EXAMINING APPROACHES TO THE MONITORING OF TRAINING LOAD WITH SPECIFIC REFERENCE TO BOTH THE STIMULUS AND RESPONSE

by

JOHN KARL ANTHONY HILL

A thesis submitted to the University of Birmingham in partial fulfilment for the degree

of

PROFESSIONAL DOCTORATE

School of Sport, Exercise and Rehabilitation Science
University of Birmingham

17th November 2024

Abstract

The primary aims of sport scientists working in the applied field are focused on developing physical capabilities to enhance athletes' performance and reduce injury incidence. Elite professional football is a fast paced and high-pressure environment where practitioners require an intimate understanding of both training load demands and players physiological responses to load to effectively prepare players for the demands of competition. However, current load monitoring strategies may not capture the full spectrum of loads that players experience, with key mechanical and technical components underrepresented in contemporary datasets within elite professional practice. This thesis aims to provide practitioners with insights to support decisions around training load prescription and monitoring. To achieve this, it explores methods for identifying multiple dimensions of loading, explores a novel approach to understanding and measurement of multiple dimensions of loading, and examines physiological responses of elite professional footballers over a competitive season.

Study 1

Load monitoring is essential in elite sports to prescribe training effectively, enhance performance, and mitigate injury risk. This study aims to investigate approaches to load monitoring within the published literature that encompass multiple dimensions of load, including locomotor, mechanical, and technical aspects. Given that peer-reviewed and published literature often trails technological advances and implementation in professional practice, a patent search was conducted to identify technologies that are potentially applicable in professional environments to monitor multiple aspects of load (locomotor, mechanical, technical). Using a mixed-methods approach, this study first conducted a systematic search to identify relevant approaches in the literature whilst simultaneously performing a patent search for applicable technologies. This approach identified 20 articles that addressed combined load factors. Of the 42 identified patents, none linked with a technology that met the criteria for practical use in the applied professional setting. Further refinement

of the results revealed three separate studies used foot mounted inertial sensors (F-IMU) to quantify loading across the three key parameters within a field-based environment. This review highlights the promising potential of F-IMUs for quantifying multiple dimensions of loading in the professional practice environment.

Study 2

Monitoring multiple dimensions of load is essential to understand the demands of training and competition in elite sport. The aim of this study is to explore the potential of a novel approach to load monitoring using F-IMU to detect and quantify locomotor, mechanical, and technical load in the real-world context. Data from seven elite professional footballers wearing F-IMU were collected during on pitch rehabilitations sessions. Rehabilitation was categorised into three stages: reloading, return to football, and return to performance. The approach demonstrated face validity, successfully identifying expected loading patterns, and showing sensitivity to progressive load increases across multiple parameters. The findings indicate that F-IMUs can be used effectively to quantify three primary dimensions of load in the applied setting of professional football, providing a more comprehensive view of the loading that is experienced by elite players during rehabilitation from injury. This information could be valuable to practitioners looking to advance their current load monitoring processes by including aspects of loading that may be underrepresented by contemporary locomotor-based metrics.

Study 3

Understanding a player's physiological responses to training loads is essential for developing individualised training programs and appropriate loading schemes in elite professional football. Balancing load and recovery help ensure that players can perform optimally while minimising potential injury risk. Biomarker analysis through point of care testing (POC) has become increasingly common in elite sports to assess recovery status, however limited research exists connecting loading parameters with biomarker responses. This study aims to investigate the relationship between load

(total distance TD, sprint distance SD) and physiological response. Using a sample of 21 elite professional footballers, inflammatory responses (high-sensitivity C-Reactive Protein, hs-CRP) and oxidative stress markers (FORT, FORD, Oxidative Stress Index, OSI) were taken on match day plus two (MD+2) (n=40). Response data were correlated against with multiple loading windows (4, 7, 14, and 28 days) for total distance (m) and sprint distance (m) over a full competitive season. Overall results showed weak association between load and response variables. Most notably, results indicated weak positive correlations between both TD and SD and inflammatory response (hs-CRP) in the 4-day loading window (TD=0.20, SD=0.22), with similarly weak positive correlations observed between OSI and in the 28-day window TD=0.29, SD=0.27). While no definitive relationships were established, findings suggest nuanced interactions between hs-CRP, OSI, and loading across different time frames with large individual differences. These results highlight the complex and multifactorial nature of load-response interactions, underscoring the need for further hypothesis-driven research in elite professional football.

Dedication

Natalie, thank you for the support, patience, and commitment to me and this project. I know you have put thousands of hours into our family to enable me to take this on. I appreciate and value everything you do for me and our family. I love you.

Daisy and Charlie, you are both the inspiration and motivation for everything I do. This process has been one of the hardest things I have ever done, it has taken time away from us in the short term, but I hope the journey will benefit us all in the long run. I am better for the struggles of trying to achieve something I truly never thought I could do. If you read this one day, know that you can have anything in life the price is how much you want to commit to it.

Acknowledgements

I would like to acknowledge and thank Liverpool Football Club for their support in funding my studies and the investment in my personal and professional development. This process has undoubtedly been amongst the most challenging periods of my life, and the impact this journey has had on my development has been profound. I have carried this project with me each day for the past four years through major personal and professional changes. Whilst at times I have found it frustrating in the extremes, I am thankful for the support, guidance and tutelage by those around me. Jack Ade, William Spearman, Conall Murtagh, David Rydings, Steve Barret, Jordan Milsom and Carl Todd thank you for the help, guidance and support you've given me. Through some difficult periods you have helped me more than you know. I'm forever grateful to have worked alongside some truly exceptional practitioners and for their input whilst navigating this process. Arriving at a point where I have the option to undertake doctoral study would not have been possible without the encouragement of my family and their support to choose my passions where others would take the safe bet. Ann Tonks, thank you for the unwavering support and encouragement throughout both my academic and professional career. Finally, but no means least, Barry Drust. Professor I could not have gotten to this point without you. Your patience and guidance have made this process both enjoyable and rewarding. You have taken me past the perceived limits of my abilities. At times I know I have been "a challenge" but I am truly grateful for the opportunity to have worked with you. Your commitment to my development academic, professional and personal will stay with me forever, I am now proud to call you a friend.

Contents Listing

Table of Contents

List of Figures

List of Tables

List of Abbreviations

A+D	Acceleration and Deceleration
COD	Changes of Direction
EIMD	Exercise Induced Muscle Damage
EPL	English Premier League
F-IMU	Foot-Mounted Inertial Sensors
FORD	Free Oxygen Radical Defence
FORT	Free Oxygen Radical Test
GCT	Ground Contact Time
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
GRF	Ground Reaction Force
HID	High Intensity Distance
HR	Heart Rate
hs-CRP	high-sensitivity C-Reactive Protein
HSR	High Speed Running
HSRD	High Speed Running Distance
IMU	Inertial Measurement Unit
LiDAR	Light Detection and Ranging
LPS	Local Positioning System
MDT	Multi-Disciplinary Team
OSI	Oxidative Stress Index
POC	Point Of Care
ROS	Reactive Oxygen Species
SD	Sprint Distance
RPE	Rating of Perceived Exertion
TD	Total Distance
THSR	Total High-Speed Running
TRIMP	Training Impulse
TSD	Total Sprint Distance
VHSR	Very High-Speed Running

CHAPTER 1

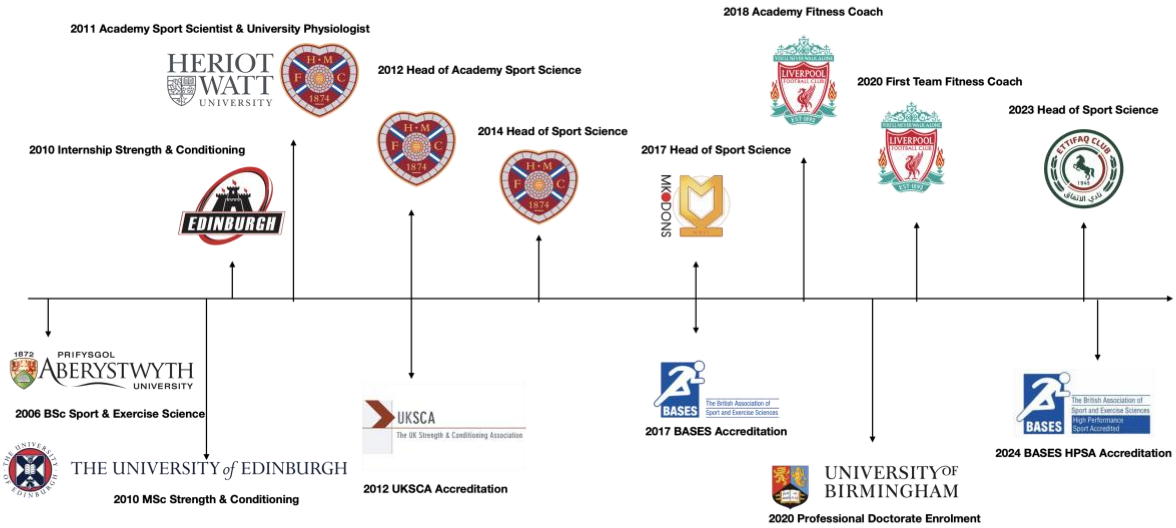
GENERAL INTRODUCTION

Introduction to the Research Project

With over 13 years of professional experience in full-time football, I have developed a broad skillset due to the multiple roles I have held throughout my career (Figure 1-1). My professional background includes roles where I have been responsible for design and implementation of training load monitoring strategies to develop athletic performance, as well as the prescription and delivery of both on and off field strength and conditioning strategies for players. More recently I have held positions that have a large focus on load monitoring and recovery aspects of performance. My involvement at various levels of operation within different organisations has provided valuable insight into the evolving demands placed on elite footballers. These demands are increasingly shaped by the pressures of success. Sustaining financial growth for football organisations is largely dependent on team success and the ability to generate revenues through performance in competitions and by attracting external investment for high performing teams (Rohde and Breuer, 2016). To meet these demands, football support teams including coaching, medical, and sports science professionals are becoming more specialized. As the game has evolved, so too have the complexities of managing player performance, necessitating a more scientific approach to training prescription and injury reduction/rehabilitation strategies (Bartlett and Drust, 2021).

Figure 1-1 Career timeline

The figure shows my career timeline which includes both professional and academic milestones. Professional appointments are displayed above the central timeline and key academic dates below.



This increased scientific approach has driven specialization in many facets of athlete support. Coaching, strength and conditioning, nutrition, and recovery have all experienced growth in the number of specialists, with teams now recruiting large support staff teams to gain a competitive advantage (Drust, 2019). Although the training strategies for elite footballers are complex, they can be simplified into two primary components: improving performance and reducing injuries. To perform at the highest level, athletes must overcome significant metabolic and mechanical demands while maintaining technical proficiency under fatigue (Mohr et al., 2005; Cormack et al., 2008; Nedelec et al., 2012).

Crucially, this level of performance is only sustainable if players remain injury-free and available for selection. Loading prescriptions aiming to maximise performance and knowledge of players' responses to stimuli (readiness) play a key role in preparing players for the demands of competitive football. Successful planning and preparation appropriate of training also mitigates the risk of injury by conditioning player to tolerate the varying stresses experiences throughout the training cycle (Gabbett, 2016; Impellizzeri et al., 2019a; Kalkhoven et al., 2021).

Players must not only exhibit high levels of physical fitness (Bangsbo et al., 2006b) but also tolerate high training and game loads, particularly in the context of congested fixture schedules that allow minimal recovery time (Drust et al., 2007). Given these constraints, training load management, and player readiness assessment are critical to maintaining performance while reducing injury risks.

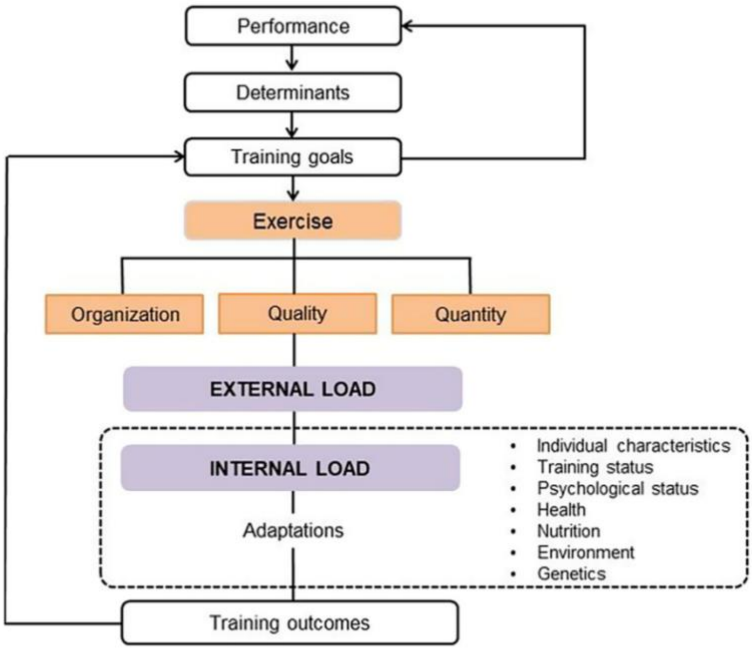
Training in sport has been defined as the systematic process of performing exercises to improve physical abilities and acquire skills related to the technique of the sport (Viru and Viru, 2000). Training prescription in football should therefore be considered as the systematic process of prescribing drills, exercises, and activities that prepare players for the demands of competition. However, inaccurate load prescription can lead to suboptimal performance and elevate injury risk due to either overtraining generating excessive fatigue or undertraining leading to a poor capacity to tolerate the load required to perform at an elite level. It is therefore intuitive that accurate measurement of training load should be used to quantify loading and assist in the design and application of training.

Equally important are measures of a player's response adaptation to training stimuli, as these indicate their capacity to tolerate future loading. Stimulus can broadly be defined in two main categories external and internal loading. In the context of professional football, external load references the physical work performed by a player, that is often quantified by variables such as distance covered, speed, and number of accelerations/decelerations (Impellizzeri et al., 2019a), internal load reflects the physiological stress imposed by external demands (Halson, 2014). Both load measurement and response monitoring must work in concert to enhance performance while minimising injury risk. However, significant challenges remain in achieving the optimal balance between these objectives. The theoretical and practical challenges associated with assessing and managing load in athletes are complex and multifaceted. Figure 1-2 illustrates the load and response relationship, highlighting critical factors for consideration in improving training outcomes.

A fundamental challenge highlighted in Figure 1-2 is the internal load response and subsequent adaptive response experienced by players. Not only is there significant variation in individual tolerance to load, but no two athletes will exhibit the same response to a given stimulus. Individual characteristics such as muscle fibre type or architecture have differing tolerances to mechanical stresses (Bahr and Krosshaug, 2005). Differing pre training level phenotype (initial level of fitness) between individuals will affect molecular signalling in response to high-intensity training (Impellizzeri et al., 2007; Mann et al., 2014). Research into individual responses provides strong evidence of significant heterogeneity in markers of response to physical activity (Bouchard and Rankinen, 2001).

Figure 1-2 Training and response framework

Taken from Impellizzeri et al. (2019a) as a theoretical framework for the training process. The figure details varying factors associated with the implementation of training goal and subsequent external and internal load.

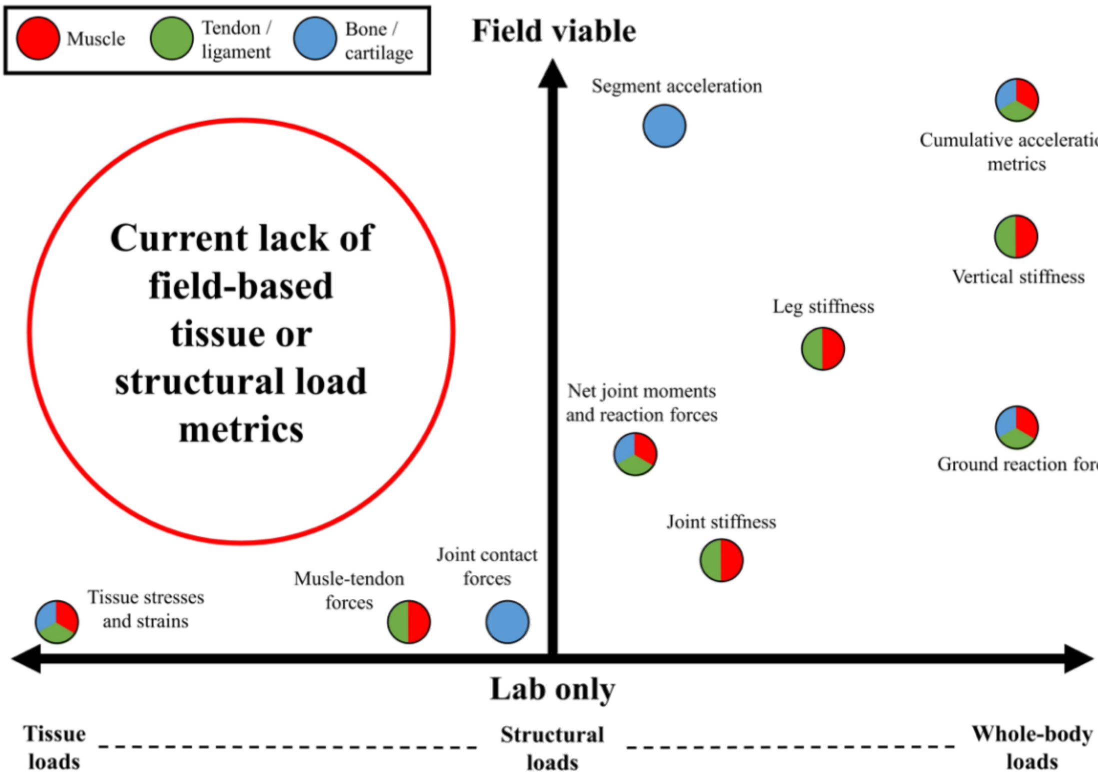


In addition to the theoretical challenges, there are fundamental practical concerns to consider when investigating the load-response relationship. Load, experienced differently by various tissues in the body, highlights significant variability in tolerance and response across structures (Wdowski et al., 2023). Current technologies employed in athlete monitoring often provide only a partial view of this these loads and struggle to adequately quantify this phenomenon. Many devices excel at quantifying external load metrics such as distance and speed, yet they often fall short in capturing the nuances of an athlete's internal physiological response (Halson, 2014; Impellizzeri et al., 2019a). Contemporary approaches to load monitoring such as locomotor metrics derived from Global Positioning Systems (GPSs) which quantify training by velocity may not be suitable to capture all aspects of physical performance. With critical components of loading, such as mechanical stresses imposed during breaking (Harper et al., 2019; Dos'Santos et al., 2022) or high velocity technical actions (Lewis et al., 2022) underrepresented in the available data.

Different types of loading experienced by players during training elicit varying tissue responses to stimuli. Mechanical stresses such as those imposed from breaking or propulsive actions, lead to distinct musculoskeletal responses (Harper et al., 2019), while physiological load involves biochemical reactions that are vital to sustain energy production (Franchi et al., 2017). The difficulty of accurately measuring theses loads, particularly the biomechanical stresses sustained from external load is highlighted by Verheul et al. (2020), whose research on the lab-to-field gap (Figure 1-3) emphasises a lack of field-based measures in the quantification of tissue or structural loading. One of the fundamental barriers to accurate quantification of structural loading comes from the varying distribution of loading across different tissues. Ground reaction forces (GRFs) measured at the foot apply differently across bones, ligaments, muscles, and tendons due to each tissue structural and functional differences Each tissue reacts to these forces uniquely, bones are primarily load bearing, while tendons and muscles manage tensile forces, and ligaments maintain joint stability (Ker et al., 1987; Altai et al., 2024).

Figure 1-3 Biomechanical training load measures

Taken from Verheul et al. (2020) as a theoretical framework of assessment of biomechanical training load measurement in both lab and field.



Even if valid measures of load and individual response can be implemented in an applied environment, there remain significant practical obstacles to generating actionable data that can inform training load prescription and monitoring processes. These factors must be carefully considered by practitioners when working with competitive athletes. These practical issues necessitate thoughtful coordination between players, coaches, and support staff, as the work required to generate data and provide insights into quantification of load and response to training programs can be demanding. The need for rapid data turnaround to inform decisions is a significant obstacle, alongside collecting, analysing, and reporting data that requires substantial time, resources, and expertise. The narrow windows of opportunity between fixtures exacerbate these challenges for applied practitioners. Moreover, some measures in the pursuit of response data, such as blood sampling for biomarkers, may pose compliance issues with players, require specialist skills to obtain, and result in data that is difficult to interpret. Whilst other performance measures aiming to quantify fatigue such as jumps, measures of tissue strength or neuromuscular function, may induce additional muscle damage or fatigue creating a risk reward trade off (Impellizzeri et al., 2006; Claudino, 2017; Sharma et al., 2021).

Increasing the analysis of stresses placed on players through improved load monitoring strategies and mapping responses to various stimuli may help clarify the relationship between load and response. With advancements in sports science and the increasing importance of performance and success, the need to address the existing gaps in our understanding of load-response dynamics is crucial. A more comprehensive approach to loading is warranted, encompassing locomotor, mechanical, and technical aspects in a field-based environment to give a more holistic view of the total load experience during the training cycle. Additionally, evolving the understanding of the dose-response relationship should be a priority in the progression of sports science in elite professional football. By developing more effective training prescriptions and reducing injury risk through a better understanding of how players tolerate load and assess their readiness to perform, we can enhance overall training effectiveness and athletic outcomes.

Research Aims and Objectives

To support the design and effectiveness of the project, the aim of the thesis is to improve our understanding of factors affecting training load and the associated responses in elite professional association footballers.

Aim: Critically examine approaches to the monitoring of training load with specific reference to both the stimulus and response.

The aim of the thesis will be fulfilled with the following objectives:

Objective One: Examining current approaches to load monitoring.

Objective Two: Develop a novel conceptual approach to quantify different types of load associated with football.

Objective Three: Explore the relationship between training load and biomarker response.

Thesis Map - A guide to the overall structure of this thesis

The purpose of this section is to describe the overall layout of the thesis. As this thesis follows a non-traditional format, it is important to help navigate the reader to the purpose and location of each of the key components. Showing the overall layout of the thesis (Figure 1-4) illustrates the path this project has taken to achieve the research aims and objectives described in the general introduction.

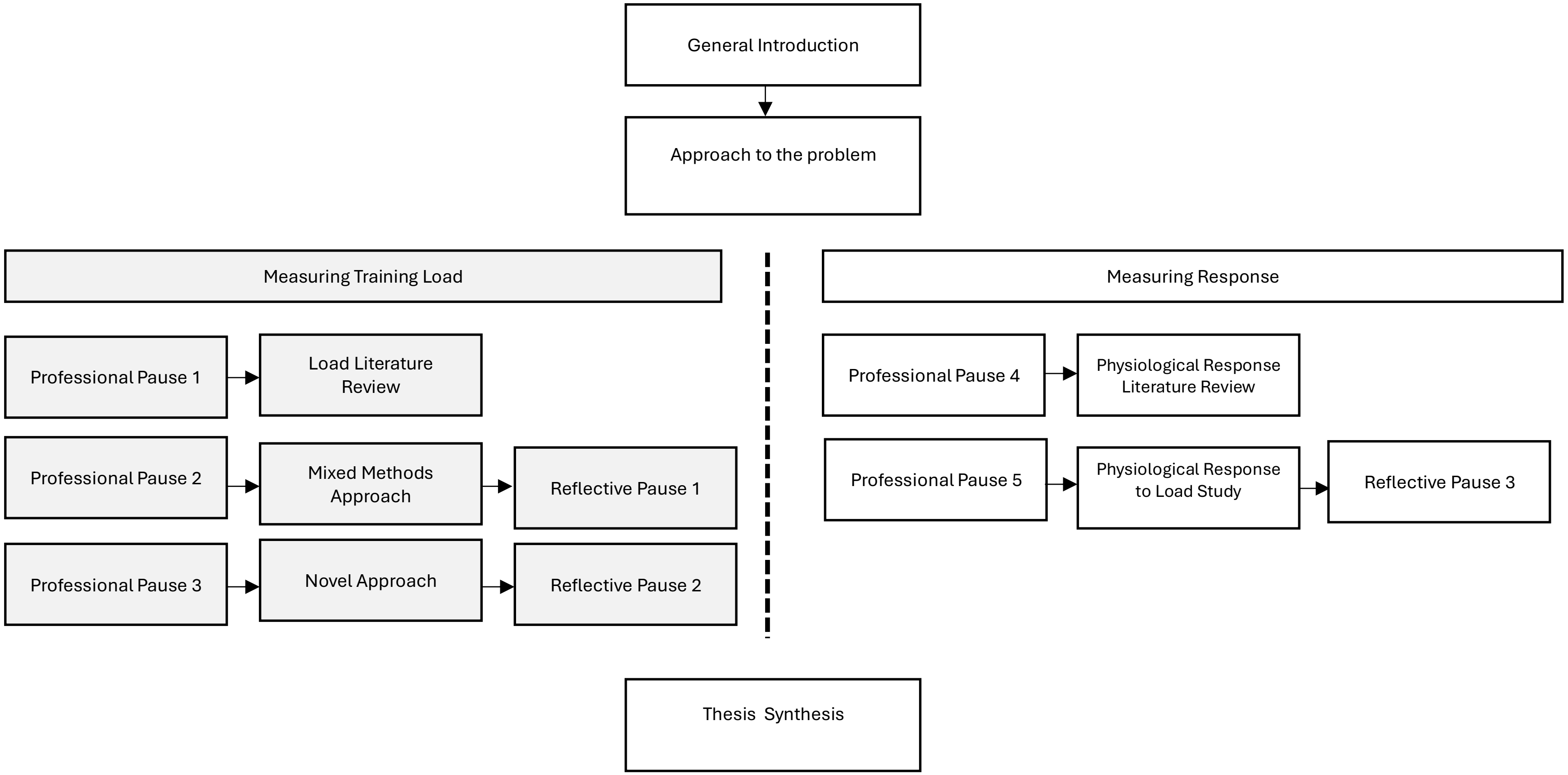
Following on from the approach to the problem section (Chapter 2) it is important to note that thesis focuses on two primary areas of investigation, training load and adaptive response. Although these areas are presented sequentially in this thesis, the investigations occurred simultaneously. This was due in part to the nature of my role as an applied practitioner and the model of investigation crafted to conduct research within the real-world professional sporting environment in which I practice.

Each literature review is introduced by a professional pause and each of the thesis' composite studies are framed by a professional and reflective pause. The professional pauses provide an insight into the identified problem, organizational collaboration and the iterative cycles of planning, refinement and implementation of each of the research chapters. The reflective pauses, following the studies, serve to provide context around the integration of the research findings within the organisation as well as my own reflections on the research process and its findings.

These pauses allow context to the real-world scenarios of conducting research in the applied field and demonstrate the tacit knowledge generated as part of this investigation. Alongside describing the relationship between different chapters, the thesis map (Figure 1-4) shows how all studies are interrelated, with aspects of one influencing the other. This concludes in the project synthesis which provides a comprehensive review of the research and directions for future investigation. A detailed presentation of the methodological approach crafted towards achieving the aims and objectives of this thesis and justification for its format will be presented in the approach to the problem section (Chapter 2).

Figure 1-4 Thesis map

The thesis follows an 'Action Research' model of investigation and is presented with an non-traditional layout. Therefore, the purpose of this section is to help orientate the reader whilst navigating each chapter. This figure provides a brief outline of how the thesis is constructed to meet the aims and objectives.



CHAPTER 2

APPROACH TO THE PROBLEM

"Sports scientists must have an intimate understanding of the determinants of performance, the complexities of the adaptive response, the nature of the training stimulus and its assessment" – Tom Reilly et al. (2009).

Introduction

The purpose of this chapter is to establish the context for the research, positioning myself as a practicing sport scientist currently employed within an elite sporting environment. My role is multifaceted covering a broad spectrum of responsibilities however, my primary areas of interest lie in monitoring training load and understanding individual responses to training stimulus. Given the practical constraints of working full time in professional football whilst simultaneously conducting research this thesis will be presented in a non-traditional format. To remain grounded in academic practise, I have chosen to adopt Action research as a methodological approach. This method of research provides a structured yet flexible approach to achieving the aims and objectives of the thesis whilst navigating the day-to-day challenges of working within elite professional sport.

Theoretical Approach

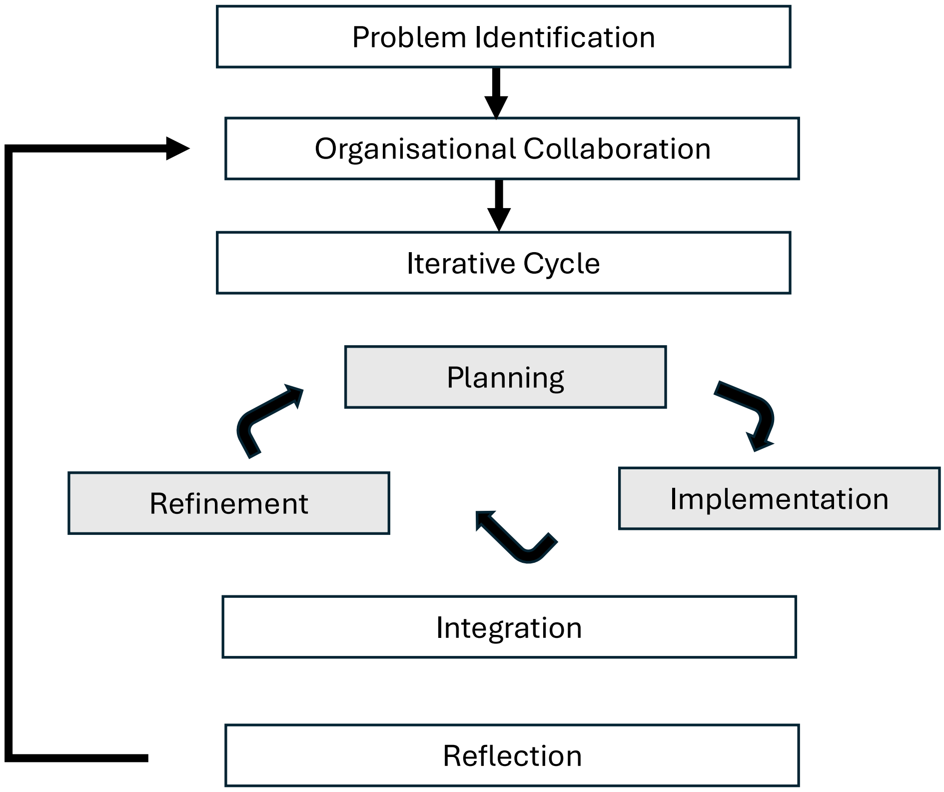
Action research is a dynamic and collaborative process with the dual focus of solving practical real-world problems and generating new knowledge. Action research is a method that facilitates understanding and improvement within an environment by the process of transformation (Kemmis, 2007). To provide a framework for the thesis I have created a theoretical model of the action research process within my thesis. The model is synthesised from the core principals of action research from the foundational works of (Kemmis et al., 2014; Coghlan, 2019) but tailored to reflect action research within my professional environment.

This approach has often been observed in the social sciences, however in more recent years action research has successfully been used in multiple research areas (Rowell et al., 2017; Cordeiro and Soares, 2018). Furthermore, systematic reviews into action research concluded that action research had the potential to be useful in multiple areas of innovation and development, service improvement and knowledge development whilst facilitating practitioner understanding and stakeholder engagement (Waterman et al., 2001).

The method of action research is focused on inquiry and improvement of practises within situations the researcher finds themselves (Kemmis, 2007; Kemmis et al., 2014). The nature of the action research methodology contributes to its potential for improving practise in complex environments such as elite sport. In my context of elite professional football, the action research approach will allow me to address questions related to athletic performance that are essential to my role as an applied practitioner whilst applying a rigorous scientific process of investigation. The collaboration between my journey as a doctoral researcher and an applied professional will focus on the improvement of current processes within my organisation following influence of scientific investigation.

Figure 2-1 Action research framework

A theoretical framework to guide the use of action research throughout the research project. The framework progresses from problem identification through stages of organisational collaboration, planning, integration and finally reflection.



Reflective Practise

The proposed action research theoretical model (Figure 2-1) relies heavily on effective reflection to underpin important context surrounding the key objectives of this thesis. Without effective reflective practise it is inherently difficult to provide a justification for decisions made regarding the implementation of ideas or overcoming points of challenge without providing context of the real-world scenario as they occurred. This section will expand on my reasoning for adopting reflective practise and provide theoretical support for the proposed framework.

Successful action research is underpinned by the researcher's ability to adapt to real world scenarios, an ability that is effectively navigated through effective reflective practise. Reflection is essential in action research because it enables researchers to evaluate and adapt their approach as they encounter practical challenges and respond dynamically to emergent insights, thereby fostering continuous learning and improvement. Adaptability and reflexivity are considered core components of action research, which integrates research with practice to produce results that are directly applicable and relevant in real-world settings (Herr and Anderson, 2014; Kemmis, 2007). Reflection and reflective practises in the applied world are widely accepted as good for coaching and coaching practise, with several studies indicating the potential benefits of reflective practise to practitioners (Knowles et al., 2001; Knowles et al., 2007; Knowles and Gilbourne, 2010). Knowles et al. (2001) frequently discuss the theoretical benefits of reflection as a means of education and development of tacit knowledge which is crucial to this process of investigation.

The professional environment in which I work and attempt to conduct research has been described as a fast paced, high-pressure industry with coaches and athletes striving to achieve elite levels of performance. I navigate this complex setting by managing a range of demands that stem from a need to get the best out of both the athletes I am responsible for and the performance environment in which I operate Reflection will not only enable the identification of development needs (Schön, 1979; Knowles et al., 2001; Knowles et al., 2007; Knowles and Gilbourne, 2010) but it is also thought to create the opportunity for the exploration of good practice, the identification of areas for improvement and the formulation of ideas for change (Gibbs, 1988). Engaging in critical reflection will facilitate a commentary throughout the thesis providing important context and insight from the real-world practise environment whilst simultaneously providing a platform to demonstrate learning and understating around the research.

Professional & Reflective Pauses

To evidence the action research framework employed throughout this thesis I will use a series of professional and reflective pauses. These pauses will be interspersed throughout key components of the thesis to provide context that is not covered in the constituent studies. These sections of reflection will offer my perceptions of the practical, professional and organisational factors that influenced my decision making.

Each professional pause will provide a commentary on what was happening within my personal and professional environment. The reflections will focus on the context of the decisions I made, the professional constraints I encountered as well as the interactions with key stakeholders such as coaching staff, multidisciplinary support staff as well as third parties contracted to the organisation. These reflections will serve as a justification offering real-world perspective on the project whilst illuminating the complexities and challenges of conducting research within elite professional sport.

The pauses will broadly cover several key themes:

Problem Identification: These sections will discuss how performance related questions were identified within the organisation and what the implications were for professional process. I will reflect on how the priorities of my role as a sport scientist within the organisation drive the need for investigation and how identified problems informed the direction of research.

Organisation Collaboration: reflecting on the collaborative process of conducting research within the environment. This will cover conversations with various stakeholders and highlight how organisational dynamics influenced the planning and execution of various studies. These sections will provide additional context on collaborative efforts and competing priorities that shaped the research design.

Iterative Cycles: In keeping with the cyclical nature of action research these sections of the pauses will describe the processes of planning, piloting, and refining research investigations. I will discuss how the initial ideas were tested and how feedback from the practise environment influenced refinement, as well as how each cycle of the project was moulded through ongoing discussion. This aims to provide insight towards the adjustments made to ensure that the research remained relevant and practical within the applied sport context.

In addition to the professional pauses included throughout the thesis, I will incorporate a series of reflective pauses to provide much needed context after the individual research studies had been implemented. Again, these sections are designed to give a deeper understating into elements of the action research process that are not captured by traditional components of the project. Reflecting on the impact of research within the organisation alongside personal reflections of each study, I hope to increase the understanding of the impact the research may have across a spectrum of positive and negatives throughout the doctoral journey.

Each reflective pause will also broadly cover the following areas:

Integration of research within the organisation: here I will explore how the research findings were accepted within the organisation. I will document both my own and stakeholder views and feedback during the process. I will detail times where the research may impact on decision making processes and the practical application of findings within my role.

Personal Reflections: following each study I will include my personal reflections and analysis to document my thoughts and feelings around the time of each study. These will include critical reflections on challenges faced as well as any successes of the studies. From this I aim to achieve a deeper understanding of what I have learned from the process and provide evidence of personal development from conducting research in an applied environment.

By including these pauses I aim to provide much needed context to the reader about what was happening at the time in my professional practise environment and how the action research framework helped underpin my decision-making processes. With these sections I hope to bridge the gap between the theoretical and practical aspects of the research.

Methodological Approach to the Research

This section will begin by detailing the methodological approach I adopted towards the thesis. Following this I will summarise the approaches used within each of the component studies and their objectives in line with the overall thesis aims. I will present the objective of each study and detail how this aims to fulfil the corresponding aim of the thesis to offer some explanation for my investigative approach and justification for my research methodology. Although the thesis has clear aims and objectives the nature of experimenting in the applied environment lends itself to a level of unpredictability and constant change. Each day working within professional football provides a series of challenges. The nature of sport means schedules can change at short notice due to not only team performance, but external factors driven by governing bodies and stakeholders whilst access to players depends largely on their availability to train and remain injury free. This makes it inherently difficult to plan successfully. The research framework I have implemented allows a degree a flexibility to enable a pragmatic approach to problem solving and methodological design in this environment.

In the context of this project the methodology can be viewed as the scaffolding around the project which supports but enables flexibility in the application of a scientific approach. Below I will provide an insight into how I plan to tackle each phase of the project as well as demonstrate the organisational collaboration, iterative cycles, implementation and reflective components of the actions research model (Figure 2-1) presented above.

Thesis objective 1: Examining current approaches to load monitoring

To complete this initial objective, I will adopt a dual methodology. Firstly, I will conduct a systematic review of the literature focusing on identifying approaches to training load monitoring. Secondly, I will search for potential technological solutions that could be implemented within my practice environment. This study aims to provide a comprehensive examination of contemporary methods used to quantify multiple facets of training load, particularly those that may be underrepresented in current training load monitoring techniques. By separating approaches into those that capture locomotor, mechanical and technical loads I hope to identify techniques that represent multiple facets of loading.

Whilst recognising that methods employed by sport scientists and practitioners in the applied field often precede academic publication, I will extend the review to include a search for emerging technologies. Using a patent search the study aims to identify potential innovative technologies that could be adapted as monitoring devices. This approach will ensure that in addition to established methods, cutting edge and novel solutions that may not yet have well-known academic recognition but may hold practical relevance for implementation in professional sport are captured.

The systematic literature review will focus on methods of load monitoring that not only cover the facets of loading believed to be underrepresented but also those that apply to various environments relevant to the applied field. These include training, competitive games, field tests and laboratory settings. Approaches will be evaluated based on the number of components of load they quantify and the environments they can be deployed in. The patent search will also target innovative solutions that address these facets providing technologies they could be integrated into existing load monitoring frameworks.

Although it is clear that an investigation into load monitoring systems and the implications of technological innovation could form an entire thesis, this section has a primary focus on identifying practical methods and relevant technologies that are available, scalable and able to be integrated into my specific practice environment. The quantification of training load is a key role of my position within the organisation, where accurately assessing the demands of the training cycle has important ramifications for decision making. The aim therein is to determine which approaches may offer the most comprehensive quantification of loading parameters and to understand the environments in which they have been successfully implemented.

Thesis objective 2: Develop a novel conceptual approach to quantify different types of load associated with football

As previously discussed, the thesis employs an action research framework that lends itself to change within the environment but provides a framework for scientific investigation. The objective of this second study in the thesis is to build on the information generated in study one from the identification of approaches and technologies and develop a novel approach to training load monitoring. It is widely recognised within circles of modern practitioners that certain aspects of loading are underrepresented within current approaches. Similarly, my role involves the assessment of training load where I have observed gaps in our monitoring processes particularly in the quantification of mechanical and technical actions.

To achieve this objective, I will focus on addressing these underrepresented areas of loading. The aim therefore is to develop a system that is capable of quantifying three key types of load locomotor, mechanical and technical. The proposed method needs to be able to differentiate between these types of loading, be sensitive to changes in both volume and intensity and characterise different types of sessions, particularly where variations in loading are planned or expected to occur. Achieving this objective will offer a more comprehensive presentation of the load experienced across the training process and drive innovation in training load prescription.

The guiding theoretical methodology for the thesis will provide the scientific structure for this investigation where decisions will be explained in the professional and reflective pauses that accompany this chapter.

Thesis objective 3: Explore the relationship between training load and biomarker response

Referencing the opening quote of this section by the late Professor Tom Reilly, an intimate understanding of stimulus (load) and adaptation are inherently important to the successful operation of sport scientist. It is critical that the applied practitioner especially those employed in elite sport understand this relationship in the context of athletic training. The aim of this section of the thesis is to determine what relationships exist between biomarkers measuring different types of response and training load. More specifically this chapter seeks to explore how various biomarkers responded to different types of loading in elite professional footballers, thus offering insights into the potential physiological adaptations that occur as a response to training.

Within my organisation a biomarker profiling and monitoring strategy is employed with to assess individual responses to both training and match load. Within my role and responsibilities, I am responsible for the data collection and feedback of these biomarker results. The biomarkers currently assessed focus on the inflammatory response, as measured by high-sensitivity C-reactive protein (hs-CRP), which has emerged as a particularly important indicator of fatigue. hs-CRP in widely recognised for its role in reflecting systemic inflammation and recovery following physical exertion (Fischer, 2006; Fragala et al., 2011). In addition to hs-CRP, three other biomarkers are also assessed, free oxygen radical test (FORT) measuring oxidative stress, free oxygen radical defence (FORD) measuring antioxidant resource and oxidative stress index (OSI) which provides a balance between reactive oxygen species (FORT) and antioxidant capacity (FORD).

