

# **Submaximal running testing to monitor training responses in elite Australian rules football players**

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This thesis is submitted in accordance with the requirements of The Graduate Research Office, Australian Catholic University for the degree of Doctor of Philosophy by Kristopher Veugelers.

## **Declaration**

This thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No parts of this thesis have been submitted towards the award of any other degree or diploma in any other tertiary institution. No other person's work has been used without due acknowledgment in the main text of the thesis. All research procedures reported in the thesis received the approval of the relevant Ethics/Safety Committees (where required).

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Date: 21/12/17

## Published Works by the Author Incorporated into the Traditional Thesis

The following is a description of the contribution of the main and co-authors for the published manuscript incorporated into the traditional thesis. Evidence of the publication is illustrated in Appendix 1.

- 1) Veugelers KR, Naughton GA, Duncan CS, Burgess DJ, Graham SR. Validity and Reliability of a Submaximal Intermittent Running Test in Elite Australian Football Players. *J Strength Cond Res.* 2016;30(12):3347-53

<b>Author</b>	<b>Roles</b>	<b>Contribution</b>
Kristopher Veugelers	Conceived and designed experiments Analysed data Preparation of initial draft manuscript	65%
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I hereby declare that my contribution to the published manuscript, as outlined above, to be accurate and true.

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## **Abstract (Traditional Thesis Format)**

Monitoring training load and training responses in professional football continues to inform athlete management, injury prevention and player welfare. Maximising fitness and minimizing fatigue are finely balanced and differ within phases of the periodised year. It is possible that submaximal exercise tests are more useful than maximal exercise testing to regularly monitor individual training responses in a team environment.

The overarching aim of this thesis was to demonstrate the effectiveness of using heart rate measured during a novel submaximal intermittent running test to monitor training responses throughout a season in elite Australian rules football players. The thesis comprised systematic and narrative reviews of the literature, focussing on advances in athlete monitoring within professional football codes. Findings informed the next three studies of original research.

This sequence commenced with the establishment of the concurrent validity and day-to-day reliability of a submaximal intermittent running test. Concurrent validity was supported by large inverse correlations reported between two, three, and four minute HRex during the SIR test and YYIR2 test performance ( $r = -.58 - -.61, P < 0.01$ ). Submaximal intermittent running test HRR<sub>120s</sub> and HRR<sub>180s</sub> were also moderately correlated to YYIR2 test total distances ( $r = .32 - .35, P < 0.05$ ). Day-to-day reliability was supported by strong correlations for ICCs among all HRex and HRR measures ( $r = .90 - 0.97$ ) (1). CV ranged between 1.3% and 9.2% for all variables.

The second study determined the influence of external and internal training load measures on heart rate responses to the submaximal intermittent running test during a six-week pre-season period. First, results of the log-linear modelling suggested that a 1% increase in weekly Z4

running distance decreased  $HR_{ex}$  by 0.02% [-0.04, -0.01]. Second, each 1% increase in weekly Z6 running distance was associated with a 0.01% [0.00, 0.02] increase  $HRR_{60s}$ . Third, a 1% change in weekly Z5 running was associated with a 0.03% [0.01, 0.04] increase in  $HRR_{180s}$ . Playing position was deemed to have no significant influence on the relationship between SIR test HR responses and measures of TL.

The final study extended the investigations into associations between submaximal heart rate responses and in-season training loads as well as match exercise intensity during competition, relative to playing position. First, no external or internal TL parameters were significantly related to SIR test  $HR_{ex}$  or  $HRR_{60s}$  in midfielders from training. However, from matches there was a very likely, strong, negative correlation between  $HR_{ex}$  and Z5 distance ( $r = -0.58$ , 90% CL: [-0.83, -0.13], MBI: 0%/2%/98%) and a likely, weak, negative relationship ( $r = -0.28$ , 90% CL: [-0.67, 0.24], MBI: 7%/17%/76%) between  $HR_{ex}$  and total distance in midfielders. Second, no significant correlation was observed between any external or internal TL parameter from training and SIR test HR responses in hybrids. Third, weekly cumulative Z4 distance from training showed a significant and almost certain, very strong, negative relationship ( $r = -0.83$ , 90% CL: [-0.94, -0.57], MBI: 0%/0%/100%) with  $HR_{ex}$  in key position players. Additionally a significant, very likely, strong, negative correlation existed between  $HR_{ex}$  and cumulative weekly Z6 distance ( $r = -0.59$ , 90% CL: [-0.83, -0.15], MBI: 0%/1%/96%) and cumulative weekly total distance ( $r = -0.52$ , 90% CL: [-0.80, -0.05], MBI: 1%/3%/96%), respectively.

The findings from this field-based prospective program of research have the capacity to advance the understanding of the effectiveness of submaximal exercise testing in team sport environments. Specifically, this thesis supports the use of a modified submaximal intermittent running test to estimate Yo-Yo intermittent recovery 2 test performance and provide useful

information about the training dose-response relationship in elite ARF players throughout a periodised training year. Importantly, playing position emerged as influential on the relationship between training load and submaximal test heart rate responses during the *in-season* but not during the *pre-season*.



## Table of contents

Declaration .....	ii
Published Works by the Author Incorporated into the Traditional Thesis .....	iii
Acknowledgements .....	v
Abstract (Traditional Thesis Format).....	vi
Table of contents .....	ix
List of tables.....	xvi
List of figures .....	xviii
List of definitions .....	xxii
Chapter One: Introduction .....	1
Chapter Link: Summary of introduction.....	4
Chapter Two: Narrative literature review .....	5
2.1 Overview of the exercise dose-response relationship .....	5
2.1.1 Introduction .....	5
2.1.2 Evolution of the exercise dose-response relationship.....	6
2.1.3 Exercise dose-response relationship section summary.....	11
2.2 Quantifying and monitoring training load in team sports .....	11
2.2.1 Introduction .....	11
2.2.2 Quantifying external training load using micro-technology.....	14
2.2.2.1 External load monitoring using GPS technology .....	15
2.2.2.2 External load monitoring using accelerometers within GPS devices.....	17
2.2.2.3 External quantification of training load section summary.....	18
2.2.3 Quantifying internal training load .....	19

2.2.3.1 Monitoring exercise intensity with heart rate .....	19
2.2.3.2 Monitoring internal training load with heart rate .....	21
2.2.3.3 Monitoring exercise intensity with rating of perceived exertion.....	22
2.2.3.4 Monitoring internal training load with session rating of perceived exertion .....	23
2.2.3.5 Monitoring internal training load section summary .....	25
2.3 Monitoring fatigue and maladaptive responses to training .....	26
2.3.1 Overview of fatigue as a response to training .....	26
2.3.2 Fatigue accumulation: the overtraining process .....	29
2.3.3 Sports-specific markers of fatigue and overtraining.....	36
2.3.3.1 Heart rate to assess autonomic nervous system fatigue.....	37
2.3.3.2 Subjective ratings of fatigue and wellbeing .....	40
2.3.3.3 Counter movement jump testing to assess neuromuscular fatigue.....	42
2.3.3.4 Blood and saliva markers .....	43
2.3.3.5 Monitoring fatigue and maladaptive responses section summary.....	44
2.4 Summary and implications from literature review.....	45
2.5 Research direction.....	46
2.5.1 Aims.....	46
2.5.2 Hypotheses.....	47
2.5.3 Scope of the thesis .....	49
2.5.4 Beyond the scope of the thesis .....	49
Chapter Link: Summary of narrative literature review .....	51
Chapter Three: Athlete monitoring strategies in elite football: Are they indicative of fatigue? A systematic review.....	52
3.1 Introduction .....	52
3.2 Methods.....	55

3.2.1 Literature search .....	55
3.2.2 Selection criteria .....	55
3.2.3 Study selection.....	58
3.3 Results.....	59
3.3.1 Monitoring overview .....	66
3.3.2 Quality assessment .....	67
3.4 Discussion .....	67
3.4.1 Prevalence of time-based measures to quantify external load.....	68
3.4.2 Opportunity to expand investigations into relationships between external training load and fatigue .....	70
3.4.3 Associations between internal TL and fatigue responses .....	73
3.4.4 Limitations of load and fatigue monitoring.....	75
3.4.5 Practical considerations .....	79
3.4.6 Directions for future research.....	80
3.5. Conclusion.....	81
Chapter Link: Summary of systematic literature review study .....	82
Chapter Four: Methodology.....	83
4.1 Research design.....	83
4.1.1 Participants in studies 2 - 4.....	84
4.1.2 Inclusion criteria .....	84
4.1.3 Exclusion criteria.....	85
4.2 Generic measurements applicable to studies 2-4. ....	85
4.2.1 Description of Yo-Yo intermittent recovery level 2 test .....	86
4.2.2 Description of submaximal intermittent running (SIR) test .....	87
4.2.3 Measuring heart rate responses and from the SIR test .....	89

4.2.4 Submaximal exercise heart rate (HR <sub>ex</sub> ).....	90
4.2.5 Heart rate recovery (HRR) .....	91
4.2.6 Quantification of internal load using session rating of perceived exertion .....	94
4.2.7 Quantification of external load using global positioning system technology .....	96
4.2.8 Subjective wellness questionnaire .....	97
4.2.9 Summary of statistical analyses.....	99
Chapter Link: Summary of methodology .....	101
Chapter Five: Validity and reliability of a submaximal intermittent running test in elite Australian football players.....	
5.1 Introduction .....	102
5.2 Methods.....	105
5.2.1 Participants .....	105
5.2.2 Study design .....	105
5.2.2.1 Yo-Yo intermittent recovery 2 test.....	107
5.2.2.2 Submaximal intermittent running test .....	107
5.2.2.3 Measuring heart rate responses to exercise .....	108
5.2.3 Statistical analyses .....	108
5.2.3.1 Concurrent validity .....	108
5.2.3.2 Reliability .....	109
5.3 Results .....	109
5.3.1 Concurrent validity.....	109
5.3.2 Reliability .....	114
5.4 Discussion .....	116
5.5 Conclusions and practical applications .....	119
Chapter Link: Summary of validity and reliability study .....	120

Chapter Six: Associations between submaximal intermittent running (SIR) test heart rate responses and training load during an elite ARF pre-season .....	121
6.1 Introduction .....	121
6.2 Methods .....	125
6.2.1 Participants .....	125
6.2.2 Study design .....	125
6.2.3 Training load quantification .....	127
6.2.4 Subjective responses to training .....	127
6.2.5 Submaximal intermittent running test .....	128
6.2.6 Measuring heart rate response and rating of perceived exertion to the SIR test .....	128
6.2.7 Categorising players into positional groups .....	129
6.2.8 Statistical analyses .....	130
6.3 Results .....	131
6.3.1 HR <sub>ex</sub> .....	136
6.3.2 HRR <sub>60s</sub> .....	136
6.3.3 HRR <sub>120s</sub> .....	137
6.3.4 HRR <sub>180s</sub> .....	137
6.4 Discussion .....	139
6.5 Conclusions and practical applications .....	147
Chapter Link: Summary of pre-season study.....	148
Chapter Seven: Associations between SIR test HR responses, in-season TL and match exercise intensity in elite ARF players .....	149
7.1 Introduction .....	149
7.2 Method .....	153
7.2.1 Participants .....	153
7.2.3 Study Design.....	153

7.2.3 Training load quantification .....	156
7.2.4 Submaximal intermittent running test .....	157
7.2.5 Measuring heart rate response and rating of perceived exertion to the SIR test .....	157
7.2.6 Positional classifications.....	157
7.2.7 Statistical analyses .....	158
7.3 Results.....	160
7.3.1 Midfielders.....	162
7.3.2 Hybrids .....	163
7.3.3 Key Position Players.....	164
Chapter Link: Summary of in-season study.....	177
Chapter Eight: Summary and Conclusions.....	178
8.1 Overview .....	178
8.2 Summary of major findings .....	179
8.3 Strengths.....	182
8.4 Limitations .....	184
8.5 Practical Applications .....	187
References.....	191
Appendix 1 – Evidence of publication.....	215
Appendix 2 – PEDro marking criteria for articles included in systematic review .....	217
Appendix 3 – Ethics approval, information letters and consent forms.....	223
a) Ethics approval.....	223
b) Permission letter for release of player data from Port Adelaide Football Club.....	227
c) Participant information letter .....	228
d) Consent forms .....	231
Appendix 4 – Subjective wellness questionnaire.....	233



## **List of tables**

Table 2.1 Common methods used to quantify and monitor training load

Table 2.2 Central and peripheral mechanisms of fatigue

Table 2.3 Common performance symptoms of fatigue

Table 2.4 Possible symptoms of the overtraining process

Table 2.5 Common hypotheses of the overtraining process

Table 3.1 Explanation of exclusion criteria for systematic review

Table 3.2 Summary of articles included for systematic review

Table 4.1 Variables common to most results chapters

Table 4.2 Foster's modified RPE Scale.

Table 4.3 Scope of statistical analyses within results chapters.

Table 5.1 Typical pre-season training schedule including testing protocol for validity

Table 5.2 Descriptive statistics for validity testing

Table 5.3. Pearson's correlations between heart rate response and YYIR2 test distance

Table 5.4 Descriptive statistics for reliability of SIR test

Table 5.5 Inferential statistics for reliability of SIR test

Table 6.1 Typical pre-season training schedule for Chapter 6 investigations.



Table 6.2 Relationship between HR responses from SIR testing and external training load measures

Table 7.1 Typical in-season training schedule for Chapter 7 investigations

Table 7.2 Positional Group Classifications

Table 7.3 Descriptive statistics for in-season SIR testing

Table 7.4 Descriptive statistics for cumulative weekly in-season training load

Table 7.5 Descriptive statistics for physical match output

## **List of figures**

Figure 2.1 Fitness-fatigue theory

Figure 2.2 Positive adaptation (super-compensation) to training

Figure 2.3. Possible outcomes resulting from the process of intensified training

Figure 3.1 Flow chart illustrating the study selection process for systematic review

Figure 4.1 Outline of studies

Figure 4.2 Comparison of protocols for intermittent running tests.

Figure 4.3 Example heart rate trace from SIR testing, including measurement time points of selected heart rate indices.

Figure 5.1 Relationship between 4 min HR<sub>ex</sub> during the SIR and YYIR2 tests and YYIR2 test performance.

Figure 6.1 Mean HR<sub>ex</sub> from SIR testing throughout the six week pre-season training period.

Figure 6.2 Mean HRR at different time points from SIR testing throughout the six week pre-season training period.

Figure 6.3 Mean weekly running distance across different velocity zones throughout the six week pre-season training period.

Figure 7.1 Pearson correlation coefficient value (y axes) for the relationship between select measures of in-season TL (x axes) and SIR test HR responses by playing position.

Figure 7.2 Pearson correlation coefficient value (y axes) for the relationship between select measures of match running output (x axes) and SIR test HR responses by playing position.

## List of abbreviations

<b>ARF</b>	Australian rules football
<b>AFL</b>	Australian Football League
<b>GPS</b>	Global positioning system
<b>HR</b>	Heart rate
<b>HR<sub>ex</sub></b>	Exercise heart rate
<b>HRR</b>	Heart rate recovery
<b>HRR<sub>60s</sub></b>	Heart rate recovery after 60 seconds
<b>HRR<sub>120s</sub></b>	Heart rate recovery after 120 seconds
<b>HRR<sub>180s</sub></b>	Heart rate recovery after 180 seconds
<b>HRV</b>	Heart rate variability
<b>HR<sub>max</sub></b>	Maximal heart rate
<b>RPE</b>	Rating of perceived exertion
<b>sRPE</b>	Session rating of perceived exertion
<b>SIR Test</b>	Submaximal intermittent recovery test
<b>TL</b>	Training load
<b>TRIMP</b>	Training impulse
<b>CMJ</b>	Countermovement jump
<b>PEDro</b>	Physiotherapy evidence database
<b>cm</b>	Centremetres
<b>m</b>	Metres
<b>km</b>	Kilometres
<b>km h<sup>-1</sup></b>	Kilometres per hour
<b>min</b>	Minutes
<b>m min<sup>-1</sup></b>	Meters per minute
<b>kg</b>	Kilograms
<b>°C</b>	Degrees celsius
<b>GAS</b>	General adaptation syndrome
<b>YYIR1</b>	Yo-Yo intermittent recovery I test

<b>YYIR2</b>	Yo-Yo intermittent recovery II test
<b>Z4</b>	Zone 4 running zone velocity
<b>Z5</b>	Zone 5 running zone velocity
<b>Z6</b>	Zone 6 running zone velocity
<b>Total HSR</b>	Total high speed running
<b>r</b>	Pearson correlation coefficient
<b>R<sup>2</sup></b>	Coefficient of determination
<b>SD</b>	Standard deviation
<b>ICC</b>	Intra-class correlation coefficient
<b>CV</b>	Coefficient of variation
<b>TE</b>	Typical error of measurement
<b>SWC</b>	Smallest worthwhile change
<b>AIC</b>	Akaike information criteria
<b>CL</b>	Confidence limits
<b>ANCOVA</b>	Analysis of covariance
<b>VIF</b>	Variance inflation factor
<b>MBI</b>	Magnitude based inferences

## List of definitions

**Periodisation:** Concept of organising the annual plan of training to: 1) allow for smaller and more manageable training phases, and 2) manipulate various training methods to optimise sports-specific movement qualities (2).

**Macrocycle:** Longest phase of the periodised training plan, generally spanning the entire length of the season and comprised of a number of mesocycles.

**Mesocycle:** Medium-term training phase, generally between several weeks to months in length and comprised of a number of microcycles.

**Microcycle:** Shortest periodised training phase, usually lasting from few days up to a week in duration.

**Training frequency:** Frequency of training, usually represented in number of sessions per day or week.

**Training intensity:** Intensity of training calculated via both internal (e.g. rating of perceived exertion) and external (e.g. running distance and velocity) measures.

**Training volume:** Volume of training, usually represented in total duration of training in minutes per day or week.

**Training load (TL):** The product of training frequency, intensity, and volume calculated via both internal and external measures.

**Internal training load:** The physiological stress imposed on the body during physical activity that is responsible for training induced adaptations (3). Most commonly measured using rating of perceived exertion or heart rate.

**External training load:** The amount of physical work completed during exercise (4). Most commonly measured using GPS and accelerometer devices that calculate key movement characteristics such as distance, speed, and impacts.

**Rating of perceived exertion (RPE):** Subjective rating of perceived exertion for a bout of physical work based on Foster's modified RPE scale. This RPE value is used as an estimate of training intensity (5).

**Session rating of perceived exertion (sRPE):** Product of an individual's RPE and the duration of a training session in minutes. The resultant value represents a single internal training load score in arbitrary units.

**Heart rate:** number of heart beats per unit of time; usually measured per minute.

**Exercise heart rate:** heart rate measured during exercise; generally calculated as the average heart rate over a 30 second period and expressed as a percentage of maximal heart rate (6).

**Heart rate recovery:** the rate at which heart rate declines post-exercise; most commonly measured over a timeframe of between one to three minutes post-exercise (7).

**Global positioning system (GPS) device:** Portable time-motion analysis device sampling at 15 Hz that is worn by each athlete for all outdoor training sessions. The GPS device is positioned between the scapula on the upper back and housed within a custom-designed pouch inside the athletes's jersey. The objective quantification of sport-specific movement patterns including duration, speed, and distance is calculated using satellite-based navigation technology (8).

**Accelerometer:** Device contained within the GPS unit sampling at 100 Hz that has the ability to measure the frequency and magnitude of movement within all three axes, thus offering the potential to quantify skill and contact-based movement demands (9).

**Yoyo intermittent recovery II (YYIR2) test:** Intermittent shuttle run test used to assess an individual's ability to perform intense intermittent exercise requiring large contributions from both the aerobic and anaerobic energy systems (10). Considered the gold standard test for intermittent running capacity and is often used as a physiological performance measure in intermittent team sports (10, 11).

**Submaximal intermittent running (SIR) test:** A modified submaximal version of the YYIR2 test designed to provide an alternative, non-fatiguing method to estimate intermittent running capacity using submaximal heart rate responses (12).

**Fitness:** Positive adaptation to training over a chronic period of time, characterised by improvements in physiological attributes such as endurance, strength, speed and power (13).

**Fatigue:** A state of weariness preceded by a period of physical and/or mental exertion resulting in a diminished performance capacity (14). May be indicative of negative adaptation to training over acute and/or chronic timeframes (13)



## Chapter One: Introduction

Australian Rules Football (ARF) is a contact invasion game that enforces a variety of technical, tactical, and physiological demands on players (15). The sport is distinguished by unique skills involving an oval-shaped ball that may be passed by either hand or foot (16). The Australian Football League (AFL) consists of 18 clubs throughout the nation and represents the highest standard of professional competition. The governing body of the AFL enforces a variety of equalisation measures in an effort to promote an “even playing field” for all teams. Such measures include restrictions on total salary expenditure across player payments, football department staff wages and resources. Subsequently, clubs are under immense pressure to develop a football program within this framework that provides the best chance of success in a highly competitive environment.

High performance staff are important members of the football department structure in every AFL club. In particular, clubs are investing more heavily in the rapidly developing area of sports science to help improve overall team performance. Through advancements in technology and sports science expertise, quantification of ARF training and game demands at the elite level has evolved. For example, analyses of global positioning system (GPS) data over several AFL seasons show a general trend of increasing physical workload (17). Specifically, elite players are reported to cover total distances of approximately 12 km throughout a match, with approximately 20% of total match time spent running at speeds faster than  $14 \text{ km h}^{-1}$  (17). However, the fitness and fatigue responses from both game demands and training load (TL) are inconsistently-reported and under-researched component of elite ARF performance. Greater understanding of

these responses may enable fitness staff to more appropriately develop the physiological attributes in players necessary to promote improved performance and ultimately team success.

The implementation of a periodised training program is crucial for effectively preparing team sport athletes for the physiological demands of competition. In particular, the pre-season period is considered as one of the most vital training phases. Pre-season training provides players with a specific training overload that develops the fitness and fatigue resistance required to meet in-season demands (18). Whereas in-season TL is often managed to minimise fatigue for impending match play, the pre-season represents a timeframe in which improvements in conditioning can be the sole focus of training (19). Intensive pre-season training camps are often scheduled in elite ARF to accelerate the physiological adaptations of players. Players who complete the majority of pre-season training in running based-team sports are less likely to be injured in-season (20). Therefore, optimizing training prescription during the pre-season is crucial for athlete health and team success. In comparison, periodisation of in-season TL can be heavily influenced by match workload and the amount of time between matches. Subsequently, the focus of training shifts towards recovery and readiness for upcoming competition (21).

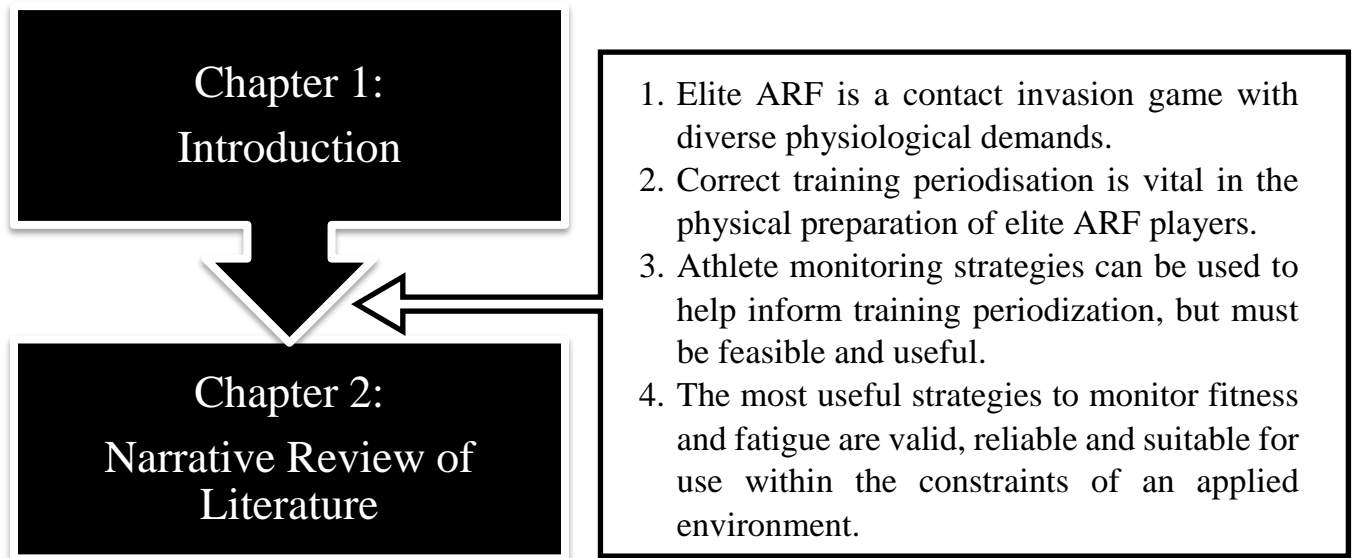
Independent of the phase of the periodised year, the ongoing challenge for sports scientists is to manage a delicate balance between TL and recovery. Theoretically, this balance promotes the physiological adaptations that enhance performance and minimise fatigue (22). Excessive TL and/or, inadequate recovery may increase residual fatigue and the likelihood of injury, whereas insufficient TL will not develop positive physiological changes (23). Effective training

prescription is further complicated in team sports in which individuals are likely to respond differently to the same training load (24). Consequently, the individualised monitoring of training responses becomes vital in assessing states of fitness and fatigue in athletes. This is particularly pertinent in the pre-season during which TL's are at their highest (21). However, the significance of individualised monitoring is not lost during the in-season as the likely decline in fitness throughout the competitive phase can make differentiating between increased fatigue and reduced fitness more problematic (25).

A wide range of athlete monitoring strategies exist with the potential to identify individuals (and perhaps teams) at risk of a negative consequence of training (26). However, there is a lack of consensus on which athlete monitoring strategies are most capable of detecting states of fitness and fatigue in elite ARF and across other team sports. An understanding of the validity, reliability and quality of available strategies is often hindered in field-based research settings, specifically sporting clubs, due to constraints such as cost, time, facilities, staff resources, relevant expertise, and player compliance. Ultimately, there is a necessity to develop a valid and reliable tool to quantify fitness and fatigue applicable within the environmental constraints encountered in elite team sports such as ARF.

This thesis presents a program of research that commenced with critical enquiry of the literature around athlete monitoring, TL and training responses. Gaps in physiological monitoring relevant to field-based settings were subsequently identified. The concurrent validity and day-to-day reliability of a novel submaximal running test were reported and the effectiveness of the test as a physiological monitoring tool was explored across two distinct phases of the periodised year.

## Chapter Link: Summary of introduction



## **Chapter Two: Narrative literature review**

The search for an advantage in the highly competitive world of professional team sport is linked to an increasingly scientific approach to the periodisation, quantification, and monitoring of the exercise-dose relationship. Accurately monitoring TL and individual responses among team sport athletes has the potential to minimize the risk of negative training consequences; thus enhancing playing availability and improving the likelihood of team success. Currently, no single definitive marker exists to accurately identify an athlete's training status. Subsequently, multiple monitoring strategies are reported in the literature and used in applied settings; each with their advantages and disadvantages. The issue of whether monitoring strategies used in applied settings are well-informed remains debatable. A greater understanding of the scientific background of current athlete monitoring strategies will aid practitioners in optimizing the performance of their athletes. This review of literature aims to discuss the evolution of the exercise-dose response relationship and how this applies to the most commonly used athlete monitoring strategies. Chapter 3 expands on this knowledge with a systematic review that provides a more rigorous discussion on how these strategies are implemented in elite football.

### **2.1 Overview of the exercise dose-response relationship**

#### **2.1.1 Introduction**

Several conceptual models have traditionally explained the dose-response relationship of exercise; forming the foundation on which training periodisation is built (2). Refinements to the

models over the years have more accurately reflected the physiological responses of athletes to training stressors and consequently inform training prescription. Investigations of the exercise dose-response relationship in elite team sport have increased substantially in recent years; possibly aligned to the professionalization of sport as a science. Increased interest has resulted in a growing expertise among researchers; concomitantly with technological advances within the domain of sports science. In light of the increasing interest, a review the evolution of fitness-fatigue theory was considered relevant. Links between historical perspectives and contemporary issues of training periodisation were explored to broaden insight into monitoring athletes for optimal performance in elite team sport.

### **2.1.2 Evolution of the exercise dose-response relationship**

The general adaptation syndrome (GAS) was the original model that inspired the concept of training periodisation (13). Proposed by Selye (27) in 1950, the GAS stated that non-specific stressors cause an interrelated adaptive response in an individual. Adaptive responses occur in three different stages: alarm, resistance, and exhaustion. The alarm stage is characterized by the *initial negative response* of individuals to increased stress. An example of the stimulus for an initial negative response would be an increased training dose (or training load [TL], as commonly referred to in contemporary literature). Following the alarm stage, the individual undertakes a stage of resistance during which a positive adaptation to the imposed stress occurs to the point of *homeostatic restoration*. With sufficient recovery from this stress, it is possible that positive adaptation in the resistance stage could result in homeostasis being superseded; often referred to as “super-compensation” (13). However, if the imposed stress continues to exceed the adaptive abilities of the individual, or if inadequate recovery from the stress is not

achieved, a more *systemic negative state* ensues; constituting the exhaustion stage. This negative state may also be termed “overtraining” when referring to prolonged exposure to excessive TL in combination with insufficient recovery.

Although the GAS model provides a basis for understanding physiological responses of athletes to training, this model is limited by the assumption that all stressors result in a similar unified response (13). Banister (28) introduced the fitness-fatigue model in 1982 to advance the understanding of the exercise dose-response relationship to performance. This model better accommodated observations that different training stressors potentially elicited diverse physiological responses. According to the fitness-fatigue model, training stress results in two contrasting effects; fitness and fatigue (Figure 2.1). Fitness is the positive outcome; low in magnitude and long in duration. In comparison, fatigue is the negative outcome; high in magnitude and short in duration. After an imposed TL, fatigue initially outweighs fitness, which predictively results in an acute negative state. However, fatigue dissipates faster than the fitness over time, ultimately inducing super-compensation.

Despite some similarity between the GAS and fitness-fatigue models, the major point of difference lies in the complexity of the dose-response relationship between theories. While the GAS model suggests the response to exercise is dependent solely on the amount of total exercise dose, the fitness-fatigue model states that both the intensity and duration of exercise will affect the response. This appears consistent with more contemporary training research in that multiple aspects of TL are likely responsible for exercise-induced adaptations (13). Nonetheless,

advancements in knowledge achieved through the introduction of the fitness-fatigue model have been challenged in recent critical appraisal of the model; suggesting that aspects of the original theory may be limited.

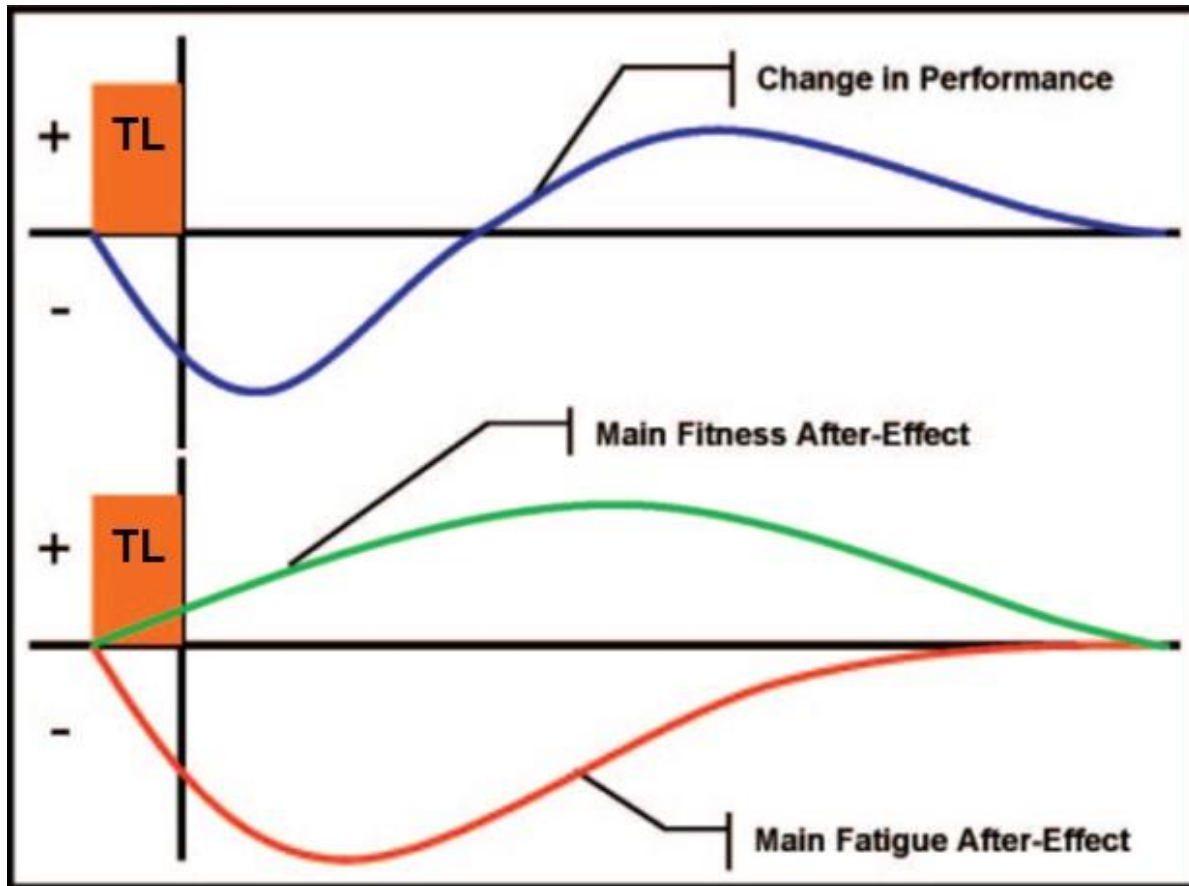


Figure 2.1 Fitness-fatigue theory (reproduced from Chiu and Barnes (13))

TL, training load; + , positive effect; - , negative effect



For example, the original fitness-fatigue model suggested that responses to a single TL occurred independent of the accumulated fatigue from past training (29). Furthermore, the existence of only one fitness after-effect and one fatigue after-effect may be misleading (13). It is argued that different training modalities may contribute to multiple fitness and fatigue responses; occurring independently of each other yet can also result in an accumulative impact (13, 29). As such, an individual's response to exercise can be quite complex.

Mathematical modelling has emerged as a potential tool for ameliorating some of these complexities and improving the predictability of responses to TL. For example, mathematical modelling the fitness and fatigue after-effects has been fitted to predictions of optimal performance of elite weight lifters (30), swimmers (29, 31), and gymnasts (32) with varying levels of success. In an effort to overcome the limitation of using single training sessions for analyses, more recent modelling takes into account the cumulative effect of TL to achieve a better fit between modelled and actual data (33). However, limitations with modelling the exercise-dose response relationship still remain, particularly within team sports where multiple factors are likely to contribute to successful performance.

Mathematical models of fitness-fatigue after-effects require regular markers of sports-related performance to ensure robustness. Traditionally, true performance markers are gained from testing requiring efforts representative of competition; often involving maximal exertion. Testing for fitness and fatigue typically involves high intensity efforts that are likely to disrupt the training program of athletes, impair recovery and add to the accumulation of fatigue.

Furthermore, practitioners within applied environments may lack the mathematical expertise to correctly implement complex models.

Despite the potential limitations associated with applying the mathematical modelling of fitness and fatigue in applied training environments, advancements in understanding the exercise dose-response relationship generated by such models retain important implications for training prescription. Currently, a paradoxical association appears to exist between the body and physiological stress, in which stress can cause both positive and negative adaptations (34). Specifically, an inverted U-shape can be used to describe the relationship between TL and the fitness-fatigue after-effects that contribute to performance (33). This implies the presence of a threshold representing the “optimal” TL to improve performance. Subsequently, decrements in performance are more likely to result from prescribed TL outside this optimal range, either due to poor fitness (low TL) or excessive fatigue accumulation (high TL).

As implied earlier in this chapter, periodisation provides a practical framework for the manipulation of fitness and fatigue after-effects via the planned variation of TL. The two main aspects of training periodisation are: 1) the division of the training plan into smaller and more manageable phases, and 2) the variation of training methods in a manner that best develops a diverse range of sport-specific bio-motor abilities (2). Ultimately, the objective of periodisation is to strategically manage the fitness and fatigue after-effects of training in an effort to promote positive physiological adaptations and avoid the potential negative consequences associated with long periods of training-induced stress (19).

