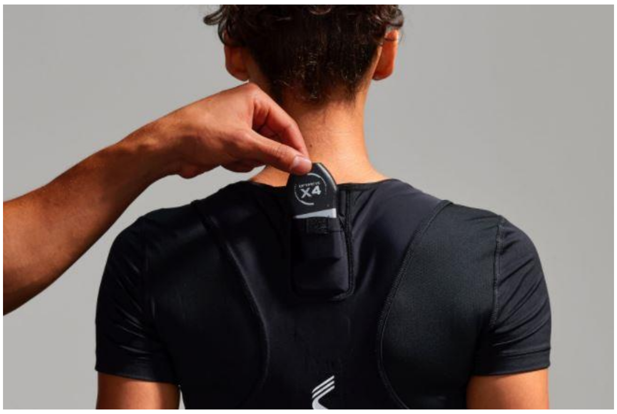
3. Do I have to take part?

It is completely up to you to decide if you would like to participate. Before you decide to take part we will describe the project and go through this information sheet with you. If you agree to take part, we will ask you to sign a consent form. However, if at any time you decide you no longer wish to participate you are free to withdraw, without giving a reason.

4. What will I have to do?

In the first stage you will be asked to wear a Global Positioning System (GPS) unit and a heart rate monitor. The devices are going to be switch on five minutes before the game and immediately switched off at the end. This will not change any of you match routine preparation.

The GPS will be worn using an adjustable neoprene harness between the shoulder blades. A heart rate monitor chest strap will be worn around the upper rib cage.



In the second stage, you will be invited to perform four tests:

- A VO2Max lab based treadmill running test with incremental speed and inclination protocol until exhaustion;

- Yo-yo Level1 (field test): Repeated 20m shuttle running of increasing speed with an active 10 seconds rest between each shuttle until exhaustion;

- Bronco Test (field test): Participants are require to run to 20 m and back, then 40 m and back and 60 m and back. The aim of the test is to repeat five times without rest and record the time;

- 40m sprint test (field test): Fastest time in a 40m sprint from three attempts.

5. What are the exclusion criteria?

Referees who officiate below RFU level 7 will not be included.

6. What are the possible benefits of taking part?

A detailed result of the match analysis and the fitness tests will be given to you and therefore provide you with relevant information for your training programme and how your match running performance and heart rate responses compare with the average of other referees according to their level.

7. What are the possible disadvantages and risks of taking part?

There are no disadvantages to you taking part in the project.

8. Will my participation involve any discomfort or embarrassment?

All tests require you to exercise to your maximum capacity and therefore will cause breathlessness and you might feel some discomfort, such as nausea and dizziness. These effects will be temporary and subside as you recover.

8. Who will have access to the information that I provide?

Only the research team will have access to the information that you provide. All records will be treated as confidential. Summary information divided by level will be provided to your referee manager or fitness coach, but your individual data will be anonymized and therefore not identified.

9. What will happen to the data collected and results of the project?

You will not be able to be identified in any follow-up publications. Data will be stored on a secure database for which access will only be available to the researchers of this investigation. Data will be stored long-term for the potential use to compare with similar data from future seasons.

11. Who has reviewed the project?

This project has been given a favorable opinion by the University of Bath, Research Ethics Approval Committee for Health (REACH) [reference: EP 17/18 112].

12. How can I withdraw from the project?

If you wish to stop participating before completing all parts of the project, you can inform one of the above identified researchers in person, by email or telephone. You can withdraw from the project at any point without providing reasons for doing so and without consequence for yourself.

If, for any reason, you wish to withdraw your data please contact an identified researcher within two weeks of your participation. After this date, it may not be possible to withdraw you data as some results may have already been published. You individual results, however, will not be identifiable in any way in any presentation or publication.

13. What happens if there is a problem?

If you have a concern about any aspect of the project you should ask to speak to the researchers who will do their best to answer any questions. If they are unable to resolve your concern, or you wish to make a complaint regarding the project, please contact the Chair of the Research Ethics Approval Committee for Health

Dr. James Betts
Email: j.betts@bath.ac.uk
Tel: +44 (0) 1225 38 3448

14. If I require further information who should I contact and how?

Thank you for expressing an interest in participating in this project. Please do not hesitate to get in touch with us if you would like some more information.

Name of Researcher: Msc. Ricardo Tannhauser Sant'Anna

Contact details of Researcher:
e-mail:rtsa20@bath.ac.uk
Telephone: 01225 385430
Mobile: [redacted]

Name of Supervisor: Prof Keith Stokes

Contact details of Supervisor:

e-mail: spsks@bath.ac.uk

Telephone: 01225 384190

Second Supervisor: Dr Simon Roberts

e-mail: s.p.roberts@bath.ac.uk

Telephone: 01225 384531

Consent FORM

The Physiological Demands of Refereeing Rugby Union

Researcher:

Name: Msc. Ricardo Tannhauser Sant'Anna

e-mail:rtsa20@bath.ac.uk

Telephone: 01225 385430

Mobile: [redacted]

Supervisors:

Name: Prof Keith Stokes

e-mail: spsks@bath.ac.uk

Telephone: 01225 384190

Name: Dr Simon Roberts

e-mail: s.p.roberts@bath.ac.uk

Telephone: 01225 384531

Third Supervisor: Dr Lee Moore

e-mail: l.j.moore@bath.ac.uk

Telephone: 01225 384205

Please initial box if you agree with the statement

1. I have been provided with information explaining what participation in this project involves. ☐

2. I have had an opportunity to ask questions and discuss this project. ☐

3. I have received satisfactory answers to all questions I have asked. ☐

4. I have received enough information about the project to make a decision about my participation. ☐

5. I understand that I am free to withdraw my consent to participate in the project at any time without having to give a reason for withdrawing. ☐

6. I understand that I am free to withdraw my data within two weeks of my participation. ☐

7. I understand the nature and purpose of the procedures involved in this project. These have been communicated to me on the information sheet accompanying this form. ☐

8. I understand and acknowledge that the investigation is designed to promote scientific knowledge and that the University of Bath will use the data I provide only for the purpose(s) set out in the information sheet. ☐

9. I understand the data I provide will be treated as confidential, and that on completion of the project my name or other identifying information will not be disclosed in any presentation or publication of the research. ☐

10. I understand that my consent to use the data I provide is conditional upon the University complying with its duties and obligations under the Data Protection Act.

11. I hereby fully and freely consent to my participation in this project. ☐

Participant's signature: ______________________ Date: ______________

Participant name in BLOCK Letters: ______________________

Researcher's signature: ______________________ Date: ______________

Researcher name in BLOCK Letters: ______________________

If you have any concerns or complaints related to your participation in this project please direct them to the Chair of the Research Ethics Approval Committee for Health, Dr James Betts (j.betts@bath.ac.uk, 01225 383448)

APENDIX C

Slide used during the RFU Advanced Match Official Award strength & conditioning module.