It occurred to me our understanding of the link between biomarker measures and training load was speculative at best, requiring investigation and refinement to ascertain any dose response relationship that may exist. To this end this chapter will explore the surrounding literature through comprehensive review to identify possible quantities and frequencies of training load variables that could potentially influence biomarker response data.

To achieve the thesis objectives, I will assess the relationship between training load metrics establishing critical time windows in which variables would be most relevant for assessing their relationship on biomarker response. Once these windows are established, performing correlations will help determine any potential relationships between training load variables and biomarker response data before exploring individual relationships within the dataset. This analysis aims to identify associations between players loading volumes and intensities and their biomarker responses.

This investigation will contribute to a deeper understanding of how training load influences physiological markers of fatigue and recovery, providing practical insight to player health improve monitoring of their readiness to perform.

Chapter Summary

The action research model of investigation employed for this research project is the result of a process of navigation. Over the course of this thesis, I will examine current training load monitoring strategies, search for contemporary approaches, and develop a novel approach as a solution to address identified gaps within the monitoring process. Furthermore, I will explore adaptive response to stimuli with an examination of training load and biomarker response. I consider these two areas of research to be fundamental to my successful operation as a sport scientist not only within my current position but overall career. In line with the aims of a professional doctorate, whilst this methodological process addresses the aims and objectives of my research project, it will also develop skills and competencies that will allow me to fulfil my potential as a researching professional, undoubtedly making me a more effective applied practitioner.

Professional Pause 1

“Not everything that counts can be counted, and not everything that can be counted counts.” - William Bruce Cameron (1963).

There are numerous quotes and anecdotes that could be used to analogise various aspects of athletic training, take a walk past a treatment room or to the coaches’ office in most football clubs and it won’t be long before you hear one or two. Unfortunately, even though many of these conversations offer a succinct frame of reference they are seldom supported by evidence-based practise.

Over the course of my career, it has become increasing evident that as we aim to be more specific in our approaches to managing athletes more and more areas of uncertainty are uncovered. These ‘grey’ areas could be viewed in several ways, firstly as problems to be solved or accepted that some things are beyond our current understanding however, in my experience certain stakeholders in professional sport use these grey areas as opportunities to exploit an agenda that may be difficult to challenge in the absence of available evidence.

During a training session I was challenged by a senior member of staff over a recommendation I had made when reintegrating a young player to training after rehabilitating a serious injury. The recommendation was the player should be exposed to a modified period of training with the team (manipulating training volume and intensity), before beginning unrestricted training and gradual exposure to match play. The coach felt this approach was too conservative, largely due to the fact this player was considered a talent who had already missed a considerable number of games that season. I tried to expand on my rationale and used terms like tolerance and load to argue that there were elements of competitive training that are more fatiguing than we can replicate during rehabilitation, and as a result would require additional time for the player to adapt thus reducing the risk of reoccurrence. This was met with the statement that “our training is harder and more intense than a game so he can play the games", insinuating that he should be able to take an accelerated route back into match play. I felt this was completely opposite to my own views and tried to argue my case. After a back and forth of points it became evident that I was consistently trying to describe facets of loading that I could not quantify to support my claims. I was trying to convey that whilst we can measure a lot of variables concerning training demand, there are intricacies, and movement demands that cannot currently be quantified or are underrepresented in our data as some actions occur at relatively low speed or aren't performed over large distances but require maximal force expression. These demands may have important ramifications for players currently returning from injury and whilst we know they are there these demands maybe overlooked when not reported with more familiar metrics. In the absence of evidence, I felt I was unable to defend my position leading to a stalemate in a conversation that I felt should have required a simple resolution.

This type of conversation did not occur in isolation, across multiple aspects of my role I was met with challenge and the demand for supporting evidence (which I did not view as a problem, I feel constructive challenge can lead to improvements in practise). My concern was that this evidence was occasionally refuted in place of an individual's opinion and validated by their lived experience "when I played". I felt many outcomes following decisions on player health and performance could be improved through more open discussion between varying stakeholders. This instance presents a scenario where I felt the coach was "cherry picking" points to support an argument which is common when someone feels strongly tied to an idea. Research into biases in decision making and coaching demonstrate how well-intentioned leaders may fall into selective recall, exhibiting confirmation bias which impacts on discussions and decision outcomes (West et al., 2021). Whereas the inclusion of both quantitative data and qualitive reflections could foster a more objective yet flexible approach, reducing the potential for bias (Creswell and Clark, 2017).

Problem identification

The underlying problem is that whilst sport science practitioners may have an intuitive view of the external loading parameters, we are at a loss to provide valid and reliable measures of multiple aspects of the game with current monitoring strategies. Furthering my understanding in this area was a primary driver for undertaking the professional doctorate and provides the starting point for the investigations in this thesis.

The first step to solving this problem is to understand more of the demands of the game. There is a belief within contemporary sport scientists, evidenced in discussion with multiple practitioners (both within and outside of my organisation), that aspects of loading such as mechanical and technical facets are noticeably underrepresented compared with locomotor counterparts. Specifically identifying the gaps that exist within our current monitoring processes allows us to explore options to implement new approaches to load monitoring. Conducting a review of the literature surrounding training load monitoring will provide the scientific background of the problem and serve as a platform guiding further investigations. This knowledge base allows us to identify approaches that maybe beneficial to our existing strategies in providing a more comprehensive view of loading.

CHAPTER 3

LOAD MONITORING IN PROFESSIONAL FOOTBALL

Literature Review – Load Monitoring in Elite Professional football

Introduction

Understanding the demands of elite professional football is important for organisations aiming to maximise performance through athlete management and the appropriate prescription of training load. To support athletes, it is important for practitioners to have an detailed knowledge of the demands placed on athletes during training and competition (Ritchie et al., 2016). To successfully design and implement effective monitoring strategies that can be used in applied environments and have the potential to impact on professional practice it is important to understand what has come before. Thus, providing potential gaps within our currently knowledge base and highlighting areas for investigation.

Training load through monitoring of performance related variables generally falls into two broad categories internal and external workload (Impellizzeri et al., 2019a). Monitoring these variables can give coaches and practitioners crucial insight into the level of stress imposed on players that are experienced through a variety of stimuli. However, the effectiveness of these strategies remains unclear and further research is needed to establish optimal monitoring protocols and their relationship to physiological responses in elite football players. The aim of this literature review is specifically focused on current methods used to establish the demands of elite professional soccer.

Overview

The review begins by discussing our current understanding of physical demands of the game discussing the evolution of load monitoring techniques before highlighting important components of sporting demands. The review culminates in exploration of contemporary issues related to training load monitoring including the under representation of certain types of loading (mechanical and technical) as part of overall training cycle monitoring.

Physical Demands

Football is an intermittent team sport with teams consisting of 11 players competing over two 45-minute periods, with players will typically covering between 10-13km during a 90-minute match (Barnes et al., 2014). Due to its relatively extensive duration and the high-intensity, intermittent nature of match play, soccer is primarily considered an aerobic sport. However, matches are characterized by frequent fluctuations between high- and low-intensity activities (Bangsbo et al., 2006a; Drust et al., 2007; Reilly et al., 2009). Elite players require well developed cardiovascular, aerobic, neuromuscular, and musculoskeletal systems to execute repeated high intensity running efforts, changes of direction, and sport specific actions, all of which are integral to soccer performance (Rahnama et al., 2003; Buchheit et al., 2010a; Buchheit et al., 2010b; Akenhead et al., 2014; Akenhead et al., 2016).

The demands of football are consistent when observed across the top European leagues, which show similar trends regarding the external load experienced by players at the highest levels. Notable differences do exist in locomotor demands between playing positions, with central midfielders covering, on average, the greatest distance (12,027m ± 627m) compared to their defensive and attacking counterparts (Stolen et al., 2005; Di Salvo et al., 2007; Di Salvo et al., 2009a; Di Salvo et al., 2013a). Understanding the varying demands between positions and levels (Di Salvo et al., 2013b) of competition provides important context for investigations into training load and monitoring practises. Understanding which positions experience load in different ways, for example greater number of technical actions or changes of direction, would have important implications of successful training load prescription (Reilly et al., 2000; Andrzejewski et al., 2015).

Football Science

Understanding the specific demands of the sport has become an important area of investigation for support teams working at the elite level with the ever-increasing pressures for teams to attain a consistent level of success (Carling, 2013).

Due to the global reach and financial incentives associated with success in soccer, research and development has expanded exponentially since the 1980s (Kirkendall, 2020) and now has a large body of work dedicated to incorporating science into the planning and execution of training programmes (Impellizzeri et al., 2004). Early research on soccer's demands primarily focused on physiological and energetic aspects, reporting cardiovascular outputs like heart rate (HR) response (Bangsbo, 1994; Stolen et al., 2005). These initial studies laid a foundation for subsequent research into soccer's physiological demands (Kirkendall, 2020) which has proved a consistent theme throughout the literature largely due to technological advancements of monitoring tools

Football at an elite level is highly demanding and requires significant energy expenditure to sustain performance throughout a 90-minute match (Krustrup et al., 2006). The energetic demands of soccer are predominantly met through aerobic metabolism, with up to 95% of energy produced via oxidative metabolism (Bangsbo et al., 2006b). Studies have shown that elite players exhibit high aerobic fitness, with maximal oxygen uptake (VO2max) values ranging between 55-70 mL/kg/min, signifying the importance of a well-developed aerobic system for maintaining performance (Stolen et al., 2005; Krustrup et al., 2006; Rebelo et al., 2014).

The metabolic cost of these locomotor activities is often assessed using velocity-based metrics from GPS to measure external load and heart rate monitors to evaluate internal response (Varley et al., 2014; Akenhead and Nassis, 2016). Numerous articles have attempted to quantify movement demands by focusing on locomotor activities within predefined speed thresholds. These activities are typically categorized into bands: 0-11 km/h (standing, walking, jogging), 11.1-14 km/h (low-speed running), 14.1-19 km/h (moderate-speed running), 19.1-23 km/h (high-speed running), and >23 km/h (sprinting) (Di Salvo et al., 2007; Di Salvo et al., 2009a; Di Salvo et al., 2013b; Barnes et al., 2014). However, training and match play are not solely comprised of movements that can be accessed via locomotor performance. Unique sport-specific actions that require maximal expression of force such as changes of direction, breaking actions and technical movements are a few examples that maybe overlooked by solely assessing locomotor demands (Owen et al., 2014; Harper et al., 2019).

These previously described movement demands provide a simplistic physiological view of load which assumes that greater distance, higher speed, and longer durations result in higher energy expenditure and greater fatigue. Research has shown that physical performance in running-based sports can be impaired by the acute effect of muscle fatigue following high metabolic demand activities, such as high-speed running or sprinting, and these activities hinder the resynthesis of ATP at a rate sufficient to sustain energy demands (Bangsbo, 1994; Reilly et al., 2009). While locomotor activities are emphasized, the total energetic demands of soccer are not exclusively dictated by them, indicating that other factors contribute to overall demand. Identifying these factors through exploring various actions from the overall movement profile of football could provide some context around what drives the energetic demand outside of locomotor activity (Osgnach et al., 2010; Casamichana et al., 2013; Harper and Kiely, 2018).

Mechanical Demands

In the context of training load monitoring in sport, mechanical demands refers to the physical forces, stresses and strain placed on tissues of an athlete's body during the varying actions for example accelerations, decelerations, jumping and landing that comprise overall movement demands (Hewit et al., 2011; Harper and Kiely, 2018; Harper et al., 2019). This section aims to provide context around the terminology used to describe this type of loading and where mechanical stresses maybe exhibited within the training and competitive cycle.

Concentric and eccentric muscle actions performed during sport specific movements generate physiological and physical signalling that drives adaptation within tissues in response to mechanical stress (Griffin and Guilak, 2005). Whilst both "mechanical" and "biomechanical loading" are used interchangeably in the literature, they reflect the many types of stresses and strains imposed by external load demands, and so whilst they may not be universally accepted definitions they could be considered (currently) as our best descriptors of theses specific demands (Greig et al., 2006; Harper et al., 2022).

As previously stated, match play fluctuates between periods of high and low intensity movement, requiring not only well-developed cardiovascular and aerobic energy systems but also high-functioning neuromuscular and musculoskeletal systems, which are crucial for executing repeated high-intensity movements, changes of direction, and sport-specific actions (Rahnama et al., 2003; Buchheit et al., 2010b; Buchheit et al., 2010a; Buchheit et al., 2014) that contribute to the overall mechanical demands of the game.

Players typically perform 1,000 to 1,500 discrete movements during a match, with activity changes every 3.5 seconds and a high-intensity action occurring approximately every 60 seconds. Maximal effort activities happen every 4 minutes on average (Stolen et al., 2005; Bloomfield et al., 2007). Frequent turning, technical skill execution, and interactions with opponents' critical components of movement patterns during match play place varying degrees of stress and strain on players, thereby creating biomechanical loads on athletes (Stolen et al., 2005; Bloomfield et al., 2007). Whilst a universal classification of biomechanical demands in soccer does not exist yet, it is widely accepted that these demands stem from sport specific movements, with forces imposed on soft tissues (internal load) resulting from external kinematic demands, such as propulsive and braking forces against the ground (Vanrenterghem et al., 2017).

Changes of direction (COD) have been shown to generate higher mechanical loads, leading to increased tissue damage and fatigue (Dos'Santos et al., 2022; Kalkhoven et al., 2021; Harper and Kiely, 2018) and potentially serving as a non-contact injury mechanism (Della Villa et al., 2020).

Research on English Premier League academy players found that they performed approximately 300 turns per match (Morgan et al., 2022a), indicating the significant contribution of non-linear movement to overall biomechanical loading. Complex movements like accelerations, decelerations, and changes of direction place high mechanical stress on the body, these movements which may have a higher metabolic cost than linear locomotor activities can happen more frequently and are more relevant to performance (Morgan et al., 2022a) but aren't always distinguished within datasets despite their contribution to fatigue and so should be incorporated into load monitoring strategies (Harper et al., 2019).

Technical Demands

Technical loading forms another important part of the puzzle for practitioners trying to effectively quantity training load demand that maybe overlooked. Quantifying the volume and intensity of technical actions performed by players may have important implications for training load prescription (Andrzejewski et al., 2014) due to the associated mechanical stresses (Lees and Nolan, 1998).

In addition to movement related demands, such as accelerative efforts and changes of direction, technical actions are fundamental to match play and contribute to mechanical strain. Ball striking for example requires explosive concentric and eccentric contractions, placing significant mechanical and tensile stress on the muscle, especially during repetitive kicking motions (Mendiguchia et al., 2013; Jokela et al., 2023). Injuries to muscles in the lower limbs particularly the rectus femoris are common in football, with many resulting from ball striking actions (Jokela et al., 2023). Due to the rectus femoris' role as both a hip flexor and knee extensor, it is highly engaged during high-intensity, dynamic actions like kicking and sudden changes in direction, making it vulnerable to injuries. This kind of technical loading is crucial to consider, especially in injury rehabilitation (e.g. quadriceps muscle or knee ligament strains), given the high stress placed on these tissues (Jokela et al., 2023; Mendiguchia et al., 2013). However, currently there are limited resources available to practitioners to assess these demands in the field (Russell et al., 2013).

Technical loading during training cycles is an emerging area of research and there have been significant approaches to the quantification of technical actions however these have largely employed video and notational analysis techniques. Emerging research using foot-mounted inertial sensors now allow practitioners to accurately quantify both the volume and intensity (e.g. the speed of foot movement when contacting the ball) of technical actions (Lewis et al., 2022). As coaches often allocate a substantial portion of training to technical exercises, likely due to the relationship between technical performance and match success (Ade et al., 2016), it is important to consider how these unique stresses contribute to the overall loading experienced.

These examples demonstrate that relying solely on traditional locomotor metrics may not provide a complete picture of the physical and mechanical demands of elite soccer. Although these actions may have varying importance for load monitoring at different times during training cycle it is important to consider their relation to injury and performance. For example, whilst not all technical actions have implications for injury, high velocity ball striking has a clear association with quadriceps strains (Mendiguchia et al., 2013; Jokela et al., 2023). Therefore, a deeper understanding of the frequency and magnitude of discrete technical actions and mechanical strain is essential to comprehensively assess the overall demands placed on players during training and match play.

Training Load Monitoring

Training prescription and load monitoring are critical components of successful performance in team sports. To optimize performance and mitigate injury risk, coaches must carefully design training programs that align with the specific demands of the sport and the needs of individual athletes. It is well established that optimal loading of the aerobic, cardiovascular, and musculoskeletal systems leads to preferential physical and physiological adaptations that enhance sporting performance by improving strength, speed, and power (Gabbett, 2016). However, suboptimal loading can lead to injuries, which occur when single or repetitive forces are applied to biological tissues beyond their strength and capacity for repair (Bittencourt et al., 2016).

In football, periodization typically follows a cycle of training, tapering, competition, and recovery over a weekly period (Silva et al., 2018). Although these cycles can fluctuate based on match schedules, they generally recur throughout the season, which dependant on team success can span more than 40 weeks. Excessive training load during phases intended for recovery and regeneration can increase injury risk, decrease fitness, and negatively affect performance (Carling et al., 2010). Balancing these factors requires an understanding of the principles of periodization and individualization, and crucially needs to be supported by effective training load monitoring. Successful deployment of these strategies can help coaches and practitioners make evidence-based decisions about appropriate loading schemes (Akenhead and Nassis, 2016; Akenhead et al., 2016).

A review of current training load monitoring practices across elite football clubs in Europe, the United States, and Australia aimed to assess the perceived impact of these strategies on injury prevention and performance (Akenhead and Nassis, 2016). It found that the most monitored variables were total distance, distance covered at speeds greater than 5.5 m.s, accelerations at various speed thresholds, estimated metabolic power, and heart rate exertion. All surveyed teams used GPS units and heart rate monitors, but no universally adopted method of training load assessment existed. The review highlighted the low perceived impact of monitoring strategies on injury prevention and performance, citing poor coach buy in and limited sensitivity of field-based measures as barriers to effective monitoring strategies. These findings suggest the need for more tailored and customized approaches to improve monitoring efficacy may gain greater support from coaches and stakeholders within organisations.

Traditional metrics, such as total distance, speed, and heart rate, while commonly used, may not provide a complete picture of the demands contributing to injury and performance (Malone et al., 2017; Carling et al., 2018). Research indicates that these metrics may only explain a small portion of the variance in match performance, let alone the overall training demand (Malone et al., 2015a; Malone et al., 2015b). Parameters that identify mechanisms with high associated physical costs such as changes of direction or explosive technical actions (mechanical loading) are often overlooked when developing training load metrics (Pleša et al., 2022).

The reliance on technology in contemporary load monitoring practices may in part be creating a dependence on metrics that lack sufficient practical usefulness for informing training prescription. Metrics such as Catapult Sports' PlayerLoad™ and STATSports' Total Loading are designed to offer practitioners a simplified single value that integrates mechanical demands into load monitoring systems. Although some research supports the use of these measures (Green et al., 2023), they remain 'black box' outputs that do not provide a clear causal link between mechanical load and physiological or performance responses (Kalkhoven et al., 2021). For example, PlayerLoad™ derived from tri-axial accelerometery data embedded within a GPS unit, is strongly correlated with total distance covered, which raises questions about whether it provides truly independent mechanical load information (Vanrenterghem et al., 2017). Furthermore, the standard placement of a single accelerometer imbedded in a vest worn between the scapulae (standard practise for players competing in team sport) limits the capture of key sport-specific movements, particularly in running-based, skill-dominant sports such as football. These include important lower limb actions like kicking, cutting, and rapid footwork are either underrepresented or missed entirely. Evidence suggests that multiple accelerometers positioned on distal segments (e.g., feet) are needed to better quantify these complex movement patterns (Palucci Vieira et al., 2022).

As currently, no standard classification of movements exists, it makes it difficult to objectively assess a largely theoretical concept. To improve the efficacy of training load monitoring, alternative metrics that more comprehensively capture the demands of elite soccer should be considered. In essence, manufacturers have attempted to quantify a highly complex phenomenon into a simplistic, single-figure metrics with low practical value for influencing mechanical load prescriptions. A variety of internal and external load measures are used to quantify training load and assess injury risk, yet these measures are speculatively linked to causation due to a poor understanding of the interaction between mechanical load and adaptive pathways (Kalkhoven et al., 2021).

Tensile, compressive, and shear forces act on physical structures to varying degrees depending on the action type, velocity, orientation, or magnitude of movement. These forces clearly indicate that mechanical load is a major contributor to tissue damage and injury, and training load monitoring should reflect this reality (Kalkhoven et al., 2021). However, the link between training load and tissue damage mechanisms remains poorly understood.

Monitoring mechanical stresses on the musculoskeletal system presents significant challenges in applied environments. Invasive techniques are needed to measure joint contact forces or muscle-tendon loads, but these methods are often confined to the laboratory, where they have limited ecological validity in real-world practice. A recent review, *Measuring Biomechanical Loads in Team Sports: From Lab to Field* (Verheul et al., 2020), highlighted the current lack of viable options for assessing these stresses in training and competitive settings. While tissue-specific stresses and strains can be measured in controlled lab environments, these metrics have low field viability, limiting their usefulness for practitioners. Acceleration-based metrics, derived from accelerometer-embedded GPS devices, offer better field viability but have low validity in accurately measuring tissue specific loading. Thus, finding a perfect solution remains elusive, though whole-body loading measures may provide a practical starting point.

Development and Application of Theoretical Football Movement Framework

As previously highlighted in this review no gold standard or model exists to classify football movements physical or physiological demand. To refine further investigations, it is important to frame these movements with specific context to football movement demands. Through critical analysis of the identified literature, we proposed a novel framework that presents a classification of movements (Figure 3-1). Football specific movements have been defined by what presents a metabolic challenge and what presents a more mechanical one and movements that may be both (Figure 3-1). The inner red circle or 'key actions' includes movements that may be of higher priority due to their importance in relations to performance, frequency, and theoretical ease of measurement. The outer circle contains movements that may occur less frequently or be difficult to identify and with current available technology.

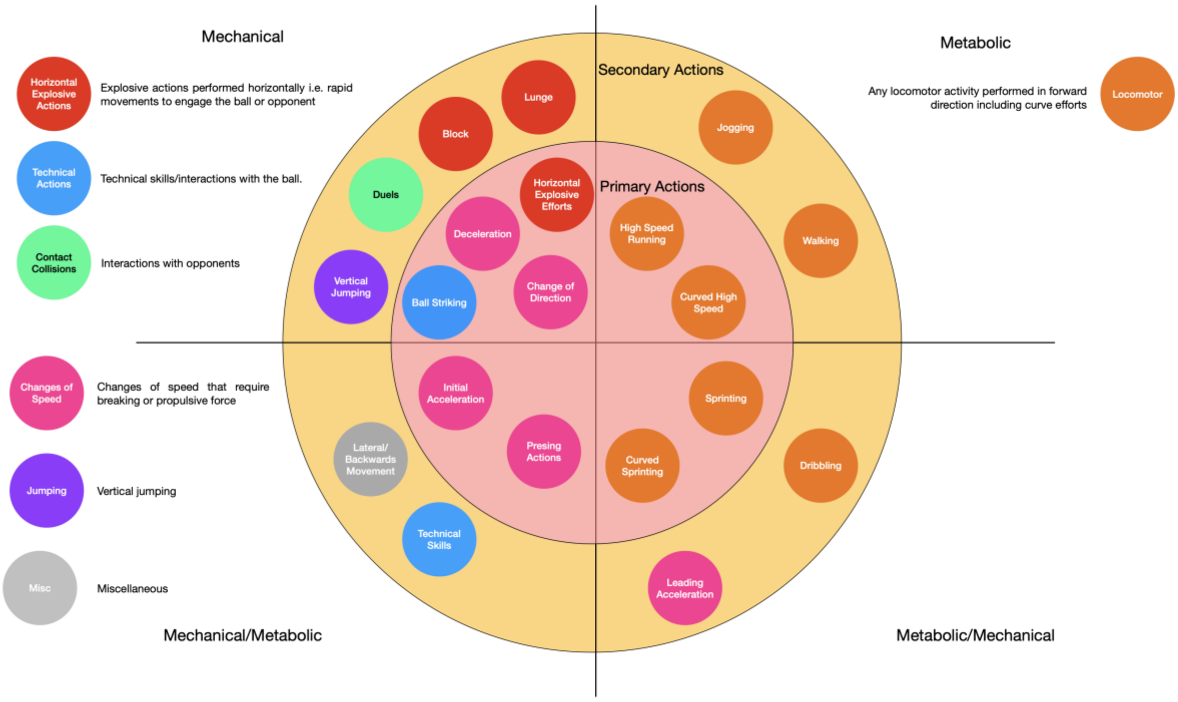
The Football Movement Framework was developed through a collaborative process involving discussions with practitioners, coaches, and a multidisciplinary team, alongside my own experience of the key determinants of physical football performance. This model reflects a synthesis of expert insights and practical application, focusing on critical movements in the sport, such as sprinting, change of direction and technical skill execution, which are essential for performance and injury prevention.

The framework was iteratively refined through feedback from real-world applications, adjusting to the dynamic nature of football. As part of the process key stake holders were consulted and asked if they would make any additions or modifications. Testing the model in alongside industry experts helped to validate its relevance and effectiveness in capturing the key biomechanical and physiological demands of the sport.

This iterative development process ensures that the framework is continuously updated, drawing on new data and insights to remain applicable in performance and rehabilitation contexts (Vanrenterghem et al., 2017).

Figure 3-1 Football movement framework

Proposed theoretical framework of football specific movements divided into categorised by the perceived *mechanical and metabolic challenge.*



Summary

Identifying key movements related to physiological demands should be a primary concern for effective load monitoring and training prescription. Studies have emphasized the importance of movements such as changes of direction and horizontal explosive efforts, which occur frequently but are often overlooked in training cycle assessments (Akenhead et al., 2015; Murtagh et al., 2019). Additionally, traditional time-motion analysis metrics like total distance and high-speed distance may fail to capture the total physiological demands of team sports, as they often neglect acceleration (Tang et al., 2018). Therefore, future research should investigate the frequency and magnitude of mechanical actions imposed on player during the training cycle.

This review has identified the low utility of current load monitoring strategies employed by elite football teams to monitor biomechanical load and resulting mechanical stress. The analytical methods that underpin our understanding of movement demands are limited in their ability to describe the full spectrum of activities integral to soccer performance. Current metrics suffer from low coach buy in and efficacy in designing optimal training programs. Emerging frameworks suggest separating metabolic and mechanical loading, prompting further investigation into optimal training load prescriptions. Furthermore, a lack of field viable measures for assessing mechanical load calls for innovative solutions.

Professional Pause 2

"There are more questions than answers" – Johnny Nash

A song sung in jest at the start of my career by a close friend when discussing sport science in the applied field, but on reflection it is probably true. Performing a review of the literature undoubtedly gave me additional insight into the demands of the game and certainly frames the need to separate aspects of load monitoring to incorporate mechanical and technical activities that are currently not separated or quantified within current approaches.

Problem identification

The issue I now face is understanding contemporary approaches to monitoring multiple facets of loading in the applied field. This present us with two issues, conceptually we need to have a different approach to load monitoring that encompasses the multiple facets of loading that we think are important. Secondly, we are looking for a pragmatic solution that could be implemented within the real world setting of my practise environment to try and quantify these loads.

Organisational collaboration

My doctorate is funded by my employer therefore the aim of my project is twofold, firstly to provide me with opportunities to develop my skills as an applied practitioner. Secondly, to provide value to the organisation through improved practice and process through application of scientific investigation. It is important to provide context here that this has been an established goal within the organisation to conceptualise loading not currently quantified as part of the current monitoring process, however the opportunity arose following my promotion within the organisation to address this through scientific investigation. Conversations within the multidisciplinary team often focus on which players may be at increased risk of injury or underperformance because of fatigue/overtraining. These conversations are often based on subjective interpretation of data to infer the external loading a player has experienced. It is therefore very important to consider the role of my research in improving processes through more informed decision making within the organisation. Although I need to be mindful that it is inherently difficult to create opportunities for change within the professional environment especially within the competitive season due to a demanding and changeable training, travel, and competition schedule.

Iterative cycles

I decided to utilise a systematic review of the literature to identify approaches to load monitoring or quantification specifically targeting those approaches that may combine differing facets of loading and are tested in multiple environments. However, knowing that approaches and technologies are often employed in the applied field long before a body of peer-reviewed evidence is available, I will also search for available technologies that could be used. It is important to consider that although a search may yield an abundance of potential solutions my practise environment has specific constraints. With limited resources at my disposal any identified approach or technology must be practically and commercially available. It must also be scalable so it can be applied to multiple users and not require specialistic analytics or data processing beyond the means of the department. This critical thinking is supported by the conceptualised model by Windt et al. (2020) in their “to Tech or Not to Tech” decision making framework for implementing technology into applied practise. The framework supports the notion that to successfully integrate technology within your practise environment you should first ask a series of questions to evaluate the cost benefit of a technological investment.

Figure 3-2 To tech or not to tech

Conceptual model taken from (Windt et al., 2020) “To Tech or Not To Tech” framework on the decision making process prior to implementation of technology.

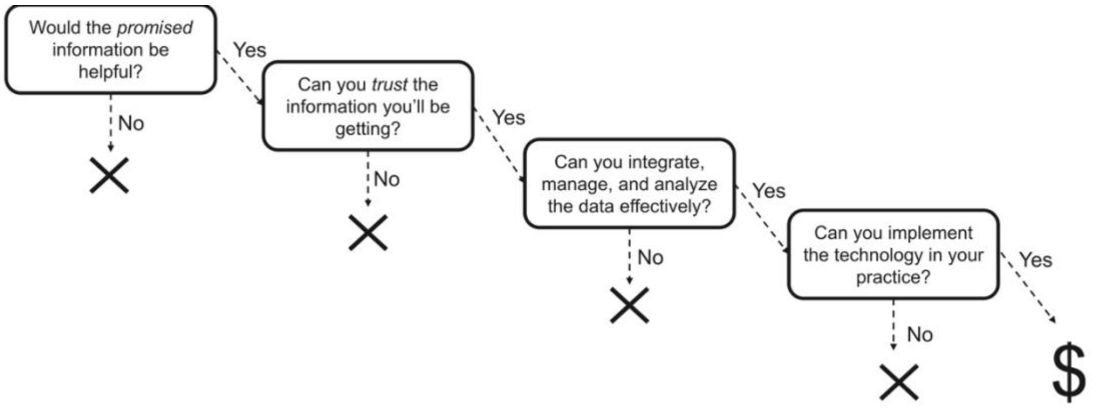


Figure 1. A critical decision-making framework for integrating technology in sport.

Identifying approaches via the Preferred Items for Systematic Reviews and Meta Analysis (PRISMA) (Page et al., 2021) is clear route and framework that can be used to identify relevant literature (Page et al., 2021), but I wasn’t aware of any formal search strategy for identifying technologies. A pilot search yielded limited results but did identify a few websites that offered comparative articles between already implemented tech but nothing new. Conversations with my supervisory team led to the idea of looking for patents. Having no prior knowledge of patent searching I began reviewing blog articles and came across Google Patent Search which allowed me to employ a similar search strategy to a database search for literature.

CHAPTER 4

A MIXED METHODS APPROACH TO IDENTIFYING LOAD MONITORING SOLUTIONS IN PROFESSIONAL FOOTBALL

Introduction

Training load monitoring is a crucial component of sport science, particularly in elite athletic environments where effective training prescription is necessary to optimise performance and minimise injury risk (Impellizzeri et al., 2004; Bourdon et al., 2017). The ability to effectively monitor training load requires the accurate quantification of both external and internal demands placed on athletes over the training and competitive cycle. External load, which includes the physical forces (braking and propulsion) exerted on athletes and internal load which references their physiological responses (heart rate) are essential components in understating athletic response (Impellizzeri et al., 2023).

Current training load monitoring methodologies, however, are often limited to a few variables which fail to comprehensively capture the multifaceted nature of the demands of the game (Impellizzeri et al., 2005; Coutts, 2014). External load can broadly be defined as any exertional exposure related to training, practise and competition (Foster., 1998). Attempts to quantify this complex phenomenon have resulted in thousands of variables being created (largely by technology providers) to assist practitioners in measuring dimensions of loading however, these approaches are overwhelmingly derived from locomotor movements or metabolic estimations of energy demand which negating the mechanical and technical stresses imposed on athletes (Coutts and Duffield, 2010; Buchheit and Simpson, 2017).

This review seeks to address these limitations by proposing a novel framework of investigation. The initial literature review of the thesis highlights three distinct facets of loading namely locomotor, mechanical technical components that contribute to overall physical demands. This approach aims to provide a more comprehensive and nuanced account of the varying dimensions of training load. Maintaining the reviews grounding as a search for solutions to an applied problem it is important to conceptualise loading in a framework that can be utilised in professional practise (Malone et al., 2017).

Given the fast paced and evolving environment of elite sport it is possible that approaches could be implemented in real world applied environments before publication of peer reviewed investigation. To bridge this potential gap between research and practise the review incorporates a systematic search for technologies through patent searching alongside the academic literature review. This dual approach will identify both established and emerging technologies capable of measuring and quantifying combined aspects of training load in multiple environments. The objectives of this review are twofold. Firstly, to synthesise existing research and identify methodologies for the quantification of multiple dimensions of load. Secondly to explore new and potentially innovative technologies that may not yet be extensively covered in peer reviewed publications.

The findings from this review will be evaluated for their feasibility in the real-world context of applied training load monitoring and their utility in elite professional football.

Research aims and objectives

Aim: Examine current approaches to load monitoring and potential solutions within sport.

How?

1. Perform a systematic review of the literature for approaches that could be implemented in elite football.

2. Perform a patent search to identify technologies that could be implemented in elite field-based setting.

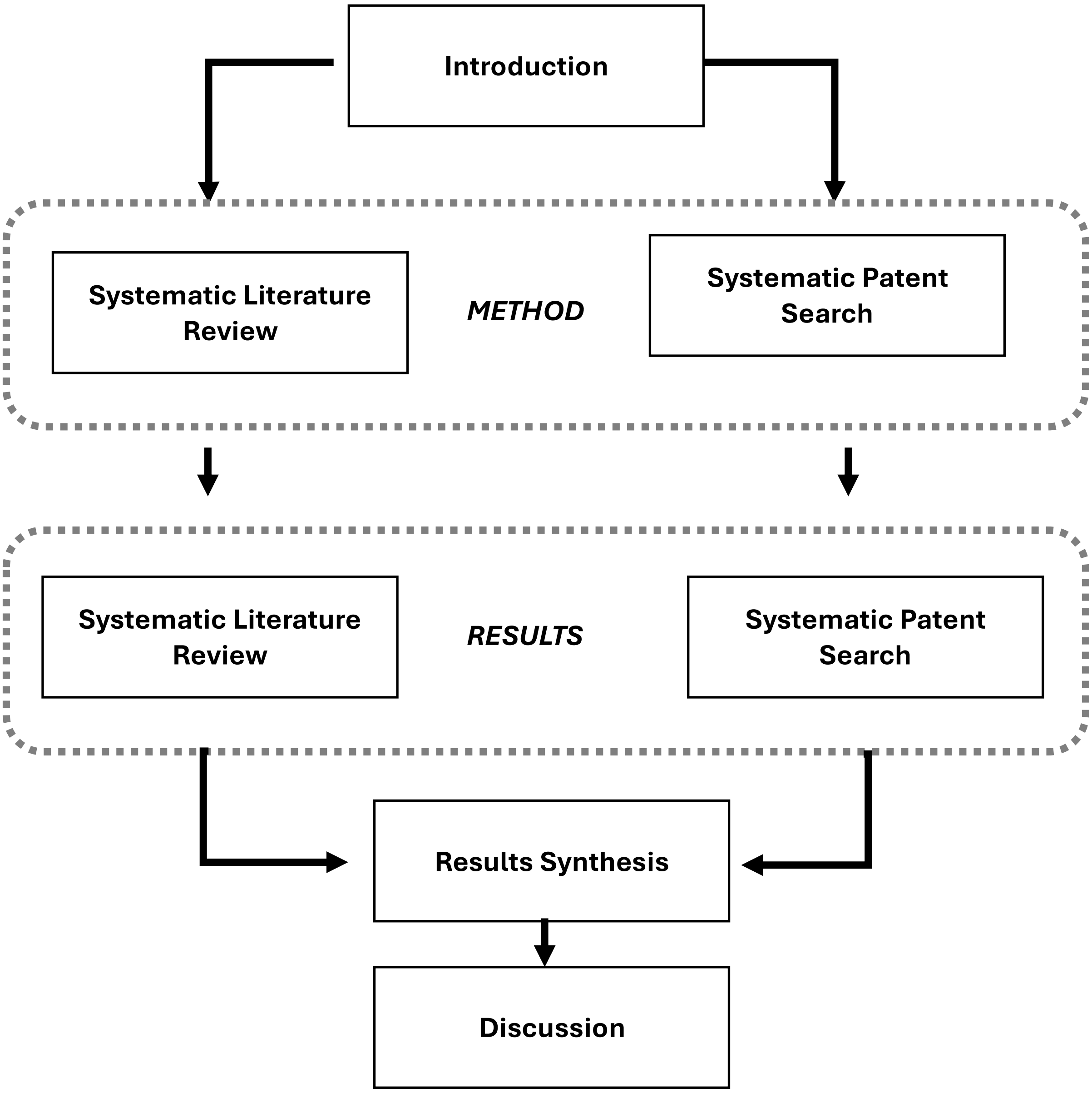
3. Highlight findings and potential strategies that could be implemented within professional applied environment.

Methods

As this investigation follows a non-traditional format (Figure 4-1) helps understand the flow. Although the sections are presented linearly, they should be considered occurring simultaneously. The methods of each 'side' of the investigation will be presented followed by the results. A synthesis of results will follow to combine the two areas and establishing findings alongside the studies aims.

Figure 4-1 Mixed methods study map

The figure presents an overview of the flow of the overall project detailing the order in which sections of the thesis will be presented.



Systematic Literature Review

Search strategy

The review utilised the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA). No consent was required during this manuscript, due to the nature of the systematic review. Through researcher discussion, the following databases were chosen to search for the key words, which have been previously utilised in systematic reviews in this field (Sarmento et al., 2024). These are PubMed and EBSCO SportDiscus & Medline (combined searches). For all databases the search for literature was performed within the last 10 years, with searches conducted between the 1st of March 2024 through to the 31st of April 2024.

The key words selected as part of the search criteria fell into different categories of the search which included, 1) the sport, 2) the device, 3) the measurement, 4) the research objective, with all search terms shown in Table 4-1. As part of the inclusion criteria, the search also required articles to be, 1) original research articles, 2) written in English, 3) published in a peer reviewed journal, 4) published since 2014 (10-year period from the search date), 5) abstract available for screening in the respective database 6) The full text needed to be available to download. Where full text articles were not available for specific texts research used a combination of Google Scholar (Google, Redmond, Washington, USA) and 'Research Gate' as an alternative route of access.

Search terms

Table 4-1 Literature Search

Search terms used in database search to identify relevant literature.

PubMed
((((((((((football[Text Word]) OR (soccer[Text Word])) OR (association football[Text Word])) AND (inertial measurement unit[Text Word])) OR (imu[Text Word])) OR (global positioning system[Text Word])) OR (GPS[Text Word])) OR (global navigation satellite system[Text Word])) OR (GNSS[Text Word])) AND (mechanical load[Text Word])) OR (biomechanical[Text Word])) OR (change of direction[Text Word])
EBSCOhost Sport Discus & Medline combined
(association football OR soccer OR football AND inertial measurement unit OR accelerometer OR mems sensor OR (global positioning system or GPS) OR global navigation satellite systems (GNSS) OR tracking system OR pixel recognition AND kicking OR mechanical load)

Study selection

All retrieved studies were downloaded and stored within a journal database software Endnote (EndNote™, version 20.6, Clarivate Analytics, Philadelphia, PA, USA). Results from the initial search criteria were cross-referenced and duplicate studies were removed from the final review. Two reviewers independently reviewed all the articles as per the inclusion criteria set out in the current section, to assess the eligibility of research articles to be included in the review.

Articles were excluded based on their relevance to the aims of the study. Records were screened by title and abstract for their suitability for inclusion. Articles that did not quantify a measure of loading that could be defined in components of locomotor, mechanical or technical loading were excluded. As well as articles that on face validity did not reflect the potential to be included in the practise environment.

Reflections and feedback on the current searches were performed by the two researchers during the screening period, with online meetings taking place bi-weekly to address challenges with the search criteria and inclusion criteria (Levac et al., 2010; Shushan et al., 2022). A third independent reviewer was consulted throughout the process to ensure search criteria were valid. Once the papers had been assessed, the two reviewers met after the review process to discuss the challenges and any uncertainties in relation to the analysis, to assess if any further filtering of the inclusion/ exclusion criteria was required (Levac et al., 2010; Shushan et al., 2022).

Data extraction

All details to identify the article were exported from the journal database software into a google sheets (Google, Redmond, Washington, USA) to allow the two reviewers to cross-reference the articles that met the inclusion criteria. This included the papers author, title, abstract and the publishing journal. Based on these details, two reviewers independently reviewed the subject of each paper.

As previously established, although the review follows an academic format the purpose of this exercises is to identify approaches to load monitoring that can effectively be deployed in a real-world setting by incorporating the technology into existing monitoring strategies within the organisation without requiring specialist expertise required to perform the analysis. Therefore, it was logical to extract the data most relevant to the application of the approach to the professional practise environment. To ensure consistency reviewers created definitions (Table 4.2, Table 4.3 & Table 4.4).

If the subject was deemed relevant to the current review, the following assessments were then made 1) the sport profiled in studies methodology 2) the type of technology used to quantify load (4.2) 3) the category of load with which the variables were used to identify (4.3) 4) the metrics used 5) category of environment the technology was tested in (4.4).