The practical application of fitness-fatigue theory within the concept of periodisation remains a challenge, particularly in elite team sports in which several factors are likely to influence effective training prescription. Team sport challenges to periodisation of training include: the prolonged competitive season, variability and individuality of training goals, the time constraints of developing both physical and tactical attributes, and the impact of physiological and psychological stress from matches (19). These complications place even greater pressure on sports scientists within elite sporting teams tasked with the responsibility of prescribing TL's that allow athletes to "peak" for performance on a regular basis.

### **2.1.3 Exercise dose-response relationship section summary**

The evolution of knowledge surrounding the exercise-dose response relationship continues (35, 36). Ultimately, it appears that optimal physical performance is more likely during periods of maximal fitness and minimal fatigue (13, 28). Thus, the appropriate periodisation, quantification and monitoring of both TL and training responses are vital for managing physiological adaptations to improve performance and reduce the risk of negative consequences.

## **2.2 Quantifying and monitoring training load in team sports**

### **2.2.1 Introduction**

The ultimate objective in the physical preparation of elite athletes is to prescribe TL's conducive to increased and sustained performance (26). Historically, coaches have combined experience and intuition to prescribe TL in athletic populations. However, a number of strategies to assist in

managing TL have been identified, particularly in team sport environments. The greatest challenge lies in understanding how sufficient TL can be balanced with adequate recovery from fatigue to encourage physiological adaptations that enhance performance (37). To this end, diligent and individualised quantification and monitoring of TL is of paramount importance in high performance settings. Indeed, TL quantification forms the basis for the effective periodisation of training (38).

Quantification and monitoring of TL in team sport settings is confounded by the variance of individual responses to a standardized TL (24). As such, an individualized approach to TL is required (35). Individualized athlete monitoring may identify differences between the prescribed and actual dose of training completed. Ideally, this level of identification guides subsequent exercise prescription; optimising periodised exercise programs for positive physiological adaptations (4, 39).

Currently no universally accepted standard exists for monitoring TL in team sport athletes. Subsequently, a combination of strategies is often used (40). These strategies generally involve objective and subjective methods. The nature of objective and subjective TL methods can be categorized as either internal or external (Table 2.1). Internal TL is defined as the physiological stress imposed on the body during physical activity that is responsible for triggering training induced adaptations (3, 4). In contrast, external TL denotes the amount of external physical work completed during exercise (4). While external TL measures such as time or distance are often

simpler to describe, the quantification of internal TL may be deemed more important due to its direct association with the individualised physiological responses of the athletes (40).

Given that TL is a combination of the frequency, volume and intensity of exercise (2), singular measures of TL hold limited practical relevance. This is particularly pertinent in elite team sport environments in which multi-dimensional training demands cause difficulties with the accurate quantification of TL. Subsequently, a sport-specific battery of TL quantification and monitoring techniques is necessary to assist with the effective periodisation of training. As such, it is important to have a thorough understanding of rigour surrounding current strategies to better inform TL quantification and monitoring in applied settings.

Table 2.1 Common methods used to quantify and monitor training load (adapted from Soligard, Schwelnus (35))

<b>Load Category</b>	<b>Monitoring Example</b>
<i>External Load</i>	Training or match time
	Training or match frequency
	Global Positioning System (GPS) analysis (e.g. distance, speed, acceleration)
	Accelerometers (e.g. forces)
	Neuromuscular function (e.g. counter movement jump, plyometric push up)
	Count of repetitions
<i>Internal Load</i>	Rating of Perceived Exertion (RPE)
	Heart Rate Indices (HRex, HRR, HRV, TRIMP)
	Psychometric Questionnaires
	Biochemical, hormonal and immunological assessments

HRex, exercise heart rate; HRR, heart rate recovery; HRV, heart rate variability; TRIMP, training impulse score.

### **2.2.2 Quantifying external training load using micro-technology**

Recent developments in micro-technology such as global positioning system (GPS) devices with in-built accelerometers have become a popular means of quantifying external TL. A major

advantage of micro-technology is the capacity to provide objective and non-intrusive measures of multiple movement characteristics including but not limited to: distance covered, relative exercise intensity, maximal velocity, distance covered in specific speed zones, accelerations, decelerations, change of direction, and repeat high intensity efforts (8). The ability of micro-technology to derive multiple measures of speed, direction and intensity has resulted in widespread implementation in team sports with intentions of quantifying and monitoring external TL. The use of micro-technology has also extended to comparisons of both acute and chronic training and game demands across different sports, positions, and competition levels, as well as improving the specificity of training prescription.

#### **2.2.2.1 External load monitoring using GPS technology**

The rapid growth of commercially available and sport-specific GPS devices to quantify and monitor external TL is apparent in both research and applied sports science settings. Global position system technology uses satellite-based navigation systems to transfer positional signals between multiple satellites in orbit to receivers on earth; determining the location of the GPS device (41). Despite being limited to collecting data from outdoor training sessions, GPS devices are popular for several reasons: the amount of data collected simultaneously is only limited by the number of GPS devices available, live movement viewed using proprietary software enables real-time feedback, data processing and analyses are relatively automated, and governing bodies across a variety of sports now permit the use of GPS devices in competition.

The validity and reliability of GPS devices to quantify aspects of external TL remain equivocal and appear dependent on the sampling rate of the device and the sport-specific movement of focus. Currently, a variety of GPS devices is commercially available from which data collection can occur at sampling rates of 1, 5, 10, and 15 Hz. Higher sampling rates provide greater validity and reliability across a range of distance and speed metrics. For example, improved validity and reliability of 5 Hz compared with 1 Hz GPS devices were reported for straight line, change of direction, and custom designed team circuit running drills (42). Additionally, 10 Hz GPS devices were 2 to 3 times more valid and 6 times more reliable than the 5 Hz devices for measuring instantaneous velocity of acceleration, deceleration, and constant motion during straight line running (43). However, improvements in measurement accuracy remain unreported for comparisons between 10 and 15 Hz GPS devices (44). This finding may be explained by the fact that GPS devices with different sampling rates were provided by opposing manufacturers. Further investigation is warranted to determine the accuracy of newer 15 Hz GPS devices. Nevertheless, several considerations are required prior to practitioners choosing which GPS devices to use as a monitoring tool. Furthermore, inconsistencies of the validity and reliability between GPS devices highlight the difficulties in attempting to compare movement data collected using GPS devices from different manufacturers, with varying sampling rates.

The best available evidence validates some of the advantages of the latest 10 Hz GPS devices (45, 46). However, the ability of current GPS devices to accurately measure team sport movement demands remains questionable. Sport-specific factors reported to negatively influence the validity and reliability of GPS metrics in some team sports include faster running velocities (42, 47), shorter activity periods (42, 48, 49), and more frequent changes of direction (42, 50,



51). Additionally, inter-device variability (48, 52), proprietary software upgrades (53), time of day (49), number of available satellites (41), and signal obstructions (41) may also affect the accuracy of GPS technology. Therefore, despite widespread implementation, considerable progress is needed before GPS devices can be universally recognised as a valid and reliable tool to quantify external TL across the variety of movement demands associated with team sport competition. Currently, accurately monitoring change in some crucial sports-specific movement patterns using GPS technology remains acceptable rather than optimal.

#### **2.2.2.2 External load monitoring using accelerometers within GPS devices**

Advancements in micro-technology and the desire to circumvent the limitations associated with GPS have supported the introduction of accelerometers as a tool to quantify external TL.

Accelerometers have the ability to detect changes in the frequency and magnitude of movement within the anterior-posterior, medial-lateral and longitudinal axes (9). A modified vector magnitude can be calculated using the sum of the data from all three axes that has the potential to quantify the skill-based movements, collisions and other non-running related external TL demands typical of a specific team sport (9). Additionally, accelerometers now housed within GPS devices possess indoor capabilities and higher sampling rates than previous models of GPS devices (54); thus generating substantial interest from applied sports scientists working in high performance team sport; who need to monitor both indoor and outdoor TLs.

Due to the relatively recent introduction of accelerometers in high performance settings, the ability to accurately quantify external TL in team sport remains limited. Laboratory and field assessment of accelerometers in ARF has resulted in acceptable levels of within and between

device reliability, as well as the sensitivity to detect actual changes in activity intensity (9). Further research in elite and sub-elite ranks of competitions in ARF has found that accelerometers are able to detect differences in physical demands between training and matches, playing position and competition level (54). Additionally, accelerometers have been reported to discriminate between tackles of differing intensity in ARF (55). This level of ecological validity may imply that accelerometers may have the ability to assess impact forces in contact sports.

Despite the exciting potential of accelerometers to quantify complex movement demands that contribute to external TL, limitations still require cautious consideration prior to their implementation (56). While it is possible to quantify tackle events using accelerometers, the exact nature of the tackle and the point of impact on the player cannot yet be ascertained without analysing accelerometer data combined with video footage. This process is time and labour extensive and beyond the capacity of most practical settings even in professional team sports.

### **2.2.2.3 External quantification of training load section summary**

Advancements in technology and the constant pressure for professional sporting clubs to gain a competitive edge have led to the proliferation of performance data in elite team sports. The reliance on micro-technology such as GPS devices and accelerometers to quantify and monitor external TL is now commonplace in professional sporting clubs. Despite GPS devices providing great potential as a TL monitoring tool, practitioners must equally be aware of the associated limitations.

Systematic error remains even in the most recent GPS devices. Errors also appear dependent on the sport-specific movement demand being monitored. The recent integration of accelerometers with GPS may have enhanced the ability of micro-technology devices to quantify non-running related movement demands; subsequently providing a more comprehensive measure of external TL. However, the understanding of the optimal benefits of using accelerometers to quantify EL in team sport remains a work in progress. Therefore, the caution inherent from a strong understanding of the existing limitations is advised when using data derived from micro-technology to inform important decisions in applied settings.

### **2.2.3 Quantifying internal training load**

As previously stated, internal TL encompasses the magnitude of physiological stress placed on the body's systems during exercise and is considered the catalyst for training induced adaptations (3, 4). Therefore, effective quantification of internal TL is a vital component of athlete monitoring. This is particularly pertinent among team sports in which the prescribed external TL may be the same for each athlete but the internal TL may differ due to individual variations in fitness level, fatigue, injury, illness and psychological factors (57). Subsequently, an individualised approach to the monitoring of internal TL is necessary among team sport athletes. Typically, internal TL is monitored by combining the volume and frequency of training with measures of training intensity, such as heart rate (HR) and/or rating of perceived exertion (RPE).

#### **2.2.3.1 Monitoring exercise intensity with heart rate**

Before heart rate can be discussed as an internal TL monitoring strategy, it is salient to reiterate that TL has essentially three components: frequency, duration, and intensity. Heart rate can be an objective estimate of exercise intensity and has become highly accessible in field settings due to recent advancements in heart rate monitoring systems (6). Monitoring HR is particularly popular in endurance sports given the theoretical linear relationship between maximal oxygen uptake and HR during steady-state exercise across a range of submaximal intensities (58). Subsequently, HR can be used to estimate maximal oxygen uptake and thus provide an accurate estimate of exercise intensity under steady-state conditions (58). The availability of portable wireless HR devices has enabled easy implementation of HR monitoring within field settings in which real-time feedback can be used to monitor and adjust the intensity of exercise to ensure prescribed workloads are adhered to.

Despite the advantages associated with HR monitoring, a myriad of factors may influence HR response to exercise in field settings, impacting on the accuracy of measurement. Factors such as mode of exercise, training status, exercise duration, environmental conditions, time of day, hydration status, caffeine intake, and normal day-to-day variation may also effect the linear relationship between HR and exercise (59). The standardization of these conditions is necessary to improve the accuracy of monitoring HR. However, delivering standardized conditions for predominantly outdoor-based team sports remains difficult, if not impossible.

In addition to these practical limitations, the merit of using HR to measure exercise intensity in the absence of a steady-state workload is questioned by some studies (58, 60). This may be more pertinent in team sports often characterised by periods of high intensity intermittent exercise interspersed with low intensity activity and a variety of skill demands. Furthermore, HR is considered a less suitable estimate of the specific exercise stress associated with other forms of physical activity commonly prescribed for team sport athletes including resistance, interval, and plyometric training (57, 61). Subsequently, monitoring HR to measure exercise intensity has application across some but not all team sport activities.

#### **2.2.3.2 Monitoring internal training load with heart rate**

The combination of exercise HR (intensity) and exercise duration (volume) provides an objective means to quantify internal TL for a given training session (24). Several derivatives of HR load have been proposed in the literature, the most common of which are training impulse (TRIMP) (28) and the summated HR zones method proposed by Edwards (62). Training impulse is considered the most popular method of HR-derived TL; the equation for which is detailed by Banister et al. (28). Briefly, TRIMP is calculated by multiplying the duration of exercise in minutes by the average intensity determined from percent of HR reserve, presented in arbitrary units (28). The resultant score is considered an extremely convenient single measure of internal TL in endurance-based sports (63). However, the effectiveness of TRIMP relies on a steady-state HR response to exercise; limiting its useability during high intensity intermittent activity (24).

The summation of HR zones method was designed to improve quantification of HR-derived internal TL during the intermittent exercise demands of team sport. For example, this method divides the duration of exercise across five different training intensity zones (62). The amount of time spent in each zone is then multiplied by an arbitrary factor that weights higher intensity zones more heavily than lower intensity zones (24). The summated HR zone method is considered more appropriate than TRIMP for measuring HR-derived internal TL because it takes into account the distribution of exercise across different intensity levels rather than relying on average HR across the entire session (24). However, it should be noted that these internal TL quantification methods remain subject to limitations previously mentioned relating to the monitoring of HR across a variety of exercise modes, intensities and environmental challenges.

### **2.2.3.3 Monitoring exercise intensity with rating of perceived exertion**

Rating of perceived exertion can be used as a measure of exercise intensity to aid in the quantification of TL. Borg's RPE scale was developed to estimate the rating of perceived exertion for a bout of physical activity, in which perceived exertion refers to the degree of strain experienced according to a specific rating scale (64). Using RPE was recommended for estimating the intensity of exercise; acknowledging that perceived exertion and exercise intensity are considered closely related concepts (64). Indeed, research indicates that RPE is strongly correlated with objective measures of exercise intensity such as HR, maximal oxygen consumption and blood lactate concentration in a variety of populations (5, 65).

Several factors are likely to influence an individual's RPE, including musculoskeletal, cardiovascular and pulmonary stress, as well as psychological and contextual factors related to the individual and the task specific demands (64, 66). The interaction between these multiple factors provides the basis for an individual to evaluate the effort required to complete a specific task at any point in time (64).

The original Borg RPE scale consists of a 15 grade scale with verbal anchors and was intended to mirror the relatively linear increase of maximal oxygen consumption and HR during incremental exercise (64). Later, a category ratio 10 scale was designed to allow for a simpler and more flexible means of evaluating a variety of sensory perceptions (64). This scale was further refined by Foster et.al. (5); targeting the use an athlete's RPE value to quantify the global intensity of a training session. This method requires athletes to rate their perceived exertion using the refined scale by answering the question "How was your workout?" (67). The single value determined by multiplying the given RPE value by the duration of the exercise session in minutes represents a quantitative measure of internal TL for that training session, commonly referred to as session rating of perceived exertion (sRPE) (39).

#### **2.2.3.4 Monitoring internal training load with session rating of perceived exertion**

Session RPE has been used extensively to monitor internal TL across a range of different sports. Several advantages are associated with sRPE that unequivocally form the basis for its popularity. For example, sRPE is simple, time-efficient and affordable, convenient for both athletes and

sports science staff to implement, and is considered the only method that can quantify TL across all modalities of training.

Session RPE was originally designed for use in endurance-based sports and its suitability for quantifying internal TL is supported by associations with indices of HR and lactate accumulation (68, 69). However, the practicality of sRPE to quantify internal TL has also triggered extensive research to assess its validity and reliability within the team sport setting. For example, correlations varying from moderate to near perfect in magnitude have been reported between sRPE and HR across a range of team sports including soccer (57, 60), basketball (70), rugby league (71), ARF (72), Canadian football (73) and water polo (74). In combination with the convenience and adaptability of sRPE, this acceptable level of support has ensured its proliferation in team sport environments as a means to quantify internal TL.

While the literature largely supports sRPE as an acceptable method to quantify internal TL in a variety of team sports, the disparity in correlations reported between studies highlights important considerations for its use. These inconsistencies may be explained by differences in the inherent nature of each sport (72). For example, research suggests that sRPE and HR methods of TL quantification are more strongly related during endurance training in comparison to the high intensity and intermittent demands commonly associated with team sport activity (60, 61).



Although HR is often used as the criterion method on which the validation of sRPE is based, it is possible that factors other than HR contribute to an individual's RPE for a given training session (60). Factors likely to impact an individual's RPE include: hormone concentrations, substrate concentrations, ventilation rate, neurotransmitter levels, environmental conditions, and psychological traits (39). Furthermore, the overall RPE may also be affected by the amount of muscle groups used, fibre type recruitment, number of joints involved, order of exercise performed and the experience level of the athlete (40). The complex interaction of factors associated with sRPE suggests that it may represent the best available method of quantifying internal TL in intermittent team sport activity. Additionally, the significant intra-individual correlations reported between sRPE and various other measures of internal and external TL in both rugby league (71) and Australian football (72) suggest that sRPE may also be able to account for individual variation in TL resulting from different positional demands in contact sports. Subsequently, sRPE may also have merit as a global measure of TL in team sport.

Additional limitations to the use and reliability of sRPE are provided in Chapter 3.

#### **2.2.3.5 Monitoring internal training load section summary**

Quantification and monitoring of TL remain fundamental to understanding the effectiveness of training periodisation. Ideally, TL quantification methods provide practitioners with a means to assess whether the delicate balance between sufficient TL and adequate recovery has been achieved. Training load can be quantified in relative (i.e. internal) or absolute (i.e. external) terms; thus ensuring that individualised monitoring of TL is vital. Understanding TL responses is particularly important within team sports in which individual athletes may respond differently to

similar external TL's. No gold standard of TL quantification currently exists; hence, multiple methods are often used. It is imperative that practitioners understand the broader context and capacities of the available methods to support effective implementation and provide accurate data for the optimisation of training processes.

## 2.3 Monitoring fatigue and maladaptive responses to training

### 2.3.1 Overview of fatigue as a response to training

As previously stated, optimal athletic performance is most likely to occur during periods of maximal fitness and minimal fatigue (13). However, it is important to understand that an acute fatigue response is an essential component of the training process as it can lead to super-compensation when managed effectively with recovery (Figure 2.2).

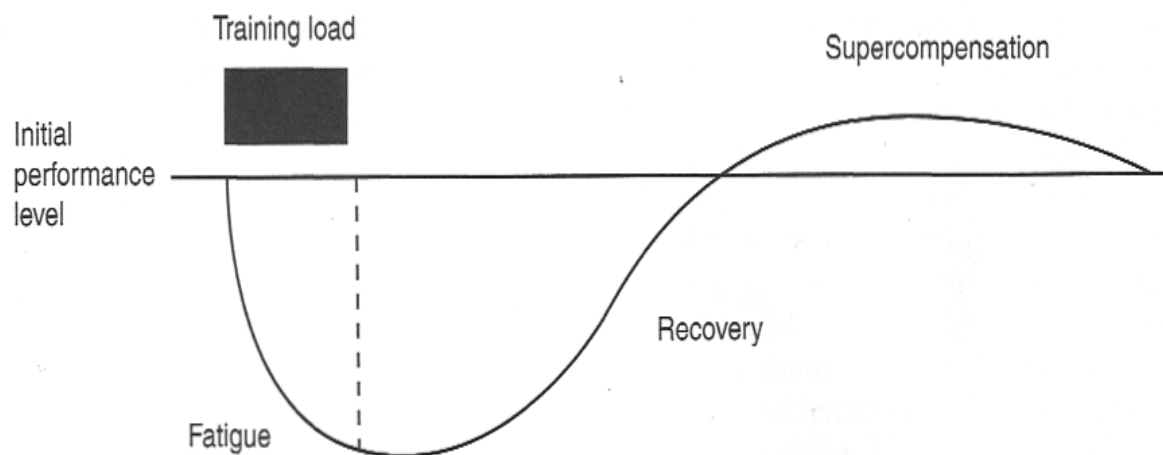


Figure 2.2 Positive adaptation (super-compensation) to training (75)

Fatigue originates from either “central” or “peripheral” sources. Central fatigue arises from the central nervous system, whereas peripheral fatigue manifests at muscular level (76). Several of the mechanisms associated with central and peripheral sources of fatigue are listed in Table 2.2; highlighting the multifactorial nature of fatigue. Additionally, Table 2.3 lists some of the commonly reported symptoms of fatigue that can negatively impact performance. Fatigue can be considered as a continuum, ranging from the acute stress of normal training to the chronic effects associated with the long-term imbalances from excessive TL and insufficient recovery (75). Consequently, distinguishing between necessary “planned” fatigue and chronic “unplanned fatigue” is vital for optimising athletic performance.

Table 2.2 Central and peripheral mechanisms of fatigue (76)

<b>Mechanisms of Central Fatigue</b>	<b>Mechanisms of Peripheral Fatigue</b>
Loss of recruitment of high threshold motor units	Loss of electrical conduction from muscle membrane to tubule system
Reduced central drive from increased inhibitory interneuron input to motor cortex	Impaired calcium release from sarcoplasmic reticulum (excitation-contraction uncoupling)
Central conduction block from demyelination or motor neuron dropout	Impaired interactions between myosin and actin during cross-bridge cycling
Increased negative feedback from muscle afferent types III and IV sensory neurons	Impaired reuptake of calcium
Loss of positive feedback from muscle spindle type I sensory afferents	Bioenergetic failure due to impaired oxidative phosphorylation, glycolysis, or both

Table 2.3 Common performance symptoms of fatigue (77)

<b>Performance symptoms</b>
↓ Whole-body work rate/velocity, inability to surge, ↑ rest periods, cessation of exercise
↓ Technique execution, ↑ error rate, ↑ mental lapses
↓ Muscle force/power, ↓ stride frequency, ↓ range of motion, ↑ time to completion
↑ Perceived exertion, ↑ perceived fatigue, ↑ perceived muscle soreness
↓ Motivation, ↓ self-efficacy, ↑ anxiety

### **2.3.2 Fatigue accumulation: the overtraining process**

Maladaptation resulting from unplanned, excessive or chronic fatigue are often explained by the process of “overtraining”. Overtraining is ranked as the most serious maladaptation along the continuum of fatigue and is preceded in severity by both the normal acute response to training and the state of “overreaching” (22). Periods of excessive TL coupled with insufficient recovery may predispose athletes to the negative consequences associated with these conditions.

Overreaching is defined as a short-term decrease in performance resulting from training and/or non-training stressors that can be physical or psychological in nature (78). This state of overreaching is often deliberately induced during a typical training cycle and may therefore be deemed as the “planned” fatigue necessary to help promote super-compensation. Ideally, super-compensation results in what is termed “functional overreaching” (79). Short-term decrements associated with functional overreaching may last between several days to weeks (26). If the imbalance between training and recovery continues beyond the most acute effects, non-functional overreaching and the overtraining syndrome may develop (Figure 2.3). This “unplanned” fatigue has the potential to cause long-term performance decrements requiring several weeks or months to rectify (79). Thus, prolonged periods of imbalance can have serious individual and team-based consequences.


PROCESS	TRAINING (overload)	INTENSIFIED TRAINING 		
		OUTCOME	ACUTE FATIGUE	FUNCTIONAL OR (short-term OR)
RECOVERY	Day(s)	Days – weeks	Weeks – months	Months - ...
PERFORMANCE	INCREASE	Temporary decrement (e.g., training camp)	performance (e.g., training camp)	STAGNATION DECREASE DECREASE

Figure 2.3 Possible outcomes resulting from the process of intensified training (Reproduced from Meeusen, Duclos (26)).

Symptoms associated with the development of non-functional overreaching and overtraining remain unclear, and are sometimes anecdotal and multiple in their presentation (Table 2.4). Limitations in the literature such as multiple definitions, interchangeable terminology, lack of performance validity comparisons and the inability to purposely elicit the overtraining process are also apparent (26, 80). Furthermore, a number of hypotheses have been proposed to explain the pathophysiology of the overtraining process; each with advantages and disadvantages (Table 2.5). Collectively, these factors ensure that accurately identifying the presence and extent of the overtraining process in individuals remains a significant challenge. Arguably, the most vital concept for practitioners to understand is that potential maladaptations resulting from the imbalance between TL and recovery are often heavily influenced by factors external to the sport (35). These factors may include daily stressors, family or relationship concerns, and other negative life events (26, 35). Variation in the physiological and psychological responses to both sport and non-sport related stressors are likely to vary between individuals, further complicating the accurate diagnosis of athletes along the continuum of overtraining (35).

Table 2.4 Possible symptoms of the overtraining process (22, 81).

<b>Parasympathetic effects</b>	<b>Sympathetic effects</b>	<b>Other</b>
Fatigue	Insomnia	Poor sleep quality
Depression	Irritability	Weight loss
Bradycardia	Agitation	Difficulty concentrating
Loss of motivation	Tachycardia	Muscle soreness
Decreased resting HR	Hypertension	Anxiety
Faster HR recovery	Restlessness	Illness
	Increased resting HR	Decreased performance

Table 2.5 Common hypotheses of the overtraining process (Modified from Kreher and Schwartz (22)).

<b>Hypotheses</b>	<b>Theory</b>	<b>Advantages</b>	<b>Disadvantages</b>
Glycogen hypotheses	Decreased glycogen causes fatigue and decreased performance	Low glycogen can be associated with decreased performance and exercise-induced fatigue	<ul style="list-style-type: none"> <li>- No proven correlation between low glycogen and overtraining</li> <li>- Athletes with normal glycogen levels can still become overtrained</li> <li>- Does not explain all symptoms</li> </ul>
Central fatigue hypotheses	Increased tryptophan uptake in the brain leads to increased neurotransmitter serotonin causing both central and mood symptoms	<ul style="list-style-type: none"> <li>- Exercise associated with increased tryptophan, serotonin, and fatigue</li> <li>- Selective serotonin re-uptake inhibitors decrease performance</li> <li>- Supplementation of branch chain amino acids reduce fatigue</li> </ul>	<ul style="list-style-type: none"> <li>- Few studies measure serotonin directly</li> <li>- Mood changes and subjective fatigue are influenced by many other factors</li> <li>- Does not explain all symptoms</li> </ul>
Glutamine hypotheses	Decreased glutamine causes immune dysfunction and increased susceptibility to infection	<ul style="list-style-type: none"> <li>- Glutamine does decrease after prolonged exercise</li> <li>- In vitro immune cell function is compromised with decreased glutamine</li> <li>- Athletes are more susceptible to upper respiratory tract infections after “intense” exercise</li> </ul>	<ul style="list-style-type: none"> <li>- In vivo, decreased plasma glutamine not necessarily correlated with decreased bioavailable glutamine</li> <li>- Glutamine supplementation does not improve post-exercise impairment of immune cells</li> </ul>



			<ul style="list-style-type: none"> <li>- Inconsistent relationships reported between low glutamine in athletes and upper respiratory tract infections</li> <li>- Glutamine can be influenced by many other factors</li> <li>- Does not explain all symptoms</li> </ul>
Oxidative stress hypotheses	Excessive oxidative stress causes muscle damage and fatigue	Resting markers of oxidative stress are higher in overtrained athletes and increase with exercise	<ul style="list-style-type: none"> <li>- Studies have been small</li> <li>- Lack of clinically relevant research</li> <li>- Does not explain all symptoms</li> </ul>
Autonomic nervous system hypotheses	Parasympathetic nervous system predominance causes many symptoms of overtraining syndrome	<ul style="list-style-type: none"> <li>- Variability in autonomic nervous system (heart rate variability) with exercise versus rest</li> <li>- Decreased awakening heart rate variability in overtrained athletes suggests disruption of autonomic nervous system modulation</li> </ul>	<ul style="list-style-type: none"> <li>- Inconsistent association between heart rate variability and exercise</li> <li>- Studies with methodological differences in calculation of heart rate variability are hard to compare</li> <li>- No difference in heart rate variability/autonomic nervous system influence between overtrained and control athletes during sleep, when free of external</li> </ul>

			influences - Does not account for all symptoms
Hypothalamic hypotheses	Dysregulation of the hypothalamus and hormonal axes cause many symptoms of overtraining syndrome	Endurance athletes have activation of the hypothalamic-pituitary-adrenal axis compared with controls	- Contradictory data in terms of activation of hypothalamic-pituitary-adrenal/hypothalamic-pituitary-gonadal axes in overtrained athletes and levels of ACTH, cortisol, testosterone - Other factors can influence hypothalamic-pituitary-adrenal/hypothalamic-pituitary-gonadal axis activation - Does not account for all symptoms
Cytokine hypotheses	Inflammation and cytokine release causes most of the effects and symptoms of overtraining process	- Unified theory accounting for many symptoms of overtraining process and why it develops - Cytokines may act on hypothalamic centres to	- Little evidence verifying increased cytokines in overtrained athletes - No studies looked at long-term responses to training/ Overtraining

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regulate sickness behaviour, causing mood changes and fatigue	- No change in cytokine levels shown in study on overtrained cyclists
- Subacute muscle injury and cytokines decreases glucose transport into muscles, decreases glycogen, and causes fatigue	
- Tryptophan is used to synthesize inflammatory proteins and decreases with systemic inflammation	
- Cytokines activate the hypothalamic-pituitary- adrenal system (increasing cortisol) and inhibit the hypothalamic-pituitary-gonadal system (decreasing testosterone)	
- Inflammation causes activation of glucose/protein metabolism and decreased glutamine	

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### **2.3.3 Sports-specific markers of fatigue and overtraining**

Strong demand remains for tools with sufficient rigour and sensitivity to identify the accumulation of fatigue in athletes. Despite on-going debate on the definition and pathophysiology of overtraining (Table 2.5), its diagnosis is generally overtly detected via a decrease in sport-specific performance that persists irrespective of recovery interventions (26). In this context, it makes sense that sport-specific performance should be monitored regularly, ideally with the use of maximal tests that closely resemble competition demands. However, a number of limitations are associated with this approach in applied settings. First, regular maximal performance testing is likely to add to the accumulation of fatigue and potentially compromise performance during competition. Second, defining maximal performance is extremely difficult, particularly in team sports in which the competition demands are multiple and varied in their influence. Third, it is desirable to identify the accumulation of fatigue prior to any negative change in performance. As such, practitioners are often forced to rely on indirect measures of performance or underlying physiological and psychological markers to quantify fatigue in athletes.

Given the multifactorial nature of fatigue, a variety of markers are often used to indicate maladaptive responses. These include changes in performance, mood state, physiology, biochemistry, glycogen depletion, immunology and hormonal balance (80). Effective athlete monitoring necessitates a thorough understanding of these markers so that responses to training can be accurately interpreted. The following section outlines a range of fatigue markers with particular emphasis on those commonly used within applied team sport settings.

### **2.3.3.1 Heart rate to assess autonomic nervous system fatigue**

Although HR has been previously discussed in relation to TL quantification (Section 2.2.3.2), the multi-systemic response of the autonomic nervous system to exercise means that HR may provide information on training responses, including accumulated fatigue. In healthy individuals, the modulation of HR is largely determined by the combined effects of both the sympathetic and parasympathetic branches of the autonomic nervous system (58). This link between HR and the autonomic nervous system underpins the widespread use of HR to monitor TL and performance capacity. The autonomic nervous system plays a crucial role in the response to training stress. Therefore, any signs of negative adaptation to training that are triggered by the autonomic nervous system may be also be reciprocated in HR response (58, 82). As such, a number of HR-derived measures can reflect the accumulation of fatigue in athletes.

Increased resting HR is one of the earliest reported signs of the overtraining process and has also gained significant attention in contemporary literature. Recent reviews refer to an unclear relationship between increased resting HR and overtraining processes over longer time frames. However, there is merit in using resting HR as an indicator of short-term fatigue (58, 82). Sleeping HR also has potential as a marker of fatigue (58) and is theoretically less likely to be influenced by the sensitivity of the autonomic nervous system to environmental conditions such as noise, light and temperature (6). The effect of sleep patterns and quality on HR is not fully understood and requires further investigation before sleeping HR can be considered a valid marker of fatigue.

Resting heart rate variability (HRV) is increasingly popular due to the recent availability of a range of portable monitoring devices enabling measurement in applied settings (83, 84). Resting HRV is the beat to beat variation in time of consecutive heart beats between peaks of the QRS complex (R-R interval) and is indicative of the efficiency and adaptability of the autonomic nervous system (85, 86). It is postulated that routine monitoring of HRV may provide useful information about an individual's fitness status, including tolerability of the prescribed TL and readiness to perform (86, 87).

Traditionally, high HRV is suggested to reflect a positive physiological state, whereas low HRV is often associated with maladaptation (85). More recent reviews suggest that the relationship between HRV and readiness to perform is more complex; in which both increases and decreases in HRV can be associated with accumulated fatigue (6, 82, 87). However, studies within applied settings have found that measures of HRV lacked the sensitivity to provide meaningful information regarding changes in training status among professional soccer players throughout a competitive season (83, 88).

The methodological diversity among studies may have contributed to the equivocal results, particularly relating to the numerous HRV indices available in the literature. Currently it appears that time-related indices of HRV generally have a lower typical error of measurement than spectral-related indices (87). Collectively, the correct interpretation of HRV changes may rely on the context of the specific training phase, the consideration of other fatigue markers, and knowledge of the typical error associated with the various HRV measurement methods (6).

Measurement of maximal HR is another potential monitoring tool to identify fatigue. Decreased maximal HR is currently the only HR variable known to be altered by both acute and chronic increases in TL (82); thus providing a useful sign of the development of non-functional overreaching and overtraining. However, the resultant fatigue from testing that elicits maximal HR response is likely to compromise subsequent training and/or match performance (25); thus regular maximal testing remains difficult to schedule during periods of the year when optimal performance is a priority. Alternatively, monitoring HR during submaximal exercise may provide a less exhaustive and therefore more practically effective method of determining the accumulation of fatigue in athletes. While no direct performance measure is available from submaximal fitness testing, changes in heart rate for fixed bouts of submaximal exercise can provide useful information about the training dose-response relationship of individuals.

Both submaximal exercise heart rate (HR<sub>ex</sub>) and heart rate recovery (HRR) are possible indicators of training status that can be monitored during submaximal fitness testing in applied settings (83, 84). For example, faster HRR and decreased HR<sub>ex</sub> are associated with the accumulation of fatigue (82, 89). Conversely, slower HR recovery and increased submaximal exercise HR are potential markers of deconditioning (59, 90). However, it should be noted that faster HRR and decreased HR<sub>ex</sub> may also be indicative of improved fitness in certain situations (59, 91). Subsequently, accurately interpreting the nature of HR change during submaximal fitness testing is complex and requires consideration of the exact training context and results from other physiological markers, over time. Furthermore, the normal day-to-day variation in

HR can mask potential changes in training status if exercise intensity and environmental factors are not adequately controlled during testing (59, 92).

### **2.3.3.2 Subjective ratings of fatigue and wellbeing**

Self-analysis tools that require athletes to rate factors such as fatigue, perceived exertion, muscle soreness, sleep quality, and mood disturbances may provide a convenient and effective means to quantify both training and non-training stressors. Changes in subjective “wellness” are associated with variations in TL that has led to the widespread implementation of questionnaires to monitor fatigue and prevent the overtraining process in athletic populations (93). Indeed, a number of studies have found that subjective questionnaires are more accurate at identifying negative adaptation to training compared to objective methods such as heart rate (83, 84, 88)

A range of questionnaires are available, the most popular of which appear to be the Profile of Mood States, Recovery Stress Questionnaire for Athletes, and custom-made situation-specific tools based upon recommendations in the literature (22, 93).

The Profile of Mood States Questionnaire was originally designed to assess the affective states of psychiatric patients (94). More recently it has become a popular choice for assessing the psychological factors associated with overtraining and is reported to be strongly associated with changes in TL (95-97). Indeed, mood disturbances are considered to be indicative of both acute and chronic training stress (93). The Profile of Mood States Questionnaire consists of 65



questions representing five negative categories (tension, anger, fatigue, depression, confusion) and one positive category (vigour). A total score for mood disturbance is calculated by summing the five negative categories, adding 100, and then subtracting the positive category score (98). Despite its reported potential to monitor some of the maladaptive responses to training, the length of the Profile of Mood States Questionnaire and its lack of sport-specific categories are considered limitations for implementation among the athletic population (94).