Tables of definitions used in the search strategy

Table 4-2 Technology definitions

A definitions table for the key terminology associated technologies used.

Technology	Abbreviation	Definition
Global Positioning System/ Global Navigational Satellite System	GPS/GNSS	Devices used by tracking radio signal to detect position on earth. Usually worn in a tight-fitting vest mounted between the shoulder blades.
Inertial Measurement Unit	IMU	A device that measures motion including acceleration and rotation.
Local Positioning System	LPS	Technology that can determine position indoors or localised environment. Like GPS but does not rely on satellites.
Motion Capture	Mo-Cap	Technology that records movement and transfers data to a computer programme for use in virtual environment.
Video Analysis	VA	Systematic examination of video footage to evaluate performance or movement.
LiDAR	Lidar	Light detection and ranging (LiDAR) is a remote sensing technology that uses lasers to measure distances.
Other	Other	Any technology that does not fall into the above categories.

Table 4-3 Parameters of load definitions

A definitions table for the key terminology associated with the load analysis.

Monitoring Category	Abbreviation	Definition	Examples of Metrics Associated with Monitoring Category
Locomotor Running Activities	Locomotor	Metrics related to a player running in a continuous action at varying speeds.	Total Distance covered, High speed running distance covered (>N m/s), Accelerations/Decelerations (m/s/s)
Mechanical	Mechanical	The accelerations placed on the body, as provided by a wearable device, typically IMU/ MEMS devices	Accelerations (g);
Change of Direction	COD	When a player stops a continuous running action, to orientate their body and running into a different direction	Angle of turn, direction of turn, ground reaction force (N)
Physiological Responses	Internal	An athlete's physiological response/stress to a certain stimulus	Heart rate, Rating of perceived exertion (RPE)
Technical Kicking Actions	Technical	Any action that involves a player interacting with the ball at their feet, including kicking, dribbling etc	Kicking velocity (m.s),
Combined	Combined	Any approach that covered multiple aspects of loading	Locomotor & Internal OR Mechanical & Technical

Table 4-4 Environment definitions

A definitions table for the key terminology associated with testing environment.

Environment	Definition
Games	Data generated from game scenario or competitive matches
Field Training	Data captured for from training environment
Field Test	Data generated on field using a component of training i.e. shuttle runs, sport specific tasks.
Lab Test	Data capture in a laboratory or closed environment
Multiple	Approach utilises multiple environments i.e. competitive game and field training data.

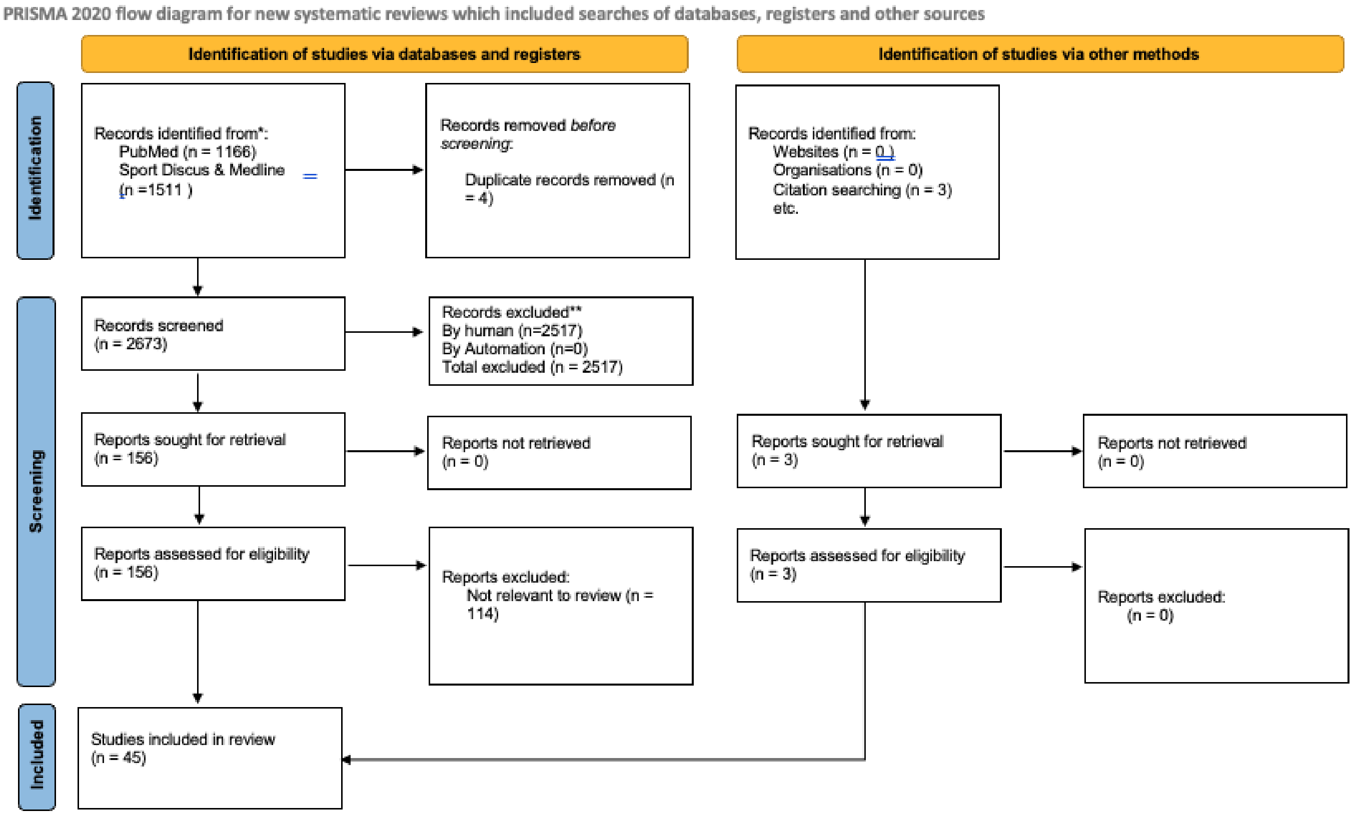
Results

The literature search was conducted between (1st March 2024 through to the 31st of April 2024) and returned 2673 articles across three databases. Four duplicate records were removed prior to the screening. 2517 article were searched via title and abstract for their relevance with 2517 excluded. 156 articles were sought for retrieval will a further three identified via citation searches. A further 144 articles were excluded based on their methodologies and lack of applicability to the project on relevance leaving 45 which met the criteria to be included in the review.

The results of the review are presented in the following section. Table 4-5 shows the overall findings of the 45 identified studies after categorization, it presents the number of studies using different technology categories. Of these studies GPS (n=17) and IMU (n=17) can be seen as the predominant technologies used to quantify loading. Figure 4-5 show that of the 45 studies, 24 were deemed to have assessed load across multiple categories (combination of one or several locomotors, mechanical, technical and internal parameters). The environments in which the studies were conducted can be seen in Figure 4-4 with eleven occurring in field test, four in laboratory conditions, eight in field training, fourteen in game conditions and eight using multiple environments. A further consolidation of the results will be presented in the results synthesis section.

Figure 4-2 PRISMA flow

PRISMA flow diagram of the systematic literature review for approaches to load monitoring.



*Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).
**If automation tools were used, indicate how many records were excluded by a human and how many were excluded by automation tools.

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71. For more information, visit: http://www.prisma-statement.org/

Table 4-5 Literature search results

An overview of all the papers returned that fit the eligible criteria within the systematic review and the specific categories of their eligibility.

Lead Author	Year	Sport	Technology Category	Category of Metrics Used	Metrics Used	Environment Category
Apte, S	2023	Soccer	GPS/GNSS	COD	3D acceleration, angular velocity, speed	Field Test
Aviles, R	2023	Soccer	IMU	COD	3D acceleration	Field Test
Barreira P	2017	Soccer	IMU	Mechanical	3D acceleration PlayerLoad™,	Field Test
Beato M	2018	Soccer	GPS/GNSS	Combined	HSR, No A+D, relative velocity, metabolic power, HR	Field Training
Buchheit	2015	Soccer	IMU	Locomotor	Metabolic Power, O2 kinetics, Velocity	Field Training
Buchheit	2014	Soccer	Other	Combined	Velocity, Horizontal Power, Horizontal Force	Field Test
Caldbeck	2022	Soccer	Other	Locomotor	Sprinting	Game
Cardoso	2023	Soccer	GPS/GNSS	Locomotor	Velocity, Acceleration Profile	Field Training
Clement	2019	Soccer	GPS/GNSS	Locomotor	TD, HSD, SD, Sprints, Accelerations	Field Training
Connor	2022	Soccer	GPS/GNSS	Locomotor	m.min	Game
Dalen	2019	Soccer	Video Analysis	Locomotor	Accelerations HSR	Game

Lead Author	Year	Sport	Technology Category	Category of Metrics Used	Metrics Used	Environment Category
Dalen	2018	Soccer	IMU	Combined	o2 uptake, HR, 3d acceleration	Field Test
Darbellay	2020	Soccer	GPS/GNSS	Combined	Velocity, Metabolic Power, Adapted MP	Field Training
Dos'Santos	2022	Soccer	Lidar	Combined	Number of turns, Categorisation of turns	Game
Emmonds	2022	Soccer	IMU	Combined	Duration, touches, releases, distance, HSR, touches, releases, Distance, HSR	Field Training
Filter	2020	Soccer	IMU	Locomotor	Kinematic GCT, EMG activity	Field Test
Green	2022	Soccer	GPS/GNSS, IMU	Combined	PlayerLoad™ PL-Min	Multiple
Grunbichler	2019	Soccer	GPS/GNSS	Combined	HR, TD, HSR, VHSR, SD, A+D, Equivalent distance	Multiple
Guerrero-Calderón	2020	Soccer	GPS/GNSS	Combined	Velocity, Metabolic Power, Metabolic work MP/Duration	Multiple
Harkness-Armstrong	2023	Soccer	GPS/GNSS	Locomotor	TD, HSR, VHSR, SPR m.min	Game
Kim	2023	Soccer	GPS/GNSS, IMU	Combined	TD, HSR, SD, A+D, HR	Game
Kubayi	2021	Soccer	Video Analysis	Technical	Shots, passes, Aerial, Tackles	Game
Tang-Yun Lo	2019	Soccer	Motion Capture	Combined	Kinematic	Lab Test

Lead Author	Year	Sport	Technology Category	Category of Metrics Used	Metrics Used	Environment Category
Marris	2022	Soccer	IMU	Technical	Touches, Release velocity	Field Training
Martínez-Hernández	2023	Soccer	Video Analysis	Combined	Contextual Info on goals	Game
Mitchell	2024	Soccer	IMU	Mechanical	Player Load Instantaneous	Lab Test
Nedergaard	2014	Soccer	Motion Capture, IMU	Mechanical	Kinematic, GRF,	Lab Test
Oliva-Lozano	2023	Futsal	LPS	Combined	Velocity, Explosive Distance, HID, A+D, Impacts	Game
Pillitteri	2023	Soccer	GPS/GNSS	Combined	Metabolic Power, %MP, Accelerometer metrics, m.min	Multiple
Riboli	2023	Soccer	GPS/GNSS	Locomotor	TD, HSR, VHSR, SPR, A+D	Multiple
Salter	2022	Soccer	IMU	Combined	Leg stiffness, RPE, GCT, Stride length	Field Training
Serpiello	2018	Non	Motion Capture, LPS	Combined	Sport specific task	Field Test
Szigeti	2023	Soccer	IMU	Combined	Football Movement Profile. PlayerLoad™	Multiple
Uysal	2023	Non	Other	COD	Change of direction speed	Field Test
Wilmes	2023	Field Hockey	IMU GPS/GNSS	Combined	Hip Load (metrics from accelerometer reprocessed).	Field Test

Lead Author	Year	Sport	Technology Category	Category of Metrics Used	Metrics Used	Environment Category
Yang	2018	Soccer	Video Analysis	Combined	Velocity, Technical descriptors	Game
Zago	2019	Soccer	Motion Capture, IMU	COD	Mechanical Work, Turn Speed	Lab Test
Murtagh	2019	Soccer	Video Analysis	Combined	Notational of accelerations, leading acceleration, sprint, jump	Game
Morgan	2022	Soccer	Video Analysis	COD	Notational info for COD in game	Game
Loturco	2022	Soccer, Handball, Rugby, Futsal	Other	COD	Speed	Field Test
Gualtieri	2020	Soccer	GPS/GNSS, Video Analysis	Combined	TD, HSR, VHSR, RPE	Multiple
Bradely	2016	Soccer	Video Analysis	Locomotor	Velocity Metrics THSR, TSD, HSR	Games
Ade	2016	Soccer	Video Analysis	Combined	Velocity Metrics, Passing, Average Position	Games
Romero-Moraleda	2021	Soccer	GPS/GNSS	Combined	TD, m.min, HSRD, AC, DC, Body Load, RPE	Multiple
Waldron	2021	Soccer	IMU, GPS/GNSS	Combined	Velocity	Field Test

Figure 4-3 Identified technologies

Figure 4-3 shows the frequency that each technology was identified in the systematic review. For studies that used two types of technology, these are both carried forward in the results.

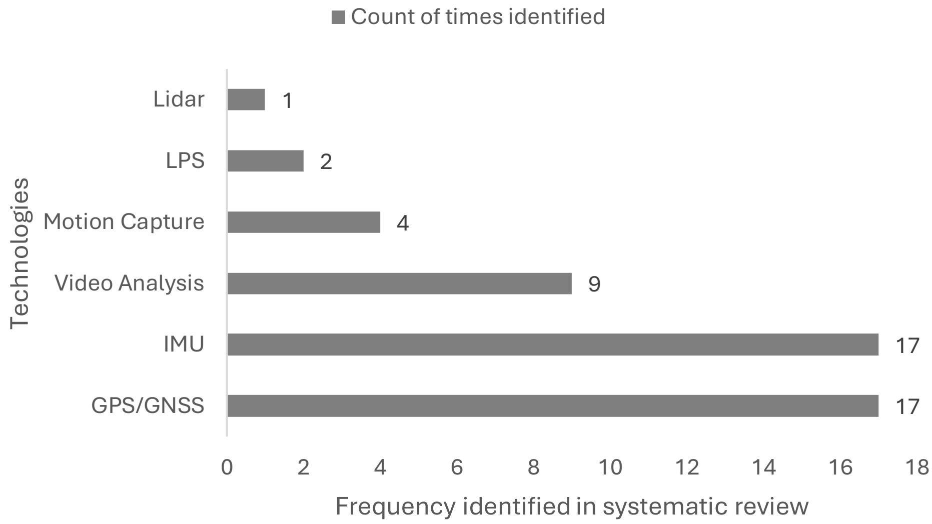


Figure 4-4 Identified environments

Figure 4-4 shows the number of times each environment was identified in the systematic review. For studies that used two types of environment, these are both carried forward in the results.

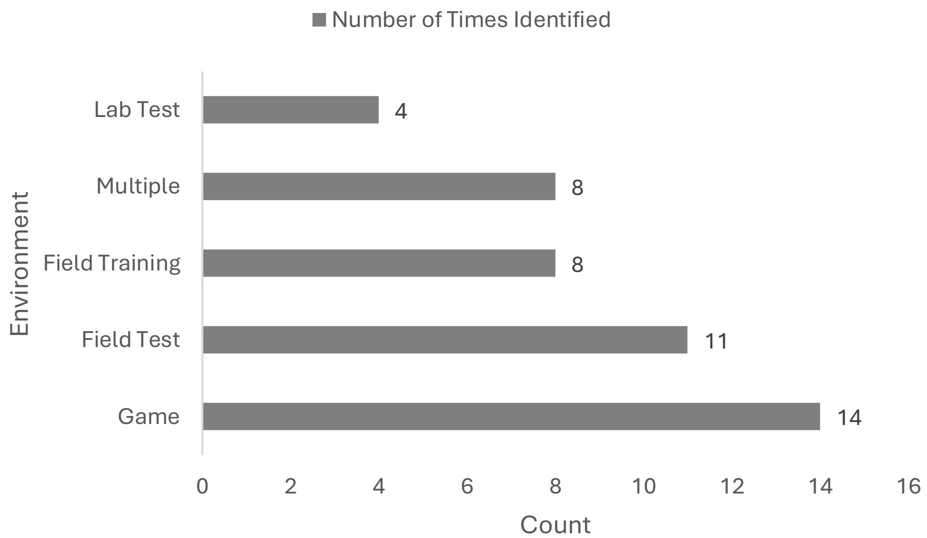
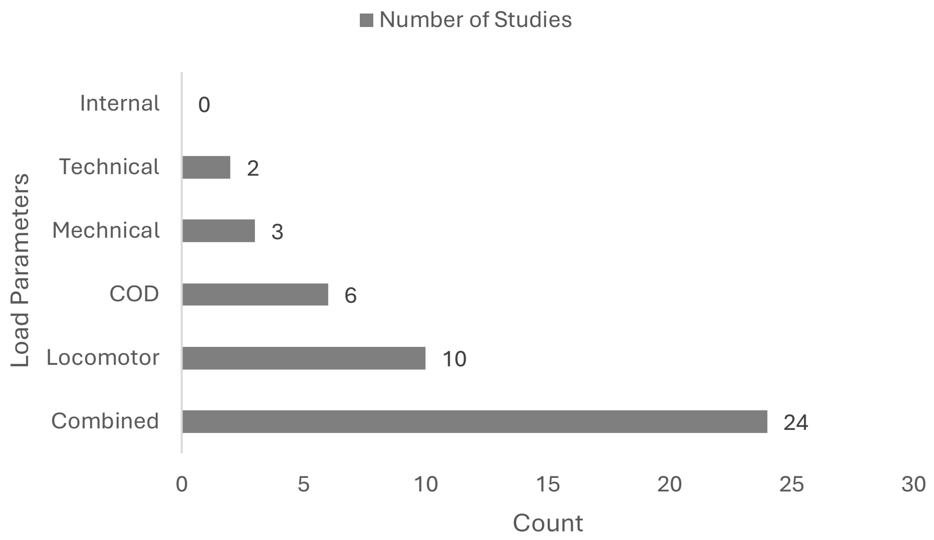


Figure 4-5 Parameters of loading

Figure 4-5 shows the number of approaches (parameters of loading) identified in the systematic review. The approaches are categorized by the parameters they have attempted to profile.



Systematic Patent Search

To uncover innovative technologies that could potentially be incorporated in the professional practise environment, reviewers conducted a patent search for international patents in relevant areas. This novel approach was refined by extensive pilot work, however it follows a systematic format like the PRISMA guidelines that support the search for approaches to monitoring identified in the literature search. Pilot research uncovered Google Patent Search (Google, Redmond, Washington, USA) which provides a search engine like Google Scholar readers may be comfortable with navigating. The search was not limited to searching known existing technologies as the aims of the review are to uncover potential novel approaches or innovative technologies.

Extensive pilot research experimented with Boolean apparatus using search terms associated with the sport (football, association football, soccer) but yielded hundreds of thousands of results pages. It became evident through some of the platforms help functions that searching for a patents function opposed to it key words could refine results yielding more appropriate matches (monitoring in sport, assessment of load). Due to current saturation of available technologies such as those evidenced in the literature search (GPS, IMU, LiDAR, LPS etc) for assessing movement demands it was important to focus on identifying new technologies reviewers implemented the following exclusion criteria:

1. Status: The patent must be an established patent. Not a grant or patent application or in filing phases.

2. Patent Office: Patent must be “International Patents” with no exclusions to specific territories.

3. Language: Patent grant and supporting materials must be available in English to determine suitability.

4. Patent must be granted within last 5 years from 01-01-2019 to 31-04-24.

Patent search terms

Table 4-6 Patent search terms

Google Patent Search
https://patents.google.com/?q=Monitoring+OR+assessment+OR+quantify+&q=Load+OR+movement+OR+performance&q=Sport+OR+athlete+OR+soccer+OR+football+&q=A63B24%2f0062&q=A61B5%2f11&q=G06V40%2f23&before=publication:20240508&after=publication:20190101&status=GRANT&language=ENGLISH&type=PATENT

Inclusion Criteria

The systematic patent search initially yielded over a hundred thousand results. After applying the exclusion criteria, 42,671 patents remained. To further refine these results, classification codes, which are assigned during the patent grant process, were employed. These codes helped to exclude patents that did not align with the functional requirements of a product intended for use in the applied practice environment.

Critical inclusion criterion was applied to assess whether the technologies identified were deemed appropriate for future investigation in real-world sports settings. This criterion evaluated the overall suitability of the technology based on its potential for integration into applied sports science, considering factors such as technological feasibility, practical application, and relevance to football performance. Specifically, patents were assessed for:

- **Technological Compatibility**: Whether the technology could be effectively integrated into existing sports monitoring systems without extensive modification to systems or infrastructure.
- **Practical Utility**: The degree to which the technology could be applied in training, rehabilitation, and performance contexts. The devices must be easily worn during training sessions.

- **Relevance to Football**: Technologies were prioritized based on their potential to address key movements and metrics specific to football, such locomotion and technical skill execution.
- **Scalability**: The ability to implement the technology across varying environments, team training rehabilitation etc.

This criterion was essential to ensure that the search focused on technologies with tangible, real-world potential. This process was discussed by the MDT an approved on the basis that it would involve minimal disruption to the existing workflow and professional practise. By filtering for technologies that could be practically applied in a football environment, this approach ensured that only the most relevant innovations were considered for further investigation. The process for refining patents through classification codes and applying Inclusion Criterion 6 is detailed in Table 4-7 and exemplified in Figure 4-6.

Table 4-7 Patent classification codes

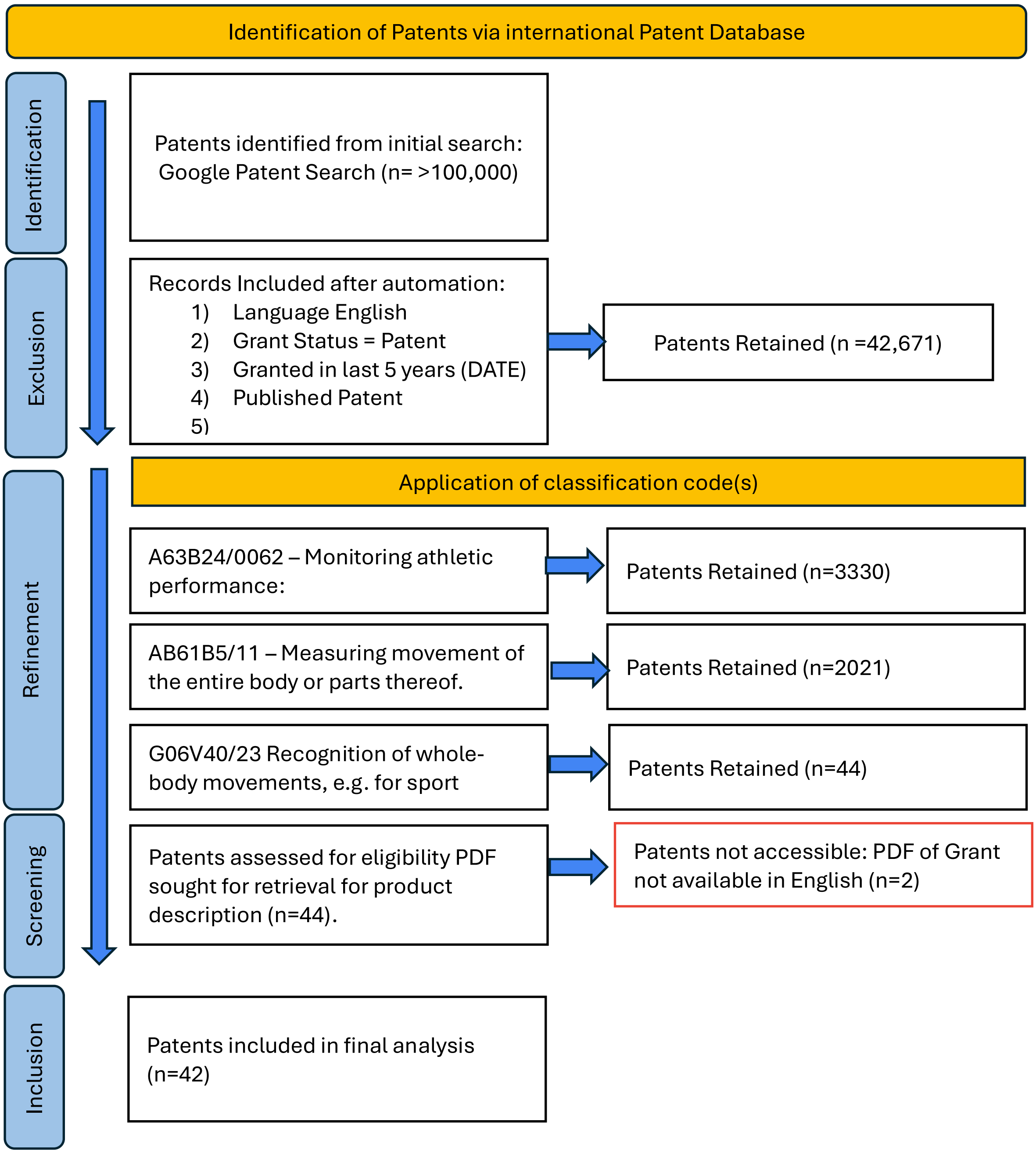
Table with details for the classification codes and corresponding function used to refine results.

Patent Classification Code	Function
A63B24/0062	Monitoring athletic performances, e.g. for determining the work of a user on an exercise apparatus, the completed jogging or cycling distance)
A61B5/11	Measuring movement of the entire body or parts thereof, e.g. head or hand tremor, mobility of a limb
G06V40/23	Recognition of whole-body movements, e.g. for sport training

Patent search flow

Figure 4-6 Patent search flow

Patent search flow using similar approach to PRISMA guidelines.



Patent Search Results

The patent search conducted between 1st March 2024 through to the 31st of April 2024 and initially returned >100,000 results. After application of the initial exclusion criteria 42,671 patents remained. Application of classification codes (

Inclusion Criteria

The systematic patent search initially yielded over a hundred thousand results. After applying the exclusion criteria, 42,671 patents remained. To further refine these results, classification codes, which are assigned during the patent grant process, were employed. These codes helped to exclude patents that did not align with the functional requirements of a product intended for use in the applied practice environment.

Critical inclusion criterion was applied to assess whether the technologies identified were deemed appropriate for future investigation in real-world sports settings. This criterion evaluated the overall suitability of the technology based on its potential for integration into applied sports science, considering factors such as technological feasibility, practical application, and relevance to football performance. Specifically, patents were assessed for:

- **Technological Compatibility**: Whether the technology could be effectively integrated into existing sports monitoring systems without extensive modification to systems or infrastructure.
- **Practical Utility**: The degree to which the technology could be applied in training, rehabilitation, and performance contexts. The devices must be easily worn during training sessions.
- **Relevance to Football**: Technologies were prioritized based on their potential to address key movements and metrics specific to football, such locomotion and technical skill execution.
- **Scalability**: The ability to implement the technology across varying environments, team training rehabilitation etc.

This criterion was essential to ensure that the search focused on technologies with tangible, real-world potential. This process was discussed by the MDT an approved on the basis that it would involve minimal disruption to the existing workflow and professional practise. By filtering for technologies that could be practically applied in a football environment, this approach ensured that only the most relevant innovations were considered for further investigation. The process for refining patents through classification codes and applying Inclusion Criterion 6 is detailed in Table 4-7 and exemplified in Figure 4-6.

Table 4-7) refined the search to retain 3330, 2021 and 44 patents respectively. Of the 44 remaining patents, two were not accessible. Of the remining 42 patents retrieved it is important to know if these technologies could be potentially used in the applied environment to capture the aspects of loading important to the applied environment. This required the technology to be scalable and not require extensive infrastructure to implement i.e. revision of training ground infrastructure, stadium video or camera equipment. The technology must also be made into a commercially available product and not a service. This would facilitate the incorporation of the technology into existing monitoring strategies without requiring specialist expertise required to perform the analysis of the dataset.

Of the 42 identified patents, further review excluded 35 due to their lack of suitability to the research aims leaving seven patents to process for data extraction. Data extraction considered the following variables to establish some continuity with the literature search methodology 1) patent holder, 2) the type of technology 3) types of data or output metrics from the device 4) environment (test environment or patent directed environment) 5) whether a commercially available product could be found through further searches and 6) if the overall technology was deemed an appropriate for future investigation for use in the applied environment (Table 4-8). Although there are some promising advancements with products to assess a combination of load monitoring factors in multiple environments, they cannot be considered viable solutions in context of the applied setting. Either the technology doesn't exist as a product (n=5) or if it does exist it has to be excluded as it is not a scalable solution for use in the environment i.e. smart phone application for use with a single user or the product is a service offered by a company.

Table 4-8 Patent results

An overview of all patents returned that fit the eligible criteria from the technology search and the specific categories of their eligibility.

Patent Holder	Technology Type	Data Output/Metrics	Category of Metrics	Environment	Found Product available	Applied Team Solution?
Bodbox Inc	Smart Phone App	Coaching Cue/Programmes	Mechanical	Field-test	Y	N
Nike Inc	Wearable Sensor (body suit)	Body positional data	Combined	Field-test	N	N
New Balance Athletics Inc	Insole load Sensor	Kinematic parameters of movement	Combined	Multiple	N	N
Nike Inc	Wearable sensor (shoe)	Kinematic parameters of movement	Combined	Multiple	N	N
Russell Brands Inc	Wearable sensor	Categorised motion of basketball handling during specific test	Technical	Field-test	N	N
Asia Air Survey Co Ltd	Wearable sensor (wrist)	Geo positional data and internal response (heart rate)	Combined	Multiple	N	N
Recruiting Analytics	Video Analysis	Computer platform for analysis and processing video generated sport specific data events	Combined	Games	Y	N

Results synthesis

The results synthesis aims to bring together the results of both the systematic literature review and the technology review providing a further exploration into potential solutions. As the search was relatively extensive with two main components trying to identify approaches within the literature and new technologies it is important to focus on the findings that will formulate the key discussion points. Firstly, reviewing approaches to load monitoring that quantified multiple facets of loading identified 20 articles (Table 4-9), these articles used a combination of load measures combined measures of in a field test, training or game environment. Secondly, although several thousand patents were identified, the technology search did not identify any viable new technologies as commercially available products that could be used in the assessment of field-based load monitoring.

Table 4-9 Literature search refined

An overview of papers that utilised wearable technology to produce combined measures of loading in real world environments.

Lead Author	Year	Sport	Technology Category	Category of Metrics Used	Environment Category
Barreira P	2017	Soccer	IMU	Mechanical	Field Test
Beato M	2018	Soccer	GPS/GNSS	Locomotor, Mechanical	Field Training
Buchheit	2015	Soccer	IMU	Locomotor	Field Training
Buchheit	2014	Soccer	IMU	Locomotor, Mechanical	Field Test
Dalen	2018	Soccer	IMU	Locomotor, Internal, Mechanical,	Field Test
Darbellay	2020	Soccer	GPS/GNSS	Locomotor, Mechanical	Field Training
Dos'Santos	2022	Soccer	Lidar	Locomotor, COD	Game
Emmonds	2022	Soccer	IMU	Technical, Locomotor	Field Training
Green	2022	Soccer	GPS/GNSS, IMU	Locomotor, Mechanical	Game & Field Training
Grunbichler	2019	Soccer	GPS/GNSS	Locomotor, Internal	Game & Field Training
Guerrero-Calderón	2020	Soccer	GPS/GNSS	Locomotor, Mechanical	Game & Field Training
Kim	2023	Soccer	GPS/GNSS, IMU	Locomotor, Internal	Game
Oliva-Lozano	2023	Futsal	LPS	Locomotor, Mechanical	Game
Pillitteri	2023	Soccer	GPS/GNSS	Locomotor, COD, Mechanical	Game & Field Training

Lead Author	Year	Sport	Technology Category	Category of Metrics Used	Environment Category
Salter	2022	Soccer	IMU	Mechanical, Locomotor,	Field Training
Serpiello	2018	Non	Motion Capture, LPS	Locomotor, COD	Field Test
Szigeti	2023	Soccer	IMU	Mechanical, Locomotor	Game & Field Training
Wilmes	2023	Field Hockey	IMU GNSS	Mechanical, Locomotor	Field Test
Gualtieri	2020	Soccer	GPS/GNSS, Video Analysis	Locomotor, Internal	Game & Field Training
Romero-Moraleda	2021	Soccer	GPS/GNSS	Locomotor, Mechanical, Internal	Game & Field Training
Waldron	2021	Soccer	IMU, GPS/GNSS	Locomotor, Mechanical	Field Test

Discussion

This is the first study to our knowledge to identify both approaches within the literature and potential technologies that could be used to quantify combined dimensions of loading (locomotor, technical, mechanical) in a field-based environment. Whilst the search strategy uncovered promising approaches within the literature to training load monitoring that could be used to enhance currents practices, no patents were identified that linked to commercially available products that could be used within the applied practice environment. The systematic review of the literature revealed several methodologies used to quantify various aspects of loading. Whilst it is theorised that, in running based sports like football, variations in mechanical and locomotor loads are generally experienced together (Vanrenterghem et al., 2017; Verheul et al., 2020) none of the identified approaches have separated the various aspects of loading into separate categories.

When considering the potential utility of identified approaches, it was important they did not rely on methodologies such as video, motion capture or notational analysis as these could not be successfully implemented in the professional practise environment and so approaches using these methodologies were removed. As per the aims of this investigation this study, approaches to load monitoring and technologies were identified that can be practically implemented and cover combined factors of loading in the applied environment.

Of the original 45 articles identified, 20 approaches used combined measures of in a field test, training or game environment. The results show 11 of the 20 articles included in the results synthesis (Table 4-9) use GPS/GNSS to quantify loading. GPS/GNSS units are traditionally used to quantify locomotor metrics across a range of speed thresholds from walking to sprinting (Di Salvo et al., 2009b), and have provided foundational insights into players movement demands during training and competition (Beato et al., 2018; Darbellay et al., 2020).

However, the evolution of load monitoring now increasingly emphasises mechanical and technical components which introduce a multidimensional understanding of players movement demands (Vanrenterghem et al., 2017). Although GPS/GNSS units are predominantly used in the quantification of locomotor load our review highlights the use of these devices in profiling other facets of loading by using the imbedded inertial measurement units (IMUs) and accelerometers within these devices.

Mechanical load monitoring in the identified approaches is largely facilitated by Inertial Measurement Units (IMUs). The units quantify the multidimensional stresses of high intensity actions like braking, accelerations and changes of direction through calculating the magnitude of g forces placed on the devices worn during training (Tang et al., 2018).

Barreira et al. (2017) highlight how IMUs can capture the eccentric demands of quick directional shifts and braking actions, which are crucial for assessing player load in dynamic sports. Salter et al. (2023) similarly demonstrate IMUs monitoring of impact forces, giving insight into the biomechanical stresses unique to football specific actions. These measurements align with the need to quantify both the intensity and frequency of physical stresses, offering a more comprehensive picture of mechanical demands that can inform training load prescription.

Beyond physical movement, technical load quantification adds another layer by tracking the frequency and context of specific actions integral to soccer performance, like technical skill execution and ball striking actions. Emmonds et al. (2023) show that combining IMU data with technical metrics provides another layer of information demonstrating how technical actions contributes to player loading.

Further exploration of the results identified three articles of interest. Research by Emmonds et al. (2023), Salter et al. (2023), Waldron et al. (2021) all used the same foot mounted inertial measurement units (F-IMUs). Furthermore, we found that these F-IMUs had been used in field training environments covering combined factors of loading (locomotor, mechanical and technical) pertinent to the research aims Although no single study was found that quantified the three areas, we are interested in the technology was used across three studies in field training environment covering locomotor, mechanical & technical aspects of loading respectively.

The main significant finding of this review is the potential of foot mounted inertial sensors to monitor multiple aspects of loading. This could represent a significant advancement in training load monitoring processes by quantifying elements of loading that are currently not incorporated within my organisation's dataset. From a theoretical perspective, this technology addresses a key challenge in load monitoring by capturing a combination of parameters that are not yet been systematically incorporated into the organisations monitoring and reporting methods. Despite this exciting potential it is important to remain cautious as the effectiveness of this approach is limited to three studies. This finding suggests further research and development maybe required before the technology can be implemented as a completed monitoring solution.

To effectively integrate new load monitoring approaches, it is essential to carefully plan how data will be collected, analysed, and interpreted, ensuring it aligns with the existing practices and needs of the applied environment. Introducing new technology into the environment brings several practical challenges, including the need for staff training, adjusting existing workflows, and ensuring athlete compliance to using the next technology. Practitioners must be trained not only to use the devices to quantify the targeted parameters of load but also to interpret the data correctly and provide feedback to various stakeholders. When making changing to any process in the applied environment particularly implementing new technology requires careful planning to educate both players and members of the Multi-Disciplinary Team (MDT) on their proposed benefits.

Limitations

The specificity of the inclusion criteria of both literature and technologies was necessary to meet the specific aims and objectives of this study which dictates a niche application of findings to the specific applied environment. As previously stated in Professional Pause 1, the evolving nature of load monitoring and technology could justify an entire thesis, and we acknowledge that our limited resources constrained the potential depth of this investigation. The patent search for identifying technologies was conducted without the involvement of a specialist in intellectual property and patents which may have limited the scope of the results identified. Engaging a specialist with more experience in patent analysis could have uncovered additional relevant technologies.

Conclusions

Through a systematic review of the literature and a novel approach involving patent searches, we have identified a potential solution that can be implemented to advance load monitoring strategies. The use of foot mounted inertial sensors offers a promising method for capturing a broader spectrum of training load parameters, which could significantly improve training load prescription and contribute to injury prevention. However, further investigation is needed to validate the integration of this technology across multiple components of load and to explore its long-term efficacy in my professional practise environment. Overall, this research lays the groundwork for more comprehensive and effective load monitoring practices, with the potential to enhance both performance and health of professional players.

Reflective Pause 1

The systematic search was a significant step to providing actionable insight to approaches that could be utilised to advance the load monitoring processes within the organisation.

Integration of research within the organisation

Main findings of the review were the identification of foot mounted IMUs that could provide a potential advancement to load monitoring processes within the organisation. The foot mounted IMUs are provided by a commercial company “PlayerMaker”. Given that PlayerMaker are a commercial company and so on the radar of some stakeholders who have prior knowledge of the technology but had not recognised the scope of its potential application. The systematic review was well received within the organisation and was described as providing a level of “kudos” not currently associated with changing processes or integrating new technology.

Discussing potential use cases with stakeholders focused around testing the technology either within the rehabilitation environment or with a group of the academies U23 players. This was to establish analysis and feedback strategies before any change of process with the first team players. Conversations factored around the potential benefits of the technology but raised questions on exactly how data would be generated (variables/metrics) and how it would be interpreted and feedback to relevant stakeholders the need to establish clear guidelines for the practical use of the devices during training. Further exploration of PlayerMaker technology highlighted at the time of writing that the devices has not yet been approved for use in competitive matches in all competitions by all governing bodies the regulate the various competitions (International Federation of Association Football - FIFA, Union of European Football Associations - UEFA, The Football Association, The Premier League).

Reflection

In contrast to the proposed decision-making process described by Windt et al. (2020) in Professional Pause 2, technologies are often implemented within organisations without due diligence or critical process and are doomed to gather dust. This is largely due to the fact as no one has considered if we should integrate the technology or whether the cost benefit to staff time, specialist skills or expertise required to analyse the data and report effectively can be implemented.

A relevant analogy is to think of incorporating a new process or technology to buying a car, there are multiple ways owning a car can improve the day to day lives of the owner but buying one without a license to drive it or resource to keep it on the road renders it practically useless. To that end, the performance and medical departments showed an appreciation for the process of systematic and critical analysis that ultimately uncovered a use for a technology currently being implemented in a limited capacity.

This process of review has developed my skill set significantly. Creative thinking around identifying technologies and developing a patent search has demonstrated how the doctorate facilitates a journey of development. I have often been reminded that to be successful as an applied practitioner I need to be able to operationalise tasks with short notice or with limited resources. This usually manifests itself in impulsive decision making where I have been guilty of providing a solution or acting before stopping to consider potential factors that may improve potential outcomes. This has been described to me as “an exercises in thinking” and is something I am consciously aware of refining throughout the doctoral journey.

Within the elite environment pressure to gain a competitive edge through innovation is driven by the need to appear at the cutting edge of performance. I have seen both my current and previous organisations adopt technology with the hope that it will improve performance of players or practise of staff in the environment. Kane et al. (2019) describe the pressure to innovate as a common theme in driving the rapid adoption of technology in both sport and business. Discussing the fear of missing out (FOMO) on gaining a competitive without critical evaluation or a deep understanding of how technologies can be integrates with existing processes can lead organisations to fail in maximising the potential benefits of technologies and lead to misaligned expectations on return on investment (Schein, 2010; Mari et al., 2024).

When starting my journey as an applied practitioner I made the mistake of lobbying for the club to invest in GPS technology without first establishing how the technology would be used, who would be responsible for the practical aspects of ensuring player wore the devices, or how feedback could impact on our processes. Conducting this review, I became acutely aware of my role in driving innovation and the responsibility to make sure I did not make the same mistakes again.

In summary, without a clear strategy for implementation of identified technologies or processes, resources to utilise the technology (trained staff), and an understanding of the theoretical and practical constraints, the organisation may adopt new tools or processes ultimately failing to provide the anticipated value. I therefore feel satisfied that the review has identified an approach to quantify multiple facets of loading, however, recognise the end for further exploration of the technology before committing its use to the applied environment.

Professional Pause 3

Introduction

Sections of this thesis that are focussed on the consideration of load evaluation has stressed the importance of quantifying the wide spectrum of stresses that contribute to the overall load experienced by athletes. Whilst I recognise the suggestion of distilling loading into three components (locomotor, mechanical & technical) could be argued to be overly simplistic, I feel that moving away from multiple training load variables in favour of a broader approach which encompasses the three main aspect of load can provide a more comprehensive view than currently exists.

Problem identification

Through the systematic review of literature and technology we Identified the potential use of foot mounted inertial sensors (F-IMU) player maker to cover multiple facets of loading. To do this I needed to develop a novel approach to understanding the measurement of multiple aspects of load.

Organisational collaboration

It is important to note that conversations with stakeholders within the organisation raised some fundamental questions that I needed to address prior to the conception of the approach. Designing a potential use case and understanding, what the technology would give us in terms of return on investment were important factors to consider. Discussion around this investigation led to the agreement that we would utilise foot mounted inertial sensors to monitor players during the rehabilitation process. Its common place for teams to use this rehabilitation environment to test things out particularly in the interests of understanding compensations or movement asymmetries post injury. It also afforded the opportunity to work with a smaller sample that makes both the practical application and data handling easier. Furthermore, the rehabilitation process provides a progressive situation of activity to and opportunity to assess all relevant components through locomotor, mechanical and technical variations in a controlled way. This did not require a change of practise that would have been necessary to test the team's training environment. Asking players to wear the devices in training would require extensive background work and negotiation whereas it was commonplace for players to be more extensively tested and profiled in rehabilitation to guide their return to play.

Further collaboration and conversation with PlayerMaker opened the possibility of a research and development opportunity with the company keen to explore the potential of the approach. To facilitate a deeper investigation into loading we were given access to raw data and metrics not current available to commercial users. This agreement allowed us to be more prescriptive around the inclusion and exclusion of various metrics. This is important to articulate as it provides some context around the formulation of composite metrics used in the analysis.

Iterative cycles

To begin to identify where types of loads maybe evidenced and quantified it is important to articulate where various components of loading are experienced as part of the movement demand of the sport. Our starting point for assessing sporting demands was to determine the movements or 'types' of movements that maybe of significance to loading. Locomotor activities are currently defined by duration or distance in set speed thresholds which has been derived as a function of a metabolic energy system (Bradley et al., 2013).

This was created at a time when sport scientists were concerned with investigating load to establish the energetic cost and metabolic pathways that contribute to performance. Our understanding of the demands of professional football has moved forward with comprehensive investigations into the demands of the game highlighting the complex multi factorial nature of sport specific actions.

Key frameworks and models have shone light on the need to improved understanding of the mechanical components of football training, particularly around establishing valid and reliable field-based measures of mechanical stresses (Vanrenterghem et al., 2017; Kalkhoven et al., 2021; Impellizzeri et al., 2023).

Several approaches have been made to quantify some of these facets and have been highlighted in the literature review sections of this thesis. Investigations into proposed monitoring strategies and research have led us to a point where companies, researchers and practitioners are attempting to quantify loads through change of direction (Dos' Santos et al., 2017; Dos' Santos et al., 2018) and technical loading as a means of addressing some of these mechanical components of load (Verheul et al., 2020; Morgan et al., 2022b). Using the theoretical framework developed as part of the literature review (Figure 3-1) as a starting point we began pilot work to establish the most effective means of capturing the varying facets of load we are interested in.

CHAPTER 5

A NOVEL APPROACH TO LOAD MONITORING IN ELITE PROFESSIONAL FOOTBALL

Introduction

Association football is an intermittent team sport where the modern player will cover between 10-13km during a 90-minute match. Due to the relatively extensive duration and high intensity intermittent nature of match play soccer is primarily regarded as an aerobic sport. However, match-play is perpetuated with fluctuations between high and low intensity activities (Bangsbo, 1994; Reilly, 2005; Bangsbo et al., 2006a; Drust et al., 2007).

Elite players require well-developed cardiovascular, aerobic energy, neuromuscular and musculoskeletal systems to perform repeated high intensity running efforts, changes of direction and execution of sport specific actions which are integral to soccer performance (Akenhead et al., 2016; Rahnama et al., 2003; Buchheit et al., 2010b; Buchheit et al., 2010a; Buchheit et al., 2015). The somewhat unpredictable actions and the interlinking metabolic and mechanical demands of sporting actions such as running, change of direction and technical skill execution contribute to complex internal physical/physiological responses.

Load monitoring is a critical component of managing the training and performance of elite professional football players (Nedelec et al., 2012; Nedelec et al., 2014). Accurately assessing the stress and strains placed on players during training and competition is essential in optimising performance, reducing the risk of injury, and ensuring long term player health (Kalkhoven et al., 2021; Impellizzeri et al., 2022). Traditionally, training load has been quantified primarily through objective measures, such as heart rate (internal; Impellizzeri et al. (2005) and distance covered in various speed and acceleration thresholds (external; Impellizzeri et al. (2005)). These metrics provide insights into the physical load of a player; however, they fail to account for the intricate interplay between the body's internal responses and the external load placed upon the body (Vanrenterghem et al., 2017).

Whilst existing measures of training load have been extensively investigated (Akenhead and Nassis, 2016), there is a growing recognition that they may fall short in providing a comprehensive account of the complex physiological responses experienced by players (Impellizzeri et al., 2019a).

Moreover, current approaches tend to overlook several aspects of 'load'. One of these is technical loading which encompass motor skills and tactical decision required to execute technical skills effectively within football (Marris et al., 2022; Lewis et al., 2022). The technical load performed by players during training sessions and matches may influence physiological response, leading to variations in energy expenditure, muscle activation, mechanical demand with serious implications for injury (Ekstrand et al., 2011; Mendiguchia et al., 2013).

A major challenge exists in the usefulness load monitoring parameters to inform practises. Many existing metrics are perceived by coaches as overly complex and by support staff as having limited practical utility in injury prevention and performance improvement (Akenhead and Nassis, 2016). Thus, there is a clear need for an intuitive system that provides actionable insights without overwhelming practitioners with data. The proposed approach aims to address this by using composite metrics that integrate locomotor, mechanical, and technical loads into a simplified framework, offering a holistic yet accessible view of the training demands.

In pursuit of a more comprehensive understanding of the physiological and physical stresses faced by elite footballers we propose to measure a range of loads that are placed on players. Whilst appreciating the highly complex and often unique nature off the stresses and strains players experience, we propose to differentiate load into mechanical, locomotor, and technical components. Instead of generating more variables in an already saturated field our aim is to combine 'like' parameters that may provide higher level descriptors that make interpretation of training data easier, resulting in better coverage of the load placed on athletes, in an easier way to understand it.

Our study aimed to provide some objective information on the progression of intensity and volume through the rehabilitation process. We believe the implementation of composite metrics will provide a comprehensive overview of the demands of various stages of the rehabilitation process. By profiling these three distinct facets of loading, we can offer practitioners more useful and actionable information to guide their decisions on training and recovery strategies. Ultimately, this novel approach has the potential to significantly enhance the training process by providing potential strategies to improve training load monitoring through more complete and easily interpretable picture of the demands placed on elite professional footballers.

Aim: Test the face validity of a novel approach to quantifying multidimensional loading within elite professional footballers.

How?

1. Examine the use of F-IMUs and novel approach of composite metrics in the quantification of football activities in elite professional players.

2. Profile high level footballers during rehabilitation sessions using F-IMUs.

3. Highlight potential strategies for improving training load monitoring & prescription.

<u>Background and pilot study</u>

Prior the initiation of the study and data collection extensive pilot work was conducted to establish how the various components of loading would be categorised and what parameters would be used to quantifying these demands. Due to the already complex nature of training load monitoring and issues with coach buy-in/efficacy of dependant variables to inform performance/injury risk (Akenhead and Nassis, 2016), instead of identifying individual movements we aimed to develop an approach that simplifies the demand of activities. This section provides contextual information around the categorisation and popularisation of the variables used in the novel approach. Whilst trying to operationalise these parameters in a real-world setting, we encountered several obstacles compromising the effectiveness of the framework presented in the conceptual framework (Figure 3-1). Firstly, it became evident that a lot of the movements such as duels, lunge type actions that occur during blocks and tackles as well as discrete technical skill are inherently difficult to define, identify or replicate within datasets. Secondly, it is also possible that these activities happen infrequently and so may not be worth the time investment to identify and monitor. This prompted us to focus efforts on covering some of the more obvious movements that may not be detected within current monitoring strategies but advance our current processes.

Continuing from the themes identified throughout this thesis we categorised loading into three distinct components (locomotor, mechanical and technical). Separating football movements into linear, non-linear and technical components allowed us to potentially link parameters that are alike and separate demands from traditional locomotor/energy system models.

<u>Proposed holistic training load measures</u>

To categorise the three areas of loading, the following three metrics were proposed to give a holistic overview of the training load measures observed in football. The following sections provide context around the categorisation of load and the creation of metrics to capture these demands. Although there was some collaboration between the researchers and technology providers to develop these metrics, decisions on equations and data generation came from the commercial companies' data science department in the 'back end' of the software.

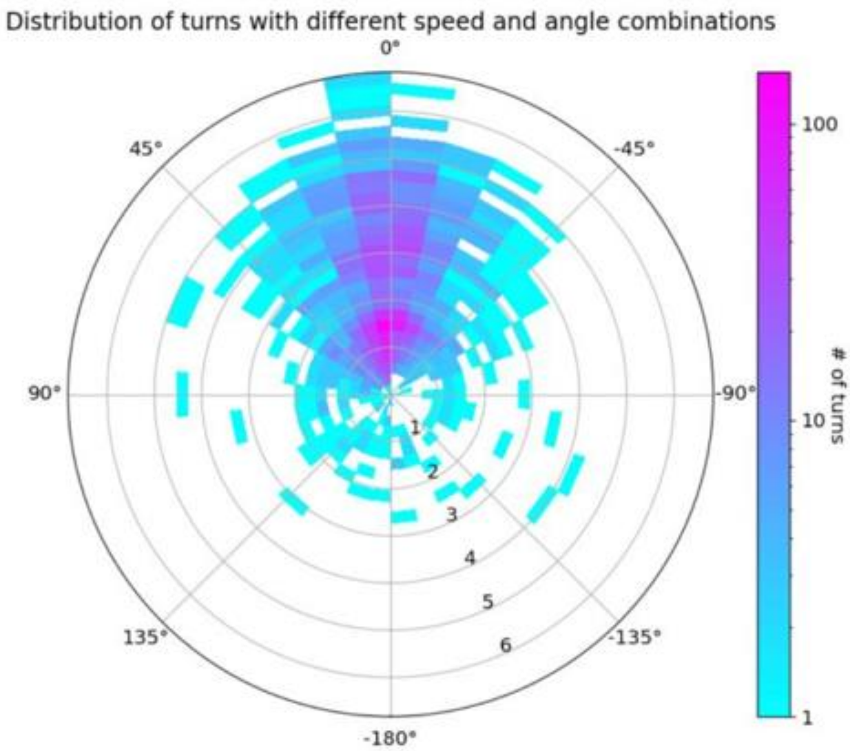
<u>Mechanical loading</u>

Whilst mechanical stresses are experience in a multitude of sport specific movements there is an acceptance that mechanical stresses occur during breaking and propulsive actions (Vanrenterghem et al., 2017). It is generally accepted that change of direction activities contributes to mechanical load through deceleration and acceleration components at varying intensities and are currently overlooked within monitoring approaches (Harper and Kiely, 2018; Harper et al., 2022; Dos'Santos et al., 2022).

To illustrate the background work undertaken in the design of composite metrics we have detailed how the F-IMU devices calculated change of directions (COD), through a proprietary method. The definition of a COD was defined as a sequence of steps that incorporate a turn as defined by the companies' gait classifier (Waldron et al., 2021). Once a COD is classified, the steps that are performed prior to and after the COD are reported to gain insights into the entry and exit speeds. The graphic is included to provide a reference for the detailed work undertaken and underpinning methodological process of creating the composite metrics used in the investigation. An example of this can be shown within Figure 5-1.

Figure 5-1 Change of direction

Graphic representation of change of direction, with the colours demonstrating where COD and pivot movements frequently occur.



The example shows a concentration of changes of direction within a 30-degree angle, through stakeholder conversations these were not thought to represent a mechanical stimulus and so it was decided to define a mechanical loading through the composite turn intensity metric detailed below.

Turn Intensity: The turn intensity was developed to evaluate mechanical demands placed on the players. The turn intensity measure accounts for the angle of the change of direction, the entry speed into the change of direction and the exit speed for the change of direction. For example, the quicker the entry speed, the larger the angle of the change of direction and the quicker the exit speed, the higher the turn intensity value. By analysing the angular velocity data derived from the F-IMU the intensity of rotational movements, such as turns and pivots, can now be classified within a session.

Locomotor loading

Whilst it is important to for this investigation to increase the scope of loading parameters it is important to recognise football is predominantly a running based sport (Bangsbo et al., 2006b; Bangsbo, 1994) and so locomotor activities should be clearly defined. Locomotor loading was categorised and define be the creation of the linear intensity metric below.

Linear Intensity: An accumulation of the movements within a straight-line, that don't exceed an entry or exit angle of 30 degrees. The quicker the entry and exit speed to a linear effort, the higher the linear intensity score. This metric was created to map the locomotor demand imposed on the players during training sessions. By integrating data from the IMU the cumulative acceleration and deceleration forces experienced by the players in a linear direction, were proposed as being categorised by this metric.

Technical loading

During pilot testing we identified that calculating kicking intensity based of mean limb speed multiplied by number of actions proposed by Lewis et al. (2022) and highlighted in (Chapter 3) may bias a large volume of lower velocity technical actions, with higher velocity kicks that occur less frequently but maybe of greater importance being underrepresented. The study used a single number of composite metrics of volume and speed of the kick to create release index (release index= number of kicks*average speed of the kicks), however this weights all technical actions the same. Through discussion we decided to weight higher speed kicks greater than those at a lower speed. This used a similar approach to training Impulse (TRIMP), where exponential weighted models have been proposed to identify total volume of activities (Stagno et al., 2007). Technical load was categorised and captured using the kicking intensity metric detailed below.

Kicking Intensity: An accumulation of all kicks a player performs within a session, with a weighting factor that provides an exponential weighting based upon the limb speed during the kick. For example, the higher the release velocity, the higher the kicking intensity. The kicking intensity metric was devised to capture the technical load experienced by players, (Lewis et al., 2022). By analysing the angular velocity and acceleration data during kicking actions, we evaluated the technical demands imposed on the lower limbs quantifying the velocity at which the foot is moving when contacting the ball.

Test environment

The club has an established approach for guiding the progression of rehabilitation and the categories certain activities will fall into (Figure 5-2). We chose to use this categorisation and long-term rehabilitation sessions as players would be exposed to controlled progressions of training load (Taberner et al., 2021). For example, initial on pitch sessions would focus on straight line running through planned increases in complexity, intensity, and volume prior to reintegration with team training and competition. This provided us with the facility to test the validity of our novel approach against planned increase in ‘load’ as players progressed through the rehabilitation process. It also enabled us to include differential data to help guide rehabilitation. Including newly available technical data to inform decisions around training prescription was particularly insightful during the reintegration process.

Figure 5-2 Rehabilitation phases overview

In line with the clubs’ current practises rehabilitation sessions were categorised as follows for data collection, similar to those outlined in previous return to play literature (Taberner et al., 2019; Taberner et al., 2021).

		Reloading	Return to Football		Return to Performance	
		Initial re-introduction of actions on the grass - Actions perfromed in a controlled and simple manor under no fatigue.	Progression of actions on the grass - New actions introduced in a simple manor under no fatigue - Already perfromed actions integrated into conditioning with increasing specificity - Isolated general conditoning top ups to be utilised whilst specfic load being progressed.		Progression to unrestriced intensity on the grass - Actions introduced in a simple manor under no fatigue and then integrated into position specific drills - Ideally all load/conditioning integrated into position specific drills replicating intense periods of play. This phase includes transition into team training and ends after match play.	
Intensity	Movements	Low 50-60% Max	Mod 60-70%	Moderate 70-80%	High 90-100%	High 100%
	Technical Actions	Low - Volley > Short Pass	Mod - Long Pass > Clip		High - Shot > Cross > Clearance	
Complexity	Simple > Complex	Simple	Complex	Simple > Complex	Complex	
	Closed > Open	Closed	Closed	Open	Open	
Volume	Acute	Low <40% (Game Load)	Mod 50%	Mod 60%	High 70%	High 70%
	Chronic	Low > Mod	Mod > High		High	

Categorising the rehabilitation process provided clearly defined stages with some objective criteria around the progression of football specific activities. This allowed us to test the novel approach’s ability to identify changes/progression in intensity/volume of football specific demands and give us a ‘real world’ practical scenario.

Activities where the prescription is given a percentage would link to an associated speed threshold such 50% of an individual’s peak speed in straight line running activities. Progressions of these activities were controlled by running speed and distance compared to a players pre-established peak values. These were defined as the highest speed a player had reached in either training or match play assessed by GPS (Apex, STATSports, Newry, UK) in training or semi-automated video tracking (Second Spectrum®) during games. Where percentage is prescribed for activities, such as change of direction or technical actions (with no prior means of quantification) these activities players were asked to perform them at a percentage of their perceived intensity. This would be evidenced by increased magnitudes of acceleration/deceleration in intensive actions (Harper et al., 2019) such as pressing and changes of direction. Technical actions were also progressed by a mixture of objective and subjectivity. Short-range passing and low velocity actions were initially prescribed before using perceived intensity to gauge exertion in ball striking actions such as crosses, shots and longer-range passing actions.

Methods

Design

Data were collected from the rehabilitation of five full time professional footballer players who were undergoing long term rehabilitation following injury. To develop our understanding of the progression and variation of demands, on pitch rehabilitation sessions profiled using foot mounted inertial sensors (F-IMU). Due to current practices at the club these methods were employed alongside existing measures to maintain current load monitoring practises alongside another level of detail provided by the F-IMU.

Participants

The present study involved five elite professional football players (mean age 23.4 ± 4.5 years). All players were monitored during their return to play protocols following a period out with injury.

Procedures

Locomotor activities, technical actions and change of direction statistics were quantified using commercially available foot-mounted IMUs (PlayerMaker™, Tel Aviv, Israel). Each F-IMU incorporated two components from the MPU-9150 multi-chip motion tracking module (InvenSense, California, USA), being a 16 g triaxial accelerometer and a 2000°•sec-1 triaxial gyroscope. Housed in manufacturer-supplied tightly fitting silicone straps, each player was equipped with two F-IMUs (one for each foot), which were located at the lateral malleoli over the player's boots. To diminish issues related to inter-unit reliability, players used the same IMUs throughout the data collection period (Buchheit et al., 2014).

Its standard practise for players to prepare for the session by collecting their boots, hydration and individual monitoring devices such as individual GPS units, vest and heart rate monitors from labelled 'pigeonholes' opposite the club's sport science office. Players in rehabilitation collected their F-IMUs along with GPS and heart rate monitor and positioned them under the supervision of the rehabilitation fitness coach prior to taking the field of their session. All devices were activated via a Bluetooth connection to an iPad (Apple Inc, California) prior to each training session. Post session all devices were returned to the 'pigeonholes' to be downloaded and charged.

<u>Analysis</u>

Data was uploaded to the manufacturer's cloud-based software (v.3.22.0.02) post-session by the club practitioners. The start and end of each training session were recorded and tagged prior to data being exported from the manufacturer's cloud-based software into Microsoft Excel and Power Bi 2020 (Microsoft, Redmond, WA, USA).

Results

To evaluate the validity of our measures this study will test the face validly of our novel approach against various components of the rehabilitation process. Firstly, we present a case study assessing the ability to differentiate loading between sessions with differing content prescription. We assessed the face validity of the approach by profiling individual sessions from each phase of the rehabilitation process. The aim of this is to ascertain if the result reflects our intuition on each of the sessions proposed demands. For example, during the "Reloading" phases the session prescribed generally low relative intensity activities such as straight line running at 50-60% of a player's maximal intensity (Figure 5-2). It is therefore intuitive that the approach should predominantly detect locomotor activity with low mechanical load and an absence of technical actions. The examples below are taken from the same individual player across three stages of rehabilitation.

Figure 5-3 Reloading session example

The figure provides an example of a prescribed session for one player during the reloading phase. This is the first session returning to on pitch training.

Session 1		
		Reloading
Decription		Initial re-introduction of actions on the grass - Actions perfromed in a controlled and simple manor under no fatigue.
Intensity	Movements	Low 50-60% Max
	Technical Actions	Low - Volley > Short Pass
Complexity	Simple > Complex	Simple
	Closed > Open	Closed
Volume	Acute	Low <40% (Game Load)
	Chronic	Low > Mod

Overview		Reloading
Details	Player	
	Date	
	Session Type	Return to Run 1
Mechanical Progressions	Movements	SLR
	Technical Actions	NA
Conditoning Focus		NA

Session Plan		Reloading
Phase	Time	
Warm Up		
Mechanical Progressions		Running Intro 15 x 60s Jog (30s Walk Recovery)
Integrated Conditioning		
Isolated Conditioning		

Table 5-1 Reloading phase load indicators

Data from the 3 buckets approach show linear intensity to be the highest indicator of load for the reloading session (Figure 5-3), there is an absence of technical load detected as there was no technical action prescribed for this session.

Load Indicators	Reload
Linear Intensity (au)	114
Non-Linear Intensity (au)	78
Kicking Intensity (au)	0

Figure 5-4 Return to football session example

The figure provides an example of a prescribed session for one player during the return to football phase of rehabilitation. This session includes a progression of mechanical loading through planned changes of direction as well as higher intensity technical actions such as long-range passing.

Session 2		
		Return to Football
Decription		**Progression of actions on the grass - New actions introduced in a simple manor under no fatigue - Already perfromed actions integrated into conditioning with increasing specificity - Isolated general conditoning top ups to be utilised whilst specfic load being progressed.**
Intensity	Movements	Mod 60-70%
	Technical Actions	Mod - Long Pass > Clip
Complexity	Simple > Complex	Complex
	Closed > Open	Closed
Volume	Acute	Mod 50%
	Chronic	Mod > High

Overview		**Return to Football**
Details	**Player**	
	Date	
	Session Type	**Extensive 2**
Mechanical Progressions	**Movements**	Increased Linear Speed
	Technical Actions	Long Passing > Shooting
Conditoning Focus		Speed Endurance 1:2

Session Plan		**Return to Football**
Phase	**Time**	
Warm Up	**10min**	Dynamics + A/D Prep
Mechanical Progressions	**10min**	Passing Drills Low > Med distance pass, Planned Cutting + Decel Patterns, "Agility" + Technical Drill
Integrated Conditioning	**30min**	5 x 3-4min (1:1) - Coach involvement (Planned movements, moderate intensity, short passing)
Isolated Conditioning	**10min**	2x4min 45:15 Runs

Table 5-2 Return to football phase load indicators

The approach shows an increase in volume of loading detected across all three parameters. Load indicators from this session show a progression of volume across all three areas of loading.

Load Indicators	Return to Football
Linear Intensity (au)	968
Non-Linear Intensity (au)	315
Kicking Intensity (au)	1769

Figure 5-5 Return to performance session example

The figure provides an example of a prescribed session for one player during the return to performance phase of rehabilitation. This session prescribed unrestricted intensity and the exposure to player position specific drills which aim to replicate peak periods of match intensity.

Session 1		
		Return to Performance
Decription		**Progression to unrestriced intensity on the grass - Actions introduced in a simple manor under no fatigue and then integrated into position specific drills - Ideally all load/conditioning integrated into position specific drills replicating intense periods of play. This phase includes transition into team training and ends after match play.**
Intensity	Movements	High 90-100%
	Technical Actions	High - Shot > Cross > Clearance
Complexity	Simple > Complex	Complex
	Closed > Open	Open
Volume	Acute	High 70%
	Chronic	High

Overview		**Return to Performance**
Details	**Player**	
	Date	
	Session Type	
Mechanical Progressions	**Movements**	Crossing Shooting
	Technical Actions	
Conditoning Focus		Peak period match intensity actions

Session Plan		**Return to Performance**
Phase	**Time**	
Warm Up	**10**	Dynamics + A/D Prep/HSR
Mechanical Progressions	**15**	Position Specific Technical Actions (Crossing/Shooting)
Integrated Conditioning	**35**	5 x 4minute position specific peak period drills

Table 5-3 Return to performance phase load indicators

The approach shows an increase in volume of load detected across all three parameters.

Load Indicators	Return to Performance
Linear Intensity (au)	1713
Non-Linear Intensity (au)	648
Kicking Intensity (au)	2322

This first section of the results shows an assessment of face validity of the approach. The approach shows an increase in the volume of load during three different sessions taken from a case study of a single players rehabilitation. Where we expect the session to have relatively low mechanical and technical loading during the reloading phase where athletes are working for shorter durations at lower intensities our load indicators match this the loading progressing plan prescribed by the club. Similarly, as the prescription increases in terms of complexity, volume and intensity we again see increases in our load indicators in the return to football and return to performance sessions (Table 5-2 & Table 5-3).

<u>Progression changes in parameters across phases</u>

The second phase of the analysis is to compare the results across the phases of rehabilitation for all players. The purpose of this section is to ascertain if the approach is sensitive to change across the phases of the rehabilitation process. Descriptive statistics including mean, standard deviation and ranges are presented for volume and intensity for linear, non-linear, and kicking intensity values, throughout the rehabilitation phases (Table 5-4 & Table 5-5).

<u>Clarification of terms</u>

In Tables 5-4 and 5-5, the metrics are labelled as "Linear Intensity," "Non-Linear Intensity," and "Kicking Intensity." These terms refer to specific types of loads measured in relation to different movement patterns. The use of the term "Intensity" is intended to represent the magnitude of physiological load associated with each respective movement type. These individual metrics were then summed to calculate the total volume of physical load associated with the respective movement patterns. This approach was used to provide a comprehensive view of the overall workload. For clarity, the summation represents the total load across distinct movement patterns, each with its own intensity characteristics. The use of the term "intensity" relates to the name of the metrics e.g. “linear intensity” that were prescribed during development of the metrics with the third party.

Table 5-4 Mean progression of load (volume)

Mean load during each phase of the rehabilitation process separated by type locomotor, mechanical and technical. This is the mean data from all players.

	Stage 1	Stage 2	Stage 3
Load Indicators	**Reloading**	**Return to Football**	**Return to Performance**
Average Number of Sessions within Stage	10±3	7±2	7±2
Linear Intensity (au)	170±111	743±359	1008±363
Non-Linear Intensity (au)	34±42	316±168	445±172
Kicking Intensity (au)	94±84	1735±593	1917±915

Table 5-5 Mean progression of load (intensity)

Mean load per minute of activity for all players across stages of the rehabilitation process.

	Stage 1	Stage 2	Stage 3
Load Indicators	**Reloading**	**Return to Football**	**Return to Performance**
Average Number of Sessions within Stage	10±3	7±2	7±2
Linear Intensity (au)	5.86±3.83	15.48±7.48	14.82±5.34
Non-Linear Intensity (au)	1.17±1.45	6.58±3.50	6.54±2.53
Kicking Intensity (au)	3.24±2.90	36.15±12.35	28.19±13.46

Reviewing the data from the second phase of our analysis we see clear progression of the volume of loading across the three phases of the rehabilitation process (Table 5-4) with all three load indicators processing across the phases. The largest increase come from players transitioning from Reloading to Return to football linear intensity +573 (au), non-linear intensity +282 (au) and kicking intensity 1641 (au). Compared with Return to football and Return to Performance showing mean increase of linear +265 (au), non-linear +129 (au) and kicking intensity +182 (au) respectively. There are some differences when reviewing intensity (Table 5-5) with an increase in load per minute observed between reloading and return to football.

Application to professional practice

A key objective of this study is to highlight potential strategies for the use of this approach in the real-world setting. Session feedback within the professional practise environment typically takes the form of a summary of the data with key variables graphed to compare between players. Dependant on the type of session data may be linked to compare external loads to match performance data. To demonstrate an example of how our approach may be used we present example feedback from two contrasting rehabilitations (Figure 5-6 & Figure 5-7). These example uses the load indicators for volume from all sessions during the rehabilitation. In the absence of match data for our 3 load indicators we have compared this sessions data to the mean data from all players throughout the full rehabilitation process (Table 5-6). This method of feedback was judged through stakeholder engagement within the organisation. Consulting member of the MDT from both medical and sport science backgrounds we created a graphical representation of the longitudinal progressions of the three loading parameters.

Table 5-6 Classification of load demand

To provide some level context to the data we have categorised each load indicator into an assigned band with each band representing 20% of the group mean for each load indicator Linear intensity 0-1500au, non-linear intensity 0-750(au), kicking intensity 0-3000(au)

	Very Light	Light	Moderate	High	Very High
Percentage of mean +STD %	<20%	21-40%	41-60%	61-80%	>80%
Linear Intensity (au)	<300	301-600	601-900	901-1200	>1201
Non-Linear Intensity (au)	<140	141-280	281-420	421-560	>561
Kick Intensity (au)	<600	600-1200	1201-1800	1801-2400	>2401

Figure 5-6 Player A rehabilitation example

The figure provided a graphic representation of load indicators for linear, non-linear and technical intensity from (Player A) full rehabilitation. The example clearly shows the low volume of load in the three parameters at the start and progression through to high and very high volumes of respective parameters towards the end of the process.

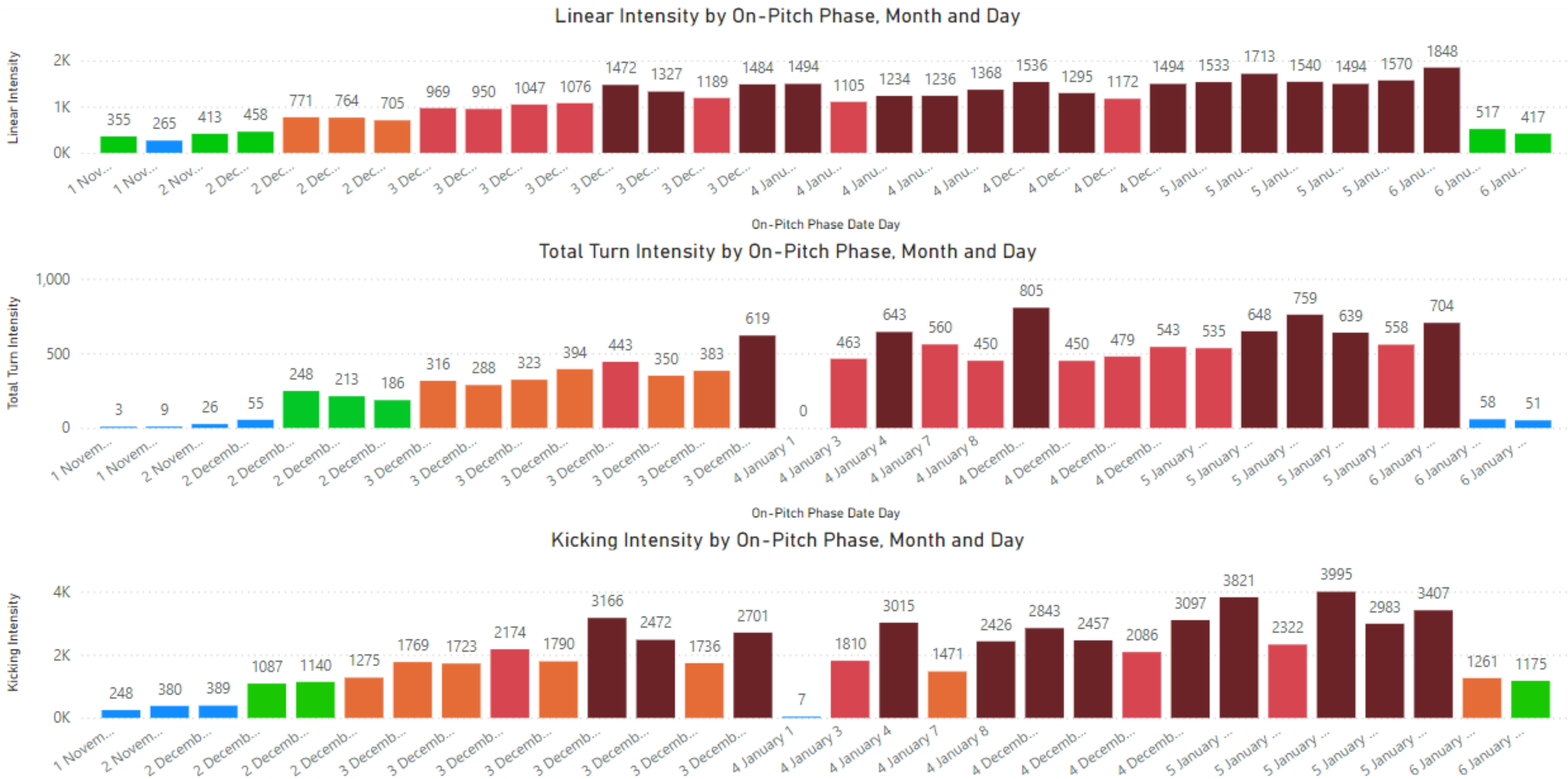
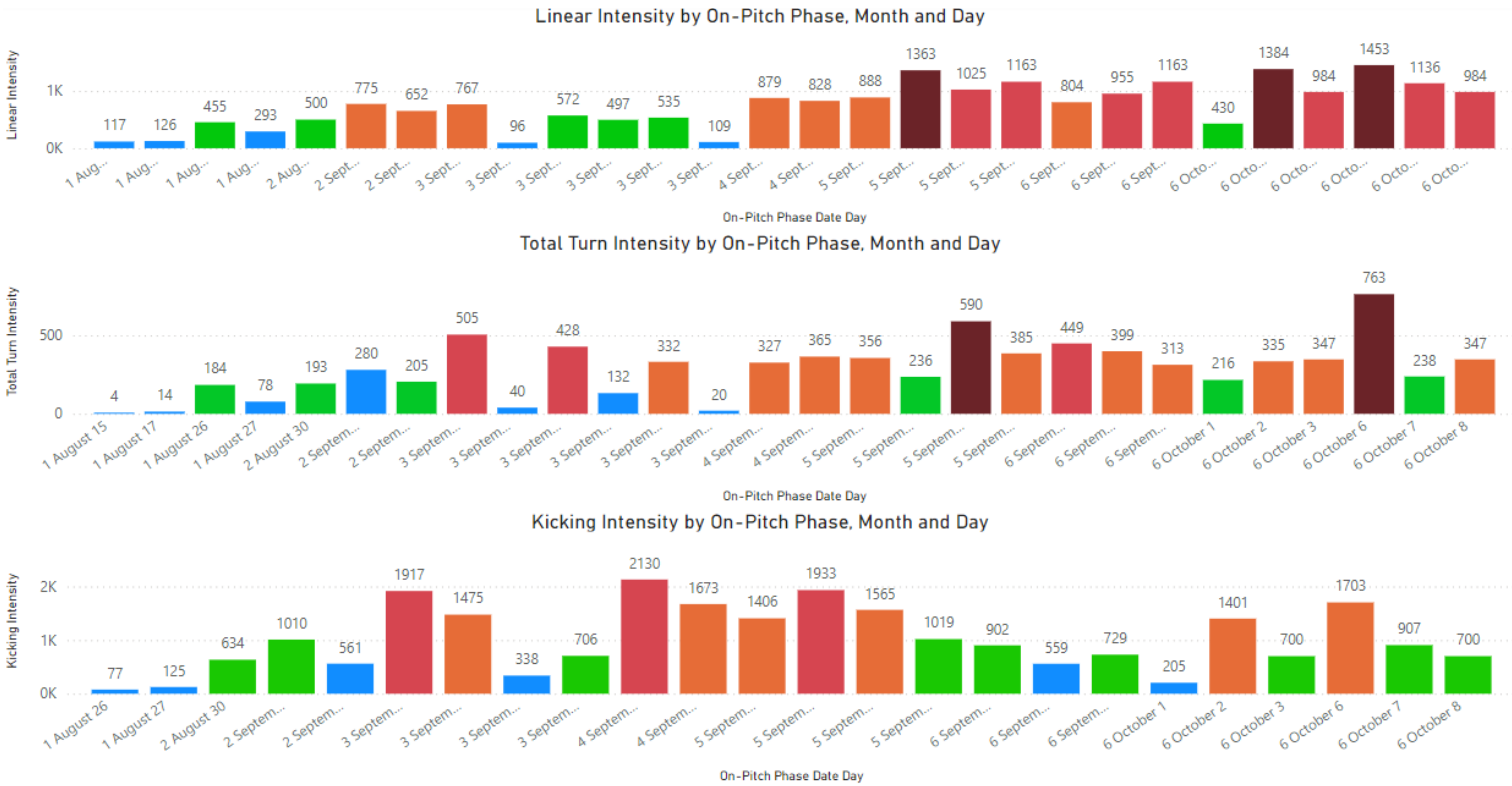


Figure 5-7 Player B rehabilitation example

The figure provided a graphic representation of load indicators for linear, non-linear and technical intensity from (Player B) full rehabilitation. The example clearly shows a differing pattern of loading identified for this player. Loading indicators here show a less linear progression of volume in each parameter compared to Player A with high moderate kicking intensities occurring early in the process and less exposure to high or very high mechanical demands towards the later stages.



Discussion

The results of this study provide initial validation for our novel approach to multidimensional load quantification. Overall, the findings demonstrate that the foot mounted inertial sensors successfully capture data across three key facets of loading: locomotor, mechanical, and technical. By testing the approaches capacity to differentiate between sessions with differing content prescription, and show progression change to parameters over time. The approach provides face validity as the data gathered aligns with theoretical expectations in the controlled rehabilitation environment, offering a promising direction for further exploration of load monitoring strategies (Impellizzeri et al., 2019a).

This approach also allows us to combine new data with existing metrics to quantify areas of loading that were previously underrepresented, providing a more comprehensive view of mechanical stresses from changes of direction and non-linear movements and technical actions. By contrasting this novel approach with conventional load monitoring systems, we are now better positioned to cover the full range of physical demands placed on athletes, offering a more comprehensive understanding of training load (Halson, 2014).

Overall, the approach shows the potential to change the way we understand and measure loading. The multidimensional approach to load monitoring could facilitate a more holistic approach to understanding the demands placed on players. Whereby our approach doesn’t provide direct measures of mechanical stress it goes some way to addressing a highlighted gap in the lack of field-based measures (Vanrenterghem et al., 2017) of mechanical loading. This holistic view could enhance our prescription of training load improving the balance between performance optimisation with injury reduction strategies.

Theoretical development

Theoretically, this study addresses a gap in the literature by quantifying types of loading that are often overlooked in traditional monitoring systems. It provides real world field-based measures of loading across multiple dimensions that maybe missing in current monitoring strategies. While locomotor demands have long been the focus of training load quantification, less attention has been paid to mechanical and technical loads, which play a significant role in overall athlete stress (Bourdon et al., 2017). This may in part be due to the adoption of created metrics driven by technology providers innovation opposed to practitioners need to answer performance questions. However, by incorporating these additional dimensions, we can now explore the complex relationship between different types of loads and athlete response.

This broader perspective allows for more precise linking of specific types of loading with physiological response and performance measures. For example, this more comprehensive view of mechanical loading and technical actions may offer new insights into the musculoskeletal and neuromuscular stresses' athletes experience (Akenhead and Nassis, 2016). Capturing these previously under-quantified loads may lead to a better understanding of how athletes respond to training stimuli and ultimately improve decision making in training prescription. By observing the distinctions between loadings prescriptions during the rehabilitation process should guide progression of mechanical and technical actions at appropriate times.

Practical development

From a practical standpoint, this multidimensional approach provides additional information that directly informs training and rehabilitation strategies. The inclusion of mechanical and technical load data allows practitioners to design more targeted rehabilitation programs. Technical loading, whilst in its relative infancy compared to contemporary methods of analysis like GPS monitoring, foot mounted IMUs used in this approach been found to reliable measure of monitoring kicking volumes which supports conclusions in the identified literature (Marris et al., 2022; Lewis et al., 2022).

Gaining an insight into the overall training demand of players in a normal schedule of training and competition should facilitate more optimal prescription of loading through the rehabilitation process, to ensure appropriate exposure to varying aspects of loading is achieved before players reintegrate. This could result in reducing the risk of re-injury and improving overall athlete readiness (Taberner et al., 2019).

Rehabilitation programs could now simulate training and match conditions more accurately by incorporating both locomotor and non-locomotor loads, such as changes of direction and technical actions. This ensures that athletes returning from injury are better prepared for the full spectrum of demands. Additionally, practitioners can use this data to fine tune training loads, ensuring that athletes are exposed to the right balance of intensity and recovery, thus enhancing performance while reducing injury risk (Jones et al., 2017). For example, certain parameters in that are essential to match play, may occur more frequent within training environments. Lewis et al. (2022) demonstrated that ball striking actions throughout the training week expose players to a frequency of high intensity actions that would be unlikely to occur in a game situation but could have important considerations for players returning to training.

Limitations

Despite these promising results, there are several limitations to this study. Firstly, a major limitation is that we outsourced the development of the composite metrics used to quantify the different facets of load to a technology provider. Although the pilot work and background research and development to this study has been presented (Professional Pause 3) the equations and a composition that underpin the metrics maybe described as ‘black box’. This reduced our control over the variables included in the analysis and may have constrained our ability to tailor the system precisely to our research needs. Outsourcing this aspect of the study also introduces potential biases in how the data is processed and interpreted (Impellizzeri et al., 2019b).

Additionally, the rehabilitation environment in which the technology was tested may not have been ideal for creating significant variations in loading. During rehabilitation, the load progression is typically more controlled, with planned increases in specific parameters, such as volume or intensity of individual actions. While this may have allowed us to observe expected changes in load, it did not fully capture the high-intensity, unpredictable nature of normal training and match play (Taberner et al., 2019).

Furthermore, limitations may exist in the prescription and implementation of the rehabilitation sessions themselves. The rehabilitation process was generally under the supervision of three "rehab" practitioners with weekly meetings to review and establish content between the sub department of the medical team. It should be acknowledged that individual philosophy's experiences and competency could heavily influence the prescription of rehabilitation from one practitioner to the next. The content of the sessions and prescribed activities in each phase of the rehabilitation process could be starkly different leading to alternative outcomes in the load indicators.