In contrast, the Recovery Stress Questionnaire for Athletes was specifically designed to monitor the stress levels and recovery capabilities of individuals within a sport-specific context. This is achieved using a 77 item questionnaire that requires athletes to rate their current state of subjective stress and recovery from fatigue (99). This comparative measure between stress and recovery provides an assessment of an individuals' tolerance of training demands (75). Recovery Stress Questionnaire scores in elite sporting populations are reported to be associated with variations in TL (100, 101), occurrence of injury and illness (102), and reductions in performance indicators (103). An abbreviated version of the Recovery Stress Questionnaire for Athletes (termed the "Recovery-Cue Questionnaire") is also available (104). The Recovery-Cue Questionnaire is purposely limited to seven items (perceived exertion, perceived recovery, recovery efforts, physical recovery, sleep quality, social recovery, and self-regulation); thus providing a more efficient and practical method for the regular assessment of recovery from fatigue in applied sports settings (104).

More recently, the use of custom-designed questionnaires to assess perceived levels of fatigue and wellness has become more prevalent in applied settings. This is particularly pertinent in team sports where a large number of players are often assessed on a regular basis. In general, these custom-made questionnaires consist of a combination of items previously recommended in the literature, including but not limited to items such as: exertion, fatigue, sleep quality, motivation level, mood disturbance, stress level, general and specific muscle soreness, self-efficacy, and wellbeing. Various examples of custom-made questionnaires are reported to be sensitive to changes in training and match demands across a number of different team sports (105-109). However, rigorous psychometric evaluation of these questionnaires is less frequently reported, so external validity may not be optimal (93).

It is plausible that custom-made questionnaires designed by sports science practitioners who have an in depth knowledge of the specific physiological, psychological, and environmental demands of the applied setting may offer greater benefit in monitoring the training responses of athletes (110). Furthermore, it appears broader subjective measures that reflect multiple constructs and encompass overall “wellness” are likely to be most effective at evaluating performance capacities and assessing the impact of training and non-training stressors (93).

### **2.3.3.3 Counter movement jump testing to assess neuromuscular fatigue**

Countermovement jump (CMJ) protocols designed to assess neuromuscular function could provide valuable information about the time-course of recovery following both training and match-induced fatigue (37, 111). Theoretically, CMJ testing may reflect the stretch-shortening capabilities of lower limb musculature and therefore indicate fatigue-induced performance

decrements (112). Using contact mats or force platforms, a number of variables can be monitored via CMJ testing such as mean power, peak velocity, contact time, flight time, jump height, and rate of force development (37). Such testing protocols have become popular in applied settings due to their objective nature (112).

Associations between changes in TL and CMJ performance in team sport athletes remain unclear. While impaired muscle function has been detected post-match by assessing flight time (107, 113) and relative power (107, 113) in rugby league players, other studies have reported inconsistent changes in the ratio of flight time to contraction time (114, 115) and vertical jump height (114) obtained from a variety of testing protocols. Thus, while collecting data from several CMJ parameters may be considered useful given that the time course for recovery of specific parameters may be different (112), variations in response render the interpretation of such data difficult. Subsequently, the true value of CMJ testing in identifying fatigue remains unknown.

#### **2.3.3.4 Blood and saliva markers**

It is possible that various biochemical, hormonal, endocrine, and immunological markers present in blood and saliva samples may provide an objective measure of an athlete's response to training. Examples of these markers most commonly reported in the literature include creatine kinase, testosterone, cortisol, glutamine, glutamate, and immunoglobulin A (26, 37, 112, 116, 117).

However, despite the large body of research which has been devoted to uncovering which biomarkers can identify the early stages of training maladaptation, their usefulness in monitoring training responses remains unclear. Indeed, a recent systematic review investigating the influence of intensified training on physiological biomarkers of performance reported a lack of practical significance and sensitivity amongst a variety of blood and saliva measures commonly used to monitor adaptation to training (118).

Large day-to-day variations, poor temporal relationships to fatigue, inconsistencies in assessment methods, and the probable inability of a single biomarker to be able to accurately reflect the multifactorial nature of fatigue are the likely reasons for the findings reported in the literature (118). Additionally, the collection and analyses of blood and saliva markers is often expensive and time consuming; further complicating their implementation in applied settings.

#### **2.3.3.5 Monitoring fatigue and maladaptive responses section summary**

Changes in performance, mood state, physiology, biochemistry, the immune system, and hormonal balance have all been investigated to improve the understanding of the potential indicators of training maladaptation (80). Such findings have varied in their consistency, likely due to the lack of standardisation in both the definition and diagnosis of overreaching and overtraining (79). The exact onset of the overtraining process is difficult to pinpoint and individual responses can be highly variable, further complicating the productivity of research in this area. Currently, the regular assessment of a variety of performance, physiological, biochemical, immunological, and psychological measures is the most effective strategy of identifying individuals potentially suffering from accumulated fatigue (26). Perhaps most

importantly, measuring both TL and the response to TL should be conducted on an individual basis to identify athletes with the disproportionate balance between TL and recovery that precedes the development of the overtraining process (26).

## **2.4 Summary and implications from literature review**

The principles of periodisation developed through the greater understanding of the exercise dose-response relationship play a vital role in the prescription of training for team sport athletes. It is clear that monitoring both TL and responses to TL are important in optimising physiological adaptations and encouraging improved physical performance. Fatigue is a necessary after-effect of training; without it, super-compensation will not occur. However, excessive cumulative fatigue has the potential to cause severe individual and team based consequences. Subsequently, regularly monitoring of both fitness and fatigue is necessary to ensure the optimisation of the training process.

Despite the availability of multiple strategies, all have limitations particularly in sport-specific application. Currently the use of a number of measures with the potential to integrate into a multi-dimensional monitoring system prevails; albeit with limited scientific evidence. Therefore, the rationale for this dissertation is based on the identified need for practical field-based monitoring of TL and responses to TL, with a specific focus on objective, easily repeatable, non-invasive, and sports-specific monitoring that minimises athlete fatigue.

## **2.5 Research direction**

### **2.5.1 Aims**

#### **General aim:**

The overarching aim of this dissertation was to demonstrate the effectiveness of using heart rate (HR) responses from a submaximal intermittent running (SIR) test to monitor training responses and help identify states of fitness and fatigue throughout a season in individuals representing an elite ARF team. The findings from this field-based, prospective research have the capacity to advance the understanding of physiological athlete monitoring in team sport environments.

#### **Study one:**

- To conduct a systematic review of the literature investigating longitudinal athlete monitoring protocols and their effectiveness in identifying fatigue in elite football players.
- Provide an evidence base that further enables practitioners to develop a comprehensive athlete monitoring battery to optimise individual and team sport performance.

#### **Study two:**

- To establish the validity and reliability of the SIR test in elite ARF players.

#### **Study three:**

- To determine the association between HR responses to the SIR test as a marker of training status and changes in TL during a pre-season meso-cycle in elite ARF players.

#### **Study four:**

- To determine the association between HR responses to the SIR test as a marker of training status and changes in TL during selected weeks of a competitive season in elite ARF players.
- To investigate the relationship between HR responses to the SIR test and match exercise intensity in elite ARF players.
- To explore the influence of playing position on relationships between HR responses to the SIR test, TL and match exercise intensity.

#### **2.5.2 Hypotheses**

##### **General hypotheses:**

Heart rate responses to the SIR test will assist in monitoring individual training responses and identifying states of fitness and fatigue in elite ARF players.

##### **Study One (Chapter Three):**

- A large range of athlete monitoring strategies to quantify TL and monitor training responses are reported in the literature.
- The effectiveness of selected athlete monitoring strategies to identify associations between TL and fatigue-related responses in elite football codes remains unclear.

**Study Two (Chapter Five):**

- Strong correlations will exist between heart rate responses to the SIR test and YYIR2 test performance in elite ARF players.
- Strong day-to-day reliability of HR responses to the SIR test in elite ARF players will be reported.
- Results for validity and reliability testing will support the use of the SIR test in elite ARF.

**Study Three (Chapter Six):**

- Heart rate responses to the SIR test will be associated with changes in TL throughout a pre-season meso-cycle in elite ARF players.
- Relationships between HR responses to the SIR test and measures of TL will be influenced by playing position.

**Study Four (Chapter Seven):**

- Heart rate responses to the SIR test will be associated with changes in TL throughout the competitive season in elite ARF players.
- Heart rate responses to the SIR test will be associated with match exercise intensity in elite ARF players.
- Relationships between HR responses to the SIR test and both TL and match exercise intensity will be influenced by playing position.



### **2.5.3 Scope of the thesis**

The following points describe the scope of the thesis:

- Recruitment targeted elite male ARF players from one Australian Football League club.
- All data were collected in an applied environment as part of routine training monitoring within the club's high performance program.
- Data collection was limited to two specific phases of the periodised year: Pre-season and in-season participation.
- Analyses conducted in this thesis during both training and competition was restricted to selected physiological and psychological aspects of performance. Specifically, analyses were performed on data obtained from micro-technology, sRPE, HR monitoring, and subjective wellness scales.

### **2.5.4 Beyond the scope of the thesis**

The following points were deemed to be outside the scope of the thesis:

- Analyses conducted in this thesis during both training and competition did not include all aspects of performance. For example, skill and tactical-related activities that are likely to contribute to overall performance were not investigated in the thesis.
- Due to regulations, Australian Football League clubs are unable to monitor the physical activity of players outside of the club environment. Any additional training completed by

players during time away from the club could not be accurately quantified and was therefore not included in the analyses.

- Despite advancements in technology, there is still some systematic error associated with the use of micro-technology such as GPS and accelerometers. Validation studies of micro-technology have been published elsewhere and have been in acknowledged however, the validity of these devices was not investigated within the thesis.
- The applied setting made it difficult to standardise all aspects that may influence TL and training responses such as nutrition and recovery practices. Although these aspects of performance are important, the capacity to monitor each of the listed factors was beyond the scope of this program of research.

## Chapter Link: Summary of narrative literature review

Chapter 1:  
Introduction

Chapter 2:  
Narrative Literature Review

Chapter 3:  
Systematic Literature Review Study

1. Principles of training periodization are founded on the exercise dose-response relationship.
2. Monitoring both training dose and response is necessary to optimise physiological adaptations.
3. Current monitoring strategies may have limited sport-specific application.
4. There is an identified need for practical field-based monitoring strategies in elite team sports.

## **Chapter Three: Athlete monitoring strategies in elite football: Are they indicative of fatigue? A systematic review.**

### **3.1 Introduction**

Explanations of the physiological responses of an individual to training stressors are predicated by Banister's fitness-fatigue model (28). The model was designed with a twofold purpose (i) to quantify the exercise dose-response relationship of an individual and (ii) to predict readiness to perform based on the amount and magnitude of the cumulative training dose (or TL) (119).

As stated in Chapter Two, training results in two contrasting effects: fitness and fatigue (28). Fitness is a positive response, low in magnitude and long in duration. In contrast, fatigue is a negative response, high in magnitude and short in duration (13). After an imposed TL, fatigue initially outweighs fitness. However, fatigue dissipates faster than the fitness over time. Thus, optimal athletic performance is most likely to occur during periods in which the positive fitness response exceeds the negative fatigue response (119).

Delicately balancing sufficient frequency, intensity, and volume (load) of training with adequate periods of recovery from fatigue is vital for promoting improved fitness (22). With insufficient recovery, fatigue may accumulate to the point at which positive responses to training are blunted and an overall negative impact on an individual's systemic physiological state eventuates (13). Fatigue can be considered as a continuum, ranging from the acute stress of normal training, to the

chronic effects leading to overreaching and the overtraining syndrome (75). Acute effects of fatigue can be identified by monitoring individual changes in physiological, psychological, and sport-specific performance markers (79). In contrast, changes in fitness are generally only observable after longer timeframes and are therefore considered more of a chronic training response (120). Consequently, regular monitoring of fatigue may be considered more vital than fitness given that changes in fatigue are likely to be observed over shorter time periods. This is particularly pertinent during the in-season phase of team sports during which optimal match performance is required on a weekly basis; thus recovery from fatigue becomes the predominant focus of athlete monitoring during this period. A stronger understanding of fatigue as a response to TL and how it can be measured may assist in improving performance, reducing injury risk, and increasing player longevity.

Quantifying TL and monitoring training responses are crucial in preventing excessive fatigue. Comprehensive athlete monitoring strategies may reduce the likelihood of negative training adaptations (22, 26). Ideally, monitoring strategies guide exercise prescription and allow optimization of a periodised program (4, 39, 121). Athlete monitoring strategies are especially important in a team sport environment in which each individual athlete's responses to the same TL are likely to vary (39).

In the absence of gold standards for quantifying TL and fatigue, a combination of methods is often used (40). Load (or in Bannister's model, "dose") can be categorized as either external [i.e. the amount of work imposed (e.g. distance)] or internal [i.e. an individual's homeostatic disturbance

resulting from the imposed work (e.g. perceived exertion)] (122). Popular internal TL measures include session rating of perceived exertion (sRPE) and heart rate-derived measures, while wearable micro-technology such as global positioning system (GPS) devices and accelerometers are commonly used to quantify external TL (122). Stand-alone fatigue markers as a “response” to the dose, are also often monitored. Fatigue responses to TL may be quantified objectively by alterations in an individual’s physiological, biochemical, immunological, hormonal, and performance traits, or subjectively via psychometric instruments (80).

Traditionally, strategies to indicate states of fatigue in elite team sport have been infrequently and inconsistently reported in peer-reviewed literature. This may be partly attributed to the unwillingness of professional clubs to disseminate research. However, publications from applied settings are increasing, particularly within high profile professional football codes (21, 84, 123-125).

Therefore, the purpose of this study was to conduct a systematic review of the literature investigating the relationship between athlete load monitoring measures and markers of fatigue in elite football players. Ultimately, the results may promote a greater understanding of the exercise dose-response relationship and assist practitioners to develop a comprehensive athlete monitoring battery to detect fatigue in elite team sport athletes.

## **3.2 Methods**

### **3.2.1 Literature search**

Potential studies for review were identified via a systematic search of four electronic databases. SPORTDiscus, Medline Complete, Web of Science, and Scopus were searched using combinations of the following keywords: (i) ‘football’, ‘soccer’, ‘Australian rules’, ‘rugby’, ‘gridiron’, ‘NFL’; (ii) ‘fatigue’, ‘tired\*’, ‘exhaust\*’; (iii) “training load”, “exertion”, “monitoring”, “analysis”, “GPS”, “heart rate”, “objective”, “subjective”, “internal”, “external”, “perceived”, “perceptual”, “blood”, “saliva”, “plasma”, “serum”, “hormon\*”. References from key and included studies were manually searched to identify any relevant articles that may not have been incorporated in the original search. The term “football” referred to generic football codes, while specific terms (e.g. “soccer”) were used to differentiate between codes. The search was run in August 2015 and updated in December 2017. It was restricted to articles published after 2000 to best represent contemporary issues, particularly with the growing popularity of GPS use in high performance sport.

### **3.2.2 Selection criteria**

Studies investigating the major football codes (soccer, ARF, rugby league, rugby union, and American Football) were included in an effort to maximise the amount of literature available and to manage heterogeneity in athlete characteristics and sport demands. Studies involving only elite adult male participants aged over 18 years were included in the search. Elite players referred to those competing at international or national level. A specific focus on elite performance was deemed to generate the most interest from applied sports scientists in professional team sports.

To enable the investigation of the dose-response relationship in elite football, only studies measuring both the dose and fatigue-related response to exercise were included. For the purpose of this review, “dose” was defined as a quantifiable amount of training or competition-specific loading over a microcycle of at least one week. The microcycle was selected to provide more insight into regular and on-going monitoring practices compared with isolated, cross-sectional testing. Although measuring fitness responses remains equally important, monitoring of fatigue is arguably more urgent in elite team sports, particularly during in-season competition phases where optimal performance is expected on a weekly basis. Consequently, fatigue was considered the most important response to target in this review of regular monitoring practices. Table 3.1 summarises the five exclusion criteria developed during screening processes.



Table 3.1 Explanation of exclusion criteria for systematic review.

Criteria	Explanation
1. Playing level	Excluded if involving non-elite participants, female participants, wheelchair athletes, referees, umpires, or participants falling outside of the specified age range.
2. Research design	Excluded in the absence of a longitudinal/ repeated measure design, technical paper (e.g. validity/reliability testing), not peer reviewed, reviews, consensus statements, or studies written in a language other than English. Individual case studies were also excluded.
3. Discipline	Excluded if investigating disciplines outside the scope of this study (e.g. sports psychology, biomechanics).
4. Ergogenic aids	Excluded if assessing the effect of ergogenic aids on performance (e.g. supplements, devices), or strategic manipulations with the environments including induced heat or altitude.
5. Lack of a dose and response marker	Excluded if no reference was made to a clear marker of TL and fatigue (e.g. articles analysing match or positional demands, or focussing on sleep alone). Absence of sport-specific training (e.g. laboratory based training).

### **3.2.3 Study selection**

One author (K.V.) was responsible for literature searches and abstract collation. Three authors (K.V., G.N., and C.D.) then reviewed each abstract for inclusion. Where an abstract lacked sufficient information, the full text version was obtained and reviewed. Disagreements among authors were discussed and resolved. After selection, a review of all full texts was conducted.

A number of quality assessment tools are available. The Physiotherapy Evidence Database (PEDro) rates quality of methodological reporting in clinical trials. Despite the focus on clinical trials, some criteria in the PEDro scale can be applied more broadly. Subsequently, in this review, the assessment of the reporting quality in the articles used a modified version of the PEDro scale. The PEDro criteria chosen were: (i) specification of eligibility criteria; (ii) inclusion of measures of at least one key outcome were evident from more than 85% of the participants initially allocated to groups; (iii) results of within-group statistical comparisons being reported for at least one key outcome; (iv) stating both point measures and measures of variability for at least one key outcome; (v) reporting results of population specific reliability. One point was assigned to each of the five identified criterion. Studies with high scores indicated a relatively high quality in reporting (Appendix 2). Some PEDro criteria were excluded as they were deemed inappropriate for the single group, non-randomised studies that typify the monitoring of TL and fatigue in applied sports science.

### **3.2.4 Data extraction**

One author (K.V.) extracted data from the included studies and created a database summarising key elements of each study. These data included information on the study aims, the code of football investigated, participant characteristics, timeframe of monitoring protocols, the methods used to measure TL and fatigue, the results obtained and the subsequent conclusions drawn.

## **3.3 Results**

After removing duplicates from the initial search, a total of 1319 studies were retrieved. Following a selection process (Figure 3.1) involving the screening of titles, abstracts and then full texts using the established exclusion criteria (Table 3.1), 31 articles were retained for review (Table 3.2). A total of 692 elite players competing in six different football codes (soccer, ARF rugby union, rugby league, rugby sevens, American football) participated in these studies. Soccer was the most commonly researched football code (n = 13 articles) followed by ARF (n = 9) rugby league (n = 5), American football (n = 3), rugby union (n = 1), and rugby sevens (n = 1). The timeframe of athlete monitoring strategies used in these studies ranged from a seven day intensified training period in soccer (126) to three seasons in ARF (106).

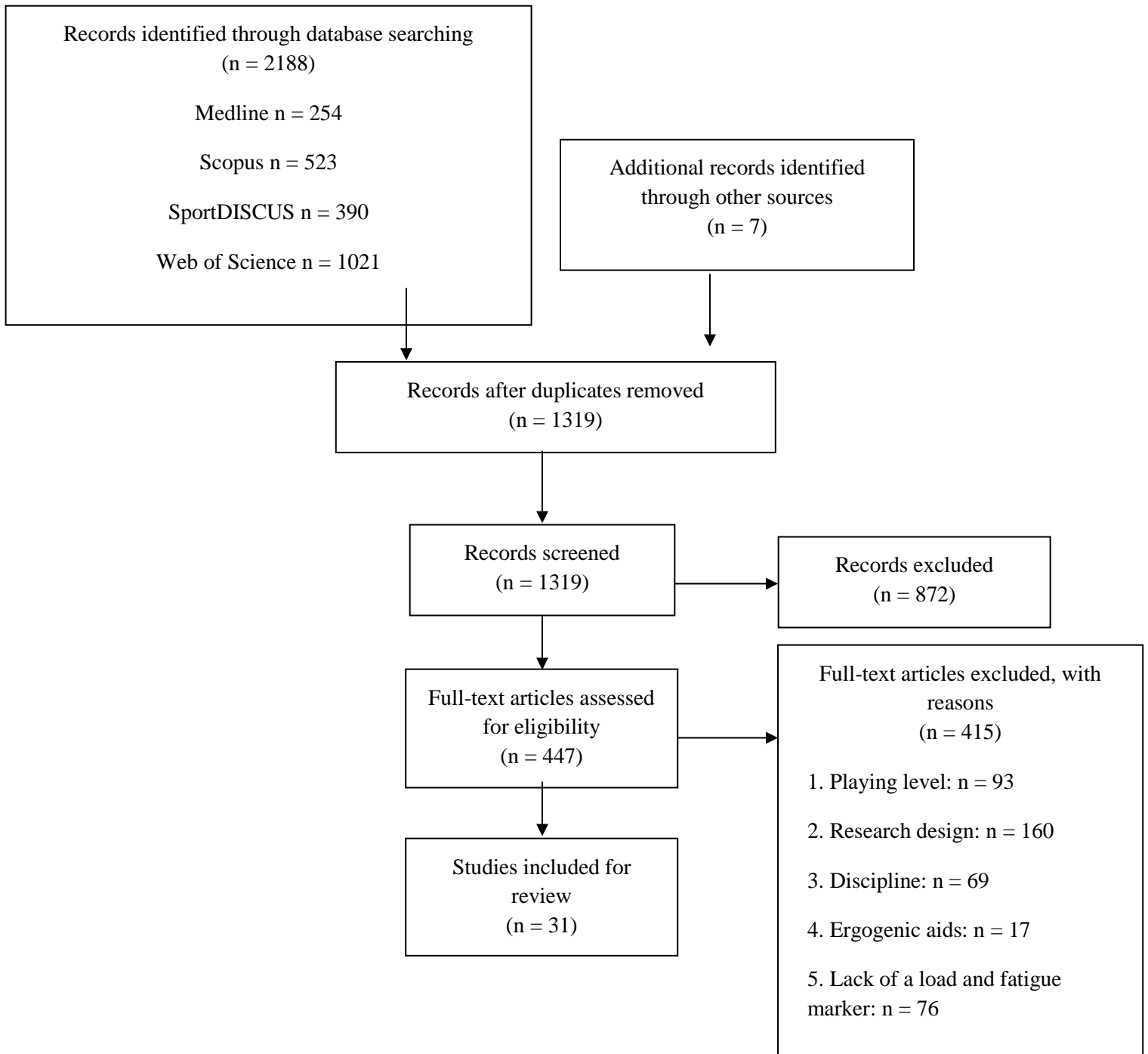


Figure 3.1 PRISMA flow chart illustrating the study selection process for systematic review (127).

Table 3.2 Summary of articles included for systematic review

<b>Study</b>	<b><i>n</i></b>	<b>Football Code</b>	<b>TL Type</b>	<b>TL Measure / Device</b>	<b>Fatigue Type</b>	<b>Fatigue Measure</b>	<b>PEDro Score</b>
Coker et al. 2017 (128)	7	Soccer	External	GPS	Subjective	RESTQ	5
Cormack et al. 2008 (115)	15	ARF	External	Training time Match time	Objective	CMJ Salivary biomarkers	3
Cormack et al. 2013 (129)	17	ARF	External	GPS Accelerometer	Objective	CMJ	4
Cunniffe et al. 2011 (130)	8	Rugby Union	External	Match time Contact events	Objective	Blood biomarkers	5
Filaire et al. 2003 (131)	20	Soccer	External	Training time	Subjective Objective	Profile of Mood States Questionnaire, blood and saliva biomarkers	4
Gastin et al. 2013 (132)	27	ARF	External	Training time	Subjective	Custom designed questionnaire	4
Heisterberg et al. 2013 (133)	19	Soccer	External	Training time Match time	Objective	Blood biomarkers	4

<b>Study</b>	<b><i>n</i></b>	<b>Football Code</b>	<b>TL Type</b>	<b>TL Measure / Device</b>	<b>Fatigue Type</b>	<b>Fatigue Measure</b>	<b>PEDro Score</b>
Kraemer et al. 2013 (134)	21	American Football	External	Resistance training volume	Objective	Blood biomarkers	4
McLellan et al. 2012 (135)	15	Rugby League	External	GPS Accelerometer	Objective	CMJ	3
Meister et al. 2013 (116)	88	Soccer	External	Match time	Objective	Blood biomarkers	5
Minetto et al. 2008 (126)	12	Soccer	External	Training time	Objective	CMJ Salivary biomarkers	5
Mooney et al. 2013 (136)	17	ARF	External	GPS Accelerometer	Objective	CMJ	4
Moore et al. 2007 (137)	9	American Football	External	Resistance training volume	Objective	Blood biomarkers	5
Silva et al. 2008 (138)	15	Soccer	External	Training time	Subjective  Objective	Profile of Mood States Questionnaire, blood biomarkers	4

<b>Study</b>	<b><i>n</i></b>	<b>Football Code</b>	<b>TL Type</b>	<b>TL Measure / Device</b>	<b>Fatigue Type</b>	<b>Fatigue Measure</b>	<b>PEDro Score</b>
Thorpe et al. 2015 (83)	10	Soccer	External	GPS	Subjective  Objective	Custom designed Questionnaire HRR, HRV, CMJ	5
Thorpe et al. 2017 (84)	10	Soccer	External	GPS	Subjective  Objective	Custom designed Questionnaire HREx, HRR, HRV, CMJ	4.5
Wellman et al. 2017 (125)	29	American Football	External	GPS	Subjective	Custom designed questionnaire	5
Bouaziz et al. 2016 (139)	16	Rugby Union	Internal	sRPE	Subjective	Custom designed Questionnaire	5
Buchheit et al. 2013 (105)	18	ARF	Internal	sRPE	Subjective  Objective	Custom designed questionnaire, salivary biomarkers, HREx, HRV	4
Clemente et al. 2017 (140)	35	Soccer	Internal	sRPE	Subjective	Custom designed questionnaire	4.5

<b>Study</b>	<b><i>n</i></b>	<b>Football Code</b>	<b>TL Type</b>	<b>TL Measure / Device</b>	<b>Fatigue Type</b>	<b>Fatigue Measure</b>	<b>PEDro Score</b>
Elloumi et al. 2012 (141)	16	Rugby Sevens	Internal	sRPE	Subjective	Custom designed questionnaire	4
Fessi et al. 2016 (142)	17	Soccer	Internal	sRPE	Subjective	Custom designed questionnaire	
Fowler et al. 2015 (143)	18	Soccer	Internal	sRPE	Subjective	Custom designed questionnaire	4.5
Killen et al. 2010 (144)	36	Rugby League	Internal	sRPE	Subjective	Custom designed questionnaire	5
McGuckin et al. 2014 (145)	12	Rugby League	Internal	sRPE	Subjective	Daily Analyses of Life Demands for Athletes questionnaire Karolinska Sleepiness Scale	3
McLean et al. 2010 (113)	12	Rugby League	Internal	sRPE	Objective Subjective	CMJ Salivary biomarkers Custom designed questionnaire	5



Study	<i>n</i>	Football Code	TL Type	TL Measure / Device	Fatigue Type	Fatigue Measure	PEDro Score
Moalla et al. 2016 (146)	14	Soccer	Internal	sRPE	Subjective	Custom designed questionnaire	5
Montgomery et al. 2013 (106)	64	ARF	Internal	sRPE	Subjective	Custom designed questionnaire	4
Thorpe et al. 2016 (88)	29	Soccer	Internal	sRPE	Subjective Objective	Custom designed questionnaire HRex, HRR, HRV	4.5
Gallo et al. 2017 (147)	36	ARF	External & Internal	GPS sRPE	Subjective	Custom designed questionnaire	5
Gallo et al. 2016 (124)	33	ARF	External & Internal	GPS sRPE	Subjective	Custom designed questionnaire	5
Twist et al. 2017 (111)	15	Rugby League	Internal & External	sPRE GPS	Subjective Objective	Custom designed questionnaire CMJ	5

*n*, number; TL, training load; PEDro, physiotherapy evidence database; ARF, Australian rules football; GPS, global positioning system; sRPE, session rating of perceived exertion; HRex, exercise heart rate; HRR, heart rate recovery; HRV, heart rate variability; CMJ, countermovement jump.

### **3.3.1 Monitoring overview**

Multiple TL monitoring strategies were used across the 32 included studies. A total of 17 studies used an external load measure alone to quantify TL and fatigue relationships. Of these 17 studies using a sole external TL measure, the most frequently reported was training and/or match time (n = 8), followed by GPS/accelerometers (n = 7), resistance training volume (n = 2) and contact events (n = 1).

In contrast, fewer studies (n = 12) used a sole measure of internal TL. Specifically, sRPE was used across all 12 studies investigating fatigue responses to internal TL. More recently, three studies have reported both external and internal measures in the quantification of TL in elite football codes. Each of these three studies used GPS to monitor external TL and sRPE to measure internal TL.

Similar to observations of multiple strategies used in the quantification of TL, a variety of fatigue markers was also noted across the 32 included studies. In total, 18 of the included studies used a subjective fatigue monitoring method, whereas 14 studies implemented objective fatigue monitoring. Of the 32 included studies, 8 used a combination of subjective and objective measures of fatigue.

Subjective questionnaires relating to fatigue were the most frequently investigated (n = 23) followed by objective measures of blood/saliva biomarkers (n = 11), CMJ testing (n = 9), and HR response to exercise (n = 4). Broader subjective measures of fatigue through either established or custom-designed questionnaires included variables of perceptions of recovery, sleep and mood.

### **3.3.2 Quality assessment**

Quality assessment scores for the 32 included studies with criteria scores that ranged from 59% to 100% on the modified PEDro scale (Table 3.2). All studies scored strongly for reporting specific eligibility criteria, reporting within-group statistical comparisons, and providing point measures and measures of variability. Weaknesses in reporting were apparent in other categories, with 24% of studies not reporting the results of population-specific reliability and several studies reporting whether group numbers changed at follow up. In some studies with low recruitment, it was assumed that full sets of data were pre-selected prior to analysis. Thus, an assumption of lack of drop out was made. Nonetheless the quality of reporting appeared to improve over time, with most of the more recent 2016 and 2017 scoring either 4.5 or 5 out of a possible 5 selected criteria.

## **3.4 Discussion**

A number of trends emerged from this review of the effectiveness of athlete monitoring for detecting associations between TL and fatigue responses in elite football. First, reporting of average or total time, most notable in studies prior to 2013, lacks sufficient detail for assessing the fatigue responses to external TL. Second, subjective methods remain dominant in the literature exploring relationships between TL and fatigue in elite football codes. The recent popularity of GPS technology demonstrates the scope to expand comparisons between objective measures of TL and fatigue. However, few studies extend investigations into fatigue beyond subjective methods. Third, a number of inconsistencies in reporting or quantifying athlete monitoring strategies were identified, which may impact upon their implementation. The capacity for GPS devices to quantify external TL appears to be an emerging trend within the literature; however, relationships between GPS-derived external TL and fatigue in elite football codes remains unclear.

### **3.4.1 Prevalence of time-based measures to quantify external load**

Time-based measures appeared to be the most frequently observed method for linking the monitoring of fatigue as an outcome of external TL in the studies included for review (115, 116, 126, 130-133, 138). Generally, external TL was quantified as team average or total exposure time to training and/or match play. The lack of reporting of training intensity and frequency results in insufficient detail to fully understand fatigue responses to the external TL imposed upon athletes. Furthermore, quantifying external TL using only team-based exposure calculations may risk masking vital individual differences in TL and the associated fatigue-related responses that are likely to occur within a team sport environment (39). As such, accurately identifying fatigue may not be possible from generic time-based methods of external TL quantification.

Several studies explored associations of external TL with objective changes in a variety of blood and saliva markers as measures of fatigue over the course of a competitive football season. Results from these biomarkers generally demonstrated variations of a small magnitude and values within normal ranges, without significant associations to external TL, as quantified by training and/or match exposure time (115, 116, 131, 133, 138). Periods of high intensity training in soccer were suggested to induce a decrease in serum glutamine and increases in salivary cortisol, serum uric acid and serum creatinine concentrations (131, 138). However, sufficient details of the TL involved in these intensified training periods were lacking.

Researchers in elite football have also used total time as an external TL measure to explore relationships with physical performance markers of fatigue such as CMJ testing. For example,

match exposure time was compared with pre and post-game CMJ results to investigate the presence of neuromuscular fatigue in ARF players (115). Specifically, decreases in the ratio of flight time to contraction time from pre-game to post-game were used as the marker of neuromuscular fatigue. The relationship between match exposure time and neuromuscular fatigue was reported to be small in magnitude (115). Reductions in CMJ height after intensified training in soccer were also suggested to indicate neuromuscular fatigue however, only training exposure time was described and no relationships with CMJ height were observed (126).

Associations between subjective fatigue responses and total or average time measures of external TL have also varied in elite football. Responses from the profile of mood states questionnaire in soccer players showed a trend of increased vigour levels and decreased depression, tension and fatigue levels during competition periods where winning percentage remains high (131). Interestingly, opposing trends were observed during periods of poorer performance although the direction of this relationship was unclear (131). Training periods characterised by moderate volume and high intensity were also reported to reduce vigour levels from the Profile of Mood States questionnaire (131, 138). However, without more stringent external TL quantification methods, results from subjective questionnaires are limited in their usefulness to identify and manage general fatigue.

Many of the studies selected for this review referred to the seminal work of Hooper and Mackinnon (148) to guide the subjective assessment of fatigue in athletes. Indeed, custom designed questionnaires have been used in ARF to assess negative adaptation to training and game loads.

Results showed that players' subjective wellness was poorest in the days immediately post-game and improved gradually throughout the week to the point of full recovery for the following game (132). Once again, external TL descriptions were reduced to training type and exposure time, with few other details of the imposed load (132).

Collectively, these results suggest that time-based measures of external TL such as training and/or match exposure time may lack sufficient detail to uncover meaningful associations between external TL and fatigue. Equally, the use of the term fatigue suffers from loosely and diversely defined applications in sport; including biochemical, performance and psychometric applications. This could explain some of the small relationships and equivocal findings between time-based measures of external TL and fatigue that appear in the literature.

### **3.4.2 Opportunity to expand investigations into relationships between external training load and fatigue**

The use of micro-technology such as GPS and accelerometers has increased exponentially in high performance sport over the past decade (121). Scopus attests to approximately 100 articles published within 2016 relating to the use of GPS devices within football codes alone. However, the majority of the research has focussed primarily on profiling external loading demands, movement patterns within training and competition, and associations with injury. Less than 15% of peer reviewed articles investigating micro-technology in football during this time have explored associations with fatigue; largely involving short term or cross sectional monitoring. Indeed,

results of the current systematic review suggest that prior to 2013, time-based measures were the predominant measure of external TL in studies investigating associations between TL on fatigue responses. Despite the observed increasing trend in GPS use over the past four years, relationships between external TL measured by micro-technology and markers of fatigue remain relatively unknown.

Of the 32 studies included for review, only 10 employed external TL measures from micro-technology devices in conjunction with markers of fatigue. More recently, increases have been observed in the use of accelerometers housed within micro-technology devices to quantify external TL. Measures collected using accelerometers include “Player Load”, which is calculated from the contribution of the mediolateral, anteroposterior, and vertical forces measured by an accelerometer housed within GPS devices (129). Research in ARF found that the presence of neuromuscular fatigue assessed via CMJ testing induced practically important changes in the production of player load per minute (129, 136). Thus, micro-technology devices may be a useful measure of exercise intensity and also be capable of identifying changes in movement patterns related to fatigue (129, 136).

Research within rugby league has substantially advanced the understanding of TL and fatigue. For example, fatigue-related measures of peak rate of force development ( $p = .042$ ) and peak power ( $p = .034$ ) produced during CMJ testing were significantly reduced up to 48 hours post-match (135). Moreover, external TL measures of the total number and severity of impacts assessed via micro-technology were significantly correlated to the peak rate of force development ( $r = -.61$ , large,  $p =$

.046) and peak power output ( $r = -.60$ , large,  $p = .049$ ) between 30 minutes and 24 hours post-match (135). Recently, progressive reductions in high speed match running output measured by GPS were associated with decreased CMJ performance throughout a period of congested match fixtures in an elite rugby league team (111). Collectively, these findings further highlight the exciting potential of micro-technology devices to provide objective measures of external TL that are meaningfully linked to outcomes of fatigue.