During the return to performance phase reintegration sessions were included in the dataset where players took part in some modified aspects of team training. In reality due to the congested fixture schedule these sessions were largely MD-1 (match day minus one) and MD+1 (match day plus one) which would typically be considered low volume and part of the tapering or regeneration phases (Buchheit and Laursen, 2013) of the training cycle.

The novel approach achieved face validity when differentiating between sessions with a spectrum of load prescriptions, so we can have some confidence these may not be representative of regular squad training due to the light and very light loading indicated in sessions in the final stages of Player A's example data (Figure 5-6). As these sessions may not reflect the typical loading patterns of activities seen in the regular training cycle practitioners may underestimate the perceived demands of team training particularly around reintegration of injured players.

Future directions

The next step in this research is to apply this multidimensional load-monitoring approach to regular training sessions and competitive match play. By expanding the scope to include more dynamic, high-intensity environments, we can further assess the technology's utility in capturing real-world variations in load. This will allow us to evaluate the appropriateness of this approach for routine use in both rehabilitation and regular training settings.

Testing the technology in more open environments will help determine its scalability and effectiveness under typical elite football conditions. It will also offer insights into how locomotor, mechanical, and technical loads interact in real-world scenarios, potentially leading to new discoveries regarding optimal training load management and injury prevention strategies (Windt and Gabbett, 2017). This broader application will provide practitioners with more robust data to support their decision-making in load monitoring and training prescription.

Conclusions

In conclusion, the novel approach proves face validity at differentiating and quantifying multiple aspect of loading through three composite metrics linked to three loading parameters (locomotor, mechanical and technical load). The approach used linear and non-linear movement to infer locomotor and mechanical loading. Whilst identifying parameters of loading that encompass some of the overall movement demands of the sport is a positive step towards more comprehensive load monitoring, we accept that generating parameters that encompass all movement demands is outside the current scope of available technology and this review. Advancement in measuring these parameters can help understand which facets of loading may influence physiological responses. However, future research should focus on further measures of validity for the approach incorporating both the demands of the full training cycle and competitive match play.

Reflective Pause 2

The conception and implementation of the novel approach could be considered a significant milestone achievement in both the overall project and doctoral journey. Taking the conceptual view of a need for more diverse and comprehensive load measurement through to operationalising a novel approach was both a challenging but rewarding experience.

Integration of research within the organisation

As we started profiling the players rehabilitation the data generated a lot of interest from members of the MDT. Stakeholder feedback was generally positive around the conception of the idea and the insight generated as we began to analyse sessions. It became evident, especially with the technical loading aspects of the sessions, that we were gaining insights into areas of the rehab process that challenged our thinking of training prescription. Although there was a clear focus of when to introduce higher velocity ball striking actions into the rehab processes the ability to quantify technical loading and observe where actions occur within sessions was surprising. We had previously considered shooting at goal or crossing the ball to provide the highest loading of technical actions however it became apparent that players instructed to play at 'game speed' or execute an action under pressure produced relatively high velocities through several other techniques. Although the study utilised kicking intensity to quantify session technical loading, the analysis platform allowed us to see the velocity of individual releases (ball striking actions) and track progression over time.

This led to a change in process when we compared the profile of different players rehabilitation. Although each player has different starting physical and physiological capacities, we saw large variations in the way players were rehabbed. This created extensive discussion around continuity of prescription especially when rehabilitating similar injuries. A key aspect of the results of the study was the successful integration of data generated by the F-IMU to guide the progression of ball striking actions. This was deemed especially important when players were likely to integrate into sessions where extensive “crossing and finishing” drills were included in the training content.

It was widely agreed within the MDT to maintain the use of the approach and aim to refine and develop it further. Quantifying the demands of the complete training cycle as well as establishing match loading across different positions should be included in further study. Not only would this improve our training prescription to more closely replicating the demands of competitive games, but also potentially reduce this risk of reinjury with more appropriate loading schemes from rehabilitation.

Although generally well received there was some apprehension from some parts of the MDT mainly around the use of the composite metrics and the arbitrary units they produce. Reluctance to change was evident from several stakeholders who commented they lacked understanding of the impact of training prescription on the load indicators. Whilst it is easy to achieve the necessary outputs of a prescription of distance and velocity for a session when you are using distance and velocity as outcome variables it, practitioners found it less intuitive to consider altering training content based on the novel framework, citing difficulties when constructing the quantity, order and content of sessions to match a prescription based on the proposed load indicators.

Reflection

Reflecting on the process personally, I felt a sense of satisfaction having taken an idea from conception through various stages of research and planning finally to execution. The process provides several challenges through working with a broad spectrum of stakeholders and peers. Patience is a precious commodity in the world of elite professional football and whilst in the data collection phase stakeholders were quick to expect result or for me to create actionable insights whilst the project was in its infancy. Managing expectations and required me to find ways to communicate across the MDT to maintaining engagement with the project in the absence of rapid results.

The application of scientific process in a real-world elite environment is clearly challenging as progress in academic terms could be considered slow moving compared to professional football, however I feel we have made a positive contribution to the organisation.

Possibly the most important part of this reflection comes from considering the resistance to change expressed by some members of the MDT when discussing the utility of the approach. I believe this resistance stems from a variety of organisational factors that make paradigm shift challenging. Firstly, many individuals in the fields of sports science and sports medicine, show a preference for the familiarity and routine. This is conceptualised by a phenomenon known as status quo bias (Samuelson and Zeckhauser, 1988). This bias leads people to associate greater value with their current methods and undervalue potential improvements. Practitioners may feel that if existing methods have been “good enough” or have led to success, then implementation of new systems or processes maybe unnecessary or detrimental to performance (Samuelson and Zeckhauser, 1988).

In high pressure environments practitioners may worry that using unfamiliar methods could lead to mistakes that affect player performance or risk of injury where they may be held accountable (Rogers and Singhal, 2003). This fear of negative consequences can lead to a preference for traditional methods and a reluctant to experiment with novel approaches. A lack of familiarity and confidence in interpreting novel metrics related to complex physiological variables maybe a factor in the reluctance of practitioners to engage with a new systems or dismiss the novel approach as overly complex (Greenhalgh et al., 2004). It is therefore important that I communicate a comprehensive account of the novel approach’s scientific basis to reduce scepticism of its validity or effectiveness.

Change in practise

In summary the process has helped improve professional practise in several ways. Technical loading is now quantifiable, and measures have been implemented into rehabilitations prescription to ensure players are exposed to various high velocity actions before successful reintegration to team training and competition. With more objective data on change of direction exercises in training can be manipulated to offer a more gradual increase, as well as more accurately reflect the demands reducing the risk of re injury and improving performance. Overall, we successfully achieved the aims of this study developing a novel approach to the quantification of multiple dimensions of loading and providing real world examples of how this can be used in practise.

Professional Pause 4

Introduction

Sport scientists should have an intimate understanding of load and response (Reilly et al., 2009). The purpose of these chapters is to highlight the response side of the investigation of this thesis. As mentioned previously my role is multi-functional, whilst operating as an applied practitioner coaching physical development and working to develop monitoring frameworks to inform decision making. It is therefore essential to understand the impact the training schedule has on players fitness and readiness to perform.

The club recently invested in a biomarker profiling system and part of my role was to incorporate this data into the existing "readiness" framework. The readiness framework is a collation of several points of data from multiple facets of the multidisciplinary team (MDT) including physiotherapy, medical and sport science with the primary aim to determine which players may not be showing positive response to the schedule, therefore suffering performance impairment or at a heightened risk of injury.

Problem identification

The system was sold by a third company on the potential to provide reliable and objective information on athlete health by capturing markers of systemic inflammation (hs-CRP) and redox markers of oxidative stress (FORT, FORD, OSI). Whilst there are reported benefits to understanding these markers in relation to athlete health longitudinal variations in these markers in response to training and match load were less clear.

Organisational collaboration

Given my responsibility for incorporating this data within our readiness monitoring I thought it was important to understand the interaction between these biomarkers and training load in football. This would allow us to determine the relevance to variations in these biomarkers to training load in similar populations. I decided to review the literature around these four specific biomarkers in relation to loading in professional football.

Iterative cycles

Given the pre-establish biomarkers (hs-CRP, FORT, FORD & OSI) were already part of a monitoring system planning and refinement of this review was relatively straight forward, find out more information around the utility of these biomarkers in profiling athlete health and the variations these markers have in response to loading. Answering these questions will help inform our decisions around the incorporation of this data in the readiness framework.

CHAPTER 6

PHYSIOLOGICAL RESPONSES TO LOAD

Literature Review

Introduction

Biomarkers play a pivotal role in medicine determining response of health care interventions however, more recently there is increasing application of biological measure in athlete profiling (Lee et al., 2017). Biomarkers have been used to assess athletes' physiological response to training and competition with samples typically being taken post-game or intense training to assess an athlete's response (Lee et al., 2017). These biological indicators provide insight into the levels of fatigue or physiological stress with the intention of guiding training prescriptions and recovery interventions to optimize performance and reduce injury (Anghel et al., 2023).

Specifically, biomarkers like hs-CR, FORT, FORD, and OSI are of particular interest due to the links inflammation, oxidative stress as well as antioxidant capacity which can provide important information regarding an athlete's recovery status in response to training stimulus.

- High sensitivity C-reactive protein (hs-CRP) is a sensitive marker of systemic inflammation, increases in hs-CRP can be induced by tissue damage or illness and serves as a reliable indicator of exercise induced inflammation (Pearson et al., 2003).
- Free oxygen radical test (FORT) measures the concentration of reactive oxygen species (ROS) which represents the level of oxidative stress. Elevate ROS can cause cellular damage and has been shown to increase following high intensity exercise (Nikolaidis et al., 2012).
- Free oxygen radical defence (FORD) assesses the volume of antioxidants in circulating, indicating an athlete's capacity to defend cellular damage by neutralising ROS (Lewis et al., 2015).
- Oxidative stress index (OSI) quantifies the ratio by comparing FORT and FORD results, providing a composite measure of oxidative stress levels and an indication of how athletes may be able to cope with them (Lewis et al., 2020).

The use of these biomarkers is thought to provide valuable insights into how players respond to the internal and external load demands of training and competition, supporting more effective load management and injury prevention strategies. As discussed in Professional Pause 4 this review will focus on 4 primary biomarkers currently used as part of the 'readiness' within my organisation. Whilst acknowledging the wealth of potential biomarkers that could be used to profile athletic response this review focused on the marker already utilised as part of the organizations preexisting monitoring strategy monitoring strategy to improve our understanding of these measures and suggest areas for further investigation.

Aims: Examine the factors associated with inflammation, markers of oxidative stress and training load in elite professional football.

How?

1. Conduct review of current literature exploring factors relevant to profiling specific biomarkers (hs-CRP/FORT/FORD) in high level sport.

2. Examine the relationship between specific biomarkers and training load.

3. Highlight potential factors for biomarker sampling in professional practice relating to windows of loading, training load variables and individual responses.

Profiling physiological response

Fatigue and individual responses to loading are complex and multifaceted (Silva et al., 2018) Greater neuromuscular demands within games driven by increasing volume and frequency of high intensity actions (Barnes et al., 2014; Nedelec et al., 2014), with short between game recovery periods may prompt transient fatigue (within game and intense training sessions) and exacerbate residual fatigue (post-match)(Silva et al., 2018).

The implications of these events would suggest that longer recovery periods are needed to fully regenerate (Silva et al., 2018). Impairments in neuromuscular function (decrease in force production capacity), physical performance impairments (high intensity locomotor ability), disturbances to biochemical environments (inflammatory responses) and deterioration of psychological state are often observed in the days post-match and intense training (Mohr et al., 2005; Krustrup et al., 2006; Nedelec et al., 2012; Carling et al., 2018).

These symptoms of fatigue can be categorised as central and peripheral (Tornero-Aguilera et al., 2022). These types of fatigue have been defined by Tornero-Aguilera et al. (2022) as a failure of the central nervous system of voluntarily activate the muscle (central) whilst peripheral fatigue relates to changes to biochemical changes within active muscle tissue. Both types of fatigue have been shown to be evidence up to 72 hours post competitive match play (Silva et al., 2018) with multiple factors including age, training history, level of competition/opposition, number of recovery days between matches and training demands which are likely to influence the external and internal load experienced by individual players (Silva et al., 2018).

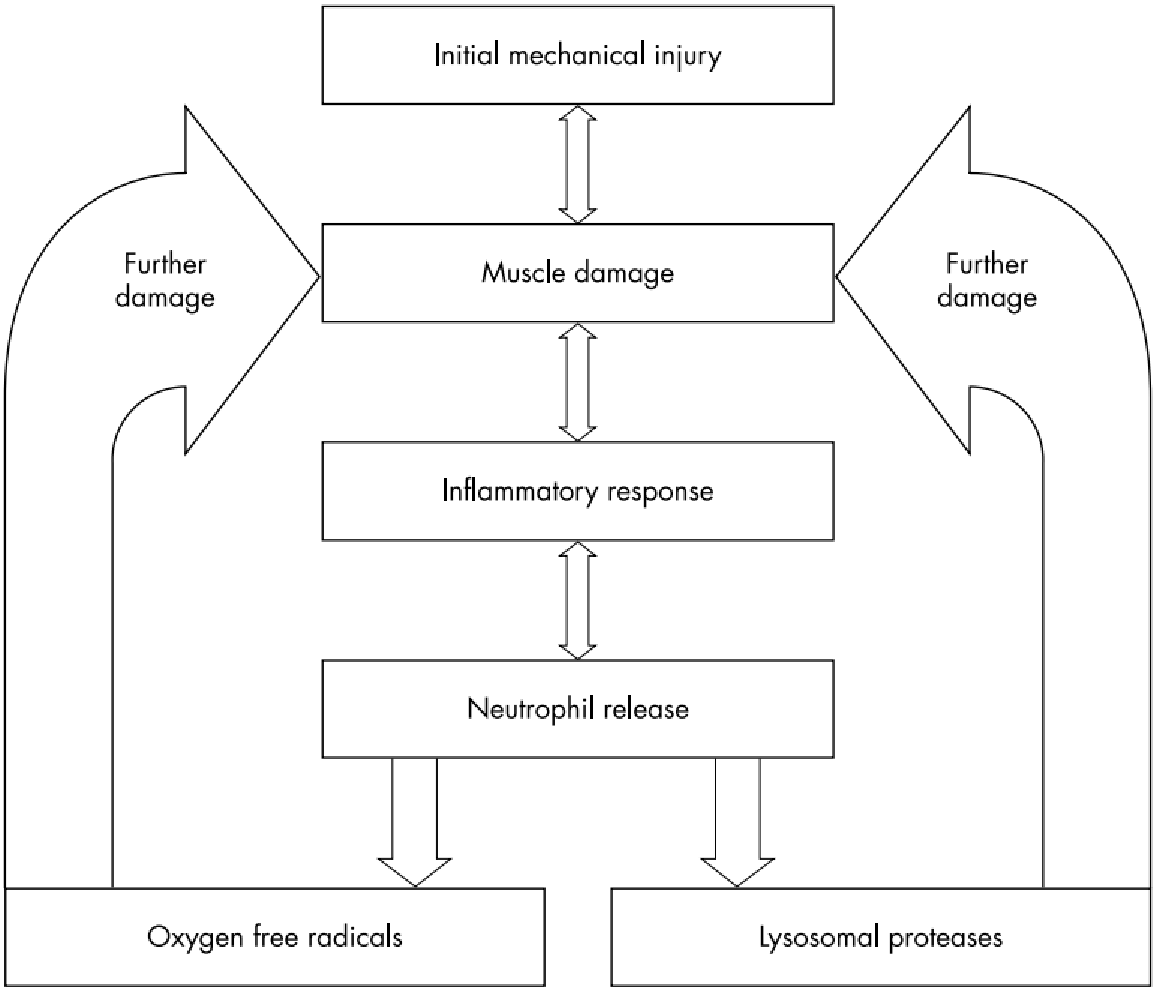
The causes of both central and peripheral fatigue in football are thought to occur simultaneous during match play (Rampinini et al., 2008), and largely attributed to the high intensity actions that are performed which expose players to both physiological and mechanical loading (Harper et al., 2019; Harper et al., 2022). Muscle damage caused by eccentric muscle actions (Harper et al., 2022) and physiological stress from metabolic processes the occur to facilitate energy production and performance (Powers and Jackson, 2008). Understanding these mechanisms of fatigue and resulting adaptive responses should be considered pertinent to understating load response pathways.

Exercise induced muscle damage

It is widely acknowledged that the mechanical demands of performing actions with a high eccentric component such as high intensity decelerations, sprinting, jumping and explosive movements lead to exercise induced muscle damage (EIMD)(Silva et al., 2013; Silva et al., 2014; Khan et al., 2016; Silva et al., 2018). EIMD can be summarised in two phases. Firstly, EIMD is observed as micro-tears in muscle fiber tissue triggering an acute phase inflammatory response to facilitate repair and adaptation (Clarkson and Hubal, 2002). The second phase damage is caused by excessive gathering and penetration of neutrophils into damaged tissue (Toumi et al., 2006; Markworth et al., 2016). This process is concisely explained in Toumi and Best (2003) mechanism of inflammatory response model (Figure 6-1).

Figure 6-1 Inflammatory response model

Inflammatory response Toumi et al. (2006). The model proposes the relationship between the inflammatory response to mechanical injury and further muscle damage.



This model shows whilst inflammation plays an important role in recovery and adaptation, excessive or prolonged inflammation can impair performance and increase injury risk through secondary damage, promoting maladaptive tissue remodelling (Markworth et al., 2016; Daniels, 2021). For elite players there are several negative consequences of EIMD. Increases in muscle stiffness, muscle swelling and soreness can lead to temporary decreases in muscle function (Silva et al., 2013; Silva et al., 2014). The extent of this deterioration if largely due to the magnitude of the structural tissue damage and associated inflammatory response (Owens et al., 2019;

Bongiovanni et al., 2020). During periods of intense training or fixture congestion where recovery time is limited may show EIMD to be a limiting factor in skeletal muscle function (Owens et al., 2019) with implications for physical performance. Therefore, mitigating EIMD through appropriate training load management and resolving the associated inflammatory response should be considered essential of athlete health and recovery (Owens et al., 2019).

Oxidative stress

Oxidative stress occurs when the production of ROS exceeds the body's ability to neutralize free radicals with antioxidants, defined as “a disturbance in the pro-oxidant, antioxidant balance in favour of the former” (Sies and Cadenas, 1985). As previously discussed football is primarily an aerobic sport, which it characterised by players involved in training and competitive games experience frequent fluctuations between high and low intensity movements, over a relatively extensive duration (Bangsbo et al., 2006b; Drust et al., 2007). Research suggests that during competition, players' heart rates range between 80-90% of their maximum heart rate (HRmax) and 70-75% of their maximum oxygen uptake (VO2max) (Bangsbo, 1994). This high internal load, combined with the frequent eccentric muscle actions (external load), leads to increased ROS production in both the blood and mitochondria of skeletal muscle (Finaud et al., 2006a; Ponce-Gonzalez et al., 2021).

Although exercise-induced oxidative stress is a stimulus for beneficial adaptations of health, with elite athletes often exhibiting lower oxidative stress levels than their sedentary counterparts due to upregulated antioxidant defences, excessive ROS (Brites et al., 1999; Daniels, 2021) production can occur under conditions of intense training or competition where there is inadequate time for recovery. This imbalance can elevate oxidative stress and potentially impair performance and increase injury occurrence (Finaud et al., 2006b). Several studies have investigated the impact of football match play on oxidative stress (redox), including lipid peroxidation, protein oxidation, and measures of total antioxidant status (Ascensão et al., 2008; Ispirlidis et al., 2008; Fatouros et al., 2010; Silva et al., 2013; Silva et al., 2018; Souglis et al., 2018). These findings indicate that football matches cause alterations in redox balance and contribute to oxidative damage to skeletal muscle alongside the exercise-induced inflammatory response. These alterations to homeostasis are associated with acute impairments in physical performance (Ascensão et al., 2008; Ispirlidis et al., 2008; Fatouros et al., 2010) which could significantly affect the outcomes for football players competition at an elite level.

Response to muscle damage and oxidative stress is believed to follow a predictable time course, with hs-CRP and oxidative stress markers (OSI) peaking between 24-48 hours post competition and gradually retuning to baseline around 72-96 hours post-game (Peake et al., 2017; Silva et al., 2018). However, the magnitude and duration of biomarker response may vary considerably between individuals based on several factors. Genetics, training status, age, training stimulus and nutrition can all affect biomarker readings (Finaud et al., 2006b; Ascensão et al., 2008; Halson, 2014). These differences are particularly evident when monitoring hs-CRP, oxidative stress markers and other indicators of muscle damage and inflammation in elite professional footballers (Ispirlidis et al., 2008; Ascensão et al., 2008; Brites et al., 1999). Although we see some associations between match play and physiological response to our knowledge there are no long-term studies investigating the relationship these markers have with athlete performance. For example we know inflammation and soreness have consequences for muscle function (Owens et al., 2019; Silva et al., 2018) however we don’t know the extent to which variations in these markers are linked with measures of performance.

<u>Response to relevant biomarkers in football</u>

The following section provides an overview of specific biomarkers used in my professional context to monitor players' physiological responses to training loads and match demands. Investigation into the utility of our biomarkers namely hs-CRP and markers of oxidative stress (protein oxidation and total antioxidant capacity) are of particular interest in football due to their association with inflammation and muscle damage (Fatouros et al., 2010; Silva et al., 2014; Silva et al., 2022). hs-CRP is frequently used to assess inflammation, as it increases in response to exercise induced muscle damage (Mohr et al., 2016). In addition to hs-CRP, oxidative stress biomarkers have been shown to be useful for evaluating players response to oxidative damage during both training and competitive match play (Ispirlidis et al., 2008). Table 6-1 provides a comprehensive view of the physiological metrics that are central to player management in elite environments.

On review several studies (Souglis et al., 2015; Mohr et al., 2016; Kotsis et al., 2018; Souglis et al., 2018; Jatene et al., 2019; Duarte et al., 2022; Saidi, 2022; Selmi et al., 2022; Clayton et al., 2023; Clayton et al., 2024; Tanabe et al., 2024) highlight the utility of hs-CRP in monitoring exercise induced inflammation. The results show CRP to be sensitive to match and intense training by showing significant increases to load. Clayton et al. (2023) demonstrates a significantly higher CRP (1082%) at 40 and 64 hours post-game compared to controls. Similarly, Daab et al. (2021) reported a 160% rise in CRP at 24- and 48-hours post-match simulation and (Mohr et al., 2016) found both CRP and oxidative stress markers in footballers remained elevated up to p48 hours following match play. Furthermore (Souglis et al., 2015) demonstrated increases in CRP in both male and female players following match game loading. Their findings were validated but further investigation (Souglis et al., 2018) which showed similar results with CRP peaking at 13 hours before returning to baseline at 37 hours. These findings likely illustrate the acute phase response that follows match play, reflecting players inflammatory reaction to movements demands experiences during the game.

Table 6-1 Physiological response literature review studies

Outlines the various studies included in this review, detailing the biomarkers investigate and its association with load to establish relevance to player monitoring.

Study	Biomarker(s)	Population	Associations with load
Ghafourian et al. (2016)	hs-CRP	N=20 recreational footballers	No significant change in hs-CRP when sampled 24 h after exposure to either high or low intensity running task.
Clayton et al. (2023)	hs-CRP	N=8 professional male footballers	hs-CRP increased 1082% in control group not given turmeric supplementation 64h post-match.
Póvoas et al. (2022)	hs-CRP	N=13 elite female footballers	No significant changes in CRP measured after games during tournament or across tournament period at group level. Two players showed large spike post-game.
Trecroci et al. (2021)	hs-CRP	N=9 male sub-elite footballers	hs-CRP taken pre- and post-match, no significant change in hs-CRP pre post.
Daab et al. (2021)	CRP	N=13 semi-professional male footballers	CRP ~160% higher than baseline at 24h and 48h post intermittent shuttle test.
Jatene et al. (2019)	CRP	N=23 academy footballers	Rise in CRP from baseline observed 2h after game for three consecutive games separated by 48 hours. Strong correlations with number of sprints per game. Multilevel linear regression, CRP as predictor of sprints R^2=0.624.
Fullagar et al. (2016)	CRP	N=20 amateur male footballers	Measured CRP pre 10h, 20h, 24h and 44h post-game no significant change from baseline.
Radzimiński et al. (2020)	CRP	N=15 professional male footballers	Measured CRP pre during and post 13-day camp. No significant change from baseline.

Study	Biomarker(s)	Population	Associations with load
Mohr et al. (2016)	CRP Oxidative stress, Antioxidant status	N=40 professional male footballers	Blood draws every day for 11 days in congested period (3 games in a week). Significant increase in CRP immediately and 24- & 48-hours post-game. CRP significantly higher than non-playing control group. No change in control group CRP. Similar increases in both pro and antioxidant after game 2 showing potential adaptive response.
Tanabe et al. (2024)	hs- CRP	N=15 male college footballers	Measured hs-CRP pre, 24h and 48h post-match. Increase in hs-CRP observed at 24h recovered by 48h. Coincides with decreased jump capabilities and increased soreness.
Clayton et al. (2024)	CRP	N=23 elite male footballers	Measured CRP 0h, 40h and 64h post-match. CRP significantly increased 40h compared with 0h post-match.
Selmi et al. (2022)	CRP	N=15 professional footballers	Measured CRP before and after 14-day intensive preseason training block. Significant increase in CRP from pre to post. Strong positive correlation with muscle soreness.
Silva et al. (2022)	CRP	N=25 professional male footballers	CRP taken before and after 3.5-month pre-season training. CRP increased. Blood draw 12 hours after last session.
Duarte et al. (2022)	CRP	N=11 male professional footballers	Measured CRP at 24 hours post-game for t3 consecutive games in congested period. Increases in CRP seen 24h post-game. Shows cumulative effect with CRP increasing after each game.
Goulart (2021)	CRP	N=10 professional female footballers	CRP measured at 24-, 48- and 72-hours post-match. No statistical increase but visible increase in some players at 24h post-match.
Saidi (2022)	CRP	N=14 elite male footballers	12-week training period 6 weeks regular 6 week congested. Significant increase in CRP during congested periods.

Study	Biomarker(s)	Population	Associations with load
McKinlay et al. (2022)	CRP	N=13 youth female footballers	5-day training camp CRP taken pre-post training. No significant effect on CRP.
Souglis et al. (2015)	CRP	N=40 20male, 20 female elite footballers	Measured CRP pregame, 0h, 24h and 48h post. Significant increase in CRP 24-hour post-game in both male and female players.
Baralic et al. (2015)	CRP, Oxidative Stress Antioxidant status	N=40 youth male academy footballers	Measured CRP, Oxidative stress markers and antioxidant status pre and post 90-day training period. 57% increase in CRP (1.26-1.98mg/L). No change in oxidative stress markers, decrease in antioxidant status.
Kotsis et al. (2018)	hs-CRP	N=22 professional footballers	hs-CRP measured pre, 2h, 24h, 48h and 72h lost intermittent fitness test. CRP elevated above pre levels at all time points.
Souglis et al. (2018)	CRP, Oxidative stress, Antioxidant status	N=120 30=male, 30=female elite footballers, 60= control	Blood draw pre, 0h, 13h,37h,61h,85h,109h post-game. CRP peaked 13h post-game compared in both returns to baseline by 37h. Oxidative stress marker significantly higher and peak 37h post-game returning to baseline by day 5. Antioxidant increased after game returning to baseline 37h. Notes differences in playing position.
Silva et al. (2014)	CRP, oxidative stress, Antioxidant status	N=14 male professional	Measured biomarker at 4 time points. Increases in CRP in season vs start of season. Increase in oxidative stress markers through season, slight decrease in antioxidants status.
Mello et al. (2017)	Oxidative stress, Antioxidant status	N=22 male professional footballers	Blood samples taken pre and 5min post simulated match. No significant increase in oxidative stress but significant decrease in antioxidant observed.

Study	Biomarker(s)	Population	Associations with load
Ponce-Gonzalez et al. (2021)	Oxidative stress, Antioxidant status	N=65 professional male footballers	Blood draw week 1 of season and after 18 weeks. Significantly decreased total antioxidant status, led to increase in oxidative stress/antioxidant ratio.
García-Cardona et al. (2021)	Oxidative stress, Antioxidant status	N=22 male university footballers	Blood taken during simulates congested schedule. Biomarkers significantly affected by intense micro cycle. Increase in oxidative stress over course of micro cycle, decrease in antioxidant status both returning to baseline 7 days post.

Individual variability has been demonstrated in CRP responses that should be considered. For instance, Jatene et al. (2019) found significant correlations between CRP levels and the number of sprints performed across three consecutive matches in elite south American academy players suggesting a link between certain activities and biomarkers response. In contrast both Radzimiński et al. (2020) and Póvoas et al. (2022) reported no significant changes in CRP level during controlled training periods, which may indicate the impact of training loads that do not exceed individual threshold for recovery or groups of players that maybe 'non-responses'. These findings have several implications for practice. Firstly, in terms of analysis results may be impacted by variations in players physiological fitness. As players fitness improves their physiological response to match play may vary. Secondly, this raises important considerations for appropriate training prescription and recovery interventions to ensure players are not only prepared for the load demands, but also prescribed appropriate regeneration at times they may be exposed to demands outside their tolerance (Carling et al., 2018).

Use of biomarkers to detect oxidative stress has also highlighted important factors to understanding redox balance in athletes. Football match play has shown significant alteration in redox biomarkers, reflecting the oxidative damage players experience because of competition (Ispirlidis et al., 2008; Ascensão et al., 2008). The results of these studies indicate that oxidative stress levels are significantly elevated after matches due to high aerobic and eccentric load demands (Powers and Jackson, 2008; Harper et al., 2022). These findings are supported by (Silva et al., 2014) who noted a progressive decrease in antioxidant resource throughout the season.

Interestingly Brites et al. (1999) suggest that physiological fitness may increase antioxidant upregulation showing lower oxidative stress levels than less trained individuals. Their results suggest long term training may enhance a player's ability to minimise oxidative damage, but excessive training volume and inadequate recovery can still tip the balance reducing antioxidant defence and increasing oxidative stress (Finaud et al., 2006b). Some research exists which point to a cumulative effect in biomarker response when matches are played in close succession (Duarte et al., 2022). Increases in CRP were also observed exponentially when taken between matches during a period when players participated in three games in an eleven-day period (Duarte et al., 2022).

Similarly, Selmi et al. (2022) demonstrated an significant increase in CRP following an intensive two pre-season training block which also positively correlated with muscle soreness. These markers not only reflect acute responses to individual games but also accumulation of inflammation across periods of fixture congression and intense training. The time course of biomarker responses is also an important area of consideration when considering the application to athlete monitoring strategies. The reviewed literature shows several instances of inflammatory biomarkers peaking between 24-48 hours (Daab et al., 2021; Goulart, 2021; Duarte et al., 2022; Tanabe et al., 2024) which suggests a window for effective monitoring of players recovery status.

These issues create a challenge for both practitioners and researchers attempting to link physiological response to match load. Not only are there varying windows of opportunity to assess specific biomarker responses, but the cumulative fatigue also experienced during periods of fixture congestion mean that variations in biomarkers maybe reflective of the accumulated load during a period of loading and no single game or event. Furthermore, players experiencing different loading schemes during this period may exhibit different response (Silva et al., 2018) adding another layer of complexity to biomarker response profiling.

<u>Practical considerations for monitoring response</u>

Monitoring hs-CRP, FORT, FORD and OSI can provide valuable information on the acute and cumulative effects of training load. Monitoring hs-CRP and OSI over the course of the training cycle may provide insights into how players recovery from training and game. For example, detecting elevated hs-CRP after players are exposed to repeated high intensity session or perform a relatively high number of sprint over a micro cycle may indicate systemic inflammation that could lead to fatigue and sub optimal performance if not managed correctly (Coutts et al., 2015). Similarly monitoring long term oxidative stress levels across the training cycle may help practitioners identify when athletes are experiencing chronic stress and risk cellular damage that may impact performance and health (Thorpe et al., 2015). This information could help inform decisions on training load and recovery interventions to prevent overtraining (Thorpe and Sunderland, 2012).

Although there is some evidence to support the inclusion of these biomarker in athletic monitoring strategies there are several factors which remain unclear before the information generated can be used to successfully inform decisions on training loads or recovery interventions (Thorpe et al., 2015). Further research is needed to explore how differencing types of stimuli, volume, intensity, frequency and type of load impacts these biomarkers to establish appropriate practical interventions.

Summary

The purpose to this review was to evaluate specific biomarkers of inflammation and oxidative stress in terms of their potential use in my professional practice context. Overall evidence supports the utility of inflammatory and oxidative stress biomarker testing in professional football for understanding player response to training and completion (Souglis et al., 2015; Mohr et al., 2016; Souglis et al., 2018). hs-CRP and oxidative stress markers may offer valuable insights into inflammatory responses, recovery status and the risk of overreaching. However important factors should be considered concerning individual variability in responses (Souglis et al., 2018; Póvoas et al., 2022). Further research is needed to establish how the volume and intensity of load impacts on biomarker results. There are some consistent findings within the literature time frames to detect response in these biomarkers (24-48 hours post-game) lending to practical use in elite football when assessing response post-match. However, it is less clear on how load should be quantified prior to analysis. Studies use individual games and blocks of training but only a small number of studies have investigated which training load variables maybe correlated with biomarker response, particularly in relation to training outputs and match intensity (Jatene et al., 2019). Further research into cumulative effects of load and optimal windows to quantify stimulus should be explored to establish links between training load (dose) and biomarker response.

Professional Pause 5

The physiological response to load literature review highlights some important factors for our consideration when using biomarkers to assess response. Variations in loading ‘windows’ and optimal timeframes to detect response should be considered. Individual variability as well as differences in fitness levels are some of the confounding factors, we should be mindful of when interpreting results.

Problem identification

The literature review raised some areas for further investigation that would aid to our understanding on the use of biomarkers in the practise environment. Although this furthers our understating somewhat, we require further exploration to advance our understanding. As we have both biomarker and loading data being generated by the club we need to apply more scientific process to our exploration of these interactions. Quantification of loading is an area of that needs to be explored to understand both the acute and cumulative effect on inflammatory and oxidative stress responses to loading. Furthermore, there is little research on which training load variables maybe linked with variations in biomarker data. Some evidence was highlighted in the review to suggest sprinting as an indicator of high intensity match activity may influence inflammatory response, however further investigation is warranted into the effects of volume and intensity of loading and response. Individual differences are also an area which are poorly understood in the identified literature. Establishing “responders” and “non-responders” highlighting which individuals maybe exhibit more profound inflammatory responses. Theoretically we need to address the shortcoming in our knowledge of what types and quantity of load may stimulate biomarker response. Exploring these links will allow us to foster a greater understanding of the nature of relationships between load and response.

Organisational collaboration

We decided to conduct a study to explore the gaps in our understanding of how biomarker response interacts with loading namely, which variables maybe linked to variation in response, what window or quantity of load in most influential to response and what are some of the individual differences between players. Conversations within the MDT highlighted the importance of understanding how the biomarker can be impacted by loading. Although conversations around player readiness are based on mostly objective data the interpretation of these measures can often become subjective. It was clear through discussion that some members of the MDT felt exposure to high intensity activities like sprinting were negatively impacting on several readiness outcome measures. We therefore decided to refine our approach to look at total distance and sprint distance as these were two load variables that often became the points of discussion in conversations around loading and training prescription as proxy measures of volume (total distance) and intensity (sprint distance).

Iterative cycles

Collection of biomarkers was a previously established process within the organisation with data collection (blood draw) taking place on each MD+2. Research into the time course of response to load indicated a 24–48-hour window for peak inflammatory response following activities that contribute to EIMD. Given the day after the game is a recovery focus with players staying indoors for treatment and regeneration it makes sense for players to be profiled MD+2 ahead of returning to on pitch training. Identifying players who may be exhibiting a raised inflammatory response or high levels of oxidative stress prior to training affords us the opportunity to intervene with potential load modifications prior to training so we decided to keep the blood draw the same. The data for this analysis was taken from the club's current load monitoring strategy which includes both training and match data (Table 6-2).

Table 6-2 Example load monitoring data (GPS)

The table provides an example of the data the club currently uses when analysis training and games. The example provided has the players name and playing duration removed to maintain anonymity.

Type	Distance	m.min	Max speed (m.s)	High Speed Distance (m)	Sprint Distance (m)	Total High Speed Distance (m)
Match	9315	88.9	34.9	435	217	
Training	1695	42.7	22.3	10	0	10
Training	4623	53.6	29.3	164	39	203
Match	2977	87.8	29.3	154	51	205
Training	3981	49	34.5	378	155	533
Training	4025	48	28.8	131	19	150

CHAPTER 7

PHYSIOLOGICAL RESPONSES TO LOAD ACROSS A COMPETITIVE SEASON IN ELITE PROFESSIONAL FOOTBALL

Introduction

Biomarkers, which have their origins in medical research, have been increasingly adopted in professional sports for their utility in assessing physiological stress, recovery, and adaptation (Lee et al., 2017). In football, specific biomarkers such as creatine kinase (CK), C-reactive protein (CRP), and oxidative stress markers have been widely applied to monitor players' responses to training and competition (Silva et al., 2014; Clayton et al., 2023). Biomarker data can provide valuable insights into muscle damage, inflammation, and oxidative stress, offering a deeper understanding of an athlete’s internal load in response to external stresses, experienced throughout the training cycle (Sharma et al., 2021).

Despite the increasing adoption of biomarkers in professional football, several important knowledge gaps exist. While biomarkers are valuable in quantifying acute physiological responses, the long-term variations in these markers are less clear (Silva et al., 2014). There is limited understanding of how biomarkers vary over entire training cycles, from pre-season, across different match and competition schedules and periods of fixture congestion (Mohr et al., 2016; Póvoas et al., 2022). Additionally, there is a lack of comprehensive research that explores the relationship between biomarker fluctuations and performance outcomes, such as fatigue, recovery time, and injury risk. Although biomarkers like CRP and CK are widely studied, the context of their fluctuations and how these should be interpreted remain a key area for further investigation (Daab et al., 2021).

Understanding these fluctuations across the entire training and game cycle is crucial for improving players “readiness”. Biomarkers have the potential to provide objective data of an athlete’s physiological status (illness, injury, fatigue), helping support staff make informed decisions regarding training load prescription, medical interventions and recovery strategies. However, the effectiveness of these interventions requires longitudinal exploration of biomarkers profiles in order to map variations and interactions with performance outcomes (Radzimiński et al., 2020).

The increasing specialisations of multidisciplinary teams in elite professional football particularly in the domain of sport science has led to the incorporation of advanced monitoring techniques like biomarker analysis, with practitioners trying to establish links between load and response (Clemente et al., 2021). As clubs invest in more sophisticated technologies, biomarker use is becoming more commonplace, enhancing the scientific approach to load management and recovery. This development makes it essential for sports professionals to understand the nuances of biomarker datasets, the contexts in which they should be measured and their implications for training and recovery strategies (Silva et al., 2014). Therefore, gaining a thorough understanding of how biomarkers can be effectively incorporated within professional football load monitoring strategies is important for advancing evidence-based approaches within the sport.

Theoretical challenges

The application of biomarkers in professional football presents several theoretical challenges despite their growing adoption. One of the primary issues is the sheer diversity of biomarkers available for analysis with a multitude of potential indicators of physiological stress and recovery (Haller et al., 2023). Such diversity creates uncertainty in determining which biomarkers are most relevant for specific contexts such as monitoring recovery status and readiness to tolerate training stimuli.

Another challenge exists in identifying optimal time points for sampling and analysis. The time course of biomarker response can vary significantly depending on the biomarker, individual response and type of stimulus. Whilst hs-CRP has shown a trend to peak 24-48 hours post-game giving insight into the inflammatory response of exercises induced muscle damage (Daab et al., 2021; Duarte et al., 2022), markers like creatine kinase may spike within hours of EIMD and remain elevated for several days (Silva et al., 2013; Clayton et al., 2023). The lack of longitudinal research that monitor these markers across various stages of training cycles, and under different match-play conditions, has made it difficult to pinpoint when to measure biomarkers and how to interpret changes effectively (Mohr et al., 2016).

<u>Practical challenges</u>

While the application of biomarkers in professional football may offer valuable insights into athlete health, performance, and recovery, several practical challenges exist. These challenges relate to issues such as, player compliance, data interpretation, resources and the translation of findings into actionable decisions for practitioners. The logistical challenges of co ordinating biomarker collection during the training week can present many complex practical challenges. Time and access to compliant players is limited especially during periods of fixture congestion where biomarker data maybe most relevant making frequent and accurate data collection a logistical hurdle for practitioners.

One of the most significant practical challenges in biomarker use is translating biomarker data into actionable insight that help inform the decision-making process on training and recovery prescriptions. Whilst elevated hs-CRP or oxidative stress levels may indicate physiological stress through inflammation and cellular damage, the exact implications for performance and injury risk remain speculative and the impact on player readiness unclear (Jatene et al., 2019). For example, studies that have shown that elite athletes may experience significant fluctuations in biomarker variables these changes do not necessarily correlate with decreased performance or increased injury risk (Silva et al., 2014).

Given the exploratory nature of this study, it is important to guide the reader through the rationale and objectives The primary objective of this analysis is to determine which biomarkers within the organisations current load monitoring battery are directly responsive to physical loading. The first question this study seeks to answer is, which biomarkers (if any) are responsive to physical loading in elite professional football players? This is important because, despite the common use of certain biomarkers like hs-CRP, may respond in a way that is meaningful or practical to inform training load management, the same is true for oxidative stress markers as little is known about their response to the accumulative load experienced by elite professionals (Finaud et al., 2006b; Silva et al., 2022).

Secondly, this study aims to quantify the degree of correlation between biomarker levels and physical loading measures such as total distance covered and sprint distance data. While previous research has identified elevations in biomarkers post-match (Mohr et al., 2016; Silva et al., 2022; Ponce-Gonzalez et al., 2021) and some research has been found on the impact of physical load metrics, the relationship between these biomarkers and specific types of loads remains unclear in elite populations. For instance, does hs-CRP increase in proportion to the amount of high intensity sprinting, or does it rise due to the overall volume demands of a match? Understanding these nuances can help practitioners interpret biomarker data in the context of training loads and recovery (Póvoas et al., 2022; Clayton et al., 2023).

Another important aspect is to explore individual variability in biomarker responses. Previous studies have demonstrated varying responses to similar physical loads, with some players exhibiting sharp increases in markers like CRP, while others show minimal changes (Jatene et al., 2019). This variability complicates the use of biomarkers a prescriptive guide to training decisions because of the large individual variation in responses. Identifying whether there are consistent patterns of responsiveness among certain players could help individualise training interventions (Goulart, 2021).

Aim: Explore the relationship between training load variables and specific biomarker response over a season in elite professional football.

How?

1. Determine which biomarkers if any are responsive to physical loading.

2. Examine the degree to which biomarker response is correlated with physical load measures total distance (m) and sprint distance (m).
3. Highlight potential findings and that may relate to training load prescription and further biomarker sampling in professional practice.

Methods

Participants

Prior to the commencement of data collection participants were provided with a verbal outline of the blood draw procedure and were given opportunities to ask any questions. Participants were provided with a written information sheet outlining the procedures and feedback processes (Appendix 1 informed consent form). Data from twenty-one elite level full time professional footballer players competing in the English premier league was included in the study (mean age 26.7 ± 4.6 years). Data was collected in line with the club's current load monitoring strategies. All players who participated more than 30 minutes in the previous fixture were sampled as part of the pre-existing monitoring strategy where players who participates in game (>30mins) are profiled to assess their recovery status before beginning preparation prior to the next game.

Players that that during the season were classified as having an illness or injury had their data excluded from the results until they were classified as fit and in team training but the club's doctor. To protect anonymity details of various illnesses and injuries have not been disclosed. All players were tested across the competitive phase of the season which includes domestic and international cup competitions. Individual participants are not identifiable from any of the data presented.

Testing for each was conducted at the same venue throughout (i.e. within the clubs' training facility and testing lab). Written informed consent was obtained from every participant before data collection began as blood data was stored and processed in third party software.

Design overview

As this research represents an exploratory investigation into the relationship between physical loading and biomarker responses in elite professional football players using a data driven approach, instead of following a rigid hypothesis-testing model, This approach reflects the iterative and investigative nature of the study and the action research model which guides this thesis, aiming to uncover patterns and correlations that may not have been immediately obvious at the outset.

We conducted a longitudinal analysis of training load including training sessions and fixtures during the 2022-2023 season. Data from forty competitive games (n=40) and forty (n=40) match day plus two (MD+2) sessions were included in the analysis alongside training sessions (n=186). Over the course of the season measures of hs-CRP and oxidative stress indicators FORT, FORD and OSI were taken from players post-game on match day plus two (MD+2) (approximately 40 to 44 hours post-game dependant on kick off time). All biomarker data was collected at a similar time each day 09:30am – 11:00am on arrival at the training ground and consisted of CRP and plasma redox markers (FORT & FORD) via point of care blood tests. Players were asked to report for testing in a fasted and hydrate state, where players reported breaking the morning fast, this was noted. Training schedule was prescribed by the clubs coaching staff and not influenced by the design of the study.

Load monitoring data

To describe the process of quantifying match and training load this section outline the protocols used to capture training and match loading.

Training Sessions: To quantify the demands of training sessions the GPS APEX pod (18Hz GPS, 600Hz accelerometer, MAPPS Technology and Bluetooth LE; STATSports; North Ireland) was used. Each player was assigned the same unit for the duration of the season to improve reliability (Buchheit et al., 2010a; Buchheit et al., 2010b).

Match Data: Games were analysed during the 2022-2023 season, using a multi-camera computerised tracking system (Second Spectrum Inc., CA, USA). Game minutes and locomotor metrics were recorded each game via cameras positioned in each of the stadiums and were analysed using match-analysis software (Second Spectrum Inc., CA, USA). All data from match and training was then exported from manufactures software and collated in a third-party platform (Zone 7 add details) where it was screened for anomalies and returned to the club data science team from analysis. It was important that the investigation provided context around the clubs existing monitoring strategies in relation to physiological response therefore total distance (TD) (m) and sprint distance (SD) (>25km.h-1) thresholds were maintained to maintain continuity with clubs monitoring process and data provided from the English Premier League (EPL) (Ellens et al., 2022).

Biomarker response data

Biomarker data: Data from point of care (POC) testing for individual players was exported from (Orreco Team) cloud-based analysis software into Microsoft Excel (add info) where raw data was combined with metadata to provide context around sampling such as opposition, competition and draw date. Biomarker draw and loading data were then analysed for correlations using Python (Van Rossum and Drake, 1995).

Blood sampling

Sampling was carried out by one principal investigator supported by an assistant for analysis in line with normal operating procedures at the club. Disposable latex gloves were worn for all procedures involving contact with bodily fluids and clinical waste. Consumables used in the collection and analysis of sampling were disposed of appropriately in yellow biohazard sharps containers. Participants were tested in a fasted, rested and hydrated state and blood sampling was conducted at the same time of day for each measurement (9.30-11.30am).

Blood sampling: hs-CRP

Point of care test: Whole blood capillary samples (20 μL) were taken from the participant's ear lobe, and immediately analysed at room temperature in line with the manufacturer's instructions. Inflammation was measured with an immunoturbidimetric hs-CRP assay on the Cube-S POC analyzer (Eurolyser Diagnostica GmbH, Salzburg, Austria). This photometric measurement of CRP is based on an antigen-antibody reaction between antibodies to human CRP bound to polystyrene particles and CRP present in the sample. All the biochemistry is contained within the test cartridges supplied by the manufacturer. The manufacturer reports a coefficient of variation for the assay of 2.83% for whole blood with a correlation coefficient R2 of 0.951 against a clinical laboratory gold standard. The measurement range of the analyser for whole blood is 0.5-20.0 mg/L (Daniels, 2021).

Blood sampling: Plasma Hydroperoxides/Plasma Antioxidants

Whole blood capillary samples (50 μL for FORD, and 20μL for FORT) were taken from each ear lobe (duplicate samples), processed and analysed immediately at room temperature in line with the manufacturer's instructions (Callegari SpA, Catellani Group, Parma, Italy). Briefly, heparinized capillary samples are immediately mixed with the reagent, centrifuged at 5000 r·min-1 (2000 G) for 1 min, and analysed colourimetrically in a Callegari CR3000 analyser (Callegari SpA, Catellani Group, Parma, Italy), according to the manufacturer's instructions at 37°C (Callegari SpA, Catellani Group, Parma, Italy). Lewis et al. (2016) previously published a detail the methodology for the FORT and FORD assays which includes coefficient of variations of 3.9% for FORT and 3.7% for FORD. OSI is a composite metric calculated from the ratio of FORT to FORD (plasma hyperoxides/plasma antioxidants).

Results

As this research represents an exploratory investigation into the relationship between physical loading and biomarker responses in professional football players, the results are presented in a non-traditional format. As stated in the study's methods, instead of following a rigid hypothesis-testing model, this section highlights the steps of investigation, focusing on the insights gained at each stage of the process.

The initial step in our investigation involved the graphical representation of individual load profiles in relation to biomarker responses. This process began by analysing the relationship between physical load and biomarker fluctuations. For load, we focused on two critical variables: *total distance* as a representation of training volume and *sprint distance* (defined as running at speeds >25 km.h-1) to capture session intensity. By graphing these variables against biomarker data, we aimed to visually identify any intuitive links between the physical demands of training and competition and the subsequent biological response.

This exploratory approach allowed us to profile potential patterns that could inform future analysis. The preliminary visual investigation set the foundation for more detailed statistical exploration as it highlighted areas we needed to explore biomarker response may be influenced by varying training and match-play loads.

Figure 7-1 Total Distance and Inflammatory response

This figure presents the first stage of the analysis, the relationship between TD covered by an individual player during training and matches and the corresponding hs-CRP response. The total distance, which serves as a measure of overall training volume, is represented on the left vertical axis, while hs-CRP levels (indicative of inflammatory response) are plotted on the right vertical axis. The horizontal axis represents time across multiple training and match days.

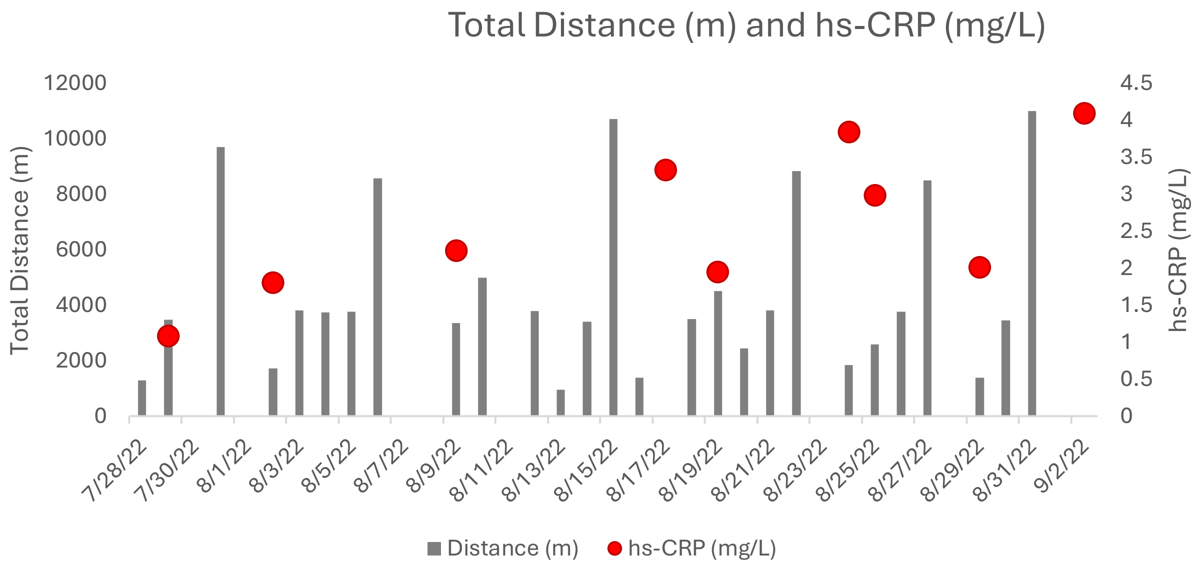
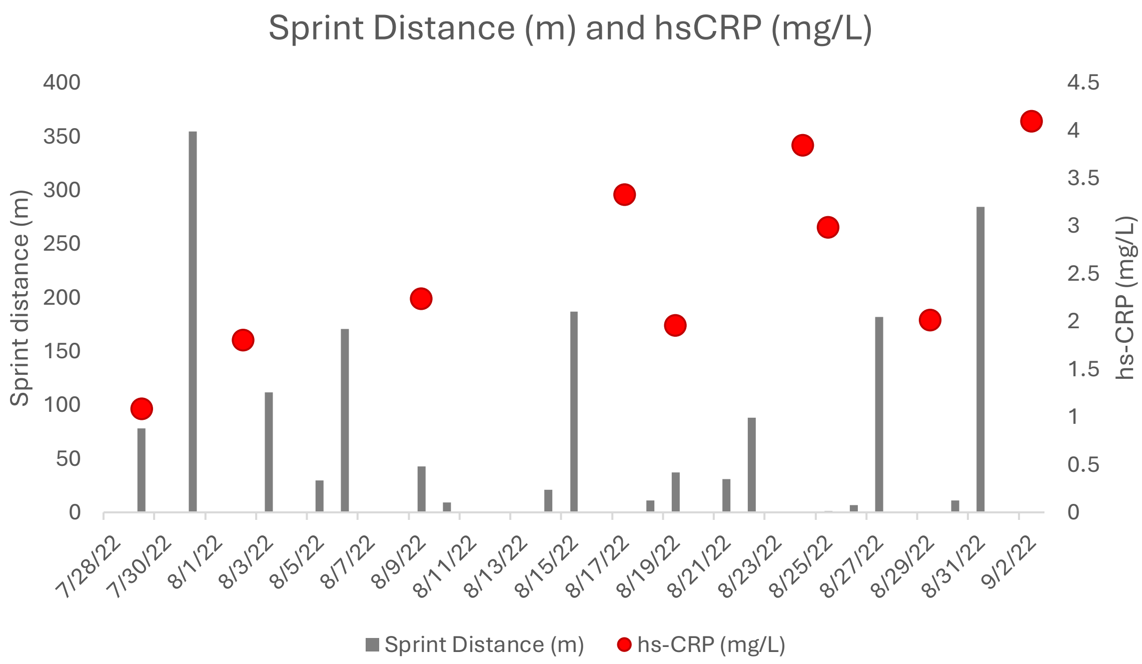


Figure 7-2 Sprint Distance and Inflammatory response

This figure focuses on the relationship between SD and hs-CRP levels for the same individual player. Sprint distance, used here as a measure of session intensity, is plotted on the left vertical axis, while hs-CRP values remain on the right vertical axis, with time along the horizontal axis.



After the graphical representation of load and biomarker response showed unclear direct relationships, we expanded the analysis to examine cumulative loading over different time periods. Specifically, we totalled the data for total distance (m) and sprint distance (m) across 4-day, 7-day, 14-day, and 28-day windows. These windows were chosen as they fell in line with typical milestones within training schedule. With biomarker response being profiled on MD+2 the 4-day window reflects the load of the match day plus one (MD+1) session and match day (MD) combined. MD+1 sessions were typically game preparation, and the only day of the week allocated to 11v11 training. This typically resulted in relatively high spring distance for some players (dependant on tactical approach) and so we wanted to incorporate this in the analysis alongside the game to reflect the total demands. The other windows 7-day, 14-day and

28-days reflective in the accumulation of load across the training cycle. The goal was to explore whether the summation of load across these windows might provide clearer insights into the correlation between physical exertion and biomarker responses. In this step, we ran correlation analyses between the aggregated load metrics and four biomarkers: hs-CRP (a marker of inflammation), FORT (reflecting oxidative stress), FORD (antioxidant defence), and the oxidative stress index (OSI, representing the balance between oxidative stress and antioxidant defence).

Table 7-1 Biomarker and load mean correlations

This table presents the relationship between biomarker responses 1) hs-CRP, 2) FORT, 3) FORD and 4) OSI ratio of FORT to FORD, alongside the cumulative total distance and sprint distance loadings over 4, 7, 14, and 28-day windows. Data are presented as correlation coefficients (r-values) between loading variables and hs-CRP across time windows.

BIOMARKER ALIAS	LOAD	WINDOW	MEAN CORRELATION
HS-CRP	Total distance	4	0.20
HS-CRP	Total distance	7	0.18
HS-CRP	Total distance	14	0.14
HS-CRP	Total distance	28	0.15
HS-CRP	Distance >25 km/h	4	0.22
HS-CRP	Distance >25 km/h	7	0.18
HS-CRP	Distance >25 km/h	14	0.12
HS-CRP	Distance >25 km/h	28	0.12
FORT	Total distance	4	0.04
FORT	Total distance	7	-0.02
FORT	Total distance	14	-0.04
FORT	Total distance	28	0.01
FORT	Distance >25 km/h	4	0.05
FORT	Distance >25 km/h	7	0.03
FORT	Distance >25 km/h	14	0.02
FORT	Distance >25 km/h	28	0.00

BIOMARKER ALIAS	LOAD	WINDOW	MEAN CORRELATION
FORD	Total distance	4	-0.04
FORD	Total distance	7	-0.06
FORD	Total distance	14	-0.08
FORD	Total distance	28	-0.15
FORD	Distance >25 km/h	4	-0.06
FORD	Distance >25 km/h	7	-0.06
FORD	Distance >25 km/h	14	-0.13
FORD	Distance >25 km/h	28	-0.14
OSI	Total distance	4	-0.06
OSI	Total distance	7	0.00
OSI	Total distance	14	0.15
OSI	Total distance	28	0.29
OSI	Distance >25 km/h	4	-0.03
OSI	Distance >25 km/h	7	0.07
OSI	Distance >25 km/h	14	0.22
OSI	Distance >25 km/h	28	0.27

The analysis of the relationship between training load and biomarker responses shows weak to very weak correlations across the different biomarkers and loading metrics.

High sensitivity C-reactive protein: hs-CRP displayed weak positive correlations with both total distance and sprint distance across various time windows. The mean correlation coefficients for hs-CRP and total distance ranged from 0.20 in the 4-day window (weak positive correlation) to 0.15 in the 28-day window (very weak positive correlation). Similarly, sprint distance had a weak positive correlation in the 4-day window (0.22), with correlations decreasing to 0.12 (very weak) in the 28-day window.

Free oxygen radical test: FORT, showed no significant correlation with either total distance or sprint distance across any time window. The mean correlations fluctuated around zero, with values such as 0.04 for total distance over 4 days and -0.02 for total distance over 7 days. These results suggest that FORT is not responsive to the types of physical loading examined in this study.

Free oxygen radical defense: FORD demonstrated very weak negative correlations with both total and sprint distance. The strongest negative correlation was observed for total distance over 28 days (-0.15), though this still falls within the "very weak" category. Sprint distance showed a similar pattern, with a maximum negative correlation of -0.14 over 28 days.

Oxidative Stress Index: OSI, which provides a global assessment of oxidative stress, showed a more complex pattern. For total distance, correlations increased from very weak negative (-0.06 at 4 days) to weak positive (0.29 at 28 days). This suggests that OSI might be more sensitive to cumulative training load over longer periods and maybe influenced by a longitudinal decrease in antioxidant resource (FORD) affecting the ratio. For sprint distance, the correlation was weak positive (0.27) at 28 days, further supporting the idea that OSI could reflect long-term response to physical loading. Due to the volume of correlations performed the findings could be influenced by the number of tests (Ranganathan et al., 2016).

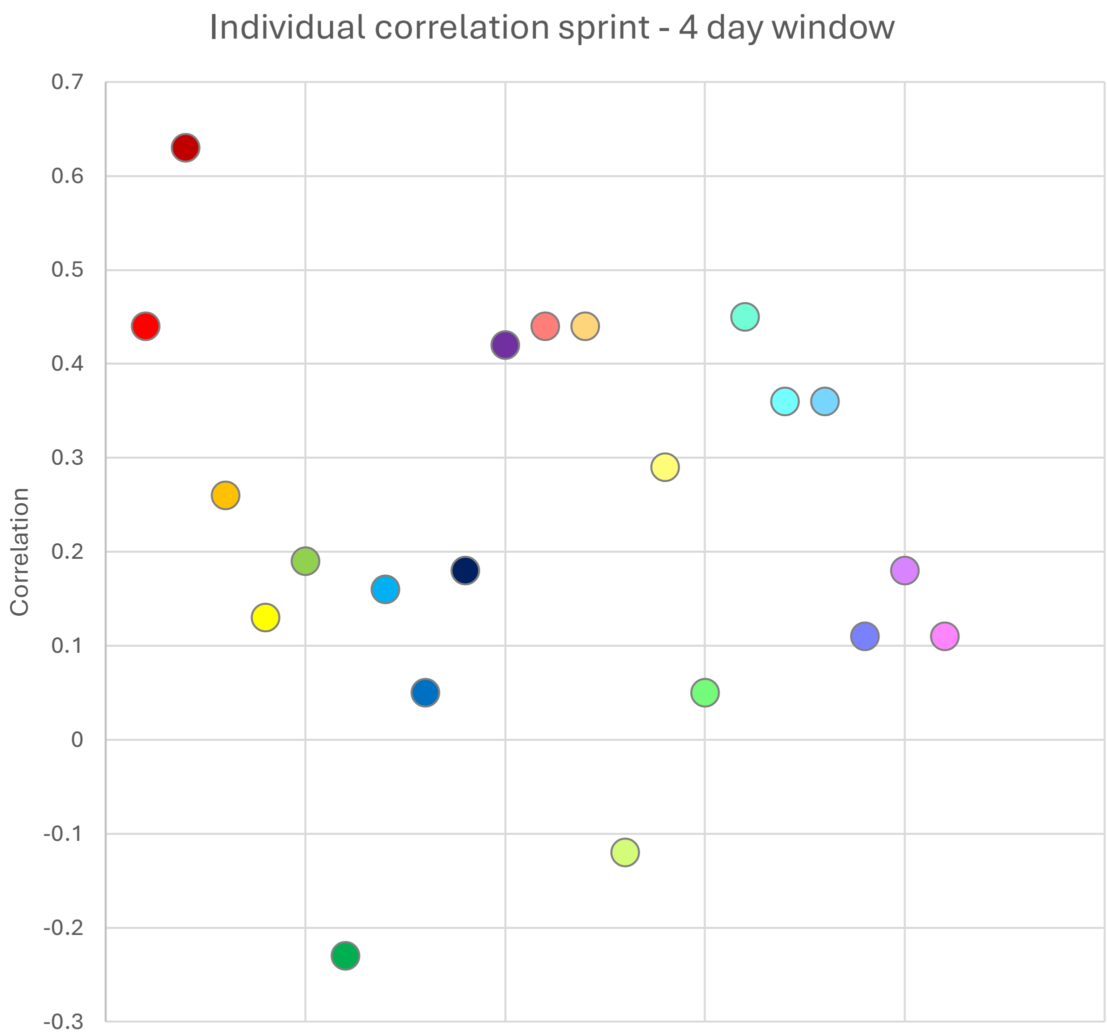
Overall, the strongest correlations found were hs-CRP in 4-day window for both sprint (0.22) and total distance (0.20), and oxidative stress in the 28-day window with sprint (0.27) and total distance (0.29).

Individual differences

To further explore the relationship between loading and biomarker response, we examined individual athletes' data to account for variability in response patterns. In our sample of 20 athletes, each with more than 10 hs-CRP measurements recorded on MD+2. In this exploration we have chosen hs-CRP because it demonstrated the most consistent correlations with sprint distance along with the 4-day window providing the strongest correlation. We observed individual differences in the correlations between sprint distance and hs-CRP levels (Figure 7-3) with the individuals spanning very weak negative to strong positive correlations.

Figure 7-3 Individual correlations 4-day sprint distance and hs-CRP

Individual correlations: data from 21 players correlation for sprint distance in the four-day window for sprint distance each player is represented by a coloured marker. The distribution of correlation coefficients shows individual variation in the loading measures not apparent when considering group correlations results.



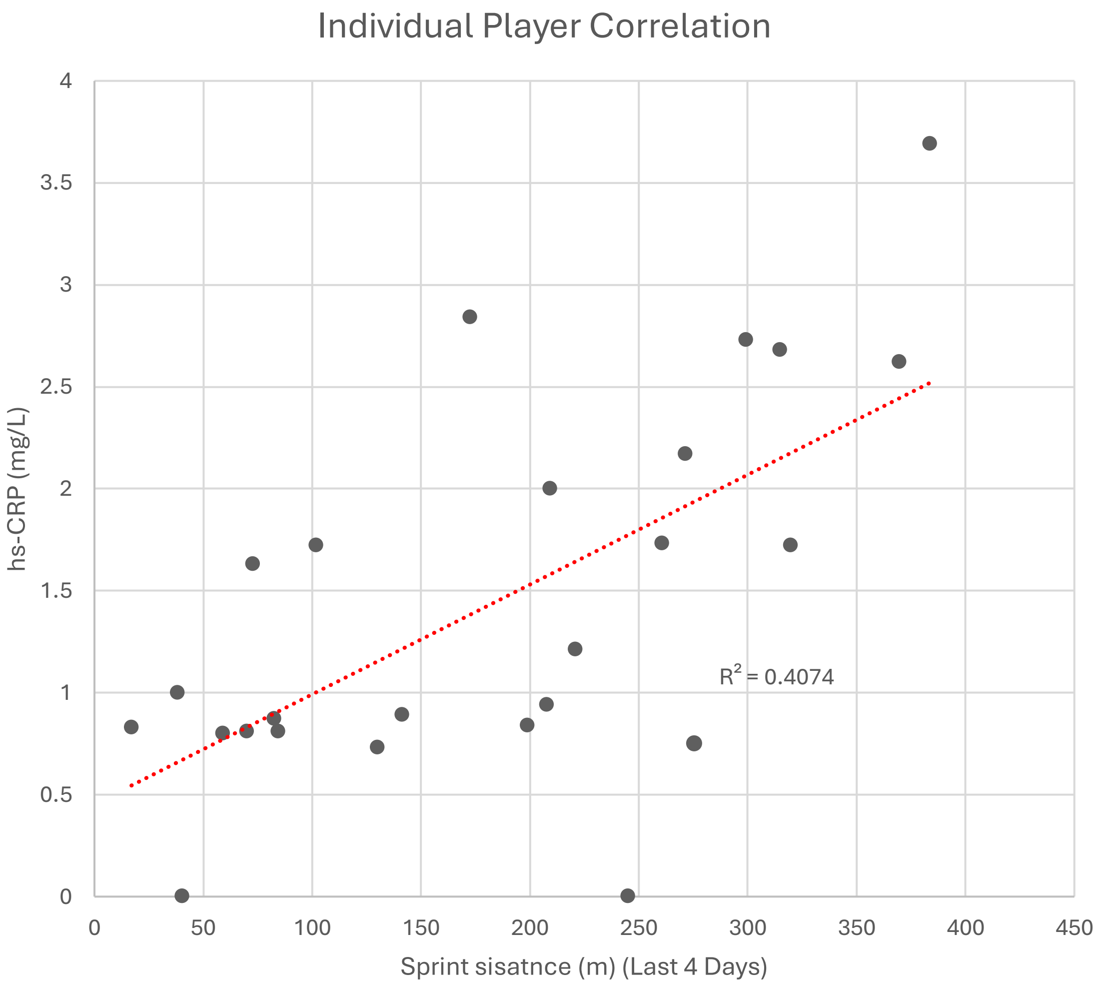
- 1 participant had a very weak negative correlation (< 0.20),
- 1 participant showed a weak negative correlation (-0.20 to 0.00),
- 9 participants exhibited very weak positive correlations (0.00 to 0.20),
- 4 participants showed weak positive correlations (0.20 to 0.40),

- 5 participants displayed moderate positive correlations (0.40 to 0.60),
- 1 participant exhibited a strong positive correlation (0.60 to 0.80).

Although the group mean correlation was 0.22, indicating a weak positive relationship (R2=0.05 ~5% of variance explained by sprint distance over the last 4 days), these results highlight significant individual variability. For one participant, the Pearson correlation coefficient was as high as 0.63 ($R^2 = 0.40$), (Figure 7-4) meaning that around ~40% of their hs-CRP variance could be explained by sprint distance exposure in a 4-day window.

Figure 7-4 Individual correlation example

The measurements of hs-CRP for a particular athlete and the volume of sprint distance performed in the previous four days for each of those measurements. The Pearson correlation coefficient is 0.63 (R2=0.40) indicating that ~40% of the variance in the hs-CRP measurement for this participant is explained by the amount of sprint distance were performed in the last 4 days prior to the measure being taken.



Discussion

The results of the study were largely inconclusive indicating weak relationships between training load variables total distance (m), sprint distance (m) and biomarker responses in elite professional football players. While hs-CRP displayed the most consistent correlations with training load, FORT and FORD showed weaker or negative correlations. This lack of correlation suggests that the biomarkers may not directly reflect the acute and accumulated loading in this sample of players (Radzimiński et al., 2020; Póvoas et al., 2022). However, we observed individual differences in biomarker response suggesting a complex interplay that requires further investigation. These variations point to factors, such as individual recovery rates, level of physical fitness and individual responses to accumulated load. This complexity suggests that whilst biomarkers may offer insights into player status, interpretation of data must account for individual variability and confounding variables not highlighted in this study. Overall, these patterns highlight the importance of longitudinal assessments in understanding individual variability and responses to training loads.

Biomarker responses to load

The findings from this study provide insight into the relationship between external load and specific biomarkers, hs-CRP and redox markers (FORT, FORD) and oxidative stress index. Whilst the results established some links between load and biomarker response, the overall magnitude and consistency of these relationships were weak. The strongest observed mean correlation for hs-CRP was with sprint distance (mean correlation 0.22), which falls into the "weak positive" category according to Pearson's correlation scale (Kirch, 2008). This suggests that while there is some sensitivity in hs-CRP to acute load the biomarker explains only around 5% (R2=0.057) of the variance in response to load at a group level. This relatively weak relationship limits the utility of hs-CRP as a robust, standalone marker of players response to external load demand (sprint distance). However, these results are consistent with existing literature indicating that hs-CRP tends to rise after acute bouts of exercise, particularly due to muscle damage from eccentric loading, as seen in sprint actions (Mohr et al., 2016; Jatene et al., 2019; Clayton et al., 2023; Clayton et al., 2024).

Over longer windows (e.g. 28 days), the correlation further weakens, aligning with research suggesting hs-CRP is less responsive to chronic loading and maybe viewed as an indicator of response to acute stimulus (Silva et al., 2014; Silva et al., 2018; Jatene et al., 2019). Though the group mean correlation was 0.22 (individual differences were pronounced. One participant, for example, exhibited a Pearson correlation of 0.63 (R^2 = 0.40), where 40% of hs-CRP variance was explained by sprint distance (Figure 7-4). This variability highlights that while hs-CRP may not show meaningful relationships with loading at a grouped level large individual differences exist that could be useful to practitioners and support staff when profiling players responses to load (Póvoas et al., 2022).

The results of the FORT correlations suggest little to no correlation with either total distance or sprint distance in any window. This indicates that this marker may not be appropriate for monitoring physical load in line with our exploratory approach. This outcome aligns with previous studies that underscore the complexity and variability of oxidative stress markers in response to exercise (Baralic et al., 2015; Póvoas et al., 2022). Similarly, FORD demonstrated only weak negative relationships with both TD & SD at 28-day windows, pointing to a potential delayed response to cumulative loading on antioxidant resources. The oxidative stress index (OSI), while similarly limited in the strength of relationship, follows patterns observed in literature concerning the impact of long-term training loads on oxidative stress and recovery (Finaud et al., 2006a; Mello et al., 2017; García-Cardona et al., 2021; Ponce-Gonzalez et al., 2021). This is consistent with findings that oxidative stress may accumulate with prolonged exposure to intense training due to a decrease in antioxidant resource to neutralise hyperoxides (Lewis et al., 2015; Selmi et al., 2022; Silva et al., 2022).

In contrast to hs-CRP, the direction of the correlation between oxidative stress markers and load are inconsistent, with fluctuating positive and negative correlations depending on the load window and marker measured. This inconsistency may suggest that external factors, not captured in this study, play a substantial role in influencing oxidative stress responses. These could include recovery strategies, diet, or individual difference between players (Powers and Jackson, 2008). Therefore, while the data offers an initial link between load and certain biomarker responses, the weak and variable nature of these relationships complicates efforts to establish firm conclusions about their applicability in load management for professional football players.

Theoretical advancement

This study provides valuable insights into the limited but developing understanding of the longitudinal relationship between physical load and biomarker responses in elite athletes. While the literature has explored acute responses such as elevated hs-CRP following exposure to high-intensity activities (Clarkson and Hubal, 2002), there remains limited data on chronic biomarker responses over extended periods of training and competitive match cycles. Our findings contribute to this gap by offering evidence of these biomarker fluctuations, particularly highlighting the distinction between acute markers like hs-CRP and chronic markers such as oxidative stress. With CRP showing strongest correlations at 4-day window and oxidative stress 28-day window for both sprint and total distance. These findings align with existing theories on inflammation and recovery in response to muscle damage (Silva et al., 2014; Baralic et al., 2015; Souglis et al., 2015; Mello et al., 2017; Souglis et al., 2018; Jatene et al., 2019; Ponce-Gonzalez et al., 2021; Clayton et al., 2023; Clayton et al., 2024).

The link between increased hs-CRP levels and high-intensity actions like sprints supports previous research, indicating that hs-CRP may reflect inflammatory responses to EIMD which could come from the eccentric muscle damage that occurs during mechanical actions such as changes of direction (Peake et al., 2017). This connection is crucial for understanding how biomarkers may signal underlying physiological changes in response to training loads, therefore adding to the body of knowledge on load management.

Although these results provide nuanced insights into how biomarkers respond to external load variables (total & sprint distance) the overall correlations suggest limited predictive capacity in this specific dataset. However, and perhaps most importantly whilst is it difficult to establish a dose response relationship from the mean data, our findings demonstrate substantial individual differences in biomarker response by players, pointing to the existence of large individual variation. These differences could have meaningful implications for individualised training and recovery protocols, reinforcing the importance of individualised monitoring strategies in sports science (Mann et al., 2014).

Practical advancements

While the results indicate potential relationships between training loads and biomarker responses, our exploratory, data driven approach means that these findings should be viewed as preliminary. This exploratory nature limits the precision of conclusions, highlighting the need for more targeted investigations that can establish a clearer dose-response relationship between physical load and biomarker fluctuations. By fostering a deeper understanding of the relationship between load and biomarker response practitioners can make more informed decisions on individualised training prescription and recovery strategies, providing actionable insights for performance and recovery management, particularly in professional football (Halson, 2014).

The identification of individual differences is response could have significant practical implications in the applied setting. Biomarker responses especially hs-CRP could aid in detecting individuals whose inflammatory response is more pronounced following certain types of loading, such as high-intensity sprint work (Owens et al., 2019). A key actionable insight of this approach is that even in the absence of strong group level correlations, specific individuals showed detectable biomarker changes in relation to their loading patterns. This suggests that for certain players, biomarker monitoring could provide valuable insights for managing training loads. For instance, the increased inflammatory response following high sprint volumes may necessitate individualized recovery interventions. These finding support the notion that recovery interventions or load modification should considered to prevent non-functional overreaching and managing fatigue during congested periods of the season (Coutts et al., 2007). Therefore, understanding individual differences in biomarker responses may offer a critical tool for optimizing both recovery and performance strategies.

No definitive relationship emerged between FORT/FORD and the loading variables in our sample of 21 elite professional players. This lack of correlation may not necessarily indicate an issue with the biomarkers themselves but may point to potential limitations in how these biomarkers were analysed in our specific context (Baralic et al., 2015; Mello et al., 2017).

<u>Limitations</u>

This study's exploratory nature presented significant challenges. Rather than being designed to rigorously test a specific research hypothesis, we set out to answer a performance question and employed an opportunistic "throw everything at the wall and see what sticks" approach. This exploratory method, while valuable for uncovering initial insights, also has limitations in terms of the robustness of the conclusions we can draw. A more controlled, hypothesis-driven study would be necessary to establish dose-response relationships between external load and biomarker responses (Bishop et al., 2008).

Several confounding factors may have influenced the results. These include the time “post loading” when measurements were taken, the match schedule, and the individual characteristics of the athletes, such as muscle fibre type, baseline fitness level, and genetic factors that influence inflammation and recovery responses (Peake et al., 2017; Murtagh et al., 2023). Although this was deemed useful in a practical sense for the blood draw to be taken on MD+2 as it allowed practitioners to detect players who were not fully recovered, hs-CRP levels which are known to peak approximately 24 hours after exercise and may have been on the decline by MD+2 (Duarte et al., 2022; Ascensão et al., 2008). This may have contributed to the variability in biomarker responses.

Additionally, our study focused solely on external load variables (total distance and sprint distance) and lacked measures of internal load. Internal load metrics, such as HR or session RPE (rating of perceived exertion), might have offered more nuanced insights into the relationship between training load and biomarker fluctuations (Impellizzeri et al., 2005). Unfortunately, the club was transitioning between technology providers during the study, and data quality issues forced us to exclude internal load measures from the analysis, which may have provided more comprehensive context for interpreting individual differences in biomarker responses (Bourdon et al., 2017).

Recovery interventions immediately post-game and the training schedule (day on or off) on MD+1 provided another confounding factor we could not control. In elite football, recovery is essential part of the training cycle for preparing athletes for subsequent matches. The interventions used during this recovery such as cold-water immersion, soft tissue therapy, and targeted nutritional support are well-known to influence biomarker responses (Minett et al., 2014; Huggins et al., 2019). However, given our dual role researcher and applied practitioner preparing players for upcoming games, we could not eliminate these interventions, and their influence on the biomarkers remains unquantified in this study.

Overall, it is possible that different time points, load measurements, or even external factors such as recovery interventions could have influenced the outcomes, necessitating further research to better define these relationships (Minett et al., 2014).

<u>Future directions</u>

Future research should aim to integrate internal load measures, such as heart rate and session RPE. Establishing connections between internal and external load metrics and their respective biomarker responses could provide a more holistic understanding of athletes' physiological stress and recovery processes (Impellizzeri et al., 2005). This would also aid in identifying relationships that were potentially masked in the present study due to our exclusive focus on external load measures.

Unlike this study's applied search for correlations between datasets, future work should adopt a more hypothesis driven approach. A controlled study designed to test the relationships between biomarker response and various loading parameters would allow for clearer interpretations and stronger conclusions about cause and effect (Bishop et al., 2008).

One of the major limitations of this study was the lack of control over confounding variables such as recovery interventions and match/ travel schedules especially when trying to establish the magnitude of relationship in MD+2 measures. Subsequent research should control for or systematically record types and frequency of recovery strategies, including cold water immersion, soft tissue therapy, and nutritional interventions, all of which have known effects on biomarker levels (Minett et al., 2014; Huggins et al., 2019).

Our study focused only on total distance and sprint distance (>25 km/h) as measures of external loading volume and intensity. Future research should consider a wider range of loading variables including mechanical and technical aspects of loading (Casamichana et al., 2013). A more diverse selection of load measures could help detect more specific physiological stress responses (particularly to mechanical stimulus) and lead to a more comprehensive understanding of how elite players physiological response may occur to different types of load demand.

Conclusions

In conclusion, this study provides initial insights into the relationship between biomarkers such as hs-CRP and oxidative stress with external load measures. Although these associations were variable, we observed some (weak) correlations, particularly with hs-CRP in response to sprint distance and total distance, these findings were inconsistent across the group, suggesting the presence of substantial individual differences in response. The lack of clear patterns in other biomarkers like FORT and FORD emphasises the need for a more controlled, hypothesis-driven approach. Future research should also incorporate internal load metrics such as heart rate, control for confounding factors such as recovery interventions, and expand the types of external load measures to better understand the association between load and response. These adjustments, along with more rigorous control of confounding variables, will help refine biomarker use as a practical tool for load monitoring and recovery management in elite sport contexts.

Reflective Pause 3

Reflecting on this study its clear this investigation sparked valuable discussion and made us think critically about our processes within the MDT. It challenged us to think more deeply around our readiness process, why and how data was generated as well as how we could develop further investigations to drive a culture that includes more academic/scientific rationale to guide our decision making. By committing to integrating scientific process of investigation within our everyday tasks we could foster a more pragmatic understanding of what our data means in the context of player health and performance.

Integration of research within the organisation

The study provided some much-needed objectivity around how we analyse and consider findings. It was important to communicate not to view the study as a failure just because it didn't find strong correlations. In fact, this result suggests that there are more complex factors at play beyond just the training load variables we analysed. The study highlighted the need to broaden our perspective and consider other elements that might influence player response to load, which may lead to deeper insights and a more comprehensive understanding of the factors that influence player readiness. Readiness in the practise environment is determined by various measures aimed at identifying players who maybe fatigued and at risk of underperformance or injury. These measures focus on both acute and chronic “spikes” in load and assessments such as range of movement testing, isometric strength and biomarker analysis to determine response.

Reflection

On reflection the process provided a valuable development opportunity to improve my skills as an applied researchers within my professional practise environment. Primarily learning opportunities around the difficultly of generating meaningful insights to impacting processes within a team with varying skillsets. Whilst the results of our analysis show weak associations between loading and biomarkers interpretation of these findings was received differently amongst stakeholders. Different perspectives and beliefs of individuals formulated from experience, knowledge and expertise or biases leave room for multiple interpretations. As previously described the elite football environment is high-pressure and fast paced. I feel in football people tend to interpret data in ways that align with their own agendas or desired outcomes. Rather than approaching the information objectively, they use it to push their message or reinforce their narrative. This selective interpretation allows them to highlight the aspects of the data that support their views while downplaying or ignoring parts that might challenge their position. Several instances occurred where conclusions were drawn from the data that did not align with the research findings but were augmented to support arguments around players training involvement. Stakeholders who wanted minimal disruption to the training schedule and a player to be involved in a session downplayed finding, whereas those exercising caution cherry picked data points to support the notion a player maybe under recovered, both using the results to validate their arguments where in reality we couldn't draw such concrete conclusions. This provided a development opportunity where I learned the value of sticking with the facts and a comfort from accepting, we cannot possibly know all the answers. Accepting that grey areas exist, and we cannot control for all confounding variables in practise allows us to acknowledge that we may make well intentioned mistakes, but that valid and reliable data can help us make more informed decisions thus blending the art of coaching with science. Generating better data however, points towards the need for a more hypotheses driven research approach within professional practise, where greater control over confounding factors reduces the ability to manipulate interpretations, encouraging objectivity and supporting collaboration across stakeholders in different departments.

CHAPTER 8

THESIS SYNTHESIS

Introduction

This chapter provides a critical reflection on the findings of this thesis, examining their alignment with the overarching research objectives. Initially, this section synthesises insights from Chapters 3-7 to demonstrate how the research addresses the aims articulated in the introductory chapter have been met. Following this, the chapter explores the core themes surrounding load monitoring and physiological response within elite professional football. Through this exploration, it expands on the theoretical, conceptual, and practical contributions of the thesis, positioning these contributions within the broader landscape of sports science literature and professional practice. The chapter concludes by identifying potential avenues for future research. These suggestions are framed to address existing gaps in the field, directing further investigations that can advance both academic understanding and applied methodologies in training load monitoring.