More recent research has also emphasised the potential capacity of using micro-technology in conjunction with multiple measures of fatigue to monitor the exercise dose-response relationship. For example, increases in cumulative high speed running distance ( $> 14.8 \text{ km h}^{-1}$ ) were associated with acute increases in HRex ( $r = .28$ , small,  $p = .02$ ) and perceived fatigue responses ( $r = -.31$ , small,  $p < .05$ ) to a subjective questionnaire in elite soccer players (84). A similar study in elite soccer also reported that daily increases in high speed running distance were related to decreases in HRV ( $r = -.24$ , small,  $p = .04$ ) and perceived ratings of wellness ( $r = -.51$ , large,  $p < .001$ ) (83). The authors of these studies concluded that responses to subjective questionnaires appeared the most effective method for monitoring changes in fatigue status related to external TL. However, the findings underlined the potential of GPS devices and HR indices as objective measures of TL and fatigue, respectively. These findings also encourage further investigation into the use of defined speed thresholds in GPS analyses to provide greater insight into relationships between external TL and fatigue responses.



### **3.4.3 Associations between internal TL and fatigue responses**

Session RPE was the most common method of quantifying internal TL in association with fatigue responses in elite football. The popularity of sRPE may stem from its practical nature; it is a relatively simple, cost effective, and time efficient method of quantifying internal TL from all forms of training and competition (57). Subjective questionnaires to assess fatigue were also frequently cited in the studies included for review. Specifically, all studies using sRPE to quantify internal TL also employed subjective questionnaires as a measure of fatigue. Of these, 12 studies used questionnaires as the sole measure of fatigue response to internal TL and/or competition. Much like sRPE, the simplicity and convenience of subjective questionnaires may largely explain their popularity within team sport environments.

In general, changes in the subjective fatigue responses of elite football players were associated with sRPE-derived internal TL. Specifically, increases in internal TL were associated with increased fatigue (small to moderate strength correlations) and poorer perceptions of wellness (small to moderate strength correlations) in all but one of the studies investigating relationships between internal TL and fatigue, despite varying questionnaire formats. The only study not to report significant relationships between internal TL using sRPE and subjective questionnaires for fatigue responses occurred in a group of rugby league players (144). The use of average weekly team scores for perceived wellness rather than the calculation of individual values may explain the absence of a relationship between internal TL and subjective fatigue in this study. However, subjective questionnaires appear to be a simple and effective tool to assess the individual fatigue response to training in elite football. Moreover, monitoring of sRPE TL and subjective

questionnaires can also provide valuable information about the perceptual responses to different between-match micro-cycles during competition phases in elite football (147)

Only four studies included for this review investigated relationships among internal TL and multiple fatigue responses (88, 105, 111, 113). Correlations of varying magnitude were reported between changes in daily internal TL through sRPE and changes in exercise heart rate ( $r = .80$ , large, CL [0.75 – 0.85]), heart rate variability ( $r = 0.51$ , large, CL [0.40 – 0.62]) and perceived wellness variables ( $r = 0.25$ , small, CL [0.14 – 0.36]) during a 2 week pre-season training camp in ARF (105). Decreases in CMJ performance and increases in perceived fatigue responses on a custom made questionnaire have also been reported in rugby league for up to 4 days post-match (113). Furthermore, changes in CMJ performance, salivary cortisol, and perceived fatigue were shown to be sensitive to variations in sRPE internal TL during between match micro-cycles of varying durations (113).

More recently, daily fluctuations in the sRPE TL of elite soccer players were associated with perceptual ratings of fatigue, sleep quality, and muscle soreness from a subjective questionnaire, but not to measures of HRex, HRR or HRV (88). However, it was postulated that the magnitude of daily change in sRPE TL may not have been insufficient to elicit significant change in any of these HR indices (88). Collectively, these results support a monitoring program which assesses the influence of TL on a variety of both objective and subjective fatigue markers to understand the multifactorial nature of fatigue, particularly during more intense periods training and competition.

Conflicting observations have been reported on the effect of air travel on relationships between internal TL (sRPE) and subjective fatigue responses in elite footballers. For example, internal TL was found to be greater after home games than away games throughout a soccer season. Despite this, there were no significant differences in perceived fatigue were observed using a customised questionnaire between home and away matches (143). In contrast, comparisons between two home and two away games in rugby league demonstrated significant differences in worse than normal fatigue response for both the Daily Analyses of Life Demands for Athletes and Karolinska Sleepiness Scale questionnaires; despite no significant differences in sRPE TL (145). Possible explanations for these opposing findings may be the specific physiological and travel demands associated with each sport, as well as the use of different questionnaires to assess perceived fatigue.

#### **3.4.4 Limitations of load and fatigue monitoring**

A number of limitations with fatigue monitoring in elite football were identified in this review. For example, the effectiveness of single and multiple biological markers to identify fatigue remains equivocal. Changes in a variety of blood and saliva markers in elite football have demonstrated variations of a small magnitude and values that remain typically within normal ranges (115, 117, 131, 134, 137). High ranges of individual variability in some blood and saliva measures also complicate the interpretation of data (112). Furthermore, the response of fatigue-related blood and saliva markers to changes in both external and internal TL remains unclear. Such findings may impede the willingness of applied sports scientists to include these objective fatigue markers in an athlete monitoring battery. Regular measurement of biochemical markers of fatigue can also be costly, inefficient and often an imposition on athletes. Currently, it may be more practical for blood

and saliva markers to be investigated only after warning signs have been triggered by other performance and or, psychometric fatigue monitoring strategies.

Physical tests such as the CMJ represent another objective measure that may be capable of estimating neuromuscular fatigue. Peak rate of force development on the CMJ test can be impaired for a period of 30 minutes to 48 hours post-match (113, 135). Furthermore, reductions CMJ performance has indicated increases in neuromuscular fatigue during congested fixture periods (111). However, the efficacy of such performance tests relies on the assumption that participants will consistently exert maximal effort and maintain similar power output between tests. Additionally, the use of both single (113, 129, 136) and multiple (84, 111, 115) CMJ jump protocols have been observed in elite football, limiting external validity.

Consensus is also lacking on the type of subjective questionnaires that best detect physical and/or psychological fatigue. Some studies in elite football have opted for validated methods such as the Profile of Mood States (131, 138) and Daily Analyses of Life Demands for Athletes questionnaires (145). Alternatively, others have chosen to develop or modify their own fatigue-related questionnaires, based on previous recommendations (84, 105, 106, 113, 132). The trend of utilising either modified or custom-made questionnaires in elite football is likely prompted by the desire to optimise both practicality and athlete compliance. Indeed, factors including the content, number of questions, frequency of completion, and implementation of technology are vital in the effectiveness of self-reporting tools (110). While these considerations are understandable in applied settings, caution should be advised not to modify questionnaires at the expense of the

psychometric qualities of validity and reliability. At the very least, validity and the reliability of popular fatigue questionnaires should be tested internally to confirm some scientific rigour of the instrument and ensure the relevance of the data being collected. Using validated questionnaires permits more meaningful comparison of results between studies, between athletes and within athletes, over time.

Inconsistencies in internal TL monitoring also exist within the use of sRPE. For example, several RPE scales are currently available, the most popular of which appear to be Borg's original category ratio 10 scale (64) and the modified version proposed by Foster et al. (5). The existence and implementation of multiple RPE scales within elite football (143, 144), along with inconsistent timing of reporting may negatively influence validity (5, 64). Although sRPE remains predominantly as a convenient method to quantify internal TL, RPE alone may be a useful measure of subjective fatigue (77) and was used as a tool to quantify perceived muscle soreness in ARF (106). However, the potential of RPE to monitor fatigue in elite football remains under-researched.

The implementation of subjective tools to assess TL and perceived fatigue have limitations. Players may choose to respond to scales or questionnaires in a way that looks favourably on their physical and/or psychological state, especially if they are aware that their responses may impact on team selection. The priority and frequency of reporting as well as the length of questionnaires are important considerations, while language and cultural differences within teams may also need to be accounted for. A fine balance must be achieved between gathering sufficient data and ensuring the process remains simple and practical to encourage compliance and validity. Despite

some obvious weaknesses with subjective measures, the sensitivity of wellness questionnaires to monitor change in perceived fatigue in response to acute fluctuations in TL are apparent (84, 88, 105, 106, 132).

This systematic review is not without limitations. First, modifying the PEDro quality of reporting scale may have resulted in an overrepresentation of high quality reporting. Nonetheless, it was a useful exercise in determining how well studies reported important issues in applied sports science such as reliability and quantification of key outcome variables.

Second, a number of well-designed studies were excluded from the systematic review because fatigue was inferred from decreases in running performance over time rather than directly measured. Although it is possible that temporal aspects of fatigue may manifest in decreased physical output during football match play, changes in performance throughout a match are likely to be influenced by a number of factors such as team tactics, opposition strength, and environmental factors (149, 150). As such, quantifying the contribution of fatigue to decreased physical output during football match play remains difficult.

Finally, although fatigue was the chosen outcome for this review into monitoring the dose-response relationship in elite football, it is acknowledged that investigation into effective measures of the fitness response would enhance the understanding of monitoring TL and training responses. This highlights the potential value of monitoring measures which may be able to identify changes in fitness and fatigue responses. However, as described in section 3.2.2,

monitoring of fatigue was believed to be of most urgency to applied sports scientists, particularly in team sports characterised by long season with regular match play.

### **3.4.5 Practical considerations**

The multifactorial nature of fatigue necessitates a range of different strategies be implemented as part of comprehensive athlete monitoring program. However, it is vital to understand that the TL distribution and physical demands may vary markedly across different football codes and as a result, so may the type and magnitude of fatigue. This may limit the usefulness of monitoring protocols to a sport-specific context. The constraints encountered in an applied sports science environment are also a vital consideration. While the validity and reliability of the chosen monitoring fatigue strategies are paramount, a number of context-specific factors need to be managed.

In any given environment, a multitude of factors such as cost, facilities, time, staff resources, and the compliance of players and coaches can impact on monitoring strategies. The interpretation of data also remains difficult, especially given that levels of reliability and typical variation can differ substantially among the most common athlete monitoring strategies (112). The establishment of normal daily variation and the smallest worthwhile change at an individual level for monitoring protocols may clarify the magnitude of change in a variable that warrants intervention (112).

Careful consideration is necessary when choosing which TL and fatigue monitoring strategies to implement in a team sport environment. Attention should be focussed on developing a comprehensive and sport-specific monitoring suite that compliments the applied setting. Collecting large amounts of data that lack practical relevance should be avoided.

### **3.4.6 Directions for future research**

The reviewed research demonstrates the need for a clearer understanding of the dose-response relationship between TL and fatigue in elite football. Specifically, a trend exists to move beyond time-based measures of external TL such as training and/or match exposure time to the more intricate details of external TL offered by micro-technology, particularly in relation to defined speed thresholds. Despite the accessibility and popularity of GPS and accelerometer devices, research within elite football linking micro-technology with fatigue appears sparse. Quantifying external TL via micro-technology has been the predominant focus of contemporary research rather than assessing the potential of micro-technology to aid in objectively identifying fatigue (55, 151, 152). However, the few studies exploring the relationship between micro-technology and traditional measures of fatigue in elite football appear promising (84, 88, 129, 135, 136).

The exciting potential of objective methods to quantify external TL also extends to the objective monitoring of fatigue. As discussed previously, the predominance of subjective methods of TL and fatigue monitoring is most likely dependent on their effectiveness and practicality within applied team sport environments. However, the inherent limitations associated with subjective measures of both TL and fatigue ensures that the monitoring of objective data is vital to provide a



more comprehensive assessment of the exercise dose-response relationship in elite football players. Indeed, the combined use of GPS technology to quantify external TL and HR indices to objectively monitor fatigue appears to hold particular promise (83, 84, 105) and therefore warrants further investigation. Additionally, exploration of monitoring methods which may be able to indicate both fitness and fatigue responses to TL would provide even greater value to practitioners in improving the understanding of the exercise dose-response relationship in elite football players.

### **3.5. Conclusion**

Vital links between both internal and external TL and multiple measures of fatigue in elite football remain unclear. While the large range of available strategies provides great scope to monitor fatigue, inconsistencies and isolated approaches in implementation and reporting may be detrimental to their effectiveness. Greater detail in the quantification of external and internal TL is necessary in studies exploring relationships between TL and training responses. Without superior depth and consolidation of knowledge, applied sports scientists remain limited in their ability effectively and comprehensively monitor fatigue in athletes.

## Chapter Link: Summary of systematic literature review study

Chapter 1:  
Introduction

Chapter 2:  
Narrative Literature Review

Chapter 3:  
Systematic Literature Review Study

Chapter 4:  
Methodology

1. Historical prevalence of time-based measures of external TL.
2. Popularity of subjective TL and fatigue monitoring strategies.
3. A number of limitations may influence practical implementation of current monitoring strategies.
4. Vital links between measures of TL and response remain unclear.
5. Identified need for further investigation of objective TL and fatigue monitoring strategies.

## **Chapter Four: Methodology**

### **4.1 Research design**

This program of research has an overarching focus on advancing the understanding of links between TL, responses to TL, and physical performance within a team sport setting. This thesis is comprised of four studies (Figure 4.1). Following a narrative review of literature, the results chapters begin with the systematic review entitled “Athlete monitoring strategies in elite football: Are they indicative of fatigue?” Study two is a concurrent validity and day-to-day reliability trial of the SIR test compared with a well-established measure of intermittent running capacity, the YYIR2 test. Having established validity and reliability, study three uses HR response to the SIR test to examine links with TL and individual responses over a six week pre-season training period. Study four extends investigations into SIR test HR responses and associations with in-season TL and match running performance.

Studies two to four present a strategic sequence of research using the same population (section 4.2) and a number of generic measurements (section 4.3) that are outlined in this chapter of extended methods. This extended methodology format has been implemented to provide greater detail around the number of measurements that are applicable across all results chapters, subsequently avoiding repetition later on in the thesis.

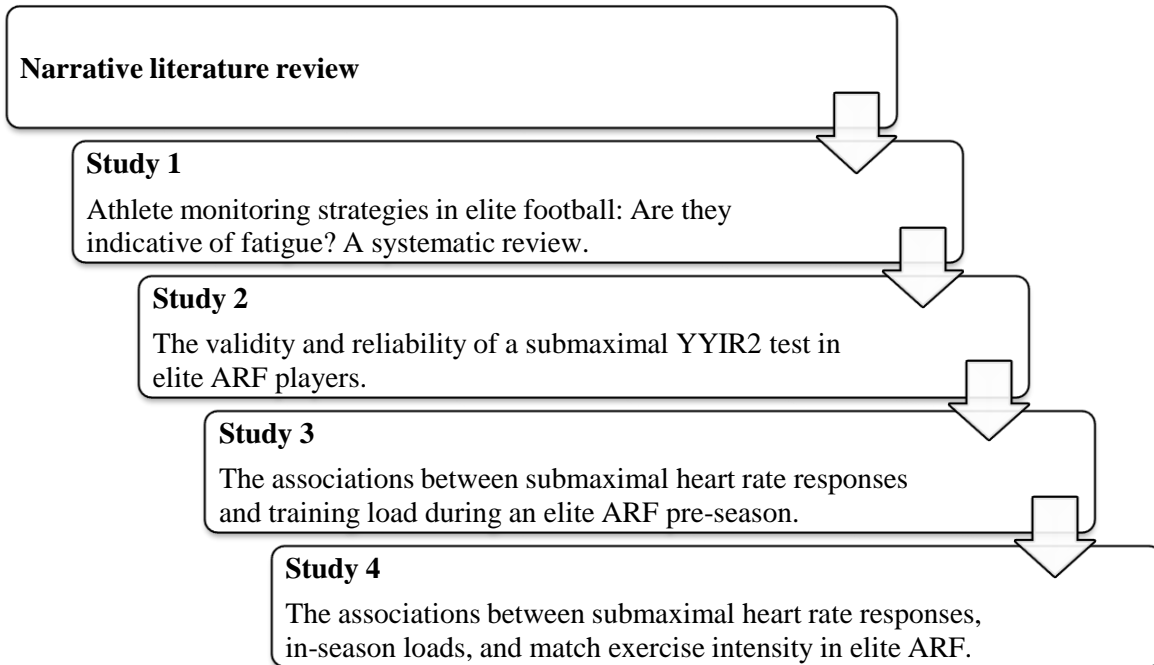


Figure 4.1 Outline of studies.

#### 4.1.1 Participants in studies 2 - 4

Participants for this research included professional ARF players from the Port Adelaide Football Club. Written informed consent was obtained from all participants to use their data for the purpose of research, following approval from the Human Ethics Research Committee at the Australian Catholic University (Appendix 3).

#### 4.1.2 Inclusion criteria

Players were invited to consent to the release of training and match data for the purpose of research (Appendix 3). Specifically, players needed to be part of the senior or rookie list within

the same elite level ARF club. Players were reminded that consent was voluntary and that withdrawal of their data was possible at any stage without consequence. Within this context, all invited players provided consent and there were no withdrawals of consent.

#### **4.1.3 Exclusion criteria**

On any given day, a player may have been excluded from testing due to current injury, illness or participation in modified training. Exclusion of a player from testing under these circumstances was the result of a collaborative decision between medical and sports science staff. Additionally, players may have been absent from testing due to other commitments such as club promotions and league duties. In total, 38 players participated in study two, 35 players participated in study three, and 34 players participated in study four.

#### **4.2 Generic measurements applicable to studies 2-4.**

Table 4.1 represents a summary of the generic measurements which were implemented across a number of studies within this traditional thesis.

Table 4.1 Variables common to most results chapters.

Measure	Study 2	Study 3	Study 4
Yo-Yo intermittent recovery 2 test	•		
Submaximal intermittent running test	•	•	•
Heart rate	•	•	•
Rating of perceived exertion		•	•
Global positioning system		•	•
Subjective wellness		•	•

#### 4.2.1 Description of Yo-Yo intermittent recovery level 2 test

A number of possible maximal tests are available to assess different fitness capacities in athletes. The intermittent running based nature of ARF imposes stress on all three energy systems (153) and therefore requires a test that can replicate these demands. The specific purpose of the YYIR2 test is to assess an individual's ability to perform intense intermittent exercise requiring large contributions from both the aerobic and anaerobic energy systems (10). Furthermore, superior YYIR2 performance is associated with greater high speed running volumes in both elite soccer (10) and ARF matches (154). Subsequently, the YYIR2 test is considered a relevant assessment of the intermittent running demands required in elite team sports. The validity, reliability, and physiological responses to the maximal version of YYIR2 test are well established (10, 11).

The YYIR2 test was performed indoors on an artificial turf surface using previously described procedures (11). The test consisted of repeated 2 x 20 m shuttle runs at a progressively increased speed. The speed was controlled by audio beeps from a pre-recorded source. Participants had a 10 second active recovery period between each 2 x 20 m shuttle run that consisted of a 5 m shuttle completed at walking pace. The first level of the YYIR2 test commenced at 13 km h<sup>-1</sup> and was followed by stepwise speed increments until either volitional exhaustion or failure to reach the finishing line occurred twice in the allocated time, as determined by multiple expert assessors. The test result was recorded as the total distance covered. Individuals completed a standardised 10 minute warm up prior to testing that involved various running exercises with increasing intensity towards test commencement. Heart rate was recorded continuously during the protocol for each athlete using a Firstbeat HR monitor (Firstbeat Technologies, Jyväskylä, Finland) placed around the chest. The HR devices are reported to correctly detect 99.98% of heart beats and possess a mean average error of 2.27% following concurrent validity testing with an electrocardiogram (155).

#### **4.2.2 Description of submaximal intermittent running (SIR) test**

A number of submaximal tests exist in the literature; however, it appears none have been designed to specifically assess the intermittent running demands associated with elite Australian football. Therefore, the SIR test followed a similar protocol to the YYIR2 test. However, modifications were made based on the following testing priorities: 1) to be of a submaximal intensity to minimise excessive additional fatigue, 2) to impose a submaximal intensity that reduces day-to-day variation in HR, and 3) to allow for easy incorporation into a warm up. As

such, the SIR test consisted of 2 x 18 metre repeated shuttle runs and terminated after four minutes (Figure 4.2).

Day to day variation in submaximal HR can be at its lowest during exercise of higher intensities, for example 85 to 90% of HRmax (59, 92). Preliminary testing in the group of athletes targeted for this thesis indicated that the relative intensity of HR at the end of the final working stage of the SIR test was  $82 \pm 4\%$  of HRmax. Given the above considerations for low HR variability and the desire for the test to be truly submaximal [i.e. illicit a HR response between 75 to 85% of HRmax (156)], it appeared that the use of a fixed four minute test protocol would provide an acceptable intensity for testing. Additionally, submaximal HR prior to, but not after four minutes of the YYIR2 test was moderately correlated to YYIR2 test performance in a group of sub-elite soccer players ( $r = -0.45$ ,  $p < 0.05$ ) (157), further strengthening the rationale for this protocol.

Following the four minutes of activity, a recovery period of three minutes was implemented in which players were required to remain in a stationary standing position. Heart rate was recorded continuously during both the active and recovery periods using a Firstbeat HR monitor (Firstbeat Technologies, Jyväskylä, Finland) placed around the chest. Details about the HR indices collected during SIR testing are described in sections 4.2.3 to 4.2.5.



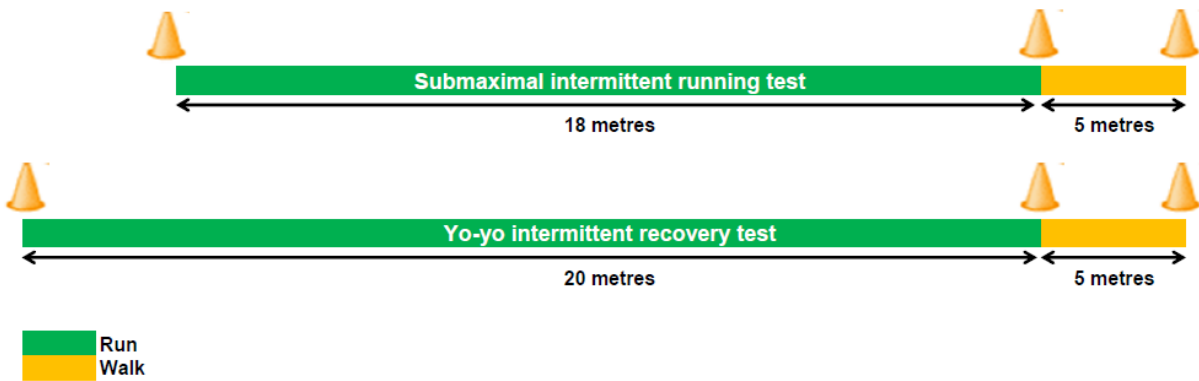


Figure 4.2 Comparison of protocols for intermittent running tests. The submaximal test was reduced by two metres to reduce the overall intensity of the test, as described in section 4.2.2.

#### 4.2.3 Measuring heart rate responses and from the SIR test

The narrative review describes a number of benefits and limitations associated with HR monitoring. Furthermore, the systematic review of literature suggests that the implementation of HR monitoring to measure fatigue is limited in elite football codes. However, with improvements in technology and testing protocols, it is possible that HR data could become more useful in assessing the training status of athletes.

As discussed in the narrative review, the relationship between HR and exercise can be influenced by a variety of factors such as mode of exercise, training status, exercise duration, environmental conditions, time of day, hydration status, and caffeine intake (59). Thus, the following standardised conditions were considered to manage environmental factors that can influence HR

- All YYIR2 and SIR testing were performed indoors at the same time of day (AM) on an artificial turf surface.
- All participants took part in a standardised warm up prior testing.
- All participants were advised to maintain their normal daily routine on the morning of testing (e.g. similar breakfast and fluid consumption, same clothing and shoes).
- The same sports science staff administered each test to ensure procedures remained consistent.

#### **4.2.4 Submaximal exercise heart rate (HR<sub>ex</sub>)**

Submaximal exercise HR was calculated as the mean HR (expressed as a percentage of maximal HR) during the final 30 seconds of the four minute active period of the SIR test (6). In addition, HR<sub>ex</sub> was also calculated at the two- and three- minute mark of the SIR test to assess the suitability of shorter testing protocols (Chapter 5). Each individual's maximal HR (HR<sub>max</sub>) was predetermined as the peak HR reached during YYIR2 testing; reported to be a valid estimate of maximal heart rate response (10).

Heart rate responses to exercise performed at less than maximal intensity are traditionally founded on the assumptions that HR<sub>ex</sub> at a fixed intensity decreases as fitness improves (59). Additionally, elevated HR<sub>ex</sub> at a fixed intensity may indicate a lack of physical conditioning (59). However, decreases in HR<sub>ex</sub> have also been associated with overreaching (158).

Collectively, such findings complicate the interpretation of HR<sub>ex</sub> data given that similar changes

can occur in both positive and negative training adaptation. As such, it is vital that any change in HR<sub>ex</sub> is interpreted in the context of the specific training phase and in conjunction with other monitoring strategies.

#### **4.2.5 Heart rate recovery (HRR)**

Day to day variation in HR recovery has been reported to be lowest during the first minute after exercise, with increased variability noted after the second and third minutes (92). Subsequently, it is suggested that the greatest sensitivity to detect meaningful change in HR recovery is most likely to occur within the first minute following exercise (92). However, these findings have not been confirmed in elite ARF players. Therefore, HR recovery was recorded after the first (HRR<sub>60s</sub>), second (HRR<sub>120s</sub>), and third minute (HRR<sub>180s</sub>) of recovery following the four minute active period of the SIR test. Heart rate recovery was calculated as the absolute difference between submaximal exercise HR and HR after each minute of the recovery period (156).

Changes in HRR are a potential response to recently applied TL's (7). For example, faster HRR is associated with improvements in training status while slower HRR is a potential indicator poor fitness (90). However, faster HRR has also been associated with overreaching in some athletes (89). Therefore, as with HR<sub>ex</sub>, the interpretation of HRR data is confounded the ambiguity of change in relation to TL. Subsequently, change in HRR generally cannot be used in isolation to accurately assess training status in athletes.

Given that the response to a standardised test may vary with a change in training status, adapting submaximal workloads to coincide with a specific intensity range may improve the measurement of HRR (159). While the individual adaptation of workload (e.g. variable distance/time) in the SIR test may be ideal, this would likely limit the external validity of the test and negatively influence its practicality in a team sport environment in which a large number of athletes is tested simultaneously. Therefore, to account for any potential change in HR<sub>ex</sub> that may have impacted the measurement of HRR, HRR data was expressed as a percentage of HR<sub>ex</sub> (156). This relative measure was also likely to minimise any interpersonal differences (7). Figure 4.3 illustrates when measures of HR were collected during SIR testing.

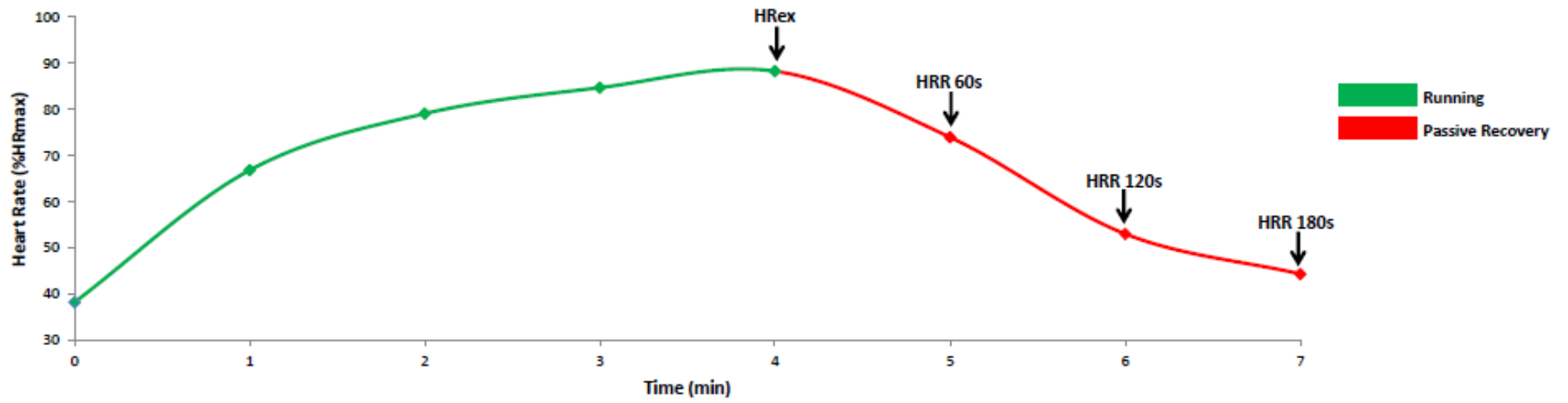


Figure 4.3 Example heart rate trace from SIR testing, including measurement time points of selected indices.

#### **4.2.6 Quantification of internal load using session rating of perceived exertion**

Training loads must be quantified in order to correctly interpret responses to training (7).

Subsequently, session rating of perceived exertion (sRPE) was used to quantify the TL from all modalities of training. The original RPE scale was designed to provide a valid and reliable measure of the perceived exertion associated with a bout of physical work (64). Exercise intensity and perceived exertion are closely related concepts. Subsequently, RPE can be used as a method to estimate the intensity of exercise (64). The presence of fatigue is likely to cause an increase in RPE during submaximal intensity exercise (77).

A modification of Borg's original RPE scale was developed to provide a simpler scale with the capability of representing the global intensity of an exercise session (5). An example of this scale is shown in Table 4.2. This method requires individuals to rate their perceived exertion using the scale by answering the aforementioned question "How was your workout?" (Section 2.2.3.3) approximately 30 minutes after the session is completed (67). Although it has been traditionally advised to collect RPE 30 minutes post-exercise to more accurately reflect the global intensity of a training session, recent research suggests that more immediate measurement does not affect an individual's RPE (160). Previously, RPE has demonstrated a strong correlation with objective measures of exercise intensity such as heart rate, maximal oxygen consumption and blood lactate concentration (5, 23, 65). Specifically, the correlation between RPE and heart rate, and RPE and blood lactate, was 0.89 and 0.86, respectively in a group of sub-elite rugby players (23). The intra-class correlation for test re-test reliability and typical error of measurement for the RPE

scale were 0.99 and 4.0%, respectively for this cohort (23). Subsequently, RPE appears to be an acceptable method of estimating training intensity in intermittent team sports.

Using the RPE scale, a single TL value can be calculated by multiplying the given RPE by the duration of the exercise session in minutes (5). This method for determining sRPE, has demonstrated concurrent validity in sub-elite ARF (72) and other elite football codes including rugby league (71) and Canadian football (73). Collectively, these results support the use of sRPE as an acceptable method to quantify internal TL.

Table 4.2 Foster's modified RPE Scale.

<b>Rating</b>	<b>Descriptor</b>
0	Rest
1	Very, Very Easy
2	Easy
3	Moderate
4	Somewhat Hard
5	Hard
6	-
7	Very Hard
8	-
9	-
10	Maximal

#### **4.2.7 Quantification of external load using global positioning system technology**

The introduction of global positioning system (GPS) technology into high performance sport has enabled the quantification of various elements of external TL. For every outdoor training session, each player wore a GPS unit (Optimeye S5, Catapult Innovation, Melbourne, Australia) sampling at 10 Hz. The devices were positioned between the scapula on the upper back and housed within a custom-designed pouch inside the player's jersey. At the conclusion of training,



the GPS units were collected and data downloaded using the proprietary software “Catapult Openfield” (Catapult Innovations, Melbourne, Australia).

Variables collected from the GPS units included total distance, distance covered per minute, high speed running distance ( $>14.4 \text{ km}\cdot\text{h}^{-1}$  [Zone 4]), very high speed running distance ( $>19.8 \text{ km}\cdot\text{h}^{-1}$  [Zone 5]), sprinting distance ( $>25.2 \text{ km}\cdot\text{h}^{-1}$  [Zone 6]), and total high speed running distance (HSR), which equated to the sum of distances covered within Zones 4, 5 and 6. Currently, there is no universally accepted speed zone thresholds used within the literature. As such, there is a varying range of speed thresholds reported, particularly from studies which emanate from practical settings. The absolute speed zones used in this thesis were consistent with those implemented by practitioners at the club for the purpose of providing ecological validity, consistency for data comparisons across seasons and for the practicality of monitoring a large group of athletes simultaneously. Global positioning system technology is reported to have acceptable levels of validity and reliability in the quantification of movement demands during both constant and intermittent running (43, 161). However, as previously stated, controversy surrounds the capacity of GPS devices to accurately detect some sport-specific movements.

#### **4.2.8 Subjective wellness questionnaire**

A recent systematic review supports the use of subjective tools to measure individual athletes responses to training stress (93). Indeed, a plethora of validated and customised questionnaires to measure various aspects of perceived wellness are reported in the literature. Factors that can

influence the implementation of questionnaires and subsequently determine their effectiveness include type and number of questions, frequency of measurement, utilisation of technology, and positive culture that fosters trust amongst players and support staff (110). Ultimately, it appears that subjective wellness questionnaires are most effective when they are tailored to meet the requirements of individuals within a specific environment (110). This is a likely explanation for the popularity of custom-made questionnaires in applied settings. Subsequently, players were asked to complete a custom-made subjective wellness questionnaire that consisted of four items deemed most important by club sports science staff; sleep quality, self-efficacy, general muscle soreness, and fatigue (Appendix 4). Each item was rated on a Likert scale ranging from one to ten, with lower scores in sleep quality and self-efficacy, as well as higher scores in general muscle soreness and fatigue, considered to indicate negative adaptation to training (Figure 4.4). This custom questionnaire was assessed internally by club sports science staff and deemed to have acceptable levels of validity and reliability in the current playing group. Players completed the questionnaire twice a week using a personal computer or smartphone and the results were forward to club fitness staff for collation and analyses.

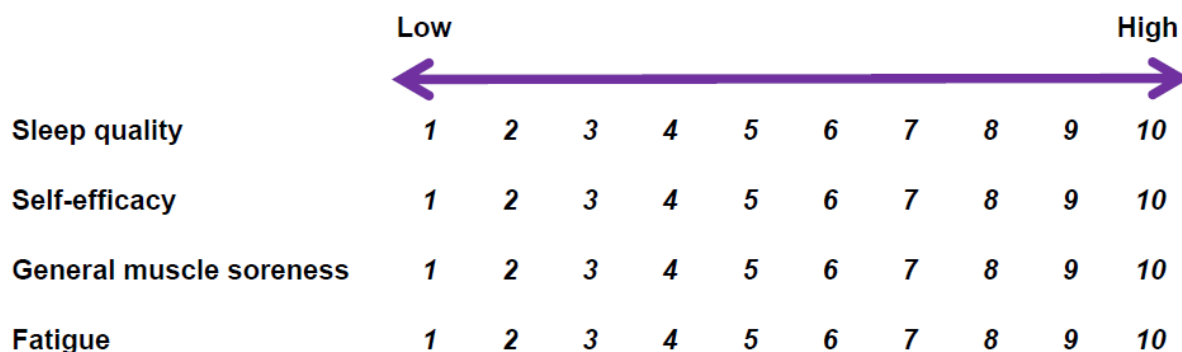


Figure 4.4 Visual representation of subjective wellness questionnaire.