Fulfilling Aims & Objectives

This thesis aims to enhance the understanding of optimal loading and monitoring practices in elite professional football. The primary objectives of this thesis were to examine two key functions of my role as a sport scientist. Understanding the demands of the elite football and exploring players response to loading. The following sections detail each research objective, explaining its theoretical and practical basis and highlighting where each objective is addressed within the thesis. This structure refines the specific contributions of each chapter towards the thesis aims.

Objective One: Examining current approaches to load monitoring.

This objective was met through contributions from multiple chapters (Chapters 3 & 4). The literature review highlights the need for a comprehensive approach to understanding the multifaceted dimensions of loading in elite football, highlighting areas currently underrepresented in monitoring practices. In response, a theoretical framework was developed to conceptualise the demands associated with football specific movements, organizing them into categories of what represents a mechanical challenge, metabolic challenge and what maybe both. Through a systematic search, the thesis identified methodologies to assess combined areas of loadings, covering both established and emerging approaches. Furthermore, this search reviewed patents and evaluated new technologies with potential applications in the professional practice environment, ensuring an informed basis for future implementation of advanced load monitoring systems.

Objective Two: Develop a novel conceptual approach to quantify different types of load associated with football

Building upon the foundations established in Objective One, the next phase of research explored a novel approach to load monitoring (Chapter 5). Here, an approach was identified that meets both theoretical and practical gaps outlined in the initial chapters, providing a framework to address loading from a multi-dimensional perspective. Using foot mounted inertial measurement units (F-IMU) to quantify loading in three distinct parameters (locomotor, mechanical and technical). This approach was deployed within an applied setting buy profiling elite players training load prescription who were engaged in rehabilitation following injury. This method provided face validity, suggesting that the approach could accurately detect and distinguish between various loading parameters under differing training prescriptions. A conceptual model was then developed, offering a detailed view of loading across the rehabilitation cycle in the three key parameters. This model highlights a nuanced view of load management not previously identified within the literature.

Objective Three: Explore the relationship between training load and biomarker response

This objective is fulfilled through both the physiological response literature review and the physiological response to load study (Chapters 6 & 7), which together lay the groundwork for examining load responses. The literature review provides essential context on the biomarkers already used by the club, focusing on the association of these biomarkers to measures of loading. This background highlights the role of biomarkers in assessing players' responses to training and match demands specifically inflammatory and oxidative stress responses. The biomarker study builds on this groundwork, investigating the relationships between specific external load variables, total distance and sprint distance and four biomarker measures. Through this approach, the study establishes load response correlations at a group level and highlights significant individual differences in response to stimulus. These findings underscore the complexity of load monitoring in elite sports and emphasize the need for individualized approaches to optimize training and recovery.

General Discussion

The sections that follow aim to critically examine how the findings related to each objective and have contributed to the body of literature on load monitoring and response within elite professional football. This examination will highlight both theoretical and practical contributions, showing how these findings support advancements in the conceptual understanding of load and offer actionable insights for practitioners in the field. Additionally, these sections will include my personal reflections on the research process. They will consider how the proposed action research model influenced not only the thesis structure but also my own professional development and learning throughout the project. By integrating both the findings and reflective insights, these sections emphasise the holistic impact of this thesis on both my professional and academic growth.

Theoretical Contributions

Load monitoring

In elite football, effective load monitoring strategies should prioritize identifying the key movements that impose distinct physiological demands on players. Traditional metrics based on time-motion analysis often lack the sensitivity to capture the comprehensive physiological and mechanical stresses associated with football activities (Akenhead and Nassis, 2016; Murtagh et al., 2019). As a result, these conventional measures may not adequately represent the full range of activities that contribute to total player load, overlooking crucial aspects of mechanical stress and technical demands.

To address these limitations, this thesis introduces a conceptual framework that categorizes movements by their perceived physiological and mechanical demands. This model helps to distinguish movements likely to elicit metabolic versus mechanical responses, as well as those that combine both types of load. This structured approach highlights the utility of expanding monitoring strategies beyond locomotor metrics to include multi-faceted measures that better reflect actual player demands. Combining alike movements (running, changes of direction and technical actions) into three key parameters also makes analysis of sessions simpler. Reducing the number of metrics practitioners need to use to interpret the demands of an activity.

Recent advancements, such as the use of inertial measurement units (IMUs), have shown promise in quantifying mechanical stresses and technical actions in practical environments, providing a more nuanced view of player demands across various movement patterns (Beato et al., 2018; Emmonds et al., 2023). These devices enable coaches and sports scientists to assess the mechanical and technical load components within training and competition settings, giving a richer perspective on load demands. Although IMUs have been previously employed to monitor football movement demands, they have not been integrated into a framework of this scope and purpose before. The framework presented in this thesis synthesizes and aligns movements and aspects of loading into a simple but comprehensive framework, offering a novel way to measure and understand the demands of football.

Novel approach

This thesis introduces a new framework by combining metrics that, while previously measured individually, are now integrated into aspects of loading that are connected to key components of football specific movements. Traditional load monitoring has heavily emphasised locomotor demands in time motion analysis which, while valuable may not fully represent the sport's mechanical and technical components (Buchheit et al., 2014; Buchheit et al., 2015; Lewis et al., 2022) Our approach expands on these metrics by incorporating measures of mechanical stress specifically, the demands associated with change of direction (COD) activities and technical actions, including touches, kicks, and ball striking. This new approach represents an innovative synthesis of the demands, organising movements into three key parameters (locomotor, mechanical and technical) more comprehensively capturing the multifaceted nature of football movements.

By adopting this broader framework, we can more precisely link types of load with physiological demands and responses, allowing for a more tailored approach to training and rehabilitation (Buchheit et al., 2014; Emmonds et al., 2023). This multidimensional perspective contributes to a more comprehensive understanding of the load players experience, which has positive implication for the design and implementation of training load prescription and rehabilitation strategies. Importantly, our approach has demonstrated face validity, differentiating between distinct types of loading, namely locomotor, mechanical, and technical across varying phases of the rehabilitation process. This capability ensures that prescribed load intensities can be effectively quantified and tracked as players prepare to return to training and competition (Harper and Kiely, 2018; Taberner et al., 2019). The approach has potential applications beyond rehabilitation, extending to the full training cycle. By monitoring these parameters across different training phases, we could refine load management strategies to incorporate currently underrepresented aspects of load, ultimately optimising training prescription with positive outcomes for performance and player availability.

Whilst the framework is useful, the metrics do require familiarisation to understand their relation to how variations in training and different types of activities (pitch dimensions, number of players, session types) affect the outputs of the variables (Buchheit and Laursen, 2013). Furthermore, working with a commercial company introduces challenges to interpretation of training data, as the equations underpinning the created metrics are proprietary or “black box”. Both linear and nonlinear movements are heavily weighted by acceleration/deceleration, whilst this effectively captures the external mechanical load demand of activities, this highlights the ongoing need to integrate measures of internal load into field-based assessments.

Response to load

In the pursuit of optimising player readiness, the club implemented a biomarker monitoring process centred around four key variables: high-sensitivity C-reactive protein (hs-CRP), a marker of pro-oxidative stress (FORT), antioxidant resources (FORD), and the oxidative stress index (OSI), calculated as the ratio between FORT and FORD. Reviewing current literature reinforces the validity and reliability of these biomarkers particularly hs-CRP and oxidative stress markers for assessing recovery status and potential overtraining risk in footballers (Mohr et al., 2016; Owens et al., 2019; Haller et al., 2023).

Given that these markers are inherently variable across individuals, interpreting them requires caution, particularly with respect to load quantification in terms of volume and intensity. Variability in biomarker response is well documented (Haller et al., 2023; Póvoas et al., 2022; Ponce-Gonzalez et al., 2021). The findings of our investigation into biomarker response to loading showed only weak associations between loading parameters and biomarker responses. Notably, the 4-day loading window revealed the strongest correlation (0.22 and 0.20 correlation coefficient) between hs-CRP and both sprint and total distance. Although at a group level this showed a weak relationship we identified “responders” and “non-responders” within our sample with some players displaying much stronger correlations (0.63 R2=0.40). These findings do support research identified in the literature review of hs-CRP's utility in reflecting short term inflammatory response to intensive load (Toumi and Best, 2003; Silva et al., 2014). Conversely, redox markers FORT and FORD showed inconsistent correlations with loading windows. The OSI displayed a promising trend in line with existing literature, supporting its potential as a chronic response marker, as evidenced by progressively strengthening correlations over the 28-day loading window (Ispirlidis et al., 2008). These findings underscore the considerable individual variability observed in biomarker responses to loading, as evidenced by the broad range of correlation coefficients. This variability suggests that other external factors, unaccounted for in the current analysis, could be influencing biomarker fluctuations.

In terms of theoretical contributions, it is important to distinguish "nice to know" from "need to know" information that can inform practical decisions. Our study only found weak associations between total and sprint distance and biomarker responses at a group level. Whilst this is theoretically interesting and "nice to know" it could complicate decision making in practice by leaving data open to interpretation. Given the complex multifactorial nature of biomarker responses in elite professional athletes our results call for more hypotheses driven testing. Establishing what factors could contribute to players being classed as responders or non-responders would produce "need to know" theoretical insight that can inform decisions in practice. Applying factors such as age, differing levels of fitness, training history and boarder range of training load dimensions to provide "need to know" insights for practitioners attempting to establish response would make the data more useful in practise.

Practical Contributions

<u>Load monitoring</u>

Foot-mounted inertial measurement units (F-IMUs) offer a contemporary, practise ready solution for quantifying the multidimensional aspects of load in professional football. These devices alongside our novel approach to load monitoring allow for a more comprehensive quantification of multiple parameters of load. Quantifying changes of direction and technical actions such as ball striking alongside locomotor parameters provides practitioners with a deeper understanding of the demands of the training and competitive cycle. This deeper insight can give practitioners clearer insights into both the mechanical and technical demands imposed on players, facilitating more informed decisions regarding training prescription and rehabilitation progressions. One area that stands out is the previously unquantified volume of technical actions within a training week, which can now be systematically integrated into training plans. This addition of technical load metrics began impacting organisational processes, particularly in rehabilitation settings with the professional practice environment. Here, the ability to quantify technical load provides practitioners with an objective measure to guide the progression of exercises, ensuring that rehabilitation aligns with the specific demands of gameplay (Emmonds et al., 2023). This aligns with recent research advocating for expanded load metrics to better represent the true demands of sports like football (Beato et al., 2018; Waldron et al., 2021).

The approach also challenged practice, as measuring specific aspects of load added a layer of accountability to session design and training prescription. Knowing that practitioners would receive feedback on technical and changes of direction performed within the session may have heightened awareness and created a more deliberate evaluation of what aspects of loading should be emphasised or controlled in each rehabilitation session. Implementing novel approaches and frameworks within applied practise that encourage critical thinking and reflection are inherently beneficial to practise (Knowles et al., 2001). It not only encourages critical thinking and challenges established methods but also fosters a culture of improvement and innovation, which can improve coaching process within our applied practice (Knowles et al., 2001).

Whilst adapting to this new framework may take some adjustment due to the novelty of the metrics compared with the current monitoring process, future investigations should focus on capturing load demands across the full training and competitive cycle.

This should include individual player profiles and understanding of position specific demands to ensure comprehensive, actionable insights for practise.

<u>Responses to load</u>

Effectively organizations want to know if the juice is worth the squeeze. Is the investment in biomarker analysis worth the return on investment through the data it generates? Currently there are large financial implications for POC biomarker testing with equipment and consumables potentially costing tens of thousands of pounds per season. The financial cost isn't the only thing teams must consider as highly skilled and trained staff are required to effectively capture data through sampling and the complex methods of blood handling and analysis. Whilst elite professional football teams may have the financial resources to cover both the cost of equipment and staff, they should consider whether resource are better placed elsewhere to improve the return on investment, especially when the data generated shows weak associations with specific load parameters at a group level.

Our investigation into biomarkers in this study highlights the potential for biomarker analysis to enhance training and recovery interventions, particularly for players identified as responders. The inclusion of biomarkers like hs-CRP and oxidative stress markers offers a unique perspective on how different loading parameters influence inflammatory and oxidative stress responses. However, the analysis also underscores that load alone (total distance, sprint distance) does not account for a player's response and so use on group level may not be worth the investment. Individual factors such as nutrition, lifestyle, and psychological stress can significantly impact response and recovery (Haller et al., 2023). Understanding these factors through biomarker analysis may provide valuable insight and actionable data securing return on the investment in POC testing however, this comprehensive view suggests that monitoring strategies must consider these broader variables alongside load to personalise interventions (Silva et al., 2014; Mohr et al., 2016) to realise any potential return on investment.

Efficacy vs effectiveness

In the field of intervention research, two distinct approaches are typically recognised: efficacy and effectiveness. Understanding the differences, strengths, and limitations of these approaches is critical for framing the current research project and situating it within the broader research landscape.

Efficacy research is typically characterised by highly controlled conditions, where the goal is to determine whether an intervention works under ideal circumstances. This approach often involves randomised controlled trials (RCTs), in which participants are carefully selected and the intervention is administered in a controlled environment, with rigorous control over potential confounding variables (Higgins, 2008). The primary strength of efficacy research lies in its ability to establish causal relationships between the intervention and outcomes, providing strong evidence of the intervention's potential effectiveness under optimal conditions Miller & Rollnick, 2013). However, a significant limitation is that the findings may lack external validity, as the tightly controlled experimental setting often fails to replicate the complexities and variability of real-world environments (Moher et al., 2009).

In contrast, effectiveness research seeks to determine whether an intervention works in real-world settings, where variables are less controlled, and participants are typically more representative of the general population (Glasgow et al., 2003). The strength of effectiveness research lies in its external validity, as it examines the performance of the intervention in the environments where it is likely to be applied in practice. However, effectiveness studies often face challenges related to smaller sample sizes, the presence of confounding variables, and a lower degree of statistical power (Tugwell et al., 2007). Despite these limitations, the effectiveness approach is crucial for understanding how interventions function when deployed outside the controlled confines of efficacy studies and is an essential to the application of action research within professional practise.

The decision to adopt an effectiveness approach in this research was driven by the unique characteristics of the professional environment of elite football support in which the research was implemented. The population under study is unique and notoriously difficult to access, which significantly constrained the ability to recruit a sufficiently large samples to conduct traditional efficacy focused research. Furthermore, the real-world application of our research project necessitated a focus on its practical utility rather than theoretical potential. By prioritising external validity, this research sought to assess outcomes under the conditions that participants would face every day within their practise environment.

Given the complexities and the inherent challenges of conducting research with elite sporting populations like professional footballers, the effectiveness approach delivered through the action research framework was deemed the most appropriate methodology for addressing the research questions. This approach allowed for a broader understanding of how the research operates in the field, where external factors and participant variability are inevitable. While efficacy studies are valuable for establishing causal mechanisms, they often fail to capture the full range of contextual factors that influence an intervention's success in practice (Shadish et al., 2002) Therefore, in this case, focusing on effectiveness was not only appropriate but necessary to answer the research question.

It is important to acknowledge the limitations associated with the effectiveness approach. The small sample size and the lack of full control over confounding variables are inherent challenges of this research design. These limitations may

Reflections on the Process

In the high-performance environment in which I am currently employed, decision making around adopting new interventions or technologies is often influenced by the urgency to gain a competitive advantage. This pressure to stay ahead of other teams and organisations can drive impulsive decisions (Kane et al., 2019). These decisions are often made with limited critical evaluation of the both the benefits and costs to the organisation (Ringuet-Riot et al., 2013). The intense drive to innovate and find immediate solutions to problems can result in a hasty implementation of new practices, without a thorough understanding of the effectiveness, suitability, or potential limitations of interventions in the specific practise environment (Kane et al., 2019).

Without critical evaluation prior to adopting new processes or technologies practitioners maybe at risk of negative consequences, leading to decisions that may not optimally serve the players or organisations long term needs. For instance, inadequate assessment of a new technologies utility in practice or its demands on resources can result in poor return on investment and reduced effectiveness in enhancing performance and player health (Robertson et al., 2023). Research suggests that decisions made without a clear, evidence-based rationale are more likely to miss their intended outcomes and even result in adverse effects, such as increased injury risk (Bahr and Krosshaug, 2005; Akenhead and Nassis, 2016). The process has shown me that in the elite professional environment pressure to remain competitive or current may drive to adoption of techniques or processed into practice without establishing a thorough rationale and due diligence. Furthermore, once established processes can become difficult to change, reinforcing the importance of critical thinking and evaluation. Integrating novel approaches and technologies can provide valuable opportunities to reflect on the effectiveness of our interventions, encouraging a more comprehensive understanding of our practice environment and our ability to impact on player performance and health.

The doctoral process has undoubtedly advanced my critical thinking at all points throughout this journey. As an applied practitioner actively engaged in research, I have been repeatedly reminded and challenged on the importance of navigating environmental pressures and implementation through critical evaluation and reflection. The action research model implemented through the thesis has provided a structured framework for me to navigate the various organisational and operational challenges when attempting to conduct research alongside practise. I strongly believe this development has been essential in developing skills for maintaining effectiveness and ensuring that the choices I make align with evidence-based practice and organisational goals (Martindale and Collins, 2007). Being mindful of these influences allows me to balance my approach to research in the field that integrates scientific processes while acknowledging the dynamic and sometimes high stakes, fluid nature of elite sports environments (Davids et al., 2013).

I also experienced that effective management of expectations requires clear communication a skilful application of scientific findings to practice, and the willingness to challenge established norms. However, this is often met with resistance, especially when changes to well-established routines are involved. Resistance to change can arise from comfort with familiar methods or a reluctance to embrace accountability for new approaches (Greenhalgh et al., 2004). Explorations into load measurement involved creating metrics to quantify parameters of loading and analysis in a novel approach that was not warmly received by several stakeholders within the MDT. This reluctance to consider new or novel approaches is particularly impactful when attempting a paradigm shift within organisational process, as it can inhibit the adoption of innovative practices that could otherwise enhance performance outcomes player health (Kane et al., 2019).

The high-pressure, fast paced environment of elite professional football coupled with the diversity of professional backgrounds within multidisciplinary teams, frequently led to differing perspectives on research findings. This variability can result in confirmation bias, where individuals interpret data in ways that align with their pre-existing beliefs or preferences (Samuelson and Zeckhauser, 1988). A common expression of this is “cherry-picking” data to support specific narratives, an approach that can diminish the objectivity of evidence-based decisions and limit the effectiveness of interventions (Nickerson, 1998; Ghosh and Vogt, 2012).

Reflecting on these experiences through both the professional and reflective pauses that run throughout this thesis allowed me to consider a balanced approach that incorporates both subjective insights (thoughts and feelings of various stakeholders) and objective data (generated by scientific exploration) is essential for overcoming challenges. By fostering a culture of openness to new evidence, applied practitioners can encourage a more comprehensive, evidence-based practice model. This approach not only builds confidence within the multidisciplinary team but also enhances decision making, ultimately benefiting both the organisations, multidisciplinary teams and the players they support (Herr and Anderson, 2014; Coghlan, 2019).

When decision-makers have access to a diverse range of information, they are better equipped to design interventions that are tailored to the unique contexts and requirements of their teams (Rynne and Mallett, 2017). Furthermore, we have shown the action research model to be an affective framework for guiding research within applied sport science. Action research allows practical insights to be considered in the planning and refinement of ideas whilst providing support for the implementation of scientific process to practice. I believe the effectiveness of the action research model has facilitated the integration of scientific principals into practice which has enabled me to generate meaningful insights that support and decision making. I believe this has ultimately led to improved outcomes for players, enhancing their performance and health in a demanding high-pressure environment.

The challenge of integrating research into thesis has been invaluable my development as a researcher. Navigating challenges of conducting research in practice, which are inherent when working with a diverse group of stakeholders, with varying backgrounds, experiences, biases, and agendas has provided opportunities for growth and change. Despite these complexities I have found collaboration between stakeholders is essential to ensure effective interventions and processes that enhance player and contribute to team success (Brookfield, 1998; Knowles et al., 2001; Anderson et al., 2004). This has undoubtedly improved my practice through communication and dissemination of results. Navigating the complex themes through the professional pause and reflective sections of this thesis, has helped me with challenging conversations and periods of frustration when trying to implement change and challenge the status quo, particularly when stakeholders have shown a reluctance to change or consider new ideas like the novel approach to load monitoring.

In summary, this section has detailed the various learning experiences discussed throughout the professional and reflective pause sections of this thesis. However there have been several key areas where I feel I have developed as a researching practitioner. Developing my research skills required adopting a balanced perspective that values both objective data and acknowledges the boundaries of application in practice. By promoting critical thinking and reflecting on the evaluation of evidence I feel I have promoted informed decision making within the environment, integrating objectivity alongside practical insights enhanced the translation of knowledge into actionable insights for practice. This allows us to make better decisions around loading schemes and individualized strategies that promote player performance and health.

Recommendations for Future Work

The work conducted in this thesis contributes to our understanding of the loading demands and physiological responses of elite professional football players in rehabilitation, training and competitive settings. However, there remain significant avenues for further exploration that could continue to refine load monitoring and response strategies.

Firstly, the novel approach to load monitoring developed and validated (face validity) in a rehabilitation setting could be tested across all phases of training and competitive cycles, examining its application in a broader performance context. Further investigations could also examine how this approach could be adapted to identify optimal training load thresholds across individual player positions. These findings could contribute to the development of a more comprehensive framework for individual player load management. Understanding these parameters holistically within different training periods such as pre-season, during the season and differing phases of the training and competition cycle would offer a deeper understanding of their fluctuations and cumulative effects on both player performance and health (Akenhead and Nassis, 2016; Gabbett, 2016). Considering the positional variations in loading such as varying mechanical and technical demands could further differentiate load patterns by position. This type of analysis would aid coaches and practitioners in designing training that provides appropriate exposure to varying aspects of loading across a cycle, therefore providing adequate preparation and readiness for match day demands and reducing the risk of overtraining and injury (Nedelec et al., 2012).

While the present study explored general associations between load parameters and biomarkers, future research into loading and response would benefit from a more hypothesis driven approach. Hypothesis driven research could deepen our understanding of how specific load types of influence biomarker response. Future work should control for additional contextual factors like nutrition, recovery interventions, and environmental influences to clarify these relationships (Jones and

Kingston, 2013). By examining the acute and chronic responses of biomarkers such as hs-CRP and oxidative stress markers, researchers could better assess players' readiness and recovery, informing practical decisions on training load and individualised player management.

Additionally, combining metrics across different load dimensions (locomotor, mechanical, technical) with biomarker analysis could create a more integrative model of load monitoring that aligns the multiple dimensions of demands with physiological response (Impellizzeri et al., 2005). This approach may enable practitioners to establish thresholds for different types of loading and adjust player preparation strategies accordingly. Through these suggested research avenues, practitioners could continue to enhance the accuracy and applicability of load monitoring approaches within the professional practise, ultimately contributing to more effective training protocols in elite football environments ultimately benefiting performance and player health.

Dissemination Plans and Impact

Effective dissemination of research findings is essential to ensure that the insights gained through this study reach both academic and practitioner audiences, thereby maximising the impact of the research. Given the applied nature of this research project, which focuses on real world effectiveness, the dissemination strategy will aim to engage a broad range of stakeholders, from academic researchers to practitioners in the field of sports science and coaching.

Academic Dissemination: The novel approach and biomarker studies arising from this research will be submitted for publication in peer-reviewed journals, with a particular focus on relevant journals in sports science, physiology, and applied research. This will ensure that the findings are disseminated to a global academic audience and contribute to the advancement of knowledge in the field.

Practitioner-Focused Dissemination: In parallel with academic dissemination, it is crucial to engage with sports science professionals, coaches, and practitioners who can directly benefit from the research. To facilitate this, findings will be shared through less formal channels such as conference presentations tailored to coaches and practitioners. These presentations will allow for a more accessible, practical discussion of how the research can be applied in training, rehabilitation, and performance monitoring contexts.

Moreover, podcast appearances and webinars will be utilised to reach a broader audience of coaches, sport science practitioners and medical professionals who may not typically attend conferences but are avid consumers of information through digital media. These platforms provide an opportunity for discussing the findings in an informal yet impactful way, ensuring that the research reaches those who are directly involved in applying sports science in practice.

Thesis Conclusions

This thesis has highlighted several key insights into load monitoring and response in elite football, suggesting avenues for improving both player preparation and injury prevention strategies.

Limitations of Contemporary Load Monitoring: Current load monitoring strategies may lack the depth needed to capture the full complexity of multiple dimensions of loading players experience. Traditional metrics often focus on locomotor aspects, potentially neglecting other important aspects like mechanical and technical load. These overlooked areas can significantly impact player performance and injury risk, suggesting the need for more comprehensive approaches.

Utility of Foot-Mounted Inertial Sensors and Novel Framework: Foot-mounted inertial sensors offer a promising solution to load monitoring by enabling practitioners to capture a multidimensional view of load. Creating a framework which encompasses, locomotor, mechanical, and technical demands may provide practitioners with a more simplistic method of field-based assessments that may better reflect the specific demands placed on players, providing a more comprehensive view of stressors across the training cycle.

Biomarker Analysis for Load Response: Biomarkers hold valuable potential for assessing player response to training loads, offering insights into readiness and recovery. However, the analysis of biomarkers must account for individual variability and specific loading quantities. The relationships between load and biomarkers are complex, with individual differences indicating that response to loading can vary widely, highlighting the need for individualised analysis to generate insights that can be used to inform decisions on individual loading schemes and recovery strategies.

Action Research as a Framework for Applied Practice: Action research emerged as a valuable framework to guide our investigations within the applied environment. By facilitating evidence-based investigation, action research can assist practitioners to making informed decisions, facilitating critical thinking, planning, refinement and reflection. For organisations, action research supports a process of continuous improvement and innovation helping to critically evaluate interventions and technologies that impact player performance and health.

I am satisfied that this thesis has achieved its overarching aim of advancing our understanding of the factors influencing training load and the associated responses in elite professional footballers. The research began by critically examining existing approaches to load monitoring, offering a comprehensive review that not only identified current practices but also highlighted important gaps in the literature and potential areas for technological innovation. Building on this foundation, a novel conceptual framework was developed to provide a more comprehensive view of the different types of loading experienced in elite football. While this remains a preliminary model, it represents an important step toward capturing aspects of training load that are often overlooked in practice. Finally, the relationship between training load and physiological response was explored using real-world data from elite players, offering valuable insights into how athletes respond to various training and match demands. Although these findings underscore the complexity of individual responses and the influence of potential confounding factors, they contribute meaningfully to both academic understanding and applied practice. Taken together, the work presented in this thesis reflects a sustained and coherent effort to address a complex problem, and I believe it provides a strong platform for further research and practical advancement in the field.

CHAPTER 9

REFERENCES

.

ADE, J., FITZPATRICK, J. & BRADLEY, P. S. 2016. High-Intensity Efforts in Elite Soccer Matches and Associated Movement Patterns, Technical Skills and Tactical Actions. Information for Position-Specific Training Drills. *Journal of Sports Sciences*.

AKENHEAD, R., FRENCH, D., THOMPSON, K. G. & HAYES, P. R. 2014. The acceleration dependent validity and reliability of 10 Hz GPS. *Journal of science and medicine in sport,* 17**,** 562-566.

AKENHEAD, R., FRENCH, D., THOMPSON, K. G. & HAYES, P. R. 2015. The physiological consequences of acceleration during shuttle running. *Int J Sports Med,* 36**,** 302-7.

AKENHEAD, R., HARLEY, J. A. & TWEDDLE, S. P. 2016. Examining the external training load of an English Premier League football team with special reference to acceleration. *The Journal of Strength & Conditioning Research,* 30**,** 2424-2432.

AKENHEAD, R. & NASSIS, G. P. 2016. Training Load and Player Monitoring in High-Level Football: Current Practice and Perceptions. *Int J Sports Physiol Perform,* 11**,** 587-93.

ALTAI, Z., HAYFORD, C. F., PHILLIPS, A. T., MORAN, J., ZHAI, X. & LIEW, B. X. 2024. Lower limb joint loading during high-impact activities: implication for bone health. *JBMR plus,* 8**,** ziae119.

ANDERSON, A. G., KNOWLES, Z. & GILBOURNE, D. 2004. Reflective practice for sport psychologists: Concepts, models, practical implications, and thoughts on dissemination. *The Sport Psychologist,* 18**,** 188-203.

ANDRZEJEWSKI, M., CHMURA, J., CHMURA, P., KONEFAŁ, M. & PUKSZTA, D. 2015. Analysis of match performance of full-backs from selected European soccer leagues. *Central European Journal of Sport Sciences and Medicine,* 11**,** 45-53.

ANDRZEJEWSKI, M., CHMURA, J. & PLUTA, B. 2014. Analysis of motor and technical activities of professional soccer players of the UEFA Europa League. *International Journal of Performance Analysis in Sport,* 14**,** 504-523.

ANGHEL, L., GURAU, T. V., GURAU, G., MUȘAT, C. L., VOINESCU, D. C., ONU, I., CORDUN, M., CODREANU, C.-M. & IORDAN, D. A. 2023. The Role of Biomarkers in Elite Sports. *Balneo & PRM Research Journal,* 14.

APTE, S., KARAMI, H., VALLAT, C., GREMEAUX, V. & AMINIAN, K. 2023. In-field assessment of change-of-direction ability with a single wearable sensor. *Sci Rep,* 13**,** 4518.

ASCENSÃO, A., REBELO, A., OLIVEIRA, E., MARQUES, F., PEREIRA, L. & MAGALHÃES, J. 2008. Biochemical impact of a soccer match—analysis of oxidative stress and muscle damage markers throughout recovery. *Clinical biochemistry,* 41**,** 841-851.

AVILES, R., SOUZA, D. B., PINO-ORTEGA, J. & CASTELLANO, J. 2023. Assessment of a New Change of Direction Detection Algorithm Based on Inertial Data. *Sensors (Basel),* 23.

BAHR, R. & KROSSHAUG, T. 2005. Understanding injury mechanisms: a key component of preventing injuries in sport. *British journal of sports medicine,* 39**,** 324-329.

BANGSBO, J. 1994. Energy demands in competitive soccer. *Journal of sports sciences,* 12**,** S5-S12.

BANGSBO, J., MOHR, M. & KRUSTRUP, P. 2006a. Physical and metabolic demands of training and match-play in the elite football player. *Journal of sports sciences,* 24**,** 665-674.

BANGSBO, J., MOHR, M. & KRUSTRUP, P. 2006b. Physical and metabolic demands of training and match-play in the elite football player. *J Sports Sci,* 24**,** 665-74.

BARALIC, I., ANDJELKOVIC, M., DJORDJEVIC, B., DIKIC, N., RADIVOJEVIC, N., SUZIN-ZIVKOVIC, V., RADOJEVIC-SKODRIC, S. & PEJIC, S. 2015. Effect of astaxanthin supplementation on salivary IgA, oxidative stress, and inflammation in young soccer players. *Evidence-based complementary and alternative medicine,* 2015**,** 783761.

BARNES, C., ARCHER, D. T., HOGG, B., BUSH, M. & BRADLEY, P. S. 2014. The evolution of physical and technical performance parameters in the English Premier League. *Int J Sports Med,* 35**,** 1095-100.

BARREIRA, P., ROBINSON, M. A., DRUST, B., NEDERGAARD, N., RAJA AZIDIN, R. M. F. & VANRENTERGHEM, J. 2017. Mechanical Player Load using trunk-mounted accelerometry in football: Is it a reliable, task- and player-specific observation? *J Sports Sci,* 35**,** 1674-1681.

BARTLETT, J. D. & DRUST, B. 2021. A framework for effective knowledge translation and performance delivery of Sport Scientists in professional sport. *Eur J Sport Sci,* 21**,** 1579-1587.

BEATO, M., JAMIL, M. & DEVEREUX, G. 2018. Reliability of internal and external load parameters in recreational football (soccer) for health. *Res Sports Med,* 26**,** 244-250.

BISHOP, P. A., JONES, E. & WOODS, A. K. 2008. Recovery from training: a brief review: brief review. *The Journal of Strength & Conditioning Research,* 22**,** 1015-1024.

BITTENCOURT, N. F., MEEUWISSE, W., MENDONÇA, L., NETTEL-AGUIRRE, A., OCARINO, J. & FONSECA, S. 2016. Complex systems approach for sports injuries: moving from risk factor identification to injury pattern recognition—narrative review and new concept. *British journal of sports medicine,* 50**,** 1309-1314.

BLOOMFIELD, J., POLMAN, R. & O'DONOGHUE, P. 2007. Physical demands of different positions in FA Premier League soccer. *Journal of sports science & medicine,* 6**,** 63.

BONGIOVANNI, T., GENOVESI, F., NEMMER, M., CARLING, C., ALBERTI, G. & HOWATSON, G. 2020. Nutritional interventions for reducing the signs and symptoms of exercise-induced muscle damage and accelerate recovery in athletes: current knowledge, practical application and future perspectives. *European journal of applied physiology,* 120**,** 1965-1996.

BOUCHARD, C. & RANKINEN, T. 2001. Individual differences in response to regular physical activity. *Medicine & Science in Sports & Exercise,* 33**,** S446-S451.

BOURDON, P. C., CARDINALE, M., MURRAY, A., GASTIN, P., KELLMANN, M., VARLEY, M. C., GABBETT, T. J., COUTTS, A. J., BURGESS, D. J., GREGSON, W. & CABLE, N. T. 2017. Monitoring Athlete Training Loads: Consensus Statement. *Int J Sports Physiol Perform,* 12**,** S2161-S2170.

BRADLEY, P. S., CARLING, C., DIAZ, A. G., HOOD, P., BARNES, C., ADE, J., BODDY, M., KRUSTRUP, P. & MOHR, M. 2013. Match performance and physical capacity of players in the top three competitive standards of English professional soccer. *Human movement science,* 32**,** 808-821.

BRADLEY, P. S., CARLING, C., MCCALL, A. & DUPONT, G. 2016. Match to match variability in high-speed running activity in a professional soccer team. *Journal of Sports Sciences,* 34**,** 2215-2223.

BRITES, F. D., EVELSON, P. A., CHRISTIANSEN, M. G., NICOL, M. F., BASÍLICO, M. J., WIKINSKI, R. W. & LLESUY, S. F. 1999. Soccer players under regular training show oxidative stress but an improved plasma antioxidant status. *Clinical science,* 96**,** 381-385.

BROOKFIELD, S. 1998. Critically reflective practice. *Journal of Continuing Education in the Health Professions,* 18**,** 197-205.

BUCHHEIT, M. & LAURSEN, P. B. 2013. High-intensity interval training, solutions to the programming puzzle: Part I: cardiopulmonary emphasis. *Sports medicine,* 43**,** 313-338.

BUCHHEIT, M., MANOUVRIER, C., CASSIRAME, J. & MORIN, J. B. 2015. Monitoring Locomotor Load in Soccer: Is Metabolic Power, Powerful? *Int J Sports Med,* 36**,** 1149-55.

BUCHHEIT, M., MENDEZ-VILLANUEVA, A., SIMPSON, B. & BOURDON, P. 2010a. Match running performance and fitness in youth soccer. *International journal of sports medicine,* 31**,** 818-825.

BUCHHEIT, M., SAMOZINO, P., GLYNN, J. A., MICHAEL, B. S., AL HADDAD, H., MENDEZ-VILLANUEVA, A. & MORIN, J. B. 2014. Mechanical determinants of acceleration and maximal sprinting speed in highly trained young soccer players. *J Sports Sci,* 32**,** 1906-1913.

BUCHHEIT, M. & SIMPSON, B. M. 2017. Player-tracking technology: half-full or half-empty glass? *International journal of sports physiology and performance,* 12**,** S2-35-S2-41.

BUCHHEIT, M.-V., MENDEZ-VILLANUEVA, A., SIMPSON, B. & BOURDON, P. 2010b. Repeated-sprint sequences during youth soccer matches. *International journal of sports medicine,* 31**,** 709-716.

CALDBECK, P. & DOS'SANTOS, T. 2022. A classification of specific movement skills and patterns during sprinting in English Premier League soccer. *PLoS One,* 17**,** e0277326.

CAMERON, W. B. 1963. Informal sociology: A casual introduction to sociological thinking. *(No Title)*.

CARDOSO, P., TAVARES, F., LOUREIRO, N., FERREIRA, R., ARAUJO, J. P., REIS, J. & VAZ, J. R. 2023. In-situ acceleration-speed profile of an elite soccer academy: A cross-sectional study. *J Sports Sci,* 41**,** 1868-1874.

CARLING, C. 2013. Interpreting physical performance in professional soccer match-play: should we be more pragmatic in our approach? *Sports medicine,* 43**,** 655-663.

CARLING, C., GALL, F. L. & REILLY, T. P. 2010. Effects of physical efforts on injury in elite soccer. *Int J Sports Med,* 31**,** 180-5.

CARLING, C., LACOME, M., MCCALL, A., DUPONT, G., LE GALL, F., SIMPSON, B. & BUCHHEIT, M. 2018. Monitoring of post-match fatigue in professional soccer: welcome to the real world. *Sports Medicine,* 48**,** 2695-2702.

CASAMICHANA, D., CASTELLANO, J., CALLEJA-GONZALEZ, J., SAN ROMÁN, J. & CASTAGNA, C. 2013. Relationship between indicators of training load in soccer players. *The Journal of Strength & Conditioning Research,* 27**,** 369-374.

CLARKSON, P. M. & HUBAL, M. J. 2002. Exercise-induced muscle damage in humans. *American journal of physical medicine & rehabilitation,* 81**,** S52-S69.

CLAUDINO, J. 2017. The countermovement jump to monitor neuromuscular.

CLAYTON, D. J., BURBEARY, R., HENNIS, P. J., JAMES, R. M., SAWARD, C., COLLEDGE, A., SCOTT, R., GILPIN, S., MCMAHON, R. & VARLEY, I. 2023. Turmeric supplementation improves markers of recovery in elite male footballers: a pilot study. *Frontiers in Nutrition,* 10**,** 1175622.

CLAYTON, D. J., BURBEARY, R., PARKER, C., JAMES, R. M., SAWARD, C., PROCTER, E. L., MODE, W. J., BAKER, C., HOUGH, J. & WILLIAMS, N. C. 2024. Combined Turmeric, Vitamin C, and Vitamin D Ready-to-Drink Supplements Reduce Upper Respiratory Illness Symptoms and Gastrointestinal Discomfort in Elite Male Football Players. *Nutrients,* 16**,** 243.

CLEMENTE, F. M., GONZÁLEZ-FERNÁNDEZ, F. T., CEYLAN, H. I., SILVA, R., YOUNESI, S., CHEN, Y.-S., BADICU, G., WOLAŃSKI, P. & MURAWSKA-CIAŁOWICZ, E. 2021. Blood biomarkers variations across the pre-season and interactions with training load: A study in professional soccer players. *Journal of Clinical Medicine,* 10**,** 5576.

CLEMENTE, F. M., SARMENTO, H., RABBANI, A., VAN DER LINDEN, C., KARGARFARD, M. & COSTA, I. T. 2019. Variations of external load variables between medium- and large-sided soccer games in professional players. *Res Sports Med,* 27**,** 50-59.

COGHLAN, D. 2019. Doing action research in your own organization.

CONNOR, M., MERNAGH, D. & BEATO, M. 2022. Quantifying and modelling the game speed outputs of English Championship soccer players. *Res Sports Med,* 30**,** 169-181.

CORDEIRO, L. & SOARES, C. B. 2018. Action research in the healthcare field: a scoping review. *JBI Evidence Synthesis,* 16**,** 1003-1047.

CORMACK, S. J., NEWTON, R. U., MCGUIGAN, M. R. & CORMIE, P. 2008. Neuromuscular and endocrine responses of elite players during an Australian rules football season. *Int J Sports Physiol Perform,* 3**,** 439-53.

COUTTS, A., REABURN, P., PIVA, T. & MURPHY, A. 2007. Changes in selected biochemical, muscular strength, power, and endurance measures during deliberate overreaching and tapering in rugby league players. *International journal of sports medicine,* 28**,** 116-124.

COUTTS, A. J. 2014. Evolution of football match analysis research. Taylor & Francis.

COUTTS, A. J. & DUFFIELD, R. 2010. Validity and reliability of GPS devices for measuring movement demands of team sports. *Journal of science and Medicine in Sport,* 13**,** 133-135.

COUTTS, A. J., KEMPTON, T., SULLIVAN, C., BILSBOROUGH, J., CORDY, J. & RAMPININI, E. 2015. Metabolic power and energetic costs of professional Australian Football match-play. *Journal of science and medicine in sport,* 18**,** 219-224.

CRESWELL, J. W. & CLARK, V. L. P. 2017. *Designing and conducting mixed methods research*, Sage publications.

DAAB, W., BOUZID, M. A., LAJRI, M., BOUCHIBA, M., SAAFI, M. A. & REBAI, H. 2021. Chronic beetroot juice supplementation accelerates recovery kinetics following simulated match play in soccer players. *Journal of the American College of Nutrition,* 40**,** 61-69.

DALEN, T., LORAS, H., HJELDE, G. H., KJOSNES, T. N. & WISLOFF, U. 2019. Accelerations - a new approach to quantify physical performance decline in male elite soccer? *Eur J Sport Sci,* 19**,** 1015-1023.

DALEN, T., OVERAS, O., VAN DEN TILLAAR, R., WELDE, B. & VON HEIMBURG, E. D. 2018. Influence of different soccer-specific maximal actions on physiological, perceptual and accelerometer measurement loads. *Open Access J Sports Med,* 9**,** 107-114.

DANIELS, D. 2021. *Blood biomarker monitoring in professional soccer: Longitudinal analysis of inflammation in English Premier League players.* School of Medicine, National University of Ireland, Galway.

DARBELLAY, J., MEYLAN, C. M. P. & MALATESTA, D. 2020. Monitoring Matches and Small-sided Games in Elite Young Soccer Players. *Int J Sports Med,* 41**,** 832-838.