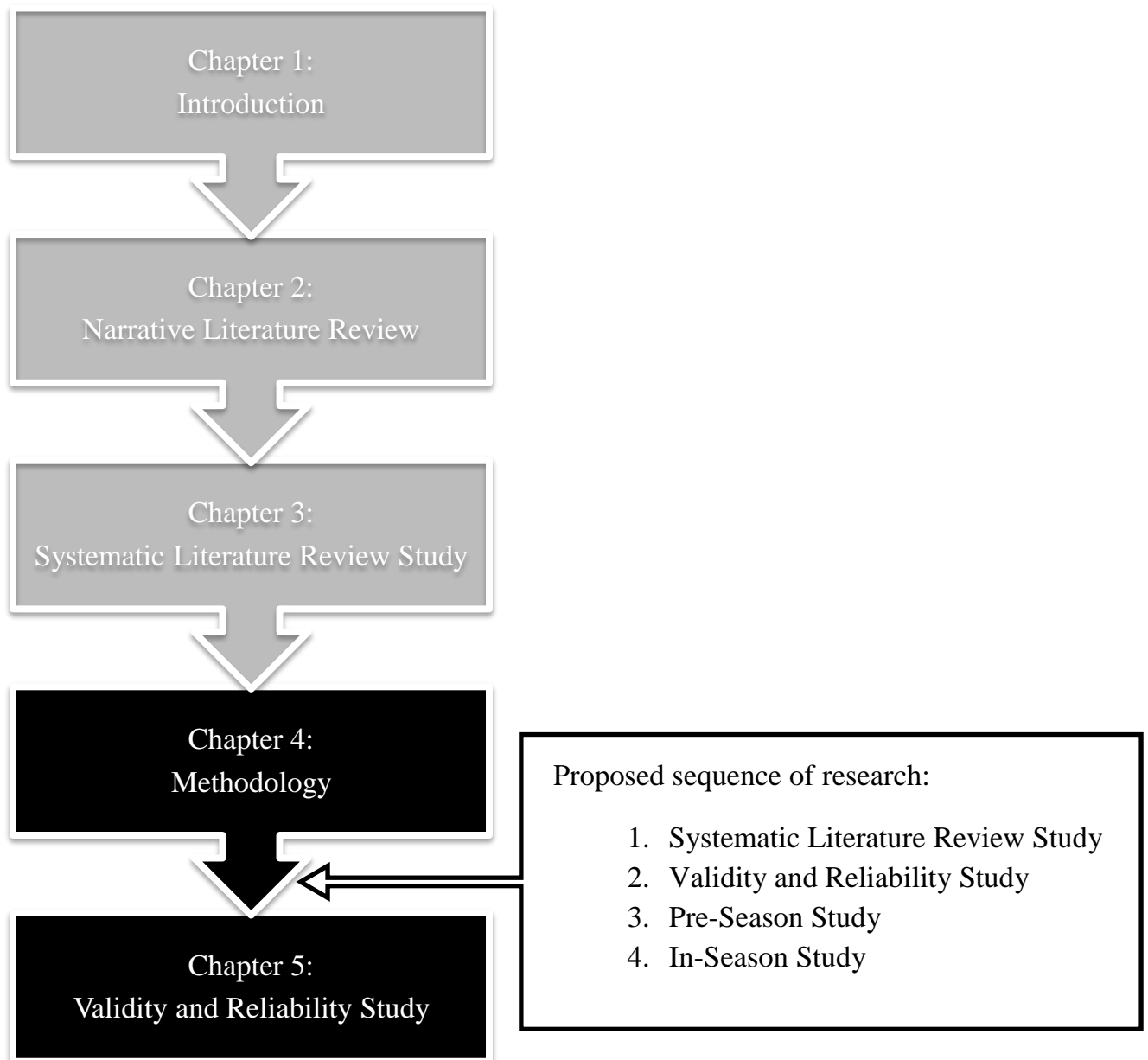
#### **4.2.9 Summary of statistical analyses**

For an expected correlation of at least 0.50 between SIR test performance and markers of fitness and fatigue, it was estimated that a minimum sample size of 30 participants was required for studies 2-4 to maintain statistical power (80%,  $p < 0.05$ ) (162). Table 4.3 represents the scope of statistical analyses for studies 2 to 4. Within studies 3 to 4, statistical comparisons were conducted to assess the influence of playing position on outcome variables.

Table 4.3 Scope of statistical analyses within results chapters.

<b>Analyses methods</b>	<b>Study 2</b>	<b>Study 3</b>	<b>Study 4</b>
Descriptive	•	•	•
Linear regression	•		
Paired t-test	•		
Intra-class correlation coefficient	•		
Typical error	•		
Coefficient of variation	•		
Smallest worthwhile change	•		
Confidence limits (95%)	•		
Confidence limits (90%)		•	•
Linear mixed effect analysis		•	•
Magnitude-based inferences			•

## Chapter Link: Summary of methodology



## **Chapter Five: Validity and reliability of a submaximal intermittent running test in elite Australian football players**

### **5.1 Introduction**

Evaluating sport-specific abilities is an important component of high performance programs (10). Physiological capacities and responses to training are ideally assessed via valid, reliable and relevant testing that requires a maximal effort representative of competition (25). For example, the Yo-Yo intermittent recovery 2 (YYIR2) test is capable of determining an athlete's capacity to perform intense intermittent exercise and is reported to have a strong positive relationship with match high speed running distance in both elite soccer (10, 163) and ARF (154). The YYIR2 test also has the potential to differentiate between fitness levels, among playing positions, playing standards, successful or unsuccessful teams, and season phases (11, 157). Importantly, research has demonstrated that ARF players who have a higher intermittent running capacity as assessed by the YYIR2 test can produce higher match exercise intensity and accrue more ball disposals during matches (136, 154). Superior YYIR2 test results are also reported to positively influence match performance as assessed by coaches votes (136). Match performance in team sports is likely influenced by a multitude of factors such as technical skill, tactical ability, team strength, opposition strength and score line (149, 150, 164). However, current research highlights the potential of the YYIR2 test in evaluating physiological capacities that can affect ARF match performance.

The validity, reliability, and physiological responses to YYIR2 test performance are well established (10, 11). However, exposing athletes to maximal testing on a regular basis is rarely appropriate in elite team sport given the resultant increase in residual fatigue would likely compromise recovery for subsequent training and competition (25). Consequently, routine fitness testing in team sport environments must be balanced with the management of player well-being and fatigue to ensure minimal disruption to the overall program (25).

Submaximal testing may provide a viable alternative for monitoring physiological capabilities and responses to training (165). In contrast to maximal testing, submaximal tests can be implemented frequently as a monitoring tool without adversely affecting the normal training process or causing excessive fatigue (25). The submaximal heart rate responses of soccer players to the Yo-Yo intermittent recovery 1 (YYIR1) and YYIR2 tests have been found to be negatively correlated with maximal test performance (10, 166). This suggests that submaximal versions of the Yo-Yo intermittent recovery tests may be capable of predicting maximal test performance. To date, previous testing has investigated only associations between heart responses and performance within the same maximal test. However, the capacity of a *standalone submaximal intermittent running test* based on the YYIR2 to evaluate the intermittent running capacity of team sport athletes is yet to be investigated.

Monitoring heart rate (HR) during submaximal exercise may also provide objective information about the body's physiological responses to variations in TL (91). Heart rate variables such as exercise heart rate (HREx) and heart rate recovery (HRR) have been used to unobtrusively and

non-invasively monitor training status in endurance sports with varying levels of success (91). For example, a more rapid HRR and decreased HRex have indicated improved fitness (59, 91) and states of overreaching (82, 89). Conversely, slower HRR and increased HRex are potential indicators of deconditioning (59, 90). When considered in the context of a specific training phase, such variables may provide valuable insight into an individual's readiness to perform that could prove to be particularly useful in high performance settings.

The benefits of using HR responses to a standalone submaximal intermittent running test for monitoring fitness and fatigue in elite team sport athletes remain uncertain. Despite potential advantages of submaximal testing, modified tests require assessment for validity and reliability before they can be deemed effective. Therefore, the aim of this study was to establish the concurrent validity and reliability of a submaximal intermittent running (SIR) test in a group of elite ARF players.



## **5.2 Methods**

### **5.2.1 Participants**

Participants were 45 senior and rookie-listed professional ARF players from one Australian Football League (AFL) club (mean  $\pm$  SD; age  $23 \pm 4$  years, height  $188 \pm 8$  cm, body mass  $85 \pm 8$  kg, time spent on an AFL list  $6 \pm 4$  years). Following approval from the Human Ethics Research Committee at the Australian Catholic University, written informed consent was obtained from all participants to use their data for research purposes (Appendix 3). All participants completed testing as part of the normal training regime and were familiar with testing procedures prior to the study. Participants were free from any injury that may have limited their ability to complete testing.

### **5.2.2 Study design**

Concurrent validity of the SIR test was investigated using correlations between HR responses from the SIR and measures from YYIR2 testing (e.g. maximal distance and HR responses). The SIR and YYIR2 tests were completed 48 hours apart. This timeframe was chosen to represent a balance between minimising residual fatigue and ensuring that fitness levels of athletes remained stable between tests. Test randomisation was not used as it was believed completing the YYIR2 test before the SIR test may result in a fatigue-related performance decrement that would influence SIR test results. The protocol was completed twice for reliability purposes, during two different weeks in the pre-season period that both followed reduced load weeks. Table 5.1 presents a typical weekly pre-season training schedule, including validity testing for the SIR test. The day-to-day reliability of the SIR test was then evaluated over three trials on successive days

following a subsequent de-loading week in the pre-season phase. HR was monitored continuously during each test using Firstbeat HR monitors and data were downloaded using the proprietary software (Firstbeat Technologies, Jyväskylä, Finland). The validity of these HR devices has been established (155).

Table 5.1 Typical pre-season training schedule including testing protocol for validity

	<b>Mon</b>	<b>Tues</b>	<b>Wed</b>	<b>Thurs</b>	<b>Fri</b>	<b>Sat</b>	<b>Sun</b>
<b>A</b>	<i>SIR test</i>	Resistance	<i>YYIR2 test</i>	Off	Skills and	Running	Off
<b>M</b>	<i>(Weeks 5 &amp; 9)</i>	Training	<i>(Weeks 5 &amp; 9)</i>		Running Conditioning	Conditioning	
		Cross					
	Skills and Running Conditioning	Training	Skills and Running Conditioning				
<b>P</b>	Resistance	Off	Resistance	Off	Resistance	Off	Off
<b>M</b>	Training		Training		Training		
	Recovery		Recovery		Recovery		

The relationship between HR and exercise can be influenced by a variety of factors including mode of exercise, training status, exercise duration, environmental conditions, time of day, hydration status, and caffeine intake (59). Therefore, the following standardised conditions were employed to minimise confounding factors with the potential to mask a change in training status:

1) all SIR and YYIR2 testing were performed indoors at the same time of day (AM) on the same artificial turf surface; 2) athletes participated in a standardised 10 minute warm up prior to testing that consisted of various running-based exercises of increasing intensity; 3) athletes were advised to maintain their normal daily routine on the morning of testing [e.g. similar breakfast and fluid consumption, caffeine intake, same clothing and shoes]; and 4) the same sports science staff administered each test to ensure procedures remained consistent.

#### **5.2.2.1 Yo-Yo intermittent recovery 2 test**

The YYIR2 testing was performed using previously established procedures (11). Heart rate was recorded continuously throughout the protocol for each athlete using a Firstbeat HR monitor placed around the chest. Please refer Section 4.2.1 for a full explanation of Yo-Yo intermittent recovery 2 test procedures.

#### **5.2.2.2 Submaximal intermittent running test**

The SIR test followed a similar protocol to the YYIR2 test. However, modifications were based on pre-determined testing priorities to: 1) impose only a submaximal intensity to minimise additional fatigue, 2) elicit a submaximal intensity that minimises day-to-day variability in HR and 3) allow for easy incorporation into a warm up. Heart Rate was recorded continuously during both the running and recovery periods using a Firstbeat HR monitor placed around the chest. Please refer to Section 4.2.2 for a full explanation of submaximal intermittent running test procedures.

### **5.2.2.3 Measuring heart rate responses to exercise**

HR<sub>ex</sub> was calculated as the average HR (expressed as a percentage of HR<sub>max</sub>) during the final 30 seconds of the four minute running period of the SIR test (156). To explore the suitability of shorter testing protocols, HR<sub>ex</sub> was also calculated at the two and three minute mark of the SIR test. In addition, HR<sub>ex</sub> was monitored throughout YYIR2 testing to provide comparisons with the SIR test. Heart rate recovery was determined at three time points; one minute (HRR<sub>60s</sub>), two minutes (HRR<sub>120s</sub>), and three minutes (HRR<sub>180s</sub>) following the four minute running period of the SIR test. Please refer to Sections 4.2.3 to 4.2.5 for a full explanation of the procedures used to measure heart rate response to exercise.

### **5.2.3 Statistical analyses**

Validity analyses were conducted with SPSS for Windows and reliability analyses were performed using a reliability-specific spreadsheet (167). Descriptive statistics are reported as mean  $\pm$  SD. A Shapiro Wilk test was used to verify the normal distribution of the data. Statistical significance was set at  $P \leq 0.05$ .

#### **5.2.3.1 Concurrent validity**

Linear regression analysis was used to examine the degree of association between SIR test and YYIR2 test HR responses and YYIR2 test performance. Magnitudes of Pearson's correlation coefficients were assessed based on the following recommendations: trivial ( $r < 0.1$ ), small ( $0.1 < r < 0.3$ ), moderate ( $0.3 < r < 0.5$ ), large ( $0.5 < r < 0.7$ ), very large ( $0.7 < r < 0.9$ ), nearly perfect ( $r > 0.9$ ) and perfect ( $r = 1$ ) (1). Paired t-tests were used to establish any differences in HR<sub>ex</sub> at

corresponding time points under maximal and submaximal conditions. Statistics were reported with 95% confidence limits.

### **5.2.3.2 Reliability**

Test re-test reliability of the SIR test was determined using a reliability-specific spreadsheet (167) that calculated the change in mean, intra-class correlation coefficient (ICC), and typical error of measurement (TE) expressed as a coefficient of variation (CV). Again, reliability statistics were reported with 95% confidence limits. The smallest worthwhile change (SWC) was also used to compliment TE and assess test usefulness. The rearrangement of Cohen's *d* effect size calculation enabled the SWC to be determined by multiplying the smallest worthwhile effect (0.2) by the between-subject SD (168). A test's capacity to detect change is considered "good" when  $TE \leq SWC$ , "satisfactory" when  $TE = SWC$ , and "marginal" when  $TE \geq SWC$  (169).

## **5.3 Results**

### **5.3.1 Concurrent validity**

Descriptive statistics for SIR and YYIR2 test protocols during validity testing are presented in Table 5.2. A total of 38 players completed submaximal and maximal testing under standardised conditions ( $21 \pm 2.1^\circ\text{C}$ ,  $41 \pm 3\%$  relative humidity). The mean distance travelled during the YYIR2 test was  $1141 \pm 318$  m. In comparison, the SIR test had a capped distance of 468 m. HR<sub>ex</sub> was consistently lower at each corresponding time point in the SIR test compared with the YYIR2 test (Table 5.2).

Results from linear regression analyses for validity testing are presented in Table 5.3.

Consistently large inverse correlations were reported between two, three, and four minute HRex during the SIR test and YYIR2 test performance, as denoted by total distance covered ( $r = -.58 - .61, P < 0.01$ ). Large inverse correlations also existed within the YYIR2 test between total distance and HRex at two, three, four, five and six minutes ( $r = -.50 - -.60, P < 0.01$ ). In contrast, the relationship between HRex at 7 and 8 minutes of the YYIR2 test and total distance covered during the YYIR2 was moderate ( $r = .42 - .48, P < 0.01$ ). Submaximal intermittent running test HRR<sub>120s</sub> and HRR<sub>180s</sub> were also moderately correlated to YYIR2 test total distances ( $r = .32 - .35, P < 0.05$ ). A small correlation was observed between HRR<sub>60s</sub> during the SIR test and YYIR2 test distance ( $r = .24, P = 0.07$ ).

The relationship between 4 minute HRex during SIR and YYIR2 test conditions and YYIR2 test performance is illustrated in Figure 5.1. Thirty percent of the variation in YYIR2 test performance was explained by HRex at the 4 minute mark of the test. In comparison, 34% of the variation in YYIR2 test performance was explained by HRex at the 4 minute mark of the SIR test.

Table 5.2 Descriptive statistics (group mean  $\pm$  SD) for validity testing (n = 38)

Test parameters	YYIR2 test	SIR test	Mean difference <sup>†</sup>
Total distance (m)	1141 $\pm$ 318	468	673.1** (587.9 – 758.2)
Two min HRex <sup>*</sup>	79.3 $\pm$ 6.9%	76.4 $\pm$ 7.1%	2.9** (2.0 – 3.8)
Three min HRex <sup>*</sup>	83.6 $\pm$ 6.3%	80.6 $\pm$ 6.4%	3.0** (2.3 – 3.8)
Four min HRex <sup>*</sup>	87.5 $\pm$ 6.1%	84.4 $\pm$ 6.3%	3.1** (2.4 – 3.9)
Five min HRex <sup>*</sup>	88.9 $\pm$ 5.7%	-	-
Six min HRex <sup>*</sup>	90.2 $\pm$ 5.4%	-	-
Seven min HRex <sup>*</sup>	91.5 $\pm$ 5.1%	-	-
Eight min HRex <sup>*</sup>	92.8 $\pm$ 4.8%	-	-
HRR <sub>60s</sub> <sup>♦</sup>	-	22.7 $\pm$ 7.0%	-
HRR <sub>120s</sub> <sup>♦</sup>	-	38.3 $\pm$ 6.8%	-
HRR <sub>180s</sub> <sup>♦</sup>	-	43.6 $\pm$ 5.8%	-

<sup>†</sup> (With 95% confidence limits)

\*\*  $P < 0.01$

<sup>\*</sup> Expressed as % of HRmax

<sup>♦</sup> Absolute difference between four minute HRex and HRR at each time point, expressed as a percentage of four minute HRex

Table 5.3 Pearson's correlations between heart rate response and YYIR2 test distance (n = 38)

Test parameters	SIR test <sup>†</sup>	YYIR2 test <sup>†</sup>
Two min HRex	-0.61** (-.74 – -.42)	-0.60** (-.74 – -.41)
Three min HRex	-0.58** (-.72 – -.38)	-0.56** (-.71 – -.36)
Four min HRex	-0.58** (-.72 – -.38)	-0.55** (-.70 – -.35)
Five min HRex	-	-0.5** (-.67 – -.28)
Six min HRex	-	-0.5** (-.67 – -.28)
Seven min HRex	-	-0.48** (-.65 – -.26)
Eight min HRex	-	-0.42** (-.61 – -.19)
HRR <sub>60s</sub>	0.24 (-.01 – .46)	-
HRR <sub>120s</sub>	0.35** (.01 – .55)	-
HRR <sub>180s</sub>	0.32* (.07 – .53)	-

<sup>†</sup> (With 95% confidence limits)

\*  $P \leq 0.05$

\*\*  $P < 0.01$



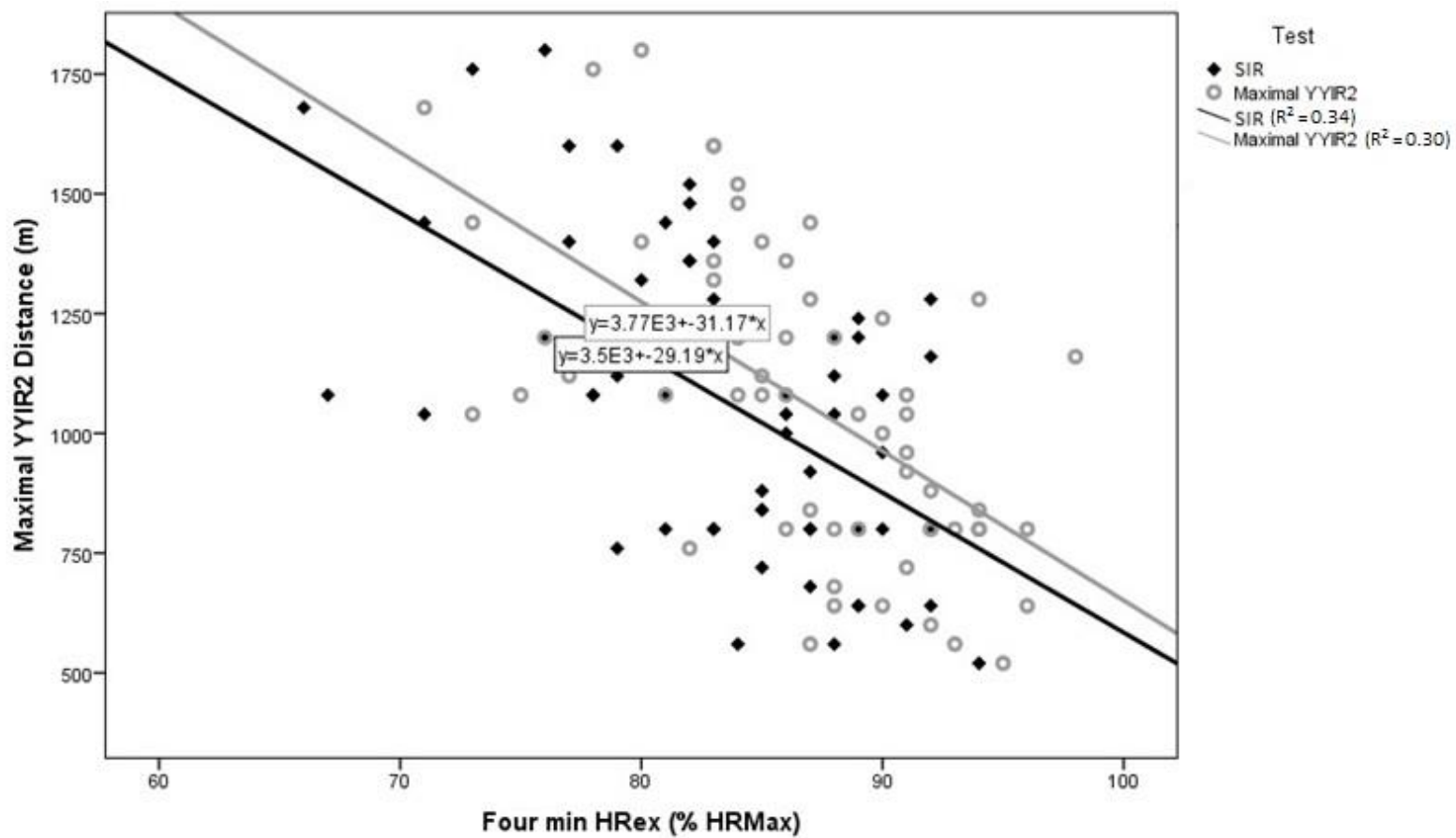


Figure 5.1 Relationship between 4 min HRex during the SIR and YYIR2 tests and YYIR2 test performance.

### 5.3.2 Reliability

Descriptive statistics for reliability testing are shown in Table 5.4. A total of 25 players completed all three SIR tests on successive days under standardised conditions ( $23 \pm 1.4^{\circ}\text{C}$ ,  $39 \pm 2\%$  relative humidity).

Inferential statistics for the reliability trials are displayed in Table 5.5. Strong correlations for ICCs were observed for all HRex and HRR measures ( $r = .90 - 0.97$ ) (1). CV ranged between 1.3% and 9.2% for all variables. Four minute HRex recorded both the strongest ICC ( $r = 0.97$ ) and lowest CV (1.3%). Of all test parameters, four minute HRex was the only variable to achieve a  $\text{TE} < \text{SWC}$ .

Table 5.4 Descriptive statistics (group mean  $\pm$  SD) for reliability of SIR test (n = 25)

Test parameters	Mean $\pm$ SD		
	Test 1	Test 2	Test 3
Two min H <sub>Rex</sub> <sup>*</sup>	74.4 $\pm$ 5.9%	75.0 $\pm$ 5.3%	75.7 $\pm$ 5.2%
Three min H <sub>Rex</sub> <sup>*</sup>	78.0 $\pm$ 5.7%	78.1 $\pm$ 5.5%	78.9 $\pm$ 5.4%
Four min H <sub>Rex</sub> <sup>*</sup>	81.5 $\pm$ 5.8%	81.8 $\pm$ 5.5%	82.4 $\pm$ 5.2%
HRR <sub>60s</sub> <sup>♦</sup>	25.6 $\pm$ 8.1%	24.3 $\pm$ 9.0%	25.2 $\pm$ 9.0%
HRR <sub>120s</sub> <sup>♦</sup>	38.1 $\pm$ 6.7%	38.9 $\pm$ 6.7%	39.1 $\pm$ 7.2%
HRR <sub>180s</sub> <sup>♦</sup>	42.2 $\pm$ 6.0%	42.8 $\pm$ 6.2%	43.3 $\pm$ 6.7%

\* Expressed as % of HRmax

♦ Absolute difference between four minute H<sub>Rex</sub> and HRR at each time point, expressed as a percentage of four minute H<sub>Rex</sub>

Table 5.5 Inferential statistics for reliability of SIR test (n = 25)

Test parameters	Change in mean <sup>†</sup>	ICC <sup>†</sup>	TE <sup>†</sup>	CV% <sup>†</sup>	SWC
Two min H <sub>Rex</sub>	.59 (-.24 - 1.42)	.93 (.87 - .97)	1.45 (1.19 - 1.89)	2.0 (1.6 - 2.6)	1.09
Three min H <sub>Rex</sub>	.49 (-.31 - 1.29)	.94 (.88 - .97)	1.41 (1.16 - 1.83)	1.8 (1.5 - 2.4)	1.11
Four min H <sub>Rex</sub>	.43 (-.18 - 1.04)	.97 (.93 - .98)	1.05 (0.86 - 1.36)	1.3 (1.1 - 1.7)	1.10
HRR <sub>60s</sub>	-.17 (-1.42 - 1.09)	.94 (.89 - .97)	2.16 (2.10 - 3.34)	9.2 (7.5 - 12.1)	1.74
HRR <sub>120s</sub>	.48 (-.83 - 1.80)	.90 (.80 - .95)	2.29 (1.87 - 2.97)	6.0 (4.9 - 7.9)	1.37
HRR <sub>180s</sub>	.54 (-.58 - 1.65)	.91 (.83 - .96)	1.91 (1.57 - 2.49)	4.4 (3.6 - 5.8)	1.26

<sup>†</sup> (With 95% confidence limits)

ICC, intraclass correlation coefficient; TE, typical error of measurement; CV%, coefficient of variation; SWC, smallest worthwhile change

## 5.4 Discussion

The YYIR1 and YYIR2 tests have been comprehensively evaluated for field-based sports science testing (10). Despite the depth of research, this appears to be the first study to investigate the concurrent validity and reliability of a SIR test in elite ARF players. Heart rate responses from the SIR test were strongly associated with YYIR2 performance in elite ARF players. Furthermore, HR responses during the SIR test were found to have acceptable day-to-day reliability, with HR<sub>ex</sub> at 4 minutes being the most reliable and sensitive measure associated with YYIR2 performance. These findings support the use of a SIR test to indicate intermittent running capacity in elite ARF players as an alternative, non-fatiguing method to maximal YYIR2 testing.

The first major finding of the study was that linear regression analyses showed HR<sub>ex</sub> at two, three and four minutes of the SIR test to have large inverse relationships with YYIR2 test distance in this study's participant cohort ( $r = -0.58 - -0.60, P < 0.01$ ). Therefore, HR responses to a SIR test lasting no longer than 4 minutes can provide a valid indicator of maximal intermittent running performance. The magnitude of relationships found between HR<sub>ex</sub> during the SIR test and YYIR2 test distance was consistent with results from previous investigations of intermittent running tests in soccer. For example, moderate inverse relationships within the same test were observed between HR<sub>ex</sub> after three minutes and YYIR1 distance (170) and also between two and three minutes and YYIR2 distance covered in elite soccer players (11, 166).

Similar relationships between submaximal HR responses and YYIR1 and YYIR2 total distances have also been reported in sub-elite soccer players. For example, moderate to large correlations

were observed between minutes two and four of HRex and YYIR1 total distances, as well as minute two of HRex and YYIR2 total distances (166). In contrast, HRex at two minutes of the YYIR2 was largely correlated with YYIR2 distances covered in sub-elite but not elite players (157). Interestingly, HR after two and four minutes of the YYIR2 tests were reported to be lower (9% and 6%, respectively) for elite compared to sub-elite players (157). It is possible that such differences may be the result of a higher fitness level and/or the greater relative intensity of training and matches in elite compared to sub-elite players. Subsequently, the most effective submaximal tests may include challenges designed to ensure that the specific population being tested generates a relative HR response within the most sensitive HR range.

The second major finding of the study was that the reliability of HR measures during the SIR test compared favourably with the lowest CV's previously recorded. For example, CV for both HRex (1.3 – 2.0%) and HRR (4.4 – 9.2%) reported in this study were lower than prior investigations (6). However, it should be acknowledged that not all results reported from previous research were obtained from testing conducted under controlled indoor conditions. Indeed, it should be recognised that the CV for HR measures can vary substantially depending upon testing protocol, training status, age, environmental conditions, and analytical variations (6, 7, 59). Nevertheless, in this group of athletes, the SIR test can elicit reliable day-to-day HR responses. Homogeneity of fitness, training and physical characteristics of players in the current study may have contributed to the low CV values observed.

Of all the SIR test HR variables collected, four minute HR<sub>ex</sub> recorded the lowest CV (1.3%) and was the only measure determined to have a TE < SWC. These findings support previous research showing HR measured during exercise of higher intensities (approximately 85-90% HR<sub>max</sub>) rather than lower intensities is more reliable and sensitive to change (59, 92). In addition, the stronger correlations reported in the current study between total distance and HR<sub>ex</sub> compared with HRR agrees with a prior investigation in elite ARF (105). Collectively, these results suggest that HR responses from a SIR test provide valid and reliable associations with YYIR2 performance in elite ARF players, with four minute HR<sub>ex</sub> providing the most sensitive and reliable measure.

Some limitations are associated with monitoring HR. The homogeneity of HR responses observed in athletes tested for the current study may not extend to other sporting populations. Subsequently, using the SIR test with different athletes may require consideration of the appropriateness of exposure to the same absolute workload. Diversity in physical attributes within any group may result in inconsistent HR responses between individual players. This may affect the interpretation of test results given day-to-day reliability of HR is improved at higher exercise intensities (92) and speed of HRR can be influenced by initial HR (171).

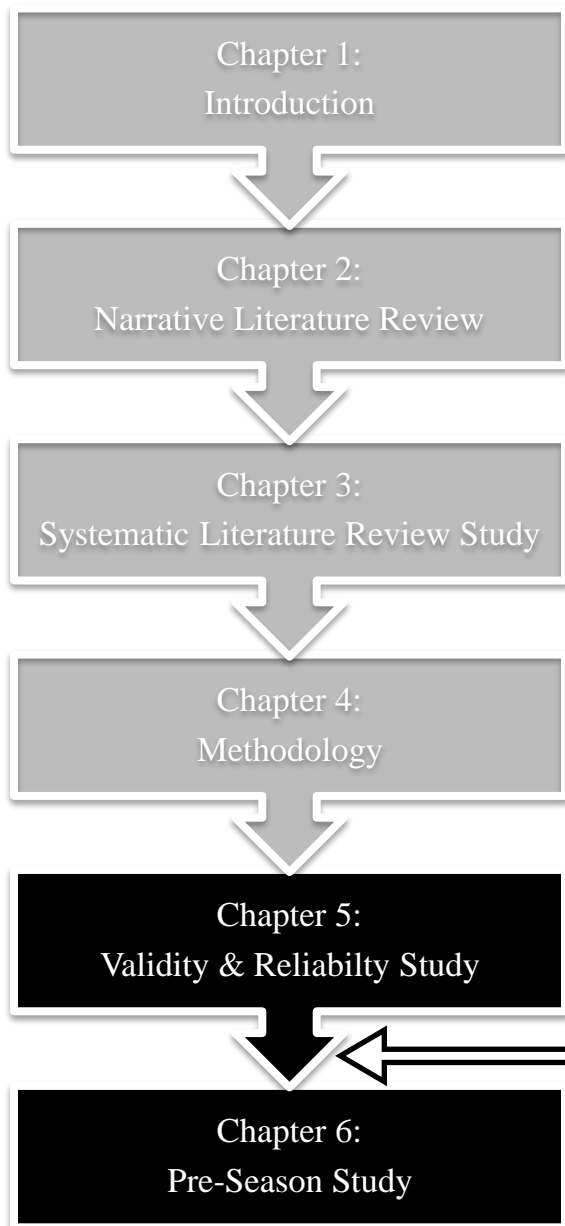
The findings from this study reflect only one of many potential modified submaximal protocols to indicate maximal YYIR2 performance. Although the modified 18 m distance of the SIR test was an acceptable protocol in this group of athletes, this modification may not be suitable for a different cohort. Shorter testing durations than four minutes may also be beneficial, although

these may not be suitable if the test is designed to double as a warm-up prior to activity. Conversely, protocols longer than four minutes may exacerbate fatigue in some players and subsequently interfere with the submaximal nature of the test. Nevertheless, the ability to modify test distance or time to coincide with the most reliable and sensitive heart rate intensities may be advantageous in a variety of team sport settings. Furthermore, there may be scope to create a number of modifications based on positional differences within team sports that have a less homogenous playing group than the one used in the current study. However, population-specific reliability would need to be established for any modifications to the current testing protocol.

## **5.5 Conclusions and practical applications**

Monitoring of HR within the SIR test can provide valid and reliable associations with YYIR2 test performance in elite ARF players. In particular, four minute HR<sub>ex</sub> in the SIR test was the most effective indicator of intermittent running capacity. The submaximal nature of the test provides broad appeal across multiple team sports: it can be administered as part of a warm-up, does not cause excessive fatigue and can be applied routinely in a large group of athletes. Further study should focus on the applicability of a modified SIR test in other team sports as well as assessing the potential of using individual HR responses to the SIR test for monitoring changes in fitness and fatigue throughout different phases of a season.

## Chapter Link: Summary of validity and reliability study



1. Heart rate responses to a modified SIR test provided a valid indicator of YYIR2 test performance.
2. Day-to-day heart rate responses to the modified SIR test were reported to have acceptable reliability.
3. Lower HR<sub>ex</sub> at the 4 minute mark of the SIR test was most strongly associated with improved YYIR2 test performance and exhibited the greatest level of day-to-day



## **Chapter Six: Associations between submaximal intermittent running (SIR) test heart rate responses and training load during an elite ARF pre-season**

### **6.1 Introduction**

Australian Rules Football (ARF) is a running-based contact sport that enforces a variety of skill, tactical and physiological-based demands on players (15). The sport is characterised by high intensity intermittent running and includes activities such as accelerations, decelerations, changes of direction and collisions (172). These challenging game demands can induce multiple symptoms of fatigue emanating from neuromuscular, psychological, hormonal and autonomic nervous system perturbations (105, 114, 132, 173). Resistance to fatigue is among multiple factors strategically supported via the implementation of a periodised training program to ensure players are suitably prepared to cope with the physiological requirements of ARF.

The pre-season period is a crucial component of a periodised training program. The principal aim of a pre-season is to provide players with a specific training overload that develops the fitness and fatigue resistance required to meet in-season demands (18). Importantly, pre-season represents the only timeframe within team sports for imposing a training overload without the need to prioritize recovery for competitive matches (19). As a result, pre-season TL is significantly greater than the TL imposed in-season (21). It is possible that players completing the majority of pre-season training are less likely to be injured in-season (20). Overall, the pre-

season training phase represents the best opportunity within a periodised training year to best prepare athletes to tolerate competitive stresses.

Training prescription within the pre-season phase requires a delicate balance between a TL that maximizes positive physiological adaptation and a TL with negative consequences such as increased injury risk and non-functional overreaching (22). Effective training prescription is further complicated by the demands of team sports in which individuals are likely to respond differently to the same TL (24). Consequently, the individualised monitoring of training responses becomes vital in assessing states of fitness and fatigue among team sport athletes.

Training capacities and responses are ideally assessed using valid and reliable performance measures that require maximal exertion representative of competitive match-play. For example, the Yo-Yo Intermittent Recovery 2 (YYIR2) test is capable of determining an athlete's capacity to perform intense intermittent exercise and has a strong positive relationship with high speed running distance observed during competitive soccer (10) and ARF (154). Furthermore, superior YYIR2 performance is associated with greater match running intensity, higher ball disposals, and positive coach's rating of performance in ARF (136, 154). It is acknowledged that team sport match performance can be influenced by a myriad of factors such as player availability, skill proficiency, tactical ability, and opposition strength (149, 150, 164). However, the available research underlines the potential of the YYIR2 to assess physiological capacities relevant to ARF match performance.

Regular maximal performance tests such as the YYIR2 are rarely suitable in elite team sport environments. The unsuitability is attributed to the resultant fatigue that may compromise subsequent physiological performance for both training and matches (25). Minimizing fatigue is an important consideration irrespective of season phase. Consequently, the use of submaximal exercise testing protocols under standardized conditions may be preferable to maximal exercise testing protocols to regularly assess the training responses in elite team sport athletes. Perhaps most importantly, the validity of any test used to monitor training adaptations is dependent on the ability of the test measures to be sensitive to fluctuations in TL (83, 88).

Monitoring heart rate (HR) responses during submaximal testing may provide a time efficient and non-exhausting method for objectively monitoring individual physiological responses to TL (25). Variables such as exercise HR (HR<sub>ex</sub>) and HR recovery (HRR) have been used to monitor training status and indicate improvements in performance testing with varying levels of success (91, 156). For example, lower HR<sub>ex</sub> during fixed bouts of submaximal exercise and faster HRR have been associated with both improvements in cardiovascular fitness (59, 91) and states of overreaching (82, 89). Conversely, increased HR<sub>ex</sub> and slower HRR are potential signs of deconditioning (59, 90). As such, it is important that changes in HR response to exercise are interpreted within the context of the specific training phase and in combination with other markers of performance and fatigue to appropriately identify either positive or negative adaptation to training (89).

Chapter Five reported the association between HRex and HRR responses to a submaximal intermittent running (SIR) test and YYIR2 performance in elite ARF players (174). Results showed concurrent validity and acceptable day-to-day reliability; thus supporting the use of HRex and HRR responses to a SIR test to assess intermittent running capacity in elite ARF players as a regular, non-fatiguing alternative to maximal YYIR2 testing. However, the influence of both external TL (i.e. the amount of work completed) and internal TL (i.e. the individual response to work completed) (122) on HR responses to the SIR test remains uncertain.

Understanding the association between TL and HR responses to regularly implemented SIR testing may allow high performance staff to identify changes in the training status of athletes. This would be particularly useful during the pre-season when TL's are generally at their highest (21). Additionally, it would be valuable to understand any position-dependent relationships between TL and HR responses to SIR testing, especially given the reported differences in match demands between different playing position (16, 175). Therefore, the aim of this study was to determine the influence of external TL (measured via GPS) and internal TL (measured via sRPE) on the HRex and HRR responses to the SIR test during a 6 week pre-season training phase in elite ARF players, relative to playing position.

## **6.2 Methods**

### **6.2.1 Participants**

Participants were 45 senior and rookie-listed professional ARF players from one Australian Football League (AFL) club. Mean  $\pm$  SD age, height, body mass and time spent on an AFL list were  $23 \pm 4$  years,  $188 \pm 8$  cm,  $85 \pm 8$  kg, and  $6 \pm 4$  years, respectively. Following approval from the Human Ethics Research Committee at the Australian Catholic University, written informed consent was obtained from all participants to use their data for research purposes (Appendix 3). All participants completed testing as part of the normal training regime and were familiar with testing procedures prior to the study. Participants were free from any injury that may have limited their ability to complete testing.

### **6.2.2 Study design**

This observational prospective research design was conducted during an elite ARF pre-season and comprised a six week training period, following a 15 day summer break. The training phase consisted of planned periodical increases and decreases in TL throughout weeks one to six. This pattern is typical of an elite ARF pre-season in which a “loading” phase is characterized by an accumulation of training stress and is subsequently followed by a “de-loading” phase (176). The periodisation of pre-season training allows for super-compensation and ultimately, improved performance. SIR testing was implemented on six occasions during the study. Table 6.1 presents a typical weekly schedule during pre-season training.

Table 6.1 Typical pre-season training schedule for Chapter 6 investigations.

	<b>Monday</b>	<b>Tuesday</b>	<b>Wednesday</b>	<b>Thursday</b>	<b>Friday</b>	<b>Saturday</b>	<b>Sunday</b>
<b>AM</b>	Skills and Running Conditioning	Resistance Training  Cross Training	Skills and Running Conditioning	Off	<i>(Complete subjective questionnaire)</i>  <i>SIR test</i>  Skills and Running Conditioning	Running Conditioning	Off
<b>PM</b>	Resistance Training  Recovery	Off	Resistance Training  Recovery	Off	Resistance Training  Recovery	Off	Off

### **6.2.3 Training load quantification**

Individual player TL was monitored daily throughout the study period. The session rating of perceived exertion (sRPE) method (5) was used to quantify internal TL for all training modalities using previously established procedures detailed in Section 4.2.6. Historically, RPE has demonstrated a strong correlation with objective physiological measures of exercise intensity such as heart rate, maximal oxygen consumption and blood lactate concentration (5, 23, 65). Session RPE has demonstrated concurrent validity (71-73) and test-retest reliability (23) in a variety of team sports. In the current study, internal TL was calculated daily for each individual using the sPRE method and expressed as their previous one week cumulative TL.

External TL was quantified for each player during all outdoor training sessions using small global positioning system (GPS) devices (Optimeye S5, Catapult Innovations, 15 Hz, Melbourne, Australia). For each training session that an individual completed, their previous one week cumulative external TL was calculated for each GPS variable. The day-to-day reliability of the external TL measures collected in the present study has been previously established (9, 43, 46, 161). Please refer to Section 4.2.7 for a full explanation of the training quantification methods used for GPS technology.

### **6.2.4 Subjective responses to training**

Chapters Two and Three in this thesis highlighted that subjective tools have typically been implemented in team sport environments to effectively monitor fatigue and player well-being (93, 105, 132). Therefore, a custom designed questionnaire was used to subjectively monitor

each individual's response to training. Athletes within this study completed the questionnaire once per week (Table 6.1) on their own smartphone device using an application linked to the clubs proprietary training monitoring database (Smartabase, Fusion Sports, Australia). All players were familiar with the well-being protocol as it was part of routine training monitoring processes. Please refer to Section 4.2.8 for a full explanation of the procedures used to monitor subjective responses to training.

### **6.2.5 Submaximal intermittent running test**

The SIR test followed a similar protocol to the previously established YYIR2 test procedures (11). The protocol was based on pre-determined testing priorities to: 1) impose only a submaximal intensity to minimise additional fatigue, 2) elicit a submaximal intensity that minimised day-to-day variability in HR and 3) allow for easy incorporation into a warm up. Heart Rate was recorded continuously during both the running and recovery periods using a Firstbeat HR monitor placed around the chest. Please refer to Section 4.2.2 for a full explanation of submaximal intermittent running test procedures.

### **6.2.6 Measuring heart rate response and rating of perceived exertion to the SIR test**

The relationship between HR and exercise can be influenced by a variety of factors including mode of exercise, training status, exercise duration, environmental conditions, time of day, hydration status, and caffeine intake (59). Therefore, a number of standardised conditions were employed to minimise confounding factors that may hinder the interpretation of HR data. Please



refer to Sections 4.2.3 to 4.2.5 for a full explanation of the procedures used to measure heart rate response to the SIR test.

Chapter Five showed that the concurrent validity and day-to-day reliability of the SIR test protocol in elite ARF players was acceptable (174). Briefly, large inverse correlations were reported between HRex and YYIR2 test distance ( $r = -.58 - -.61, P < 0.01$ ). Moderate correlations between HRR and YYIR2 distance were also evident ( $r = .32 - .35, P < 0.05$ ). Additionally, strong ICC ( $r = .90 - .97$ ) and low CV (1.3 – 9.2%) were reported for all HR variables. Collectively, these results from Chapter 5 support the procedures used to measure both HRex and HRR during the SIR test.

### **6.2.7 Categorising players into positional groups**

Individual players were categorised into one of three positional groups prior to statistical analyses in order to explore the influence of playing position on the relationships between SIR test HR responses and the various measures of TL. Positional groups were selected for players based on which position each athlete played the majority of their game time within the team structure of the football club from which the participants represented. For example, the midfield group consisted of players who played predominantly in the rover, ruck rover, centre, and wing positions. The key position group was made up of the full forward/ruck, centre half forward, full back, and centre half back positions. Finally, the hybrid group consisted of players who often shifted between flank and pocket positions while also spending a short duration of playing time in the midfield. These hybrid players predominantly spent their time in the traditional half forward flank, forward pocket, half back flank and back pocket positions.

### 6.2.8 Statistical analyses

Subjective questionnaire items were modified to ensure consistency in the direction of responses (i.e. higher scores represented superior wellness for all variables). A pre-exercise wellness Z-Score was derived by calculating the arithmetic mean of the four subjective wellness questionnaire items (sleep, fatigue self-efficacy, soreness) for each individual player and dividing the mean wellness score by each player's standard deviation (124).

The *lmer* package (177) in the R statistics programme (178) was used to perform a linear mixed effect analysis on the relationship between HR response to the SIR test (dependent variables: HR<sub>ex</sub>, HRR<sub>60s</sub>, HRR<sub>120s</sub>, HRR<sub>180s</sub>) and each external TL variable for each playing position. Total distance (m), player load, Z4 running, Z5 running, Z6 running, high speed running and pre-exercise wellness Z-score) were entered into the model as fixed effects. Except for pre-exercise wellness Z score, the explanatory variables were log-transformed before analysis and back transformed to allow the model parameters to be expressed as percentages (creating a linear-log regression model). Random intercepts were modelled for athletes and test weeks to calculate the between-athlete and between-test variance. Each model was fitted with an unstructured covariance matrix. Visual inspection of the residual plots showed no departure from normal distribution or heterogeneity.

The appropriateness of the conditional model (with all explanatory variables) relative to a null model (with no explanatory variables) was compared using Akaike information criteria (AIC) (179), in which the model with the lowest AIC score was considered the parsimonious model. For

each model, the variance inflation factor (VIF) was calculated to check for multi-collinearity between explanatory variables. A VIF between 1 and 5 was considered acceptable. Variables with  $VIF > 5$  were considered collinear and removed from the model.

Additionally, marginal and conditional pseudo  $R^2$  values were calculated in the *MuMIn* package (180) to determine the percentage variance explained by the model fixed effects alone (marginal pseudo  $R^2$ ) and both the fixed and random effects (conditional pseudo  $R^2$ ), respectively (181). The intra-class correlation (ICC) coefficient was calculated to estimate proportion of the total variance explained by between-athlete and between-test variation for each model. Model parameter estimates are expressed with 90% profile confidence limits to denote the imprecision of observed point estimates. The smallest worthwhile change (SWC) was also calculated to determine test usefulness. The rearrangement of Cohen's  $d$  effect size calculation enables the SWC to be determined for each individual by multiplying the smallest worthwhile effect (0.2) by the both the between-test and within-athlete variation (168).

### **6.3 Results**

A total of 35 players completed SIR testing across the six week pre-season testing period. Descriptive statistics for HRex during SIR testing, as well as other measures of interest, are illustrated in Figures 6.1 to 6.3. Playing position was deemed to have no significant influence on the relationship between SIR test HR responses and measures of TL; therefore data from all players were pooled together.

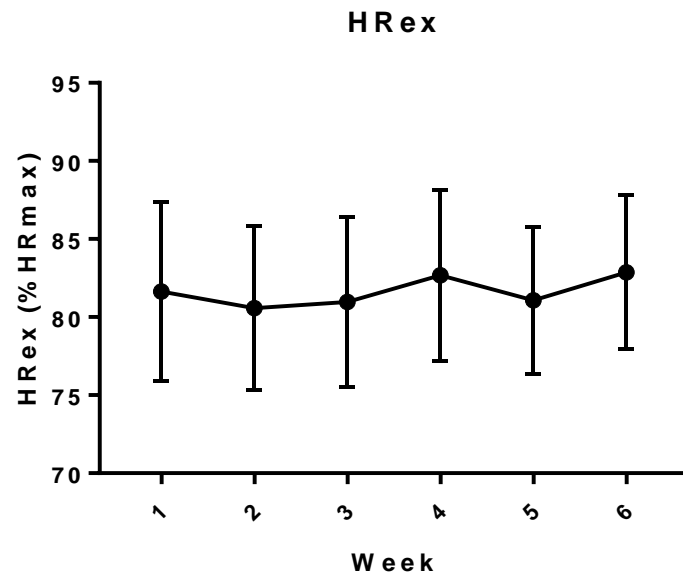


Figure 6.1 Mean HReX (with 90% confidence limits) from SIR testing throughout the six week pre-season training period.

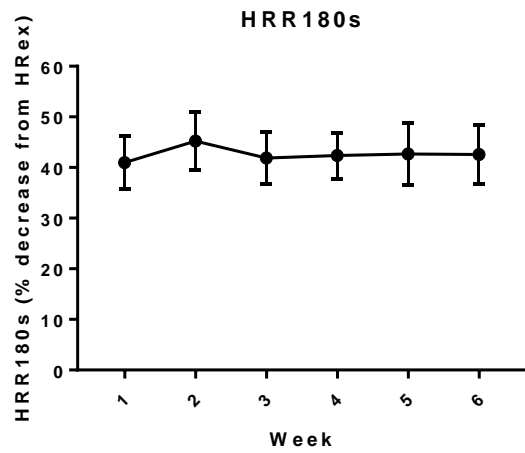
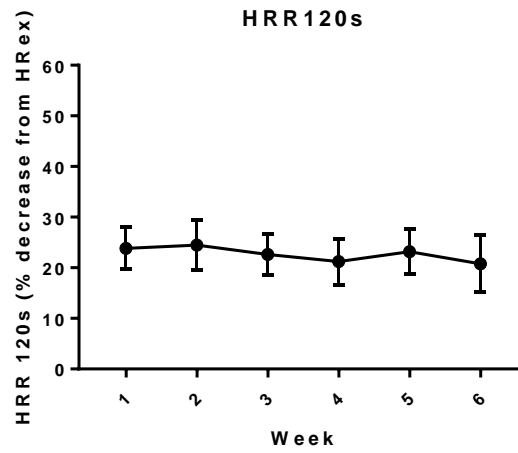
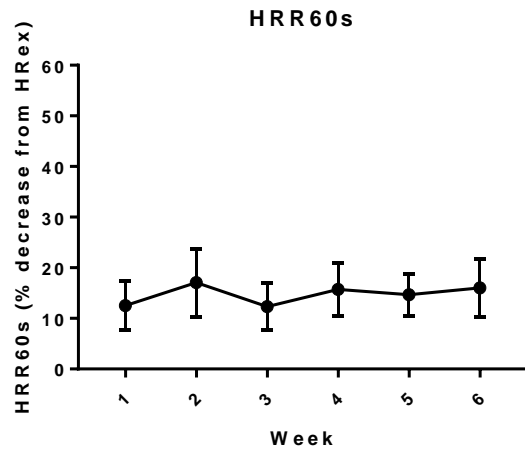


Figure 6.2 Mean HRR (with 90% confidence limits) at different time points from SIR testing throughout the six week pre-season training period.

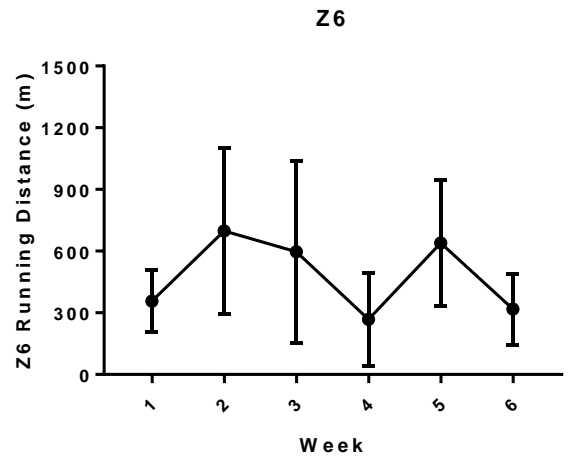
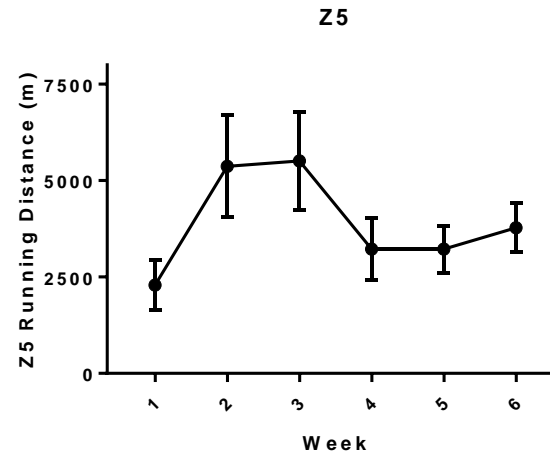
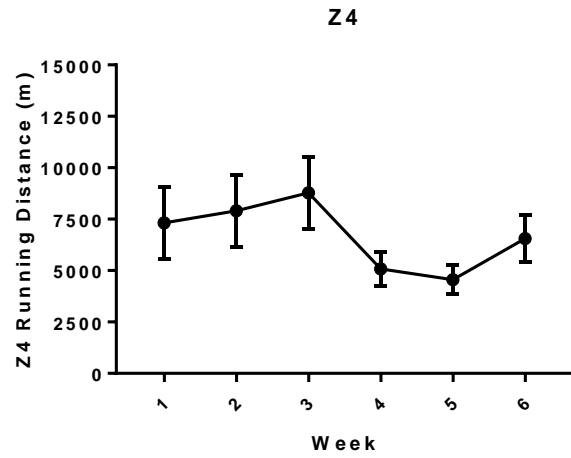


Figure 6.3 Mean weekly running distance (with 90% confidence limits) across different velocity zones throughout the six week pre-season training period.

Table 6.2 Relationship between HR responses from SIR testing and external training load measures. Parameter estimates (Est.) are expressed with 90% confidence limits (90% CL) to denote the imprecision of the point estimate. The intra-class correlation coefficient (ICC) denotes the proportion of the total variance explained by individual level (i.e. athlete) and test level variation.

<b>Fixed Effects</b>	<b>HREx</b>		<b>HRR60s</b>		<b>HRR120s</b>		<b>HRR180s</b>	
	Est.	90% CL	Est.	90% CL	Est.	90% CL	Est.	90% CL
Z Wellness					0.89	[0.34, 1.45]		
ln (Z4 Running)	-0.02	[-0.04, -0.01]						
ln (Z5 Running)							0.03	[0.01, 0.04]
ln (Z6 Running)			0.01	[0.00, 0.02]				
<b>Random Effects</b>								
Between-Athlete	4.71	[3.79, 5.85]	4.09	[3.12, 5.25]	3.00	[2.26, 3.89]	4.57	[3.59, 5.74]
Between-Test	1.06	[0.57, 1.92]	1.83	[0.94, 3.24]	1.07	[0.35, 2.06]	0.59	[0.00, 1.33]
Within-Athlete	1.97	[1.76, 2.20]	3.73	[3.34, 4.18]	3.48	[3.12, 3.88]	3.22	[2.89, 3.61]
<b>ICC</b>								
Between-Athlete	0.81		0.49		0.41		0.66	
Between-Test	0.04		0.10		0.05		0.01	
Within-Athlete	0.15		0.41		0.54		0.33	
<b>Pseudo R<sup>2</sup></b>								
Marginal	0.02		0.02		0.03		0.04	
Conditional	0.86		0.60		0.47		0.68	

### 6.3.1 HR<sub>ex</sub>

The results of the log-linear model are described in table 6.2., which suggested that a 1% increase in weekly Z4 running decreased HR<sub>ex</sub> by 0.02% [-0.04, -0.01]. From a practical perspective, a 100% increase in weekly Z4 running (i.e. doubling the Z4 TL) decreased HR<sub>ex</sub> by 1.59% [-2.67, -0.52]. The between-athlete and between-test standard deviations were 4.71% [3.79, 0.57] and 1.06% [0.57, 1.92], respectively. The within-athlete standard deviation was 1.97% [1.76, 2.20]. The model fixed effects alone explained 2% of the total variance, with 86% of the variation explained by the combination of the model fixed and random effect combined. The ICC was 0.81 between-athletes, 0.04 between test and 0.15 within athletes. The SWC necessary to indicate practically meaningful changes in HR<sub>ex</sub> when considering within-athlete and between test-variation was 0.39% and 0.21%, respectively. Therefore, the combined SWC in HR<sub>ex</sub> for an individual was 0.6% of HR<sub>max</sub>. From a practical perspective, this could be rounded up to 1% of HR<sub>max</sub>. Subsequently, in order to achieve a SWC in HR<sub>ex</sub> of 1%, weekly Z4 running distance would need to be increased by at least 55%.

### 6.3.2 HRR<sub>60s</sub>

Each 1% increase in weekly Z6 running was associated with a 0.01% [0.00, 0.02] increase HRR<sub>60s</sub> (Table 6.2). In practical terms, a 100% increase in weekly Z6 running (e.g. doubling the Z6 TL) would increase HRR<sub>60s</sub> by 0.89% [0.09, 1.67]. The between-athlete standard deviation was 4.09% [3.12, 5.25] and the between-test standard deviation was 1.83% [0.94, 3.24]. The within-athlete standard deviation was 3.73% [3.34, 4.18]. Marginal pseudo R<sup>2</sup> values suggests Z6 running alone explained 2.9% of the variance in HRR<sub>60s</sub>, whereas the fixed (Z6 running) and random effects



(between-athlete and between-test standard deviations) collectively explained 60% of the total variance. The model ICC showed that the between-athlete and between-test correlations were 0.49 and 0.10, respectively and the within-athlete correlation was 0.41. All remaining measures of external and internal TL variables were not significantly related to  $HRR_{60s}$ . The SWC necessary to indicate practically meaningful changes in  $HRR_{60s}$  when considering within-athlete and between test-variation was 0.75% and 0.37%, respectively. Therefore, the combined SWC in  $HRR_{60s}$  for an individual was 1.12%. From a practical perspective, this could be rounded up to 2%. Subsequently, in order to achieve a SWC in  $HRR_{60s}$  of 2%, weekly Z6 running distance would need to be increased by at least 450%.

### **6.3.3 $HRR_{120s}$**

A one standard deviation increase in Wellness Z score was associated with a 0.89% [0.34, 1.45] increase in  $HRR_{120}$  (Table 6.2). The model fixed effects alone explained 3% of the variance, but with 47% explained by the combination of both fixed and random effects. The standard deviation in  $HRR_{120s}$  was 3.00% [2.26, 3.89] between-athletes, 1.07% [0.35, 2.06] between-tests and 3.48% [3.12, 3.88] for with-athletes, respectively. The between-athlete and between-test ICCs were 0.41 and 0.05, respectively and 0.54 within-athletes. All other external and internal TL variables were not significantly related to  $HRR_{120s}$ .

### **6.3.4 $HRR_{180s}$**

A 1% change in weekly Z5 running was associated with a 0.03% [0.01, 0.04] increase in  $HRR_{180s}$  (Table 6.2). Thus, a 100% increase in weekly Z5 running would be associated with a 1.81% [0.74,

2.91] increase in  $HR_{180s}$ . The model fixed effects alone explained 4% of the total variance, with 68% explained by a combination of both the fixed and random effects. The between-athlete standard deviation in  $HRR_{180s}$  was 4.57% [3.59, 5.74] and the between-test standard deviation was 0.59% [0.00, 1.33]. The within-athlete standard deviation was 3.22% [2.89, 3.61]. The between-athlete and between-test ICCs were 0.66 and 0.01, respectively. The remaining external and internal TL variables were not significantly related to  $HRR_{180s}$ . The SWC necessary to indicate practically meaningful changes in  $HRR_{180s}$  when considering within-athlete and between test-variation was 0.64% and 0.12%, respectively. Therefore, the combined SWC in  $HRR_{180s}$  for an individual was 0.76%. From a practical perspective, this could be rounded up to 1%. Subsequently, in order to achieve a SWC in  $HRR_{180s}$  of 1%, weekly Z5 running distance would need to be increased by at least 47%.

## 6.4 Discussion

The first major finding of the current study was that external TL influenced HR responses to the SIR test in elite ARF players over a six week pre-season training period. Specifically, increases in external TL measures of weekly distance covered at running speeds greater than 14.4 km h<sup>-1</sup> were associated with reduced HR<sub>ex</sub> and faster HRR responses to the SIR test. Second, HR responses to the SIR tests varied minimally between the six testing occasions, with variation in HR explained more by between rather than within athlete factors. The stability of HR responses to SIR testing are likely to have influenced the small associations observed with TL, whereby only the influence of external TL on HR<sub>ex</sub> and HRR<sub>180s</sub> could be considered practically meaningful, most likely during planned stages of functional overreaching.

In Chapter Five, lower HR<sub>ex</sub> and faster HRR responses to the SIR test were associated with superior YYIR2 performance in elite ARF players. The current chapter extends this finding into associations with key measures of TL during the pre-season. Specifically, increases in the external TL metrics of weekly Z4, Z5 and Z6 running distance were associated with reduced HR<sub>ex</sub> and faster HRR responses to the SIR test. These findings suggest that increases in cumulative weekly distance covered at high speeds may improve ARF-specific running fitness, as evidenced by the small yet favourable associations with HR responses to SIR testing. Collectively, these findings support the broader use of HR monitoring during and after standardised bouts of submaximal exercise as an objective, non-invasive, and easily accessible method to monitor individual athlete responses to training during intensive pre-season programming.

The autonomic nervous system controls the increase in HR at exercise onset and also the decrease in HR post exercise (7). It is generally accepted that decreased HR<sub>ex</sub> for standardised bouts of submaximal exercise is a potential indicator of positive adaptation to endurance training that is attributed to decreased sympathetic activity of the heart (58, 91). Faster HRR may also indicate improved training status, whereby the rate of HRR post-exercise reflects multiple factors including concomitant parasympathetic reactivation and sympathetic withdrawal (7, 58). It is possible that the greater TL's associated with pre-season training compared to in-season demands (21) may augment training responses to a greater degree; thus providing a more sensitive time to detect autonomic nervous systems perturbations in relation to TL.

The influence of changes in TL on HR<sub>ex</sub> and HRR from submaximal exercise has been investigated mostly in endurance sports (6, 91, 182); however these two HR indices are rarely reported simultaneously. For example, rapid decreases in HR<sub>ex</sub> during submaximal intensity exercise were observed throughout the first 9 weeks of a one year endurance running program (183) and throughout a 20 week endurance training program in apparently healthy participants (184). Furthermore, other studies have reported associations between decreased HR<sub>ex</sub> during submaximal exercise testing and increased peak incremental running speeds (156), test performances in YYIR1 (185) and YYIR2 (105), as well as high intensity running distances during standardised drills (105) in field-based team sports. Thus, decreases in HR<sub>ex</sub> during submaximal testing are reported to be associated with both increases in TL and improved running performance.

Increased endurance performance has also been reported in trained cyclists who exhibited faster HRR following submaximal intensity exercise during and after 4 weeks of high intensity training (90, 186). Assessment of both HRex and HRR simultaneously reported progressive decreases in HRex and faster HRR responses to a five minute submaximal running test in “high responders” throughout an 8 week periodised training program in recreational runners (187). Additionally, faster HRR during submaximal exercise testing was associated with improved time trial performance and peak power output in elite (188) and well trained cyclists (189). In some but not all populations, evidence exists to support the use of HRR following submaximal intensity exercise testing to monitor responses to TL and improved performance.

The changes in HR response to submaximal exercise testing observed in this pre-season study are in contrast to some findings reported in the literature. Opposing changes in HR response (i.e. increased HRex and slower HRR) have been traditionally interpreted as markers of de-training or maladaptation. However, this appears to be based more on theoretical principles rather than a convincing body of literature (156). Indeed, recent investigation into the influence of TL on HR response suggests that similar changes in HR could be seen in both positive and negative adaptation. Along with improvements in training status, decreased HRex (158) and faster HRR (89, 190, 191) have also been associated with states of overreaching in a variety of athletes.

The HR response to exercise can also be influenced by a number of factors such as exercise intensity, duration, and mode, as well as environmental conditions, and diverse methodological calculations (7, 159). Consequently, comparing results between studies remains difficult given

the variation of these factors described in different experimental protocols in the literature. This is particularly pertinent to the measurement of HRR. Collectively, these findings highlight potential ambiguities in HR responses to TL that can complicate the interpretation of HR data.

Subsequently, using HR responses in isolation to interpret changes in training status may be misleading. As such, the consideration of other monitoring variables (i.e. RPE, subjective wellness, and performance tests) may be necessary in conjunction with HR data to provide a more accurate indication of whether an athlete is in a state of positive or negative adaptation. For example, results from the current study show that slight improvements in wellness as indicated by increased wellness Z-score were associated with faster  $HRR_{120}$  across the pre-season testing period. From a practical perspective, this suggests that players were able to cope relatively well with increases in TL. Therefore, trends in the current study of decreased HR<sub>ex</sub> and faster HRR in response to TL are more likely to be indicative of improved fitness rather than increased fatigue.

The HRR is most commonly calculated over timeframes ranging from 30 seconds to 3 minutes post-exercise (7). Importantly, HRR measured at varied time points (e.g.  $HRR_{60s}$ ,  $HRR_{120s}$ ) has demonstrated different relationships to measures of cardiovascular health and aerobic exercise performance (192, 193) and could therefore, be considered as potentially independent parameters (7). It is possible that individual variation in the rate of parasympathetic re-activation and sympathetic withdrawal during the measurement of HRR over different timeframes may explain some of the inconsistent relationships reported in the literature. Potentially, this valuable information about HR kinetics over the time-course of HRR may be misinterpreted by only

measuring HRR at specific time intervals (7). Consequently, it has been suggested that more sophisticated analytical techniques using exponential functions that can measure complete HR kinetic data may improve the interpretation of HRR (6, 171). However, the simplicity of measuring HRR using specific time intervals is a significant advantage, particularly in applied settings in which time and personnel efficient collection, analyses and interpretation of data are of paramount importance.

To the authors' knowledge, this study is the first to investigate associations between HR responses to standardised submaximal exercise testing and both internal and external measures of TL, with particular emphasis placed on distance covered in high speed running zones in a pre-season phase of a team sport. Interestingly, playing position did not influence relationships between SIR test HR responses and changes in TL. Furthermore, no significant relationships were identified between SIR test HR responses and additional external TL metrics of total distance and Player Load. Internal TL measure of sRPE also lacked an influence on the selected HR measures. This suggests that external TL derived from distance covered at higher running intensities had greater influence on HR response to the SIR test than more global measures of TL in the current group of athletes.

An explanation for these findings is not immediately clear. It may be possible that improvements in HR response to submaximal exercise testing (i.e. reduced HR<sub>ex</sub> and faster HRR) were more strongly influenced by training at higher intensities rather total volume. Different training interventions on various aspects of endurance performance were investigated in sedentary adults

(177). The program occurred over 8 weeks and demonstrated faster HRR two minutes post-maximal exercise in participants who completed low volume/high intensity aerobic interval training than individuals undertaking high volume/moderate intensity continuous aerobic training (194). In addition, participation in the low volume/high intensity interval group also resulted in lower resting HR and lower HR at rest between training intervals (194). These findings were consistent with other studies on sedentary (195) and clinical (196) populations. While it is difficult to extend these findings to other populations such as elite athletes, the stronger influence of exercise intensity than total exercise volume on HRR may warrant further investigation.

Furthermore, the different speed zones did not consistently influence the same HR response. For example, weekly Z4 running distances most strongly influenced HR<sub>ex</sub> during SIR testing. In contrast, weekly Z5 and Z6 running distances most strongly influenced HRR, albeit at different time points. Although both HR<sub>ex</sub> and HRR are vagally mediated, these HR indices may reflect different aspects of cardiac parasympathetic function and may therefore, respond differently to training interventions (197, 198). For example, HR<sub>ex</sub> is considered to be representative of the cardiac load during exercise (91, 191), whereas HRR may be more indicative of the state of the autonomic nervous system in response to recently applied TL's (191, 198). Additionally, HRR measured at different time points may reflect variation in the degree of parasympathetic re-activation and sympathetic withdrawal (192, 193). Although speculative, the differing mechanisms behind HR<sub>ex</sub> and HRR as indicators of cardiac parasympathetic function may partly explain the varying influence of TL on these separate HR indices.



It should also be acknowledged that although the GPS units used to measure external TL in this study are considered among the most valid and reliable devices current available (46), greater measurement error remains synonymous with data captured during higher velocity activities (44). As a result, some caution is advised when interpreting the influence of Z4, Z5, and Z6 running distances on HR responses to SIR testing.

The current study showed most of the variation in HR response to SIR testing occurred as a result of between-athlete factors, followed by within-athlete and between-test factors (Table 6.2). The minimal between-test variation reinforces the reproducible nature of the test reported in Chapter Five amongst the same athletic population. It is possible that the homogeneity of physiological characteristics, training background, and age of athletes tested in the current study may have contributed to the low variation observed. The results strengthen the evidence for individualised training prescription and monitoring.

Although the SIR test protocol used in the current study demonstrated low levels of variability, influences of the external TL measures of weekly distance covered at running speeds greater than  $14.4 \text{ km h}^{-1}$  were only strong enough to induce practically meaningful changes in SIR test HRex HRR<sub>180s</sub>. The large changes in external TL deemed necessary to influence practically meaningful changes in HR responses to SIR testing may be partly explained by the physiological fitness of the athletes included in this study. All athletes were elite, professional ARF players who trained and competed on a full-time basis. Additionally, these athletes were supported by a range of coaching, medical, and fitness professionals who carefully planned and periodised training to

optimise positive physiological adaptations and reduce the risk of injury and illness. It is likely that the individually focused daily management of TL and recovery that is synonymous with pre-season training strongly influenced the physiological state of players; thus contributing to the low level of within-individual variation in HR responses to SIR testing across the 6 week pre-season study. This is an inherent limitation in studies using elite athletes as participants, particularly from only one club. It is possible that changes in TL may more heavily influence HR response to SIR testing in other athletes across different teams, sports, season phases and participation levels. However, the capacity of TL to significantly impact on HR responses in other sporting settings remains speculative and requires further research.

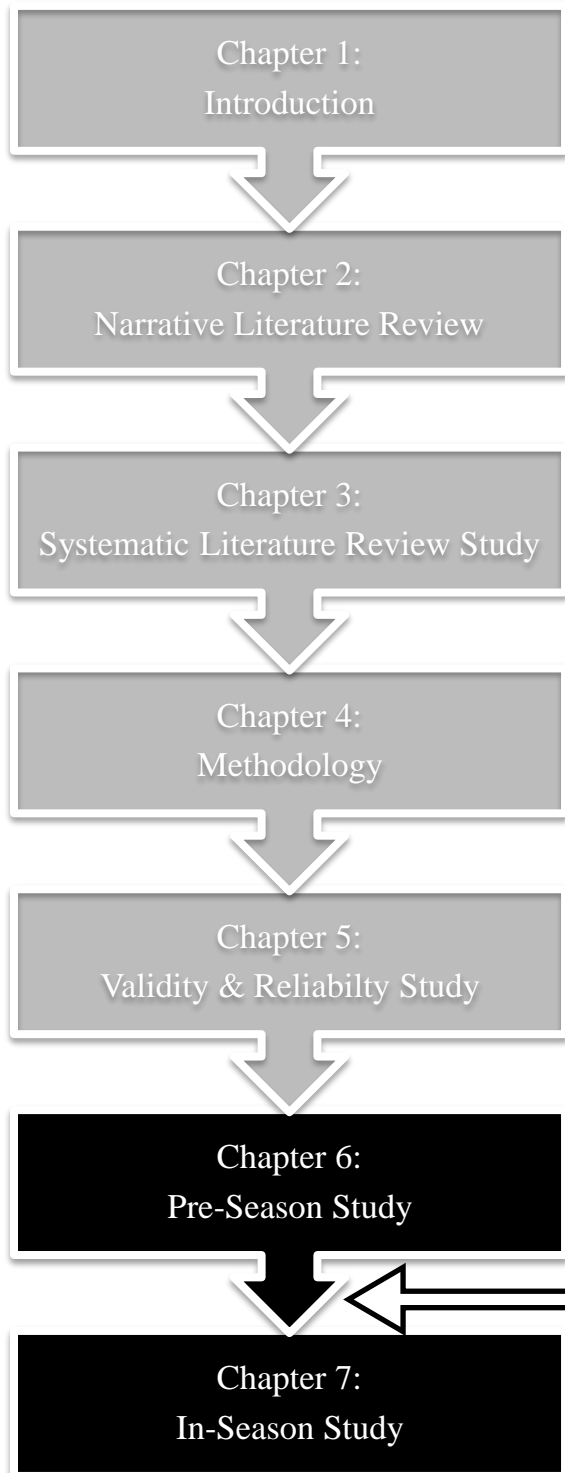
The effect of the 2 week summer break immediately prior to the six week testing period in the current study is also worthy of consideration. Previous research in elite ARF has demonstrated that upon returning from a two week summer break, players exhibited improved HR and RPE responses to submaximal intensity exercise testing, as well as increased high intensity running distance in standardised drills in comparison to pre-summer break values (199). The authors postulate that the two week summer break, characterised by 8 to 10 unsupervised running sessions, allowed players to recover optimally from intense, pre-summer break training and return with preserved or improved cardiovascular fitness. Although exercise programming during the summer break was briefly described (199), lack of sufficient detail makes it difficult to compare the exact training undertaken throughout the summer break between studies. However, it is possible that players in the current study also returned from the summer break in a state of super-compensation. Consequently, their ability to handle increases in TL would be

improved, which may potentially explain the limited variation in HR responses to SIR testing and wellness scores.

## **6.5 Conclusions and practical applications**

This current study successfully builds on previous knowledge regarding the use of a SIR test in elite ARF (Chapter 4). The aim of this original investigation was to determine the influence of external TL and internal TL on the H<sub>R</sub>ex and H<sub>R</sub>R responses to the SIR test during a 6 week pre-season training phase in elite ARF players. Results of this study demonstrate that increases in the external TL measures of weekly distance covered at velocities above 14.4 km h<sup>-1</sup> (Z4, Z5, and Z6 running bands) were associated with decreased H<sub>R</sub>ex and faster H<sub>R</sub>R from SIR testing. From a practical perspective, changes in weekly cumulative distance covered at higher speeds may influence small yet positive changes in SIR test HR responses that indicate improvements in fitness. Overall, variation in both H<sub>R</sub>ex and H<sub>R</sub>R from SIR testing was considered relatively minimal throughout the six week pre-season period. Collectively, these results suggest that the SIR test protocol implemented in the current group of athletes provided a reliable method for assessing the influence of weekly high speed running distances on individual physiological responses to a six week pre-season training period. Subsequently, regular SIR testing could be considered a useful addition to athlete monitoring practices in elite ARF to determine potential changes in training status associated with fluctuations in external TL during the pre-season period. It may be worthwhile for future studies to extend investigations into the usefulness of regular SIR testing as a monitoring tool during the in-season phase in elite ARF.

## Chapter Link: Summary of pre-season study



1. Increases in weekly distance covered at velocities above  $14.4 \text{ km h}^{-1}$  were associated with decreased HR<sub>ex</sub> and faster HRR from SIR testing.
2. Variation in HR response to SIR testing was minimal over the pre-season training period.
3. Regular SIR testing over the pre-season period may provide an indicator of individual physiological responses to changes in high speed running loads, most likely attributed to improved fitness.
4. Implementation of the SIR during the competitive season may provide different outcomes and uses.

## **Chapter Seven: Associations between SIR test HR responses, in-season TL and match exercise intensity in elite ARF players**

### **7.1 Introduction**

The dynamic balance between sufficient TL and adequate recovery from fatigue is vital to promote the physiological adaptations that enhance performance (75). Maintaining this balance may be more challenging during the competitive, in-season phase of the periodised year than in pre-season training. Indeed, as the pre-season concludes and the competition phase begins, the goal of athlete monitoring shifts from adaptation to performance.

The 23 week in-season phase in elite ARF consists of intense weekly match play that forms the basis of short and longer term TL management. Typically, in-season TLs are lower than pre-season; thus highlighting a shift in training periodisation priorities towards recovery from competition (21). If imbalances between training and recovery occur during the in-season phase, this “unplanned” fatigue has the potential to cause match performance decrements that can have serious individual and team-based consequences (79). Therefore, the effective periodisation of in-season TL is vital on two fronts; first, it ensures athletes remain suitably prepared to cope with the physiological demands of the sport (2, 19), and second; it reduces the risk of negative consequences of training such as cumulative fatigue, performance decrements, and injury (26, 200).

Regular monitoring of individual responses to in-season training and match loads is vital in optimising the performance of elite team sport athletes. Responses to training are ideally assessed using maximal fitness tests as these most likely mirror the intensive demands of competition (25). For example, the Yo-Yo intermittent recovery 2 (YYIR2) showed a strong positive relationship with match high speed running output in both ARF (154) and elite soccer (10, 163). Furthermore, YYIR2 test results are reported to differentiate between fitness levels, playing positions, playing standards, successful or unsuccessful teams, and season phases (11, 157).

Importantly, improved YYIR2 performance is also associated with aspects of superior match performance in ARF. For example, ARF players with the greatest YYIR2 test performance have produced higher match exercise intensity, accrued more ball disposals, and achieved more positive coaches' ratings of performance (136, 154). It is acknowledged that match performance in team sport is dependent on several factors including but not limited to tactical ability, team strength, technical skills, opposition strength and score line (149, 150, 164). Overall, current research demonstrates strong links between proportionally greater physiological capacities and improved match performance in ARF (136, 154, 201); thus highlighting the importance of regular physical performance testing to monitor physiological capacities.

Despite the known links between physiological capacities and ARF match performance, regular maximal performance testing is rarely appropriate given that the resultant fatigue would most likely detract from subsequent training and match performance (25). This is particularly pertinent

in-season where optimal recovery between matches is often prioritized over introducing further physiological stimulus (21). As a result, fitness is likely to decline over a long competitive season (25). However, in the absence of an effective athlete monitoring tool that can quantify changes in performance relevant to competitive match-play, it may be difficult to discriminate between indicators of increased fatigue and reduced fitness as the in-season period progresses (25).

In Chapter Four, the monitoring of HR responses to a submaximal intermittent running (SIR) test provided an indicator of both concurrent validity and day-to-day reliability in comparisons with the YYIR2 test performance in elite ARF players. Furthermore, Chapter 5 demonstrated that increases in weekly distance covered at running speeds greater than  $14.4 \text{ km}\cdot\text{h}^{-1}$  were associated with reduced HR<sub>ex</sub> and faster HRR responses to the SIR test during a six week pre-season period. These findings support the use of the SIR test as a regular and non-fatiguing monitoring tool to assess intermittent running capacity in elite ARF; thus providing a viable and relevant alternative to maximal tests such as the YYIR2 in this environment.

The ultimate effectiveness of a fitness test in an applied setting is dependent on its relevance to match performance (25). To reiterate, previous chapters have demonstrated associations between SIR test HR responses and both YYIR2 performance and pre-season high speed running loads in elite ARF. However, it is currently unknown whether HR responses to the SIR test can be used to monitor an athlete's response to TL during the less predictable and more individualised demands of in-season training. Furthermore, relationships between HR responses to the SIR test

and indicators of match exercise intensity are yet to be investigated. Exploring these relationships may better inform practitioners about the usefulness of implementing regular SIR testing during the in-season phase. Therefore, the primary aim of this study was to determine the usefulness of the SIR test as an in-season monitoring tool by investigating the influence of both external and internal TL on HR responses to the SIR test during an elite ARF in-season period. The secondary aim of this study was to explore whether in-season SIR testing can be used to assess physical match readiness by exploring associations between SIR test HR responses and indicators of physical performance during matches.



## **7.2 Method**

### **7.2.1 Participants**

As in previous chapters, participants were 45 senior and rookie-listed elite ARF players from one Australian Football League (AFL) club. Mean  $\pm$  SD age, height, body mass and time spent on an AFL list were  $23 \pm 4$  years,  $188 \pm 8$  cm,  $85 \pm 8$  kg, and  $6 \pm 4$  years, respectively. Written informed consent was obtained from each player to use data for research purposes following approval from the Human Ethics Research Committee at the Australian Catholic University (Appendix 3). All players completed testing as part of their normal training regime and were familiar with testing procedures prior to the study. Players were also free from any injury or illness that may have limited their ability to complete testing.

### **7.2.3 Study Design**

This observational prospective research design was implemented during an elite ARF in-season and comprised five matches during the season and the related preceding week of training. Data were limited to five non-consecutive weeks throughout the in-season phase due to multiple factors including; 1) availability of indoor training facilities necessary to provide the standardisation of SIR testing, 2) necessity to obtain GPS data from matches completed at outdoor stadiums, and 3) weeks with sufficient days break between games to satisfy high performance and coaching staff that SIR testing implemented prior to training would not adversely affect subsequent training and match performance. It is acknowledged that the use of a larger data set would provide a more comprehensive profile of match-to-match variability (202).

However, the five week sample provided an acceptable snapshot of total weekly in-season TL and match demands within a typical competitive week (Table 7.1).

Table 7.1 Typical in-season training schedule for Chapter 7 investigations (7 day break between games).

	<b>Monday</b>	<b>Tuesday</b>	<b>Wednesday</b>	<b>Thursday</b>	<b>Friday</b>	<b>Saturday</b>	<b>Sunday</b>
<b>AM</b>	Musculoskeletal screening	Off	Musculoskeletal screening	Resistance Training	Musculoskeletal screening	Off	Off
							(Own recovery)
	Resistance Training		Team Meeting	Pilates	Team Meeting		
			<i>SIR Testing</i>	Massage	Captains Run (Light skills)		
			Main Training (Skills, small sided games, full field match simulation drills)				
<b>PM</b>	Team Meeting	Off	Resistance Training	Off	Off	Match	Off
	Light skills session		Recovery				
	Recovery						

### **7.2.3 Training load quantification**

The session rating of perceived exertion (sRPE) method (5) was used to quantify internal TL for all training modalities and matches on an individual basis. Please refer to section 4.2.6 for a full explanation of the training load quantification methods using sRPE.

External TL was quantified for each individual during all outdoor training sessions and matches using portable global positioning system (GPS) devices (Optimeye S5, Catapult Innovations, 15 Hz, Melbourne, Australia). All match GPS variables were calculated during the on-field playing time of each participant. Excluded match-related data involved any data collected during quarterly match breaks and time spent on the interchange bench. The GPS match data were included for analyses if the participant played in  $\geq 70\%$  of total match time (154) in order to decrease the likelihood of reporting exaggerated match intensities. Please refer to Section 4.2.7 for a full explanation of the training load quantification methods using GPS technology.

For each training session that an individual completed, the sum of their previous one week cumulative internal and external TL's were calculated for each sRPE and GPS variable, respectively.

#### **7.2.4 Submaximal intermittent running test**

The SIR test followed a similar protocol to the previously established YYIR2 test procedures (11). Please refer to Section 4.2.2 for a full explanation of SIR test procedures.

#### **7.2.5 Measuring heart rate response and rating of perceived exertion to the SIR test**

Heart rate data were monitored continuously during both the running and recovery periods of each SIR test using Firstbeat HR monitors and data were downloaded using the proprietary software (Firstbeat Technologies, Jyväskylä, Finland). Please refer to Section 4.2.4 for a full explanation of HRex calculation methods.

In contrast to previous chapters, HRR was determined at a single time point; one minute (HRR<sub>60s</sub>) following the four minute running period of the SIR test. This change was made in order to shorten the overall duration of the test to more effectively fit the protocol into the in-season schedule in which multiple pre-training objectives also included musculoskeletal screening, physiotherapy treatments, group and individual meetings, and skill-based warm ups. Please refer to Section 4.2.5 for greater detail regarding the calculation of HRR.

#### **7.2.6 Positional classifications**

As described in Chapter Six, Section 2.7, positional groups were selected for players based on the on-field position each athlete played the majority of their game time within the team structure. A summary of these positional group classifications is provided in Table 7.2. It is acknowledged that playing position did not significantly influence the relationship between SIR test HR responses and measures of TL during pre-season training in (Chapter Six). However, given the addition of match data, as well as the likely increase in specificity of training associated with the competitive season, investigating the influence of playing position was still deemed to be worthwhile in this chapter.

Table 7.2 Positional Group Classifications

<b>Positional Group Name</b>	<b>Positions Included</b>
Midfielders	Rover, Ruck-Rover, Centre, Wing
Key Position	Full Forward/Ruck, Centre Half Forward, Full Back, Centre Half Back
Hybrids	Half Forward Flank, Forward Pocket, Half Back Flank, Back Pocket

### 7.2.7 Statistical analyses

Statistical analyses were performed using the R statistical programming language (R Core Development Team, 2016). Individual, within-subject Pearson's correlations were calculated between each load parameter from training and matches and each SIR test HR parameter measured over the five testing weeks using the ANCOVA method to control for repeated measures on individuals (203). All load parameters were log transformed before analysis to stabilise the variance, and thereafter separate regression models were fit to determine the influence of each TL parameter (as the explanatory variable) on SIR test HR responses (as the response variables) for each playing position group during training. Additionally, the influence of each SIR test HR response (as the explanatory variable) on match-based load parameters (as the response variables) were analysed using separate regression models for each playing position group during match play.

The corrected Akaike Information Criteria (AIC) (204) was calculated to determine goodness of fit for each regression model and was also used to determine the most important explanatory variable from the candidate model set. In both instances, a lower AIC score indicated a more parsimonious model fit. Where appropriate, multiple regression models combining the two significant explanatory variables with the lowest individual AIC score were also fit and compared against regression models that contained each constituent explanatory variable in isolation. For each multiple regression model, the variance inflation factor (VIF) was calculated to check for multi-collinearity between explanatory variables. A VIF between 1 and 5 was considered acceptable. Variables with  $VIF > 5$  were considered collinear and removed from the model.

Two-tailed statistical significance was interpreted at an alpha level of 0.05. The magnitude of Pearson correlation coefficients were interpreted as: *trivial* (0.00-0.10), *weak* (0.10-0.30), *moderate* (0.30-0.50), *strong* (0.50-0.70), *very strong* (0.70-0.90), *almost perfect* (0.90-1.00) (1). The imprecision of Pearson correlations and linear regression model parameter estimates are expressed using 90% confidence limits (CL). Additionally, magnitude-based inferences (MBI) were calculated for correlation coefficients using a custom spreadsheet and are interpreted using the following qualitative descriptors: <1%, *almost certainly not*; 1% to 5%, *very unlikely*; 5% to 25%, *unlikely*; 25% to 75%, *possible*; 75% to 95%, *likely*; 95 to 99, *very likely*; >99%, *almost certain* (205). The inclusion of magnitude-based inferences provides a more useful interpretation of whether any associations can be considered practically meaningful (206). The probabilities that the true effect of any association was either positive, trivial, or negative were reported as a percentage (e.g. positive effect % / trivial effect % / negative effect %) (206). Only correlations that were considered likely positive or negative or above (i.e.  $\geq 75\%$ ) were reported for brevity.

### **7.3 Results**

A total of 34 players completed SIR testing across the in testing period. Descriptive statistics for in-season SIR testing, cumulative weekly TL, and physical match output are displayed in Tables 7.3 to 7.5.



Table 7.3 Descriptive statistics (group mean  $\pm$  SD) for in-season SIR testing

<b>Position</b>	<b>HREx</b> <b>(% HR max)</b>	<b>HRR60s<sup>♦</sup></b>
Midfielder	85 $\pm$ 4	19 $\pm$ 5
Hybrid	86 $\pm$ 4	14 $\pm$ 5
Key Position	84 $\pm$ 6	14 $\pm$ 5

<sup>♦</sup> Absolute difference between four minute HREx and HRR at each time point, expressed as a percentage of four minute HREx

Table 7.4 Descriptive statistics (group mean  $\pm$  SD) for cumulative weekly in-season training load

<b>Position</b>	<b>Distance</b> <b>(m)</b>	<b>Zone 4 Distance</b> <b>(m)</b>	<b>Zone 5 Distance</b> <b>(m)</b>	<b>Zone 6 Distance</b> <b>(m)</b>	<b>RPE</b> <b>(AU)</b>
Midfielder	22399 $\pm$ 4015	4762 $\pm$ 926	2129 $\pm$ 628	297 $\pm$ 196	2321 $\pm$ 538

Hybrid	22656 ± 4726	4436 ± 1205	1848 ± 649	298 ± 150	2304 ± 566
Key Position	24233 ± 3904	4417 ± 1396	1582 ± 561	192 ± 95	2454 ± 479

(m) = metres

(AU) = arbitrary units

Table 7.5 Descriptive statistics (group mean ± SD) for physical match output

Position	Distance	m·min <sup>-1</sup>	Zone 4	Zone 5	Zone 6
	(m)		Distance	Distance	Distance
			(m)	(m)	(m)
Midfield	13706 ± 1448	138 ± 10	3335 ± 701	1400 ± 412	222 ± 127
Hybrid	13578 ± 1172	132 ± 11	2968 ± 517	1280 ± 323	255 ± 112
Key	14044 ± 1367	128 ± 8	2701 ± 640	855 ± 219	171 ± 100

### 7.3.1 Midfielders

No external or internal TL parameters were significantly related to SIR test H<sub>ReX</sub> or HRR<sub>60s</sub> in midfielders during training (Figure 7.1). When correlations were interpreted using magnitudes based inferences, there was a likely, moderate, positive correlation between

HREx and weekly cumulative Z6 distance during training ( $r = 0.35$ , 90% CL: [-0.16, 0.71], MBI 84%/12%/4%)

During match play, there was a very likely, strong, negative correlation between HREx and Z5 distance ( $r = -0.58$ , 90% CL: [-0.83, -0.13], MBI: 0%/2%/98%) and a likely, weak, negative relationship ( $r = -0.28$ , 90% CL: [-0.67, 0.24], MBI: 7%/17%/76%) between HREx and total distance (Figure 7.2). A linear regression model estimated that a 1% decrease in HREx was associated with a 5.1% (90% CL: [8.7, 1.4] increase in Z5 running. In addition, there was a very likely, strong, positive correlation between HRR<sub>60s</sub> and Z5 distance ( $r = 0.50$ , 90% CL: [0.03, 0.79], MBI: 95.4%/3.9%/0.8%), as well a likely, weak, positive correlation between HRR<sub>60s</sub> and total distance ( $r = 0.27$ , 90% CL: [-0.24, 0.66], MBI: 75/18/8) during match play. The results of the linear regression model indicated that a 1% decrease in HRR<sub>60s</sub> corresponded to a 2.2% (90% CL: [-0.3, -4.2]) increase in Z5 distance during match play.

### 7.3.2 Hybrids

No significant correlation was observed between any external or internal TL parameter during training and SIR test HR responses in hybrids (Figure 7.1). However, weekly cumulative Z5 distance ( $r = -0.30$ , 90% CL: [-0.63, -0.12], MBI: 3%/14%/83%) and weekly cumulative HSR distance ( $r = -0.28$ , 90% CL: [-0.61, 0.14], MBI: 4%/16%/81%) both showed a likely, small, negative, correlation with HREx when interpreted using magnitudes

based inferences. Additionally, a likely, weak, positive correlation existed between weekly cumulative Z5 distance ( $r = 0.24$ , 90% CL: [-0.18, 0.59], MBI: 75%/20%/6%) and HRR<sub>60s</sub>.

Although HRex from SIR testing was not significantly related to any GPS variables during match play (Figure 7.2), there was likely, weak, negative correlation between Z5 distance and HRex ( $r = 0.27$ , 90% CL: [-0.60, 0.16], MBI: 4%/17%/79%) when interpreted using magnitude based inferences. In comparison, HRR<sub>60s</sub> from SIR testing showed a significant and likely, moderate, negative correlation with Z6 distance during match play ( $r = -0.42$ , 90% CL: [-0.71, -0.02]). No other GPS variables were significantly related to HRR<sub>60s</sub>. The linear regression model estimated that a 1% increase in HRR<sub>60s</sub> was associated with a 2.5% (90% CL: [4.7, 0.2]) decrease in Z6 running.

### 7.3.3 Key Position Players

During training, weekly cumulative Z4 distance showed a significant and almost certain, very strong, negative relationship ( $r = -0.83$ , 90% CL: [-0.94, -0.57], MBI: 0%/0%/100%) with HRex. Additionally a significant, very likely, strong, negative correlation existed between HRex and cumulative weekly Z6 distance ( $r = -0.59$ , 90% CL: [-0.83, -0.15], MBI: 0%/1%/96%) and cumulative weekly total distance ( $r = -0.52$ , 90% CL: [-0.80, -0.05], MBI: 1%/3%/96%), respectively. Model comparison statistics from the linear regression demonstrated that a model containing only Z4 distance (AIC: 109) was more parsimonious than one containing both Z4 and Z6 distance as explanatory variables (AIC: 115). Hence, only Z4 running was included as an explanatory variable in a linear regression model,

revealing that a 100% increase in cumulative weekly Z4 distance was associated with a 4.0% (90% CL: [-5.4, -2.6]) decrease in HR<sub>ex</sub>. In comparison, whilst no significant relationships existed between external or internal TL parameters and HRR<sub>60s</sub> (Figure 7.1), there was a likely, weak positive correlation between sRPE and HRR<sub>60s</sub> ( $r = 0.27$ , 90% CL: [-0.25, 0.66], MBI: 75%/18%/8%).

Neither HR<sub>ex</sub> nor HRR<sub>60s</sub> were significantly correlated with any GPS variables during match play (Figure 7.2). However, a likely, moderate, negative correlation existed between HR<sub>ex</sub> and HSR distance ( $r = -0.32$ , 90% CL: [-0.69, 0.19], MBI: 5%/14%/81%). In contrast, a likely, moderate, positive correlation was present and between HR<sub>ex</sub> and  $m \cdot \text{min}^{-1}$  ( $r = 0.33$ , 90% CL: [-0.18, 0.70], MBI: 82%/13%/5%). Both Z5 distance ( $r = -0.35$ , 90% CL: [-0.71, 0.16], MBI: 4%/12%/84%) and Z6 running distance ( $r = -0.36$ , 90% CL: [-0.72, 0.15], MBI: 4%/1%/85%) showed a likely, moderate, negative correlations with HRR<sub>60s</sub>.

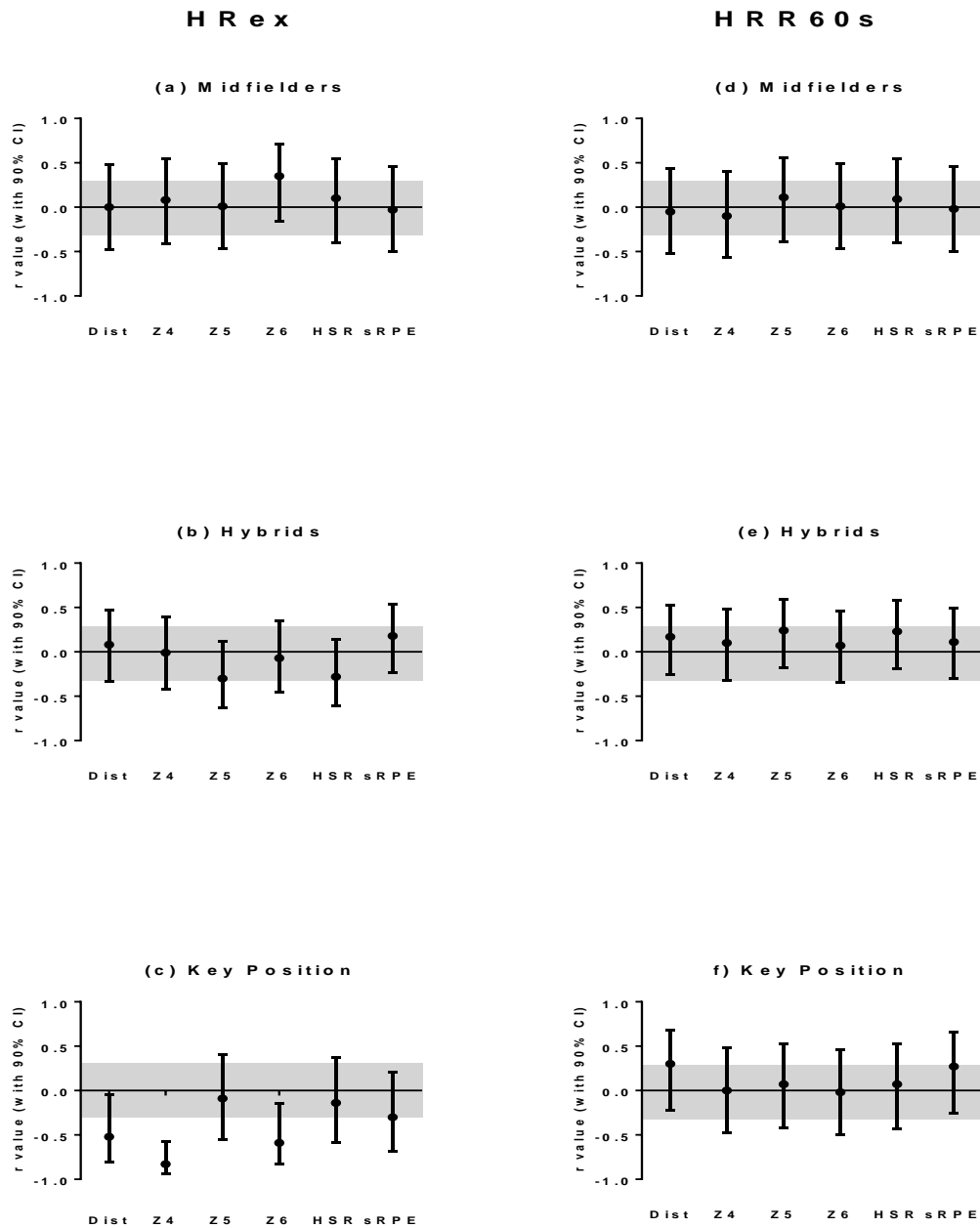


Figure 7.1 Pearson correlation coefficient value (y axes) for the relationship between select measures of in-season TL (x axes) and SIR test HR responses by playing position. Bars represent 90% confidence limits for Pearson correlation coefficient values. Shaded areas correspond to less than 75% for qualitative magnitude based inference descriptors (205).

HRex, exercise HR; HRR60s, heart rate recovery after 60 seconds; Dist, distance; Z4, Zone 4 running distance; Z5, Zone 5 running distance; HSR, total high speed running distance; sRPE, session rating of perceived exertion load.

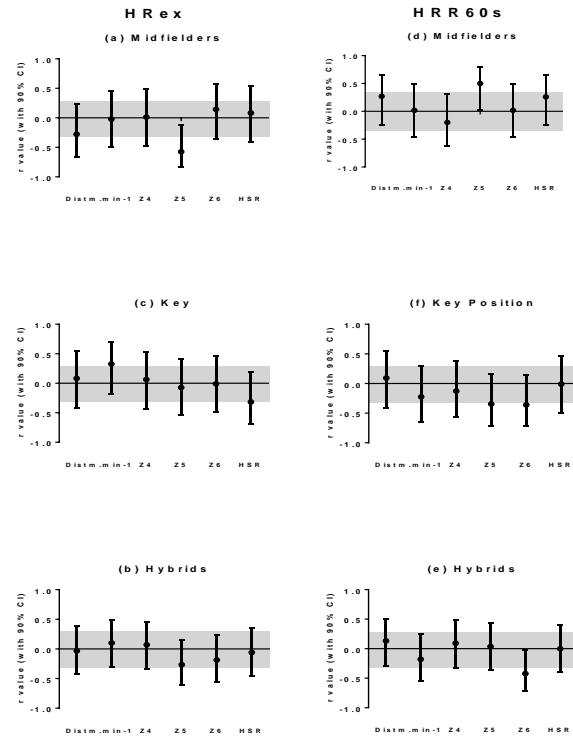


Figure 7.2 Pearson correlation coefficient value (y axes) for the relationship between select measures of match running output (x axes) and SIR test HR responses by playing position. Bars represent 90% confidence limits for Pearson correlation coefficient values. Shaded areas correspond to less than 75% for qualitative magnitude based inference descriptors (205).

HRex, exercise HR; HRR60s, heart rate recovery after 60 seconds; Dist, distance;  $\text{m min}^{-1}$ , metres per minute; Z4, Zone 4 running distance; Z5, Zone 5 running distance; HSR, total high speed running distance.

## 7.4 Discussion

The first major finding of the current study was that selected TL measures were related to HR responses to SIR testing throughout designated weeks of an ARF in-season period. Additionally, the SIR test HR responses were also associated with selected measures of match load over the same in-season period. However, not all load measures correlated with the SIR test HR responses. Importantly, relationships between the SIR test HR responses and both training and game load parameters were influenced by playing position. Stronger and more statistically significant correlations between TL and the SIR test HR responses were reported for key position players than midfield and hybrid positions. In contrast, game load was more strongly associated with the SIR test HR responses in midfielders than hybrids and key position players. These results suggest that monitoring HR responses from SIR testing during the in-season can provide valuable information about the training status and physiological performance capacity of individuals, specific to playing position.

This study builds on the knowledge of SIR testing in elite ARF players as reported in earlier chapters. Results from this study show that playing position emerged as more of an influential factor in the relationship between TL and SIR test HR responses during the in-season than pre-season period. In Chapter Six playing position was not deemed influential during the pre-season. Inconsistent responses related to playing position between pre-season and in-season training periods may be explained by differences in training prescription, load management strategies, and coaching priorities between the pre-season and in-season phases.



For example, the aim of the pre-season period is to provide a training overload that develops the fitness capacities and fatigue resistance necessary to cope with forthcoming in-season training and game demands (18). Training overload can be more heavily prioritised than recovery during the pre-season than in-season, due to the absence of regular match-play (19). As a result, TL's are generally much lower during the in-season than pre-season phase of the periodised year (21). Once the in-season period begins, training prescription is at its most specific and recovery between matches becomes a greater priority than increasing TL to improve fitness levels. Greater specificity in training prescription during the in-season period combined with regular match-play may have facilitated physiological adaptations specific to playing position; potentially contributing to the influence of playing position on the relationship between TL and SIR test HR responses.

Interestingly, relationships between the SIR test HR responses and TL measures varied by playing position. For example, the SIR test HR responses of key position players were more significantly associated with selected measures of cumulative weekly in-season TL than midfield and hybrid players. Playing position was also influential on the relationship between SIR test HR responses and measures of match load. Specifically, the SIR test HR responses of midfield players were more significantly correlated to selected measures of match load than hybrid and key position players.

Collectively, these results indicated that monitoring HR<sub>ex</sub> and HRR<sub>60s</sub> during SIR testing conducted during the in-season period may provide useful information on the training status

and physical performance capacity of players during matches. However, it is evident from these results that the relationship between SIR test HR responses and measures of training and game loads can also be influenced by playing position. Furthermore, the direction and magnitude of these associations can be inconsistent.

An explanation for the varied influence of playing position on relationships between the SIR test HR responses and selected measures of training and game load is not immediately apparent. In some instances, it could be suggested that relationships between the SIR test HR responses and measures of training and game load are influenced by playing position based on which load metrics are more commonly associated with physical performance in each position. For example, key position players covered a greater amount of weekly cumulative distance in training than midfield and hybrid players (Table 7.2-7.3). This trend may help to explain why increased cumulative weekly total distance was more strongly associated with decreased HRex in key position players than other playing positions. Specifically, decreased HRex in association with greater cumulative weekly distance may be indicative of improved fitness status in key positions players.

However, this trends in data were was not consistent across all relationships reported in the current study. For example, increased cumulative weekly zone 4 and zone 6 distances were more strongly associated with decreased HRex in key position players than midfield and hybrid players. This occurred despite key position players covering less weekly cumulative distance in these speed zones than both midfield and hybrid players. As such, it appears that

the varied influence of playing position on the relationship between SIR test HR responses and selected measures of workload cannot be fully explained by the differences in physical outputs between playing positions during either training or match play.

Varying relationships between SIR test HR responses and different speed zones were also reported in the previous chapter on pre-season training. In light of these findings between studies, it is possible that inconsistencies in the relationships between the SIR test HR responses and measures of load may be reflective of both the differing cardiac parasympathetic functions of HR<sub>ex</sub> and HRR<sub>60s</sub> (197, 198), as well as the greater measurement error associated with distance covered in higher velocity speed zones (44). It should also be acknowledged that physical match performance can be influenced by a variety of factors such team strength, opposition strength, technical ability, tactical changes, and score line (149, 150, 164). As such, higher physical match output based on running distances in selected speed zones is unlikely to be solely representative of an athlete's physical readiness to perform.

Interpreting relationships between the SIR test HR responses and various measures of load is of paramount importance to practitioners. However, results from both the current and previous studies suggest that associations may not always be conclusive. Traditionally, lower HR<sub>ex</sub> (105, 156, 185) and faster HRR (188, 189) have been considered signs of positive adaptation to training. As such, the decreased HR<sub>ex</sub> response of key position players in this study in association with increases in weekly cumulative total distance, zone

4 distance and zone 6 distance may be interpreted as a positive adaptation to higher workloads. Concomitantly, lower HR<sub>ex</sub> and faster HRR<sub>60s</sub> in midfielders could be seen as an indicator of increased physical readiness given the reported associations with increased total distance and zone 5 distance in matches.

However, similar changes in HR response to exercise have also been evident in negative states of training adaptation. More recently, decreased HR<sub>ex</sub> (158, 207) and faster HRR (89, 190, 191, 207) have been reported in overreached athletes; thus suggesting such changes in HR response to exercise may also indicate cumulative fatigue and/or deconditioning. As discussed in the in the previous chapter, it is possible that a number of factors contributed to the unexplained variance in the HR response to exercise. These may include exercise intensity, duration and mode, as well environmental conditions, genetics, nutrition, and methodological calculations (7, 159). The combination of factors influencing HR as well as the potential ambiguities in HR response to exercise can make the interpretation of data more difficult; thus hindering effective implementation as an athlete monitoring tool.

To the author's knowledge, this is the first study in elite ARF exploring the relationship between both TL and measures of physical match output with HR responses to a submaximal running test. Despite modest associations resulting from correlational and magnitude based inference analyses, this study shows that perturbations in HR responses to a novel submaximal running test are influenced by changes in weekly cumulative TL in

elite ARF players. Furthermore, results suggest that indicators of physical match output are also related to SIR test HR responses. Consequently, this study adds to the knowledge gained in previous chapters by providing further proof of concept that a novel submaximal tests can be used as an athlete monitoring tool within the important competition phase of a periodised year.

There are a number of limitations within this study requiring acknowledgement. For example, the positional groups used in this study may differ from previous reports of positional groups in elite ARF clubs. This inconsistency could make it more difficult to generalise the position-specific findings in this study across the entire competition or in comparisons with other studies. However, the positional groups used in this study were considered most reflective of the physical and tactical demands of each playing position as determined by the composition of the playing list and the game structure employed by the elite ARF club from which participants were recruited and made comparisons from previous seasons and feeder teams feasible.

A further limitation is that data collection for this study was restricted to five weeks of training and matches throughout an entire ARF season. The reasons for this are described in this Chapter (Section 7.2.1) and highlight the challenges of research within an applied environment. Although ideally a larger sample of data would be preferred, the five week sample provided a detailed snapshot of weekly training and game demands within a typical elite ARF in-season period.

Another potential limitation in the current study is the use of absolute speed zones for GPS analysis. The question of whether absolute or individualised speed zones are more accurate in determining external load using GPS has received recent attention given the proliferation of GPS data in field-based sports (121). A study in junior rugby league found that the use of absolute speed zones both underestimated and overestimated the high speed running volume of slower and faster players, respectively (208). Furthermore, research in elite soccer reported practically relevant differences in workload both within and between different players using an individualised approach based on ventilatory thresholds to determining speed zones (209). As such, it is possible that individualised speed zones may provide useful additional information to help quantify the external TL of individuals within team sports.

In contrast to these findings, other studies in junior (210) and international (211) soccer that have explored the individualisation of GPS speed zones using an array of fitness measures and have reported that the quantification of load was not improved using individualisation methods based on any single fitness metric. Despite the potential benefits of individualised speed zones, there is a lack of conclusive evidence to support their use in place of absolute thresholds, particularly in team sports where there are practical benefits to assigning well-considered speed zones across a large group of professional athletes (121, 210). While acknowledging the potential added benefit of individualised thresholds, there is acceptable

level of support within the literature for the use of arbitrary speed zones in the current study.

Finally, it should be acknowledged that  $HRR_{60s}$  used in the current study represents only one of many possible HRR calculation methods. For example, the measurement of HRR can differ based on the time length of measurement, the use of absolute or relative differences in HR, and the application of more sophisticated mathematical techniques that can quantify the exponential decay of HR over a given time period (212). However, complex and lengthy calculation methods are rarely appropriate in applied settings such as elite ARF given the necessity to provide actionable information on a large number of players within short timeframes. As such, the  $HRR_{60s}$  method used in the current study was considered appropriate within the practical constraints of the applied elite ARF setting in which data was collected.

## **7.5 Conclusions and practical applications**

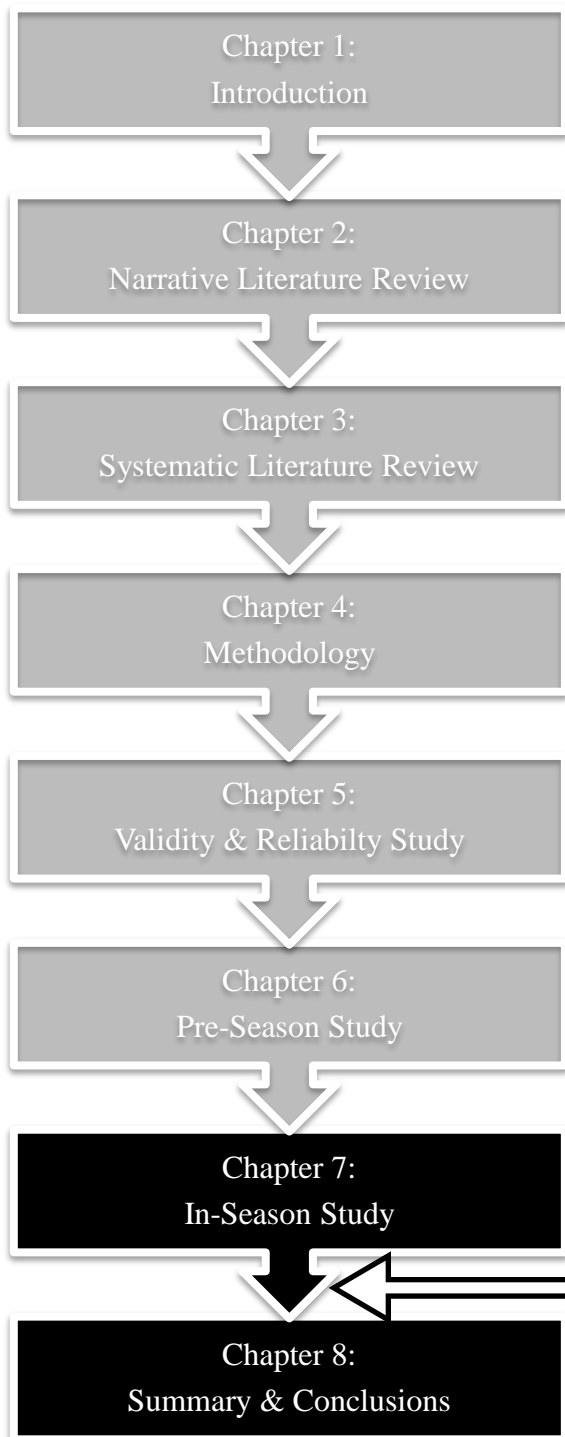
This final study further builds on the previous knowledge uncovered in Chapters Five and Six exploring the use of a SIR test in elite ARF. The first aim of this study was to assess the influence of training load on HR responses to the SIR test during an elite ARF in-season period. Second, associations between HR responses to the SIR test and measures of match load were also explored. The results of this study demonstrated that selected measures of TL were related to SIR test HR responses. Furthermore, SIR test HR responses were also

associated with certain game load metrics. Most notably, relationships between SIR test HR responses and measures of training and game load were influenced by playing position.

From a practical perspective, it is most likely that decreases in HR<sub>ex</sub> and faster HRR responses to SIR testing were associated with positive adaptation to training and improved aspects of physical game output. However, given some of the ambiguities involved with interpreting HR response to exercise, results from SIR testing may best be used in conjunction with other monitoring data to most comprehensively measure and interpret an athlete's physical readiness to perform. Collectively, these results suggest that monitoring HR responses from SIR testing during the in-season can provide practitioners with valuable information in addition to other monitoring data to indicate the training status and physiological performance capacity of individuals, specific to playing position.



## Chapter Link: Summary of in-season study



1. Associations between select weekly training load measures and SIR test HR responses were evident in-season.
2. SIR test HR responses were related to select measures of match load.
3. Relationships between SIR test HR responses and training/match load were influenced by playing position.
4. In-season SIR testing may provide information about the training status and physical performance capacity of individuals, most likely improvements in fitness.

## **Chapter Eight: Summary and Conclusions**

### **8.1 Overview**

This program of research investigated the effectiveness of using heart rate (HR) responses from a submaximal intermittent running (SIR) test to monitor training responses and identify changes in fitness and fatigue in elite ARF players throughout different stages of a periodised year. First, existing gaps in the research were identified through rigorous narrative and systematic reviews of the literature around the use of athlete monitoring strategies to quantify TL and monitor training responses of fatigue in elite football codes. Based on these findings, original investigations were undertaken to assess the concurrent validity and day-to-day reliability of a SIR test based on a popular maximal test of intermittent running capacity: the Yo-Yo intermittent recovery 2 (YYIR2) test. Evidence was then collected to assess the influence of both pre-season and in-season TL on HR responses from the SIR test as a means to monitor individual training adaptation. Additionally, data in the in-season study was used to investigate the ultimate effectiveness of the SIR test by assessing relationships between SIR test HR indices and measures of match running performance.

## **8.2 Summary of major findings**

The following section re-visits the original hypothesis and summarises the major findings of studies within the thesis.

*(i) In Chapter Three it was hypothesized that a systematic review of the literature would uncover a large range of monitoring strategies to quantify TL and monitor training responses in elite football codes, however; consensus on the effectiveness of these strategies would remain unclear.*

The systematic review revealed insufficient detail to fully understand the exercise-dose response relationship across elite football codes, specifically with regard to the response of fatigue. The quantification of TL remains the predominant focus of published research in the domain of athlete monitoring (35, 36). However, relationships between TL and training responses (i.e. fitness and fatigue) are under explored. Specifically, a gap exists in the exploration of objective measures of both TL quantification and fatigue-related training responses, highlighting a current reliance on subjective monitoring methods. Although a large range of athlete monitoring strategies are available across elite football codes, inconsistent implementation and reporting may hinder the accurate interpretation of data. Importantly, consolidation of knowledge and exploration of practical and objective methods to monitor both TL and training responses are necessary. Subsequently, the hypothesis was supported.

*(ii) In Chapter Five it was hypothesized that investigation into the concurrent validity and day-to-day reliability of the SIR test would demonstrate strong correlations between HR responses during and following the SIR test and YYIR2 test performance. Strong day-to-day reliability of HR responses was also hypothesised to be observed; thus supporting selected aspects of validity and reliability of the SIR test protocol.*

Heart rate responses from SIR testing provided a valid indicator of YYIR2 performance. In addition, SIR test HR responses were found to have acceptable day-to-day reliability. Specifically, HR<sub>ex</sub> at 4 minutes was determined the most reliable and was also highly correlated with YYIR2 performance. Collectively, results supported the use of SIR testing as a valid and reliable indicator of YYIR2 performance; thus strongly supporting the hypothesis.

*(iii) In Chapter Six it was hypothesized that 1) HR responses to the SIR test would be associated with changes in TL throughout a pre-season meso-cycle in elite ARF players, and 2) that relationships between HR responses to the SIR test and measures of TL would be influenced by playing position.*

Increases in external TL measures of weekly distance covered at velocities above 14.4 km h<sup>-1</sup> (Z4, Z5, and Z6 running bands) were associated with decreased HR<sub>ex</sub> and faster HRR from SIR testing during a six week pre-season training period. However, no influence of internal TL measured via sRPE on HR responses to SIR testing was observed.

Subsequently, the first hypothesis was supported by relationships between selected measures of external TL and SIR test responses; without similar relationships to internal

TL. However, there was no significant influence of playing position on the relationship between SIR test HR responses and measures of TL. As a result, the second hypothesis was rejected.

*(iv) In Chapter Seven it was hypothesized that 1) HR responses to the SIR test would be associated with changes in TL during the competitive season in elite ARF players, 2) the SIR test HR responses would be associated with match running output in elite ARF players, and 3) relationships between HR responses to the SIR test and match running output will differ based on playing position.*

Heart rate responses to SIR testing were related to changes in selected measures of training load and match load during the in-season testing period. However, not all load measures correlated with the SIR test HR responses. Most importantly, playing position influenced the relationship between the SIR test HR responses and both training and game load metrics. Specifically, stronger associations between training load and the SIR test HR responses were reported for key position players than midfield and hybrid positions. In contrast, relationships between game load and the SIR test HR responses were stronger in midfielders than hybrids and key position players. Collectively, these findings supported the three components of the original hypothesis.

### 8.3 Strengths

The strengths of this thesis include:

1. Advancement of current knowledge on athlete monitoring strategies to quantify TL and monitor training responses.
2. Extend the knowledge of objective measures of external TL beyond time-based measures to GPS-derived metrics of total distance and distance covered within specific speed zones.
3. Develop a greater understanding of the effectiveness of objective measures to assess responses to TL by monitoring HR during a novel SIR test.
4. Strengthened the scientific rationale for implementing and interpreting objective measures of training load (via GPS) in combination with objective measures training response (via HR) in an athlete monitoring program within an applied setting.
5. Support for the concurrent validity and day-to-day reliability of using HR responses from SIR testing to indicate performance in a well-known and widely implemented maximal test.
6. Demonstrated relationship between HR responses from SIR testing and changes in TL during a pre-season training period in elite ARF. Specifically, increases in weekly cumulative distance covered at higher running speeds were associated with decreased H<sub>Re</sub> and faster HRR responses to SIR testing, irrespective of playing position. These results were considered most likely indicative of improved fitness.
7. Established relationships between HR responses from SIR testing and changes in TL throughout select weeks of an in-season period in elite ARF, specific to playing

position. For example, stronger associations between SIR test HR responses and select measures of TL were reported for key position players compared to midfielders and hybrids. Specifically, increased weekly cumulative total distance, Z4 distance and Z6 distance were associated with decreased HRex responses to SIR testing in key position players; indicating a favourable response to increases in select measures of TL.

8. Determined associations between SIR test HR responses and relevant measures of match running output, relative to playing position. Specifically, stronger associations were reported between SIR test HR responses and select measures of match running output in midfielders compared to hybrids and key position players. For example, lower HRex responses to SIR testing were associated with increased total distance and Z5 distance covered by midfielders during match play. This suggests that lower HRex responses to SIR testing in midfielders players could be indicative of higher readiness to perform.
9. Collectively, the program of research supported the use of the SIR test as a novel athlete monitoring tool test that is submaximal in nature, relevant to elite ARF performance, conducive to whole group testing, time efficient, modifiable based on population, and routinely implementable, with the potential to indicate individual changes in fitness throughout different phases of a periodised year.

## **8.4 Limitations**

Participants included in the research represented only elite level players from one club in one professional football competition (Australian Football League). These participants could be considered highly homogenous given their elite level status, and the pre-requisite fitness levels required to be selected for an AFL playing list. Also the influence of drafting strategies whereby players may be selected based on whether they possess specific physical qualities that are likely to compliment the intended game style set by coaches can also contribute to homogeneity. The limitation of homogeneity among players can complicate statistical modelling, which works well when athletes are sufficiently different to be a random factor within the model. Significant differences between athletes are more difficult to identify, particularly in relatively small sample sizes.

Although Chapter Three focused on investigating relationships between TL monitoring strategies and markers of fatigue through a systematic review of the literature, the subsequent chapters consisted of a more global critique of responses to TL that included both fitness and fatigue. Indeed, Chapter Three identified some of the ambiguities around the definition and measurement of fatigue in applied settings. This highlighted the need to develop a monitoring method that had the potential to detect both fitness and fatigue responses from TL; thus the remaining studies directed their attention to investigating the effectiveness of using HR responses from the SIR test as a relevant, regular, and minimally fatiguing method to assess changes in training status among elite ARF players across different phases of a periodised season.



Submaximal testing was conducted during specific snapshots of a periodised year due to conditions described in Section 7.2.1. As a result, the external validity of this research may be questioned when determining the relevance of these findings across longer time periods or within other applied settings (202). However, given the novel nature of the SIR test, the first priority of the research was to provide proof of concept in the current group of athletes prior to extending investigations across longer timeframes and other team sport environments.

A further limitation may be the lack of laboratory testing in this study design. While such testing may provide useful data, access to appropriate facilities and the cost associated with testing, compromises practicality in field settings. As such, the inclusion of laboratory testing was considered undesirable in the current environment. Furthermore, such testing would also likely be considered impractical for other team sports who may wish to replicate the study design in their own setting.

Another important consideration is the likelihood that match performance can be inferred by match running output. Although previous research in elite ARF suggests that high intensity running distance during a match is related to aspects of match performance, this is considered a tenuous link by some. Quantifying actual match performance remains extremely difficult as it is highly variable and likely influenced by a number of factors previously described throughout the results chapters. However, the influence of the environment and opposition may attenuate over multiple games of data. Furthermore,

statistical analyses used in the current research involved comparisons between positions, experience, and playing level to determine the potential effect of other factors. Collectively, although match running output can be considered an important aspect of physical performance in elite ARF, it remains only one of a variety of factors that encompass total match performance. Increases in the speed of the game over decades and multiple consequences of rotation policies ensure however, that high speed running output remains a major focus of strength and conditioning programs in this sport (16, 154, 172).

As discussed previously, it is acknowledged that the use of absolute speed zones in the quantification of running-based external training load via GPS technology represent only one of many possible derivatives for assessing thresholds of running intensities. Group application of zones for running has advantages relating to comparisons within and between positional groups, across seasons, and teams. Furthermore, the provision of absolute speed zones is arguably more practical in a team sport environment in which a large number of athletes are monitored simultaneously.

Indeed, practicality becomes an important consideration for all monitoring variables in applied settings. As mentioned previously throughout this thesis, HRR can be calculated in a myriad of ways that potentially provide a variety of information about an individual's training status. It is acknowledged that the method chosen to calculate HRR may influence the strength of its relationship with changes in training load; however, the calculation methods and analyses used throughout this thesis were considered most suitable within the

applied environment from which data were collected. Ultimately, ease of implementation and the efficiency of results are of paramount importance in the athlete monitoring process. As such, the priority for applied sport scientists remains the provision of valid, reliable and relevant monitoring strategies that can be readily implemented and provide immediate results.

### **8.5 Practical Applications**

The findings presented in this thesis advance the understanding and strengthen the evidence for submaximal exercise testing in team sport environments. Despite the value of maximal exercise testing for evaluating changes in performance, the fatiguing nature of such testing may be considered an undesirable after effect. This is particularly pertinent in team sport settings in which the balance between fitness and fatigue must be closely monitored to ensure readiness for regular competition. The current research strengthens evidence that submaximal exercise testing can provide a practical, relevant and non-fatiguing estimate of fitness on a regular basis during a periodised year.

Submaximal exercise testing is also a useful tool that can complement other monitoring strategies currently used in elite ARF and other team sports. In general, subjective measures of training quantification and responses are favoured in applied settings due to their simplicity and practicality. However, HR responses to submaximal testing can be considered extremely valuable given their objective nature. The demonstrated relationships in this thesis between SIR test HR responses and measures of external training and match

load derived from GPS technology provide strong support for the implementation of objective measures in the athlete monitoring process. Indeed, a combination of both subjective and objective measures may provide a more comprehensive assessment of an individual's response to training, regardless of whether fitness or fatigue is the response of interest.

The manner in which elite ARF players from different positions are trained and monitored during the competitive season may also be positively influenced by the findings of this thesis. Specifically, results from Chapter Seven suggests that relationships between SIR test HR responses and measures of training and game load are influenced by playing position during the in-season period but not during the pre-season. As such, this thesis may provide the scope for more individualised training monitoring strategies during the in-season period based on playing position.

## **8.6 Future Directions**

The findings presented in this thesis advance the knowledge of athlete monitoring protocols in elite ARF by providing support for the regular implementation of a novel submaximal test to estimate fitness levels and monitor the training responses of individuals. The submaximal exercise testing protocol used in this thesis was supported by proof of concept evidence that has the potential to extend into other testing protocols, larger athletic populations, and a greater diversity of team sports. Indeed, the flexibility to modify

submaximal testing protocols to provide the most relevant procedure for specific positions, offers the most logical extension to the data collected in the thesis.

Although the SIR test was implemented on set days during the pre-season and in-season periods, it is possible that experimentation with the scheduling of submaximal testing within a training week may provide more valuable information. Although speculative, submaximal testing conducted closer to match day may be more reflective of readiness to perform. Therefore, submaximal testing may provide valuable information about whether training has been periodised effectively to allow each individual to peak physically for competition. Alternatively, submaximal testing implemented in the days after competition may indicate recovery status from match play, thus informing training prescription and recovery strategies for the coming week. Modified submaximal testing may also provide a safe and efficient assessment of fitness during rehabilitation from injury whereby estimates of fitness may enable practitioners to more accurately determine return to train and return to play protocols. Collectively, these possibilities further highlight the potential practicality and flexibility of modified submaximal tests as an athlete monitoring tool within applied settings.

Finally, this thesis also provides support for the continued development of partnerships between universities and elite sporting organisations. Such partnerships allow for research to be guided by academic professionals using elite athletic populations. This provides the greatest opportunity to extend knowledge by answering research questions that are relevant

to applied settings and most likely to have a positive impact on sports science practices in the real world.

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## **Appendix 1 – Evidence of publication**

Chapter Five: Veugelers KR, Naughton GA, Duncan CS, Burgess DJ, Graham SR. Validity and Reliability of a Submaximal Intermittent Running Test in Elite Australian Football Players. *J Strength Cond Res.* 2016;30(12):3347-53. Available from: DOI: 10.1519/jsc.0000000000001441.

# VALIDITY AND RELIABILITY OF A SUBMAXIMAL INTERMITTENT RUNNING TEST IN ELITE AUSTRALIAN FOOTBALL PLAYERS

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## ABSTRACT

Veugelers, KR, Naughton, GA, Duncan, CS, Burgess, DJ, and Graham, SR. Validity and reliability of a submaximal intermittent running test in elite Australian football players. *J Strength Cond Res* 30(12): 3347–3353, 2016—The aim of this article was to determine the validity and reliability of a submaximal intermittent running (SIR) test in elite Australian rules football (ARF) players. Heart rate (HR) responses of 38 elite ARF players to both the SIR and the yo-yo intermittent recovery 2 (YYIR2) tests were compared over 2 trials. Linear regression analysis was used to examine the relationship between SIR test HR responses and YYIR2 test performance. Heart rate responses of 25 elite ARF players to the SIR test were monitored over 3 trials. Day-to-day reliability was determined using intraclass correlation coefficient (ICC), typical error of measurement, coefficient of variation (CV), and smallest worthwhile change. Large inverse correlations were reported between 2-, 3-, and 4-minute HR during the SIR test and YYIR2 test distance ( $r = -0.58$  to  $-0.61$ ,  $p < 0.01$ ). Heart rate recovery after 2 and 3 minutes of the SIR test was moderately correlated to YYIR2 distance ( $r = 0.32$ – $0.35$ ,  $p \leq 0.05$ ). Strong correlations for ICC ( $r = 0.90$ – $0.97$ ) and low CV (1.3–9.2%) were reported for all HR variables. Monitoring HR during the SIR test is a valid and reliable indicator of YYIR2 test performance in elite ARF players. These findings support the use of the SIR test as a regular and non-fatiguing indicator of intermittent running capacity.

**KEY WORDS** athlete monitoring, yo-yo intermittent recovery test, fitness test, submaximal, heart rate, team sport

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## INTRODUCTION

Evaluating sport-specific abilities is an important component of high performance programs (2). Physiological capacities and responses to training are ideally assessed via valid, reliable, and relevant testing that requires a maximal effort representative of competition (26). For example, the yo-yo intermittent recovery 2 (YYIR2) test is capable of determining an athlete's capacity to perform intense intermittent exercise and is reported to have a strong positive relationship with match high speed running distance in both elite soccer (2,22) and Australian rules football (ARF) (24). The YYIR2 test also has the potential to differentiate between fitness levels, among playing positions, playing standards, successful or unsuccessful teams, and season phases (14,17). Importantly, research has demonstrated that ARF players who have a higher intermittent running capacity as assessed by the YYIR2 test can produce higher match exercise intensity and accrue more ball disposals during matches (23,24). Superior YYIR2 test results are also reported to positively influence match performance as assessed by coaches' votes (23). Match performance in team sports is likely influenced by a multitude of factors, such as technical skill, tactical ability, team strength, opposition strength, and score line (21,27,28). However, current research highlights the potential of the YYIR2 test in evaluating physiological capacities that can affect ARF match performance.

The validity, reliability, and physiological responses to YYIR2 test performance are well established (2,17). However, exposing athletes to maximal testing on a regular basis is rarely appropriate in elite team sport given the resultant increase in residual fatigue would likely compromise recovery for subsequent training and competition (26). Consequently, routine fitness testing in team sport environments must be balanced with the management of player's well-being and fatigue to ensure minimal disruption to the overall program (26).

Submaximal testing may provide a viable alternative for monitoring physiological capabilities and responses to training. In contrast to maximal testing, submaximal tests can be implemented frequently as a monitoring tool without



## Appendix 2 – PEDro marking criteria for articles included in systematic review

		Eligibility	85% of measures included at follow up	Within group statistical comparisons being reported for at least one key outcome	Point measures and measures of variability	Reliability - population specific	
<b>Title</b>	<b>Date/Author</b>	<b>P1</b>	<b>P2</b>	<b>P3</b>	<b>P4</b>	<b>P5</b>	<b>Total Score /5</b>
Multifactorial monitoring of training load in elite rugby sevens players: cortisol/cortisone ratio as a valid tool of training load monitoring	Bouazia et al. 2016	1	1	1	1	1	5
Monitoring fitness, fatigue and running performance during a pre-season training camp in elite football players	Buchheit et al. 2013	1	0	1	1	1	4
Internal training load and its longitudinal relationship with seasonal player wellness in elite professional soccer	Clemente et al. 2017	1	1	1	1	0.5	4.5
Relationship between running performance and recover-stress state in collegiate soccer players	Coker et al. 2017	1	1	1	1	1	5

Neuromuscular and endocrine responses of elite players during an Australian Rules football season	Cormack et al. 2008	1	0	1	1	0	3
Influence of neuromuscular fatigue on accelerometer load in elite Australian football players	Cormack et al. 2013	1	0	1	1	1	4
Immunoendocrine responses over a three week international rugby union series	Cunniffe et al. 2011	1	1	1	1	1	5
Monitoring training load and fatigue in rugby sevens players	Elloumi et al. 2012	1	0	1	1	1	4
Biological, hormonal, and psychological parameters in professional soccer players throughout a competitive season	Filaire et al. 2003	1	0	1	1	1	4
Changes of the psychophysical state and feeling of wellness of professional soccer players during pre-season and in-season periods	Fessi et al. 2016	1	1	1	1	1	5
Effects of regular away travel on training loads, recovery, and injury rates in professional Australian soccer players	Fowler et al. 2015	1	1	1	0.5	1	4.5

Pre-training perceived wellness impacts training output in Australian football players	Gallo et al. 2016	1	1	1	1	1	5
Self-reported wellness profiles of professional Australian football players during the competition phase of the season	Gallo et al. 2017	1	1	1	1	1	5
Perceptions of wellness to monitor adaptive responses to training and competition in elite Australian Football	Gastin et al. 2013	1	0	1	1	1	4
Extensive monitoring through multiple blood samples in professional soccer players	Heisterberg et al. 2013	1	1	1	1	0	4
Training loads and incidence of injury during the preseason in professional rugby league players	Killen et al. 2010	1	1	1	1	1	5
Changes in creatine kinase and cortisol in national collegiate athletic association division 1 American football players during a season	Kraemer et al. 2013	1	0	1	1	1	4

The effects of air travel on performance measures of elite Australian rugby league players	McGuckin et al. 2014	1	0	1	1	0	3
Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players	McLean et al. 2010	1	1	1	1	1	5
Neuromuscular responses to impact and collision during elite rugby league match play	McLellan et al. 2012	1	0	1	1	0	3
Relationship between daily training load and psychometric status of professional soccer players	Moalla et al. 2016	1	1	1	1	1	5
Indicators for high physical strain and overload in elite football players	Meister et al. 2013	1	1	1	1	1	5
Changes in awakening cortisol response and midnight salivary cortisol are sensitive markers of strenuous training-induced fatigue	Minetto et al. 2008	1	1	1	1	1	5

The effects of game and training loads on perceptual responses of muscle soreness in Australian football	Montgomery et al. 2013	1	0	1	1	1	4
Impact of neuromuscular fatigue on match exercise intensity and performance in elite Australian football	Mooney et al. 2013	1	0	1	1	1	4
Nonfunctional overreaching during off-season training for skill position players in collegiate American football	Moore et al. 2007	1	1	1	1	1	5
Psychological, biochemical and physiological responses of Brazilian soccer players during a training program	Silva et al. 2008	1	0	1	1	1	4
The influence of changes in acute training load on daily sensitivity of morning-measured fatigue variables in elite soccer players	Thorpe et al. 2015	1	1	1	1	1	5
Monitoring fatigue during the in-season competitive phase in elite soccer players	Thorpe et al. 2016	1	1	1	0.5	1	4.5
Tracking morning fatigue across in-season training	Thorpe et al. 2017	1	1	1	1	1	5

weeks in elite soccer players							
Player responses to match and training demands during an intensified fixture schedule in professional rugby league: A case study	Twist et al. 2017	1	1	1	1	1	5
Movement demands and perceived wellness associated with preseason training camp in NCAA division 1 college football players	Wellman et al. 2017	1	1	1	1	1	5

<b>Totals /32</b>	<b>32</b>	<b>19</b>	<b>32</b>	<b>31</b>	<b>27.5</b>
<b>Percentages</b>	<b>100</b>	<b>59</b>	<b>100</b>	<b>97</b>	<b>86</b>

**4.5**

## Appendix 3 – Ethics approval, information letters and consent forms

a) Ethics approval

# PERSON ETHICS APPROVAL REPORT

**Veugelers, Kristopher  
(S00162523)**

## Ethics Approvals

1 ethics applications found

ECODE	ETHICS APPLICATION TITLE	STATUS	APPLIED DATE	APPROVED DATE	START DATE	END DATE	RISK
2014 335V	Monitoring Fitness and Fatigue in Elite Australian Rules Football	Completed	26-NOV-14	03-MAR-15	04-MAR-15	31-DEC-16	Low Risk

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**Res Ethics** <Res.Ethics@acu.edu.au>

5 March 2015 at 09:14

To: Geraldine Naughton <Geraldine.Naughton@acu.edu.au>, Kristopher Veugelers <krveug001@myacu.edu.au>

Cc: Res Ethics <Res.Ethics@acu.edu.au>

Dear Applicant,

Principal Investigator: Prof Geraldine Naughton  
Co\_investigators: Dr Craig Duncan, A/Prof Darren Burgess  
Student Researcher: Kristopher Veugelers  
Ethics Register Number: 2014 335V  
Project Title: Monitoring Fitness and Fatigue in Elite Australian Rules Football  
Risk Level: Low Risk  
Date Approved: 03/03/2015  
Ethics Clearance End Date: 31/12/2015

This email is to advise that your application has been reviewed by the Australian Catholic University's Human Research Ethics Committee and confirmed as meeting the requirements of the National Statement on Ethical Conduct in Human Research.

This project has been awarded ethical clearance until 31/12/2015. In order to comply with the National Statement on Ethical Conduct in Human Research, progress reports are to be submitted on an annual basis. If an extension of time is required researchers must submit a progress report.

Whilst the data collection of your project has received ethical clearance, the decision and authority to commence may be dependent on factors beyond the remit of the ethics review process. The Chief Investigator is responsible for ensuring that appropriate permission letters are obtained, if relevant, and a copy forwarded to ACU HREC before any data collection can occur at the specified organisation. Failure to provide permission letters to ACU HREC before data collection commences is in breach of the National Statement on Ethical Conduct in Human Research and the Australian Code for the Responsible Conduct of Research. Further, this approval is only valid as long as approved procedures are followed.

If you require a formal approval certificate, please respond via reply email and one will be issued.

Decisions related to low risk ethical review are subject to ratification at the next available Committee meeting. You will be contacted should the Committee raises any additional questions or concerns.

Researchers who fail to submit a progress report may have their ethical clearance revoked and/or the ethical clearances of other projects suspended. When your project has been completed please complete and submit a progress/final report form and advise us by email at your earliest convenience. The information researchers provide on the security of records, compliance with approval consent procedures and documentation and responses to special conditions is reported to



the NHMRC on an annual basis. In accordance with NHMRC the ACU HREC may undertake annual audits of any projects considered to be of more than low risk.

It is the Principal Investigators / Supervisors responsibility to ensure that:

1. All serious and unexpected adverse events should be reported to the HREC with 72 hours.
2. Any changes to the protocol must be approved by the HREC by submitting a Modification Form prior to the research commencing or continuing.
3. All research participants are to be provided with a Participant Information Letter and consent form, unless otherwise agreed by the Committee.

For progress and/or final reports, please complete and submit a Progress / Final Report form:

[http://www.acu.edu.au/research/support\\_for\\_researchers/human\\_ethics/forms](http://www.acu.edu.au/research/support_for_researchers/human_ethics/forms)

For modifications to your project, please complete and submit a Modification form:

[http://www.acu.edu.au/research/support\\_for\\_researchers/human\\_ethics/forms](http://www.acu.edu.au/research/support_for_researchers/human_ethics/forms)

Researchers must immediately report to HREC any matter that might affect the ethical acceptability of the protocol eg: changes to protocols or unforeseen circumstances or adverse effects on participants.

Please do not hesitate to contact the office if you have any queries.

Kind regards,  
Kylie Pashley  
on behalf of ACU HREC Chair, Dr Nadia Crittenden

Ethics Officer | Research Services  
Office of the Deputy Vice Chancellor (Research)  
Australian Catholic University

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**Ms Pratigya Pozniak** <pratigya.pozniak@acu.edu.au>

21 December 2015 at 14:51

To: Prof Geraldine Naughton <geraldine.naughton@acu.edu.au>, Dr Craig Duncan <CraigD@sydneyfc.com>, Kristopher Veugelers <kristopher.veugelers@myacu.edu.au>  
Cc: Ms Pratigya Pozniak <pratigya.pozniak@acu.edu.au>

Dear Geraldine,

Ethics Register Number : 2014 335V

Project Title : Monitoring Fitness and Fatigue in Elite Australian Rules Football

Data Collection Date Extended : 31/12/2016

Thank you for returning the Ethics Progress Report for your project.

The Deputy Chair of the Human Research Ethics Committee has approved your request to extend the project. The new expiry date for the project is the 31/12/2016 .

We wish you well in this ongoing project.

Kind regards,  
Ms Pratigya Pozniak

Ethics Officer | Research Services  
Office of the Deputy Vice Chancellor (Research)

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b) Permission letter for release of player data from Port Adelaide Football Club



**PORT ADELAIDE FOOTBALL CLUB**  
Allan Scott Power Headquarters  
Brougham Place, Alberton SA 5014  
PO Box 379 Port Adelaide SA 5015  
T | 8447 4044  
F | 8447 8633  
PortAdelaideFC.com.au  
ABN: 49 068 839 547

18 November 2014

TO : **AUSTRALIAN CATHOLIC UNIVERSITY**

Dear Sir/Madam

We confirm that the Port Adelaide Football Club supports the research project titled "*Monitoring Fitness and Fatigue in Elite Australian Rules football*" undertaken by Veugelers, Naughton, Duncan and Burgess.

The Club routinely collects data from training and matches and the players understand that this data is used to optimise their health and performance. Therefore, as a part of this project, we give permission for the researchers to use the data collected (eg: training loads, heart rate, GPS, sleep, subjective wellbeing, etc.) from our 2015 and 2016 squads for the purpose of research under the following conditions:

- No players' names are to be published in any reports or other documents; and
- The data is to be used strictly for research purposes only.

Please don't hesitate to contact the undersigned if you need any additional information.

Yours faithfully

A handwritten signature in blue ink, appearing to read 'Peter Rohde'.

**PETER ROHDE**  
General Manager – Football

c) Participant information letter

## **PARTICIPANT INFORMATION LETTER**

**PROJECT TITLE:** Monitoring fitness and fatigue in elite Australian football

**PRINCIPAL INVESTIGATORS:** Darren Burgess, Craig Duncan, Geraldine Naughton

**STUDENT RESEARCHER:** Kristopher Veugelers

**STUDENT'S DEGREE:** Doctor of Philosophy

Dear Participant,

You are invited to participate in the research project described below.

### ***What is the project about?***

The research project aims to investigate individual changes in fitness and fatigue, with a specific focus on heart rate responses to submaximal fitness testing. It is hoped this research will improve the understanding of athlete monitoring in elite team sports and provide valuable information to players about your fitness and fatigue.

### ***Who is undertaking the project?***

This project is being led by Kristopher Veugelers and will form the basis for the degree of a Doctor of Philosophy at Australian Catholic University under the supervision of Geraldine Naughton, Craig Duncan and Darren Burgess.

### ***Are there any risks associated with participating in this project?***

There are no foreseeable risks associated with this project. The data obtained will be collected from routine monitoring which you are already familiar with. You will not be asked to participate in any testing outside of these routine training hours. Therefore, participation in this project will not place you at any greater risk of harm.

### ***What will I be asked to do?***

You will be asked to permit the use of data obtained from routine monitoring during competition and training for research purposes. The study will be conducted at the Port Adelaide Football Club and will include data from the following tests:

- Training and game loads (e.g. RPE, GPS)
- Submaximal fitness tests (e.g. heart rate)
- Heart rate variability
- Wellness questionnaires (e.g. perceived exertion, recovery, mood)
- Sleep quality and quantity

### ***How much time will the project take?***

Data collection for this project will span across the 2015 and 2016 seasons. Data will be collected from routine monitoring that you are already familiar with. Therefore, participation in this project will not require any further time commitment.

***What are the benefits of the research project?***

The researcher will use your data to clarify which types of routine monitoring are most effective at identifying changes in fitness and fatigue. Data collected during this project may provide sports scientists with valuable information to assist in improving the health and performance of athletes.

***Can I withdraw from the study?***

Participation in this study is completely voluntary. You are not under any obligation to take part. If you agree to participate, you can withdraw from the study at any time without adverse consequences to your contract with the Port Adelaide Football Club. If you choose to withdraw, your data will be removed from the database of the researcher.

***Will anyone else know the results of the project?***

It is planned to publish the results of this project in academic journals specialising in sports science (e.g. Journal of Science and Medicine in Sport, Sports Medicine, and British Journal of Sports Medicine). Data collected for research purposes will be non-identifiable and no names will be published in any reports to ensure confidentiality is maintained.

***Will I be able to find out the results of the project?***

A summary of results will be made available to all participants at the conclusion of the project. These results can be obtained by contacting the student researcher (Kristopher Veugelers).

***Who do I contact if I have questions about the project?***

Please contact the student researcher if you have any questions about the project:

Kris Veugelers  
Sports Science PhD Scholar  
Port Adelaide Football Club  
(T): 0417160831  
(E): kveugelers@pafc.com.au

***What if I have a complaint or any concerns?***

The study has been reviewed by the Human Research Ethics Committee at Australian Catholic University (review number 2014 0000018998). If you have any complaints or concerns about the conduct of the project, you may write to the Manager of the Human Research Ethics Committee care of the Office of the Deputy Vice Chancellor (Research).

Manager, Ethics  
c/o Office of the Deputy Vice Chancellor (Research)  
Australian Catholic University

North Sydney Campus  
PO Box 968  
NORTH SYDNEY, NSW 2059  
Ph.: 02 9739 2519  
Fax: 02 9739 2870  
Email: resethics.manager@acu.edu.au

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

***I want to participate! How do I sign up?***

If you agree to participate in this project then please return signed copies of both consent forms (participant *and* researcher) to the box outside the High Performance office at the Port Adelaide Football Club.

Yours sincerely

**Student researcher:** Kristopher Veugelers .....

**Principal investigator:** Darren Burgess .....

**Principal investigator:** Craig Duncan .....

**Principal investigator:** Geraldine Naughton .....

d) Consent forms

**CONSENT FORM**

*Copy for participant to keep*

Title of project: Monitoring fitness and fatigue in elite Australian football

Student researcher: Kristopher Veugelers

Supervisors: Geraldine Naughton, Craig Duncan, Darren Burgess

I ..... have read and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in this study conducted throughout 2015 and 2016 AFL seasons. I give permission for researchers to use routine fitness and fatigue monitoring data taken from training and matches for the purpose of research only. I understand that I can withdraw my consent at any time. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does **not** identify me in any way.

Name of participant: .....

Signature: ..... Date: .....

Name of supervisor: .....

Signature: ..... Date: .....

Name of student researcher: .....

Signature: ..... Date: .....

**CONSENT FORM**

*Copy for researcher*

Title of project: Monitoring fitness and fatigue in elite Australian football

Student researcher: Kristopher Veugelers

Supervisors: Geraldine Naughton, Craig Duncan, Darren Burgess

I ..... have read and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in this study conducted throughout 2015 and 2016 AFL seasons. I give permission for researchers to use routine fitness and fatigue monitoring data taken from training and matches for the purpose of research only. I understand that I can withdraw my consent at any time. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does **not** identify me in any way.

Name of participant: .....

Signature: ..... Date: .....

Name of supervisor: .....

Signature: ..... Date: .....

Name of student researcher: .....

Signature: ..... Date: .....