DAVIDS, K., ARAÚJO, D., VILAR, L., RENSHAW, I. & PINDER, R. 2013. An ecological dynamics approach to skill acquisition: Implications for development of talent in sport. *Talent Development and Excellence,* 5**,** 21-34.

DELLA VILLA, F., BUCKTHORPE, M., GRASSI, A., NABIUZZI, A., TOSARELLI, F., ZAFFAGNINI, S. & DELLA VILLA, S. 2020. Systematic video analysis of ACL injuries in professional male football (soccer): injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases. *Br J Sports Med,* 54**,** 1423-1432.

DI SALVO, V., BARON, R., TSCHAN, H., CALDERON MONTERO, F. J., BACHL, N. & PIGOZZI, F. 2007. Performance characteristics according to playing position in elite soccer. *Int J Sports Med,* 28**,** 222-7.

DI SALVO, V., GREGSON, W., ATKINSON, G., TORDOFF, P. & DRUST, B. 2009a. Analysis of high intensity activity in Premier League soccer. *Int J Sports Med,* 30**,** 205-12.

DI SALVO, V., GREGSON, W., ATKINSON, G., TORDOFF, P. & DRUST, B. 2009b. Analysis of high intensity activity in Premier League soccer. *International journal of sports medicine,* 30**,** 205-212.

DI SALVO, V., PIGOZZI, F., GONZALEZ-HARO, C., LAUGHLIN, M. & DE WITT, J. 2013a. Match performance comparison in top English soccer leagues. *International journal of sports medicine,* 34**,** 526-532.

DI SALVO, V., PIGOZZI, F., GONZALEZ-HARO, C., LAUGHLIN, M. S. & DE WITT, J. K. 2013b. Match performance comparison in top English soccer leagues. *Int J Sports Med,* 34**,** 526-32.

DOS' SANTOS, T., THOMAS, C., COMFORT, P. & JONES, P. A. 2018. The effect of angle and velocity on change of direction biomechanics: An angle-velocity trade-off. *Sports medicine,* 48**,** 2235-2253.

DOS' SANTOS, T., THOMAS, C., JONES, P. A. & COMFORT, P. 2017. Mechanical determinants of faster change of direction speed performance in male athletes. *The Journal of Strength & Conditioning Research,* 31**,** 696-705.

DOS'SANTOS, T., COWLING, I., CHALLONER, M., BARRY, T. & CALDBECK, P. 2022. What are the significant turning demands of match play of an English Premier League soccer team? *J Sports Sci,* 40**,** 1750-1759.

DRUST, B. 2019. Applied science and soccer: a personal perspective on the past, present and future of a discipline. *Sport Perform Sci Rep,* 56.

DRUST, B., ATKINSON, G. & REILLY, T. 2007. Future perspectives in the evaluation of the physiological demands of soccer. *Sports medicine,* 37**,** 783-805.

DUARTE, W., JÚNIOR, J. L. R., PAULA, L. V., CHAGAS, M. H., ANDRADE, A. G., VENEROSO, C. E., CHAVES, S. F., SERPA, T. K. & PIMENTA, E. M. 2022. C-Reactive Protein and Skin Temperature of the lower limbs of Brazilian elite soccer players like load markers following three consecutive games. *Journal of Thermal Biology,* 105**,** 103188.

EKSTRAND, J., HÄGGLUND, M. & WALDÉN, M. 2011. Injury incidence and injury patterns in professional football: the UEFA injury study. *British journal of sports medicine,* 45**,** 553-558.

ELLENS, S., HODGES, D., MCCULLAGH, S., MALONE, J. J. & VARLEY, M. C. 2022. Interchangeability of player movement variables from different athlete tracking systems in professional soccer. *Science and medicine in football,* 6**,** 1-6.

EMMONDS, S., DALTON BARRON, N., MYHILL, N., BARRETT, S., KING, R. & WEAVING, D. 2023. Locomotor and technical characteristics of female soccer players training: exploration of differences between competition standards. *Sci Med Footb,* 7**,** 189-197.

FATOUROS, I. G., CHATZINIKOLAOU, A., DOUROUDOS, I. I., NIKOLAIDIS, M. G., KYPAROS, A., MARGONIS, K., MICHAILIDIS, Y., VANTARAKIS, A., TAXILDARIS, K. & KATRABASAS, I. 2010. Time-course of changes in oxidative stress and antioxidant status responses following a soccer game. *The Journal of Strength & Conditioning Research,* 24**,** 3278-3286.

FILTER, A., OLIVARES-JABALERA, J., SANTALLA, A., MORENTE-SANCHEZ, J., ROBLES-RODRIGUEZ, J., REQUENA, B. & LOTURCO, I. 2020. Curve Sprinting in Soccer: Kinematic and Neuromuscular Analysis. *Int J Sports Med,* 41**,** 744-750.

FINAUD, J., LAC, G. & FILAIRE, E. 2006a. Oxidative stress: relationship with exercise and training. *Sports medicine,* 36**,** 327-358.

FINAUD, J., SCISLOWSKI, V., LAC, G., DURAND, D., VIDALIN, H., ROBERT, A. & FILAIRE, E. 2006b. Antioxidant status and oxidative stress in professional rugby players: evolution throughout a season. *International journal of sports medicine,* 27**,** 87-93.

FISCHER, C. P. 2006. Interleukin-6 in acute exercise and training: what is the biological relevance? *Exercise Immunology Review,* 12.

FRAGALA, M. S., KRAEMER, W. J., DENEGAR, C. R., MARESH, C. M., MASTRO, A. M. & VOLEK, J. S. 2011. Neuroendocrine-immune interactions and responses to exercise. *Sports Medicine,* 41**,** 621-639.

FRANCHI, M. V., REEVES, N. D. & NARICI, M. V. 2017. Skeletal muscle remodeling in response to eccentric vs. concentric loading: morphological, molecular, and metabolic adaptations. *Frontiers in physiology,* 8**,** 447.

FULLAGAR, H., SKORSKI, S., DUFFIELD, R. & MEYER, T. 2016. The effect of an acute sleep hygiene strategy following a late-night soccer match on recovery of players. *Chronobiology international,* 33**,** 490-505.

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

GARCÍA-CARDONA, D., LANDÁZURI, P. & SÁNCHEZ-MUÑOZ, O. 2021. Effect of a shock micro-cycle on biochemical markers in university soccer players. *International journal of environmental research and public health,* 18**,** 3581.

GHAFOURIAN, M., ASHTARY-LARKY, D., CHINIPARDAZ, R., ESKANDARY, N. & MEHAVARAN, M. 2016. Inflammatory biomarkers' response to two different intensities of a single bout exercise among soccer players. *Iranian red crescent medical journal,* 18.

GHOSH, D. & VOGT, A. Outliers: An evaluation of methodologies. Joint statistical meetings, 2012. 3455-3460.

GIBBS, G. 1988. Learning by doing: A guide to teaching and learning methods. *Further Education Unit*.

GLASGOW, R. E., LICHTENSTEIN, E. & MARCUS, A. C. 2003. Why don't we see more translation of health promotion research to practice? Rethinking the efficacy-to-effectiveness transition. *American journal of public health,* 93**,** 1261-1267.

GOULART, K. 2021. The effect of post-match resistance training on re.

GREEN, M., WARD, P., BICKLEY, M., GILLETT, M., O'BOYLE, A. & DRUST, B. 2023. Time to change direction in training load monitoring in elite football? The application of MEMS accelerometers for the evaluation of movement requirements. *Sci Med Footb,* 7**,** 15-24.

GREENHALGH, T., ROBERT, G., MACFARLANE, F., BATE, P. & KYRIAKIDOU, O. 2004. Diffusion of innovations in service organizations: systematic review and recommendations. *The milbank quarterly,* 82**,** 581-629.

GREIG, M. P., MC NAUGHTON, L. R. & LOVELL, R. J. 2006. Physiological and mechanical response to soccer-specific intermittent activity and steady-state activity. *Research in Sports Medicine,* 14**,** 29-52.

GRIFFIN, T. M. & GUILAK, F. 2005. The role of mechanical loading in the onset and progression of osteoarthritis. *Exercise and sport sciences reviews,* 33**,** 195-200.

GRUNBICHLER, J., FEDEROLF, P. & GATTERER, H. 2020. Workload efficiency as a new tool to describe external and internal competitive match load of a professional soccer team: A descriptive study on the relationship between pre-game training loads and relative match load. *Eur J Sport Sci,* 20**,** 1034-1041.

GUALTIERI, A., RAMPININI, E., SASSI, R. & BEATO, M. 2020. Workload Monitoring in Top-level Soccer Players During Congested Fixture Periods. *Int J Sports Med*.

GUERRERO-CALDERON, B., KLEMP, M., CASTILLO-RODRIGUEZ, A., MORCILLO, J. A. & MEMMERT, D. 2021. A New Approach for Training-load Quantification in Elite-level Soccer: Contextual Factors. *Int J Sports Med,* 42**,** 716-723.

HALLER, N., REICHEL, T., ZIMMER, P., BEHRINGER, M., WAHL, P., STÖGGL, T., KRÜGER, K. & SIMON, P. 2023. Blood-based biomarkers for managing workload in athletes: Perspectives for research on emerging biomarkers. *Sports Medicine,* 53**,** 2039-2053.

HALSON, S. L. 2014. Monitoring training load to understand fatigue in athletes. *Sports medicine,* 44**,** 139-147.

HARKNESS-ARMSTRONG, A., TILL, K., DATSON, N. & EMMONDS, S. 2023. Influence of match status and possession status on the physical and technical characteristics of elite youth female soccer match-play. *J Sports Sci,* 41**,** 1437-1449.

HARPER, D. J., CARLING, C. & KIELY, J. 2019. High-Intensity Acceleration and Deceleration Demands in Elite Team Sports Competitive Match Play: A Systematic Review and Meta-Analysis of Observational Studies. *Sports Med,* 49**,** 1923-1947.

HARPER, D. J. & KIELY, J. 2018. Damaging nature of decelerations: Do we adequately prepare players? *BMJ open sport & exercise medicine,* 4**,** e000379.

HARPER, D. J., MCBURNIE, A. J., SANTOS, T. D., ERIKSRUD, O., EVANS, M., COHEN, D. D., RHODES, D., CARLING, C. & KIELY, J. 2022. Biomechanical and neuromuscular performance requirements of horizontal deceleration: A review with implications for random intermittent multi-directional sports. *Sports Medicine,* 52**,** 2321-2354.

HERR, K. & ANDERSON, G. L. 2014. *The action research dissertation: A guide for students and faculty*, Sage publications.

HEWIT, J., CRONIN, J., BUTTON, C. & HUME, P. 2011. Understanding deceleration in sport. *Strength & Conditioning Journal,* 33**,** 47-52.

HIGGINS, J. 2008. Cochrane handbook for systematic reviews of interventions. *Cochrane Collaboration and John Wiley & Sons Ltd*.

HUGGINS, R. A., FORTUNATI, A. R., CURTIS, R. M., LOONEY, D. P., WEST, C. A., LEE, E. C., FRAGALA, M. S., HALL, M. L. & CASA, D. J. 2019. Monitoring blood biomarkers and training load throughout a collegiate soccer season. *The Journal of Strength & Conditioning Research,* 33**,** 3065-3077.

IMPELLIZZERI, F. M., JEFFRIES, A. C., WEISMAN, A., COUTTS, A. J., MCCALL, A., MCLAREN, S. J. & KALKHOVEN, J. 2022. The 'training load'construct: why it is appropriate and scientific. *Journal of Science and Medicine in Sport,* 25**,** 445-448.

IMPELLIZZERI, F. M., MARCORA, S. M., CASTAGNA, C., REILLY, T., SASSI, A., IAIA, F. & RAMPININI, E. 2006. Physiological and performance effects of generic versus specific aerobic training in soccer players. *International journal of sports medicine,* 27**,** 483-492.

IMPELLIZZERI, F. M., MARCORA, S. M. & COUTTS, A. J. 2019a. Internal and external training load: 15 years on. *Int J Sports Physiol Perform,* 14**,** 270-273.

IMPELLIZZERI, F. M., MEYER, T. & WAGENPFEIL, S. 2019b. Statistical considerations (or recommendations) for publishing in Science and Medicine in Football. *Science and Medicine in Football,* 3**,** 1-2.

IMPELLIZZERI, F. M., RAMPININI, E., COUTTS, A. J., SASSI, A. & MARCORA, S. M. 2004. Use of RPE-based training load in soccer. *Medicine & Science in sports & exercise,* 36**,** 1042-1047.

IMPELLIZZERI, F. M., RAMPININI, E., MAFFIULETTI, N. & MARCORA, S. M. 2007. A vertical jump force test for assessing bilateral strength asymmetry in athletes. *Medicine and science in sports and exercise,* 39**,** 2044.

IMPELLIZZERI, F. M., RAMPININI, E. & MARCORA, S. M. 2005. Physiological assessment of aerobic training in soccer. *Journal of sports sciences,* 23**,** 583-592.

IMPELLIZZERI, F. M., SHRIER, I., MCLAREN, S. J., COUTTS, A. J., MCCALL, A., SLATTERY, K., JEFFRIES, A. C. & KALKHOVEN, J. T. 2023. Understanding training load as exposure and dose. *Sports Medicine,* 53**,** 1667-1679.

ISPIRLIDIS, I., FATOUROS, I. G., JAMURTAS, A. Z., NIKOLAIDIS, M. G., MICHAILIDIS, I., DOUROUDOS, I., MARGONIS, K., CHATZINIKOLAOU, A., KALISTRATOS, E. & KATRABASAS, I. 2008. Time-course of changes in inflammatory and performance responses following a soccer game. *Clinical journal of sport medicine,* 18**,** 423-431.

JATENE, P., DOS SANTOS, G. S. & PORTELLA, D. L. 2019. C-reactive protein serum levels as an internal load indicator of sprints in competitive football matches. *International Journal of Sports Medicine,* 40**,** 762-767.

JOKELA, A., MECHÓ, S., PASTA, G., PLESHKOV, P., GARCÍA-ROMERO-PÉREZ, A., MAZZONI, S., KOSOLA, J., VITTADINI, F., YANGUAS, J. & PRUNA, R. 2023. Indirect rectus femoris injury mechanisms in professional soccer players: video analysis and magnetic resonance imaging findings. *Clinical Journal of Sport Medicine,* 33**,** 475-482.

JONES, C. M., GRIFFITHS, P. C. & MELLALIEU, S. D. 2017. Training load and fatigue marker associations with injury and illness: a systematic review of longitudinal studies. *Sports medicine,* 47**,** 943-974.

JONES, R. & KINGSTON, K. 2013. *An introduction to sports coaching: Connecting theory to practice*, Routledge.

KALKHOVEN, J. T., WATSFORD, M. L., COUTTS, A. J., EDWARDS, W. B. & IMPELLIZZERI, F. M. 2021. Training Load and Injury: Causal Pathways and Future Directions. *Sports Med,* 51**,** 1137-1150.

KANE, G. C., PALMER, D. & PHILLIPS, A. N. 2019. Accelerating digital innovation inside and out. MIT Sloan Management Review.

KEMMIS, S. 2007. Participatory action research and the public sphere. *The quality of practitioner research.* Brill.

KEMMIS, S., MCTAGGART, R., NIXON, R., KEMMIS, S., MCTAGGART, R. & NIXON, R. 2014. Introducing critical participatory action research. *The action research planner: Doing critical participatory action research***,** 1-31.

KER, R., BENNETT, M., BIBBY, S., KESTER, R. & ALEXANDER, R. M. 1987. The spring in the arch of the human foot. *Nature,* 325**,** 147-149.

KHAN, M. A., MOIZ, J. A., RAZA, S., VERMA, S., MY, S., ANWER, S. & ALGHADIR, A. 2016. Physical and balance performance following exercise induced muscle damage in male soccer players. *Journal of physical therapy science,* 28**,** 2942-2949.

KIM, S., EMMONDS, S., BOWER, P. & WEAVING, D. 2023. External and internal maximal intensity periods of elite youth male soccer matches. *J Sports Sci,* 41**,** 547-556.

KIRCH, W. 2008. Pearson's correlation coefficient. *Encyclopedia of public health,* 1**,** 1090-1091.

KIRKENDALL, D. T. 2020. Evolution of soccer as a research topic. *Progress in Cardiovascular Diseases,* 63**,** 723-729.

KNOWLES, Z. & GILBOURNE, D. 2010. Aspiration, inspiration and illustration: Initiating debate on reflective practice writing. *The Sport Psychologist,* 24**,** 504-520.

KNOWLES, Z., GILBOURNE, D., BORRIE, A. & NEVILL, A. 2001. Developing the reflective sports coach: A study exploring the processes of reflective practice within a higher education coaching programme. *Reflective practice,* 2**,** 185-207.

KNOWLES, Z., GILBOURNE, D., TOMLINSON, V. & ANDERSON, A. G. 2007. Reflections on the application of reflective practice for supervision in applied sport psychology. *The Sport Psychologist,* 21**,** 109-122.

KOTSIS, Y., MIKELLIDI, A., ARESTI, C., PERSIA, E., SOTIROPOULOS, A., PANAGIOTAKOS, D. B., ANTONOPOULOU, S. & NOMIKOS, T. 2018. A low-dose, 6-week bovine colostrum supplementation maintains performance and attenuates inflammatory indices following a Loughborough Intermittent Shuttle Test in soccer players. *European journal of nutrition,* 57**,** 1181-1195.

KRUSTRUP, P., MOHR, M., STEENSBERG, A., BENCKE, J., KJÆR, M. & BANGSBO, J. 2006. Muscle and blood metabolites during a soccer game: implications for sprint performance. *Medicine and science in sports and exercise,* 38**,** 1165-1174.

KUBAYI, A. 2021. Technical demands of the various playing positions in the qualifying matches for the European football championship. *International Journal of Performance Analysis in Sport,* 21**,** 374-382.

LEE, E. C., FRAGALA, M. S., KAVOURAS, S. A., QUEEN, R. M., PRYOR, J. L. & CASA, D. J. 2017. Biomarkers in sports and exercise: tracking health, performance, and recovery in athletes. *The Journal of Strength & Conditioning Research,* 31**,** 2920-2937.

LEES, A. & NOLAN, L. 1998. The biomechanics of soccer: a review. *Journal of sports sciences,* 16**,** 211-234.

LEVAC, D., COLQUHOUN, H. & O'BRIEN, K. K. 2010. Scoping studies: advancing the methodology. *Implementation science,* 5**,** 1-9.

LEWIS, G., TOWLSON, C., ROVERSI, P., DOMOGALLA, C., HERRINGTON, L. & BARRETT, S. 2022. Quantifying volume and high-speed technical actions of professional soccer players using foot-mounted inertial measurement units. *PLoS One,* 17**,** e0263518.

LEWIS, N. A., HOWATSON, G., MORTON, K., HILL, J. & PEDLAR, C. R. 2015. Alterations in redox homeostasis in the elite endurance athlete. *Sports medicine,* 45**,** 379-409.

LEWIS, N. A., NEWELL, J., BURDEN, R., HOWATSON, G. & PEDLAR, C. R. 2016. Critical difference and biological variation in biomarkers of oxidative stress and nutritional status in athletes. *PLoS One,* 11**,** e0149927.

LEWIS, N. A., SIMPKIN, A. J., MOSELEY, S., TURNER, G., HOMER, M., REDGRAVE, A., PEDLAR, C. R. & BURDEN, R. 2020. Increased oxidative stress in injured and ill elite international olympic rowers. *International journal of sports physiology and performance,* 15**,** 625-631.

LO, T.-Y., YO, C., WU-YE, C., HUANG, C. & CHANG, J.-H. 2019. Kinematics analysis of cutting with dribbling during different approach speeds and cutting directions in soccer. *International Journal of Performance Analysis in Sport,* 19**,** 216-226.

LOTURCO, I., LUCAS, A., P., VALTER, P., R., CESAR C, C., A, TOMAS, T. F., PAULO H, S., M, A. & SOPHIA, N. 2022. Change of Direction Performance in Elite Players From Different Team Sports. *Journal of Strength and Conditioning Research*.

MALONE, J. J., DI MICHELE, R., MORGANS, R., BURGESS, D., MORTON, J. P. & DRUST, B. 2015a. Seasonal training-load quantification in elite English premier league soccer players. *International journal of sports physiology and performance,* 10**,** 489-497.

MALONE, J. J., MURTAGH, C. F., MORGANS, R., BURGESS, D. J., MORTON, J. P. & DRUST, B. 2015b. Countermovement jump performance is not affected during an in-season training microcycle in elite youth soccer players. *The Journal of Strength & Conditioning Research,* 29**,** 752-757.

MALONE, S., OWEN, A., NEWTON, M., MENDES, B., COLLINS, K. D. & GABBETT, T. J. 2017. The acute: chonic workload ratio in relation to injury risk in professional soccer. *Journal of science and medicine in sport,* 20**,** 561-565.

MANN, T. N., LAMBERTS, R. P. & LAMBERT, M. I. 2014. High responders and low responders: factors associated with individual variation in response to standardized training. *Sports Med,* 44**,** 1113-24.

MARI, A., MANDELLI, A. & ALGESHEIMER, R. 2024. Fear of Missing Out (FOMO) on Emerging Technology: Biased and Unbiased Adoption Decision Making. *University of Zurich, Department of Business Administration, UZH Business Working Paper*.

MARKWORTH, J. F., MADDIPATI, K. R. & CAMERON-SMITH, D. 2016. Emerging roles of pro-resolving lipid mediators in immunological and adaptive responses to exercise-induced muscle injury. *Exercise immunology review,* 22.

MARRIS, J., BARRETT, S., ABT, G. & TOWLSON, C. 2022. Quantifying technical actions in professional soccer using foot-mounted inertial measurement units. *Sci Med Footb,* 6**,** 203-214.

MARTINDALE, A. & COLLINS, D. 2007. Enhancing the evaluation of effectiveness with professional judgment and decision making. *The Sport Psychologist,* 21**,** 458-474.

MARTINEZ-HERNANDEZ, D., QUINN, M. & JONES, P. 2023. Linear advancing actions followed by deceleration and turn are the most common movements preceding goals in male professional soccer. *Sci Med Footb,* 7**,** 25-33.

MCKINLAY, B. J., WALLACE, P. J., OLANSKY, S., WOODS, S., KURGAN, N., ROY, B. D., JOSSE, A. R., FALK, B. & KLENTROU, P. 2022. Intensified training in adolescent female athletes: A crossover study of Greek yogurt effects on indices of recovery. *Journal of the International Society of Sports Nutrition,* 19**,** 17-33.

MELLO, R., MELLO, R., GOMES, D., PAZ, G. A., NASSER, I., MIRANDA, H. & SALERNO, V. P. 2017. Oxidative stress and antioxidant biomarker responses after a moderate-intensity soccer training session. *Research in Sports Medicine,* 25**,** 322-332.

MENDIGUCHIA, J., ALENTORN-GELI, E., IDOATE, F. & MYER, G. D. 2013. Rectus femoris muscle injuries in football: a clinically relevant review of mechanisms of injury, risk factors and preventive strategies. *British journal of sports medicine,* 47**,** 359-366.

MINETT, G. M., DUFFIELD, R., BILLAUT, F., CANNON, J., PORTUS, M. R. & MARINO, F. E. 2014. Cold-water immersion decreases cerebral oxygenation but improves recovery after intermittent-sprint exercise in the heat. *Scandinavian journal of medicine & science in sports,* 24**,** 656-666.

MITCHELL, A. & GREIG, M. 2024. Peak instantaneous PlayerLoad metrics highlight movement strategy deficits in professional male soccer players. *Res Sports Med,* 32**,** 61-71.

MOHER, D., LIBERATI, A., TETZLAFF, J. & ALTMAN, D. G. 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Bmj,* 339.

MOHR, M., DRAGANIDIS, D., CHATZINIKOLAOU, A., BARBERO-ÁLVAREZ, J. C., CASTAGNA, C., DOUROUDOS, I., AVLONITI, A., MARGELI, A., PAPASSOTIRIOU, I. & FLOURIS, A. D. 2016. Muscle damage, inflammatory, immune and performance responses to three football games in 1 week in competitive male players. *European journal of applied physiology,* 116**,** 179-193.

MOHR, M., KRUSTRUP, P. & BANGSBO, J. 2005. Fatigue in soccer: a brief review. *J Sports Sci,* 23**,** 593-9.

MORGAN, O. J., DRUST, B., ADE, J. D. & ROBINSON, M. A. 2022a. Change of direction frequency off the ball: New perspectives in elite youth soccer. *Science and Medicine in Football,* 6**,** 473-482.

MORGAN, O. J., DRUST, B., ADE, J. D. & ROBINSON, M. A. 2022b. Change of direction frequency off the ball: new perspectives in elite youth soccer. *Sci Med Footb,* 6**,** 473-482.

MURTAGH, C., NAUGHTON, R., MCROBERT, A., O'BOYLE, A., MORGANS, R., DRUST, B. & ERSKINE, R. M. 2019. A coding system to quantify powerful actions in soccer match play a pilot study. *Reseach Quarterly for Exercise and Sport*.

MURTAGH, C. F., HALL, E. C., BROWNLEE, T. E., DRUST, B., WILLIAMS, A. G. & ERSKINE, R. M. 2023. The Genetic Association with Athlete Status, Physical Performance, and Injury Risk in Soccer. *International Journal of Sports Medicine*.

NEDELEC, M., MCCALL, A., CARLING, C., LEGALL, F., BERTHOIN, S. & DUPONT, G. 2012. Recovery in soccer: part I - post-match fatigue and time course of recovery. *Sports Med,* 42**,** 997-1015.

NEDELEC, M., MCCALL, A., CARLING, C., LEGALL, F., BERTHOIN, S. & DUPONT, G. 2014. The influence of soccer playing actions on the recovery kinetics after a soccer match. *The Journal of Strength & Conditioning Research,* 28**,** 1517-1523.

NEDERGAARD, N. J., KERSTING, U. & LAKE, M. 2014. Using accelerometry to quantify deceleration during a high-intensity soccer turning manoeuvre. *J Sports Sci,* 32**,** 1897-1905.

NICKERSON, R. S. 1998. Confirmation bias: A ubiquitous phenomenon in many guises. *Review of general psychology,* 2**,** 175-220.

NIKOLAIDIS, M. G., KERKSICK, C. M., LAMPRECHT, M. & MCANULTY, S. R. 2012. Redox biology of exercise. *Oxidative Medicine and Cellular Longevity,* 2012.

OLIVA-LOZANO, J. M., MUYOR, J. M., PUCHE ORTUNO, D., RICO-GONZALEZ, M. & PINO-ORTEGA, J. 2023. Analysis of key external and internal load variables in professional female futsal players: a longitudinal study. *Res Sports Med,* 31**,** 309-318.

OSGNACH, C., POSER, S., BERNARDINI, R., RINALDO, R. & DI PRAMPERO, P. E. 2010. Energy cost and metabolic power in elite soccer: a new match analysis approach. *Med Sci Sports Exerc,* 42**,** 170-178.

OWEN, A. L., WONG, D., PAUL, D. & DELLAL, A. 2014. Physical and technical comparisons between various-sided games within professional soccer. *International journal of sports medicine,* 35**,** 286-292.

OWENS, D. J., TWIST, C., COBLEY, J. N., HOWATSON, G. & CLOSE, G. L. 2019. Exercise-induced muscle damage: What is it, what causes it and what are the nutritional solutions? *European journal of sport science,* 19**,** 71-85.

PAGE, M. J., MCKENZIE, J. E., BOSSUYT, P. M., BOUTRON, I., HOFFMANN, T. C., MULROW, C. D., SHAMSEER, L., TETZLAFF, J. M., AKL, E. A. & BRENNAN, S. E. 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *bmj,* 372.

PALUCCI VIEIRA, L. H., SANTIAGO, P. R., PINTO, A., AQUINO, R., TORRES, R. D. S. & BARBIERI, F. A. 2022. Automatic markerless motion detector method against traditional digitisation for 3-dimensional movement kinematic analysis of ball kicking in soccer field context. *International journal of environmental research and public health,* 19**,** 1179.

PEAKE, J. M., NEUBAUER, O., DELLA GATTA, P. A. & NOSAKA, K. 2017. Muscle damage and inflammation during recovery from exercise. *Journal of applied physiology*.

PEARSON, T. A., MENSAH, G. A., ALEXANDER, R. W., ANDERSON, J. L., CANNON III, R. O., CRIQUI, M., FADL, Y. Y., FORTMANN, S. P., HONG, Y. & MYERS, G. L. 2003. Markers of inflammation and cardiovascular disease: application to clinical and public health practice: a statement for healthcare professionals from the Centers for Disease Control and Prevention and the American Heart Association. *circulation,* 107**,** 499-511.

PILLITTERI, G., GIUSTINO, V., PETRUCCI, M., ROSSI, A., BELLAFIORE, M., THOMAS, E., IOVANE, A., BIANCO, A., PALMA, A. & BATTAGLIA, G. 2023. External load profile during different sport-specific activities in semi-professional soccer players. *BMC Sports Sci Med Rehabil,* 15**,** 22.

PLEŠA, J., KOZINC, Ž. & ŠARABON, N. 2022. A brief review of selected biomechanical variables for sport performance monitoring and training optimization. *Applied Mechanics,* 3**,** 144-159.

PONCE-GONZALEZ, J. G., CORRAL-PÉREZ, J., DE VILLARREAL, E. S., GUTIERREZ-MANZANEDO, J. V., DE CASTRO-MAQUEDA, G. & CASALS, C. 2021. Antioxidants markers of professional soccer players during the season and their relationship with competitive performance. *Journal of Human Kinetics,* 80**,** 113.

PÓVOAS, S., ASCENSÃO, A., MAGALHÃES, J., SILVA, P., WIIG, H., RAASTAD, T., CASTAGNA, C. & ANDERSSON, H. 2022. Technical match actions and plasma stress markers in elite female football players during an official FIFA Tournament. *Scandinavian Journal of Medicine & Science in Sports,* 32**,** 127-139.

POWERS, S. K. & JACKSON, M. J. 2008. Exercise-induced oxidative stress: cellular mechanisms and impact on muscle force production. *Physiological reviews,* 88**,** 1243-1276.

RADZIMIŃSKI, Ł., JASTRZĘBSKI, Z., LÓPEZ-SÁNCHEZ, G. F., SZWARC, A., DUDA, H., STUŁA, A., PASZULEWICZ, J. & DRAGOS, P. 2020. Relationships between training loads and selected blood parameters in professional soccer players during a 12-day sports camp. *International Journal of Environmental Research and Public Health,* 17**,** 8580.

RAHNAMA, N., REILLY, T., LEES, A. & GRAHAM-SMITH, P. 2003. Muscle fatigue induced by exercise simulating the work rate of competitive soccer. *Journal of Sports Science,* 21**,** 933-942.

RAMPININI, E., IMPELLIZZERI, F. M., CASTAGNA, C., AZZALIN, A., BRAVO, D. F. & WISLØFF, U. 2008. Effect of match-related fatigue on short-passing ability in young soccer players. *Medicine & Science in Sports & Exercise,* 40**,** 934-942.

RANGANATHAN, P., PRAMESH, C. & BUYSE, M. 2016. Common pitfalls in statistical analysis: the perils of multiple testing. *Perspectives in clinical research,* 7**,** 106-107.

REBELO, A., SEABRA, A. & KRUSTRUP, P. 2014. Physical match performance of youth football players
in relation to physical capacity. *European Journal of Sport Science,* 14**,** 148-156.

REILLY, T. 2005. Training specificity for soccer. *International Journal of Applied Sports Sciences,* 17.

REILLY, T., MORRIS, T. & WHYTE, G. 2009. The specificity of training prescription and physiological assessment: A review. *Journal of sports sciences,* 27**,** 575-589.

REILLY, T., WILLIAMS, A. M., NEVILL, A. & FRANKS, A. 2000. A multidisciplinary approach to talent identification in soccer. *Journal of sports sciences,* 18**,** 695-702.

RIBOLI, A. & CASTAGNA, C. 2023. Soccer-drill specificity in top-class male players with reference to peak match locomotor demands. *J Sports Sci,* 41**,** 573-583.

RINGUET-RIOT, C. J., HAHN, A. & JAMES, D. A. 2013. A structured approach for technology innovation in sport. *Sports Technology,* 6**,** 137-149.

RITCHIE, D., HOPKINS, W. G., BUCHHEIT, M., CORDY, J. & BARTLETT, J. D. 2016. Quantification of training and competition load across a season in an elite Australian football club. *International journal of sports physiology and performance,* 11**,** 474-479.

ROBERTSON, S., ZENDLER, J., DE MEY, K., HAYCRAFT, J., ASH, G., BROCKETT, C., SESHADRI, D., WOODS, C., KOBER, L. & AUGHEY, R. 2023. Development of a sports technology quality framework. *Journal of sports sciences,* 41**,** 1983-1993.

ROGERS, E. M. & SINGHAL, A. 2003. Empowerment and communication: Lessons learned from organizing for social change. *Annals of the International Communication Association,* 27**,** 67-85.

ROHDE, M. & BREUER, C. 2016. Europe's Elite Football: Financial Growth, Sporting Success, Transfer Investment, and Private Majority Investors. *International Journal of Financial Studies,* 4.

ROMERO-MORALEDA, B., NEDERGAARD, N., MORENCOS, E., CASAMICHANA, D., RAMIREZ-CAMPILLO, R. & VANRENTERGHEM, J. 2021. External and internal loads during the competitive season in professional female soccer players according to their playing position- differences between training and competition. *Res Sports Med.,* 29**,** 449-461.

ROWELL, L. L., BRUCE, C. D., SHOSH, J. M. & RIEL, M. M. 2017. *The Palgrave international handbook of action research*, Springer.

RUSSELL, M., REES, G. & KINGSLEY, M. I. 2013. Technical demands of soccer match play in the English championship. *The Journal of Strength & Conditioning Research,* 27**,** 2869-2873.

RYNNE, S. B. & MALLETT, C. J. 2017. Coaches' learning and sustainability in high performance sport. *Sustainability in high performance sport.* Routledge.

SAIDI, K. 2022. Biochemical markers and wellness status during a c. *ijspp,* 2020**,** 0914.

SALTER, J., BLACK, J., MALLETT, J., BARRETT, S., TOWLSON, C., HUGHES, J. D. & DE ST CROIX, M. 2023. Does biologically categorised training alter the perceived exertion and neuromuscular movement profile of academy soccer players compared to traditional age-group categorisation? *Eur J Sport Sci,* 23**,** 1490-1499.

SAMUELSON, W. & ZECKHAUSER, R. 1988. Status quo bias in decision making. *Journal of risk and uncertainty,* 1**,** 7-59.

SARMENTO, H., MARTINHO, D. V., GOUVEIA, É. R., AFONSO, J., CHMURA, P., FIELD, A., SAVEDRA, N. O., OLIVEIRA, R., PRAÇA, G. & SILVA, R. 2024. The Influence of Playing Position on Physical, Physiological, and Technical Demands in Adult Male Soccer Matches: A Systematic Scoping Review with Evidence Gap Map. *Sports Medicine*, 1-24.

SCHEIN, E. H. 2010. *Organizational culture and leadership*, John Wiley & Sons.

SCHÖN, D. A. 1979. The reflective practitioner. *New York*.

SELMI, O., OUERGUI, I., LEVITT, D. E., MARZOUKI, H., KNECHTLE, B., NIKOLAIDIS, P. T. & BOUASSIDA, A. 2022. Training, psychometric status, biological markers and neuromuscular fatigue in soccer. *Biology of sport,* 39**,** 319-327.

SERPIELLO, F. R., HOPKINS, W. G., BARNES, S., TAVROU, J., DUTHIE, G. M., AUGHEY, R. J. & BALL, K. 2018. Validity of an ultra-wideband local positioning system to measure locomotion in indoor sports. *J Sports Sci,* 36**,** 1727-1733.

SHADISH, W., COOK, T. & CAMPBELL, D. 2002. Quasi-experiments: interrupted time-series designs. *Experimental and quasi-experimental designs for generalized causal inference***,** 171-205.

SHARMA, A., TOK, A. I. Y., ALAGAPPAN, P. & LIEDBERG, B. 2021. Point of care testing of sports biomarkers: Potential applications, recent advances and future outlook. *TrAC Trends in Analytical Chemistry,* 142**,** 116327.

SHUSHAN, T., MCLAREN, S. J., BUCHHEIT, M., SCOTT, T. J., BARRETT, S. & LOVELL, R. 2022. Submaximal fitness tests in team sports: a theoretical framework for evaluating physiological state. *Sports Medicine,* 52**,** 2605-2626.

SIES, H. & CADENAS, E. 1985. Oxidative stress: damage to intact cells and organs. *Philosophical Transactions of the Royal Society of London. B, Biological Sciences,* 311**,** 617-631.

SILVA, A. F., GONZÁLEZ-FERNÁNDEZ, F. T., CEYLAN, H. I., SILVA, R., YOUNESI, S., CHEN, Y.-S., BADICU, G., WOLANSKI, P., MURAWSKA-CIAŁOWICZ, E. & CLEMENTE, F. M. 2022. Research Article Relationships between Fitness Status and Blood Biomarkers in Professional Soccer Players.

SILVA, J. R., ASCENSÃO, A., MARQUES, F., SEABRA, A., REBELO, A. & MAGALHÃES, J. 2013. Neuromuscular function, hormonal and redox status and muscle damage of professional soccer players after a high-level competitive match. *European journal of applied physiology,* 113**,** 2193-2201.

SILVA, J. R., REBELO, A., MARQUES, F., PEREIRA, L., SEABRA, A., ASCENSÃO, A. & MAGALHÃES, J. 2014. Biochemical impact of soccer: an analysis of hormonal, muscle damage, and redox markers during the season. *Applied Physiology, Nutrition, and Metabolism,* 39**,** 432-438.

SILVA, J. R., RUMPF, M. C., HERTZOG, M., CASTAGNA, C., FAROOQ, A., GIRARD, O. & HADER, K. 2018. Acute and Residual Soccer Match-Related Fatigue: A Systematic Review and Meta-analysis. *Sports Med,* 48**,** 539-583.

SOUGLIS, A., BOGDANIS, G. C., CHRYSSANTHOPOULOS, C., APOSTOLIDIS, N. & GELADAS, N. D. 2018. Time course of oxidative stress, inflammation, and muscle damage markers for 5 days after a soccer match: effects of sex and playing position. *The Journal of Strength & Conditioning Research,* 32**,** 2045-2054.

SOUGLIS, A. G., PAPAPANAGIOTOU, A., BOGDANIS, G. C., TRAVLOS, A. K., APOSTOLIDIS, N. G. & GELADAS, N. D. 2015. Comparison of inflammatory responses to a soccer match between elite male and female players. *The Journal of Strength & Conditioning Research,* 29**,** 1227-1233.

STAGNO, K. M., THATCHER, R. & VAN SOMEREN, K. A. 2007. A modified TRIMP to quantify the in-season training load of team sport players. *Journal of sports sciences,* 25**,** 629-634.

STOLEN, T., CHAMARI, K., CASTAGNA, C. & WISLOFF, U. 2005. Physiology of soccer: an update. *Sports Med,* 35**,** 501-36.

SZIGETI, G., SCHUTH, G., KOVACS, T., REVISNYEI, P., PASIC, A., SZILAS, A., GABBETT, T. & PAVLIK, G. 2023. Football movement profile analysis and creatine kinase relationships in youth national team players. *Physiol Int,* 110**,** 74-86.

TABERNER, M., ALLEN, T. & COHEN, D. D. 2019. Progressing rehabilitation after injury: consider the 'control-chaos continuum'. BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine.

TABERNER, M., DISTIN, S., CHANCE, O., COHEN, D. D. & ARDERN, C. L. 2021. Clinical pearls on how practitioners can best support elite soccer players to return to peak performance after injury. JOSPT, Inc. JOSPT, 1033 North Fairfax Street, Suite 304, Alexandria, VA ….

TANABE, Y., KONDO, E., SAGAYAMA, H., SHIMIZU, K., YASUMATSU, M., NAKAMURA, D., FUJII, N. & TAKAHASHI, H. 2024. Impact of curcumin supplementation on exercise performance and muscle damage after a soccer match: a double-blind placebo-controlled cross-over study. *European Journal of Applied Physiology***,** 1-10.

TANG, R., MURTAGH, C., WARRINGTON, G., CABLE, T., MORGAN, O., O'BOYLE, A., BURGESS, D., MORGANS, R. & DRUST, B. 2018. Directional Change Mediates the Physiological Response to High-Intensity Shuttle Running in Professional Soccer Players. *Sports (Basel),* 6.

THORPE, R. & SUNDERLAND, C. 2012. Muscle damage, endocrine, and immune marker response to a soccer match. *The Journal of Strength & Conditioning Research,* 26**,** 2783-2790.

THORPE, R. T., STRUDWICK, A. J., BUCHHEIT, M., ATKINSON, G., DRUST, B. & GREGSON, W. 2015. Monitoring fatigue during the in-season competitive phase in elite soccer players. *International journal of sports physiology and performance,* 10**,** 958-964.

TORNERO-AGUILERA, J. F., JIMENEZ-MORCILLO, J., RUBIO-ZARAPUZ, A. & CLEMENTE-SUÁREZ, V. J. 2022. Central and peripheral fatigue in physical exercise explained: A narrative review. *International journal of environmental research and public health,* 19**,** 3909.

TOUMI, H. & BEST, T. 2003. The inflammatory response: friend or enemy for muscle injury? *British journal of sports medicine,* 37**,** 284-286.

TOUMI, H., F'GUYER, S. & BEST, T. M. 2006. The role of neutrophils in injury and repair following muscle stretch. *Journal of anatomy,* 208**,** 459-470.

TRECROCI, A., PERRI, E., LOMBARDI, G., BANFI, G., DEL VESCOVO, R., ROSA, E. M., ALBERTI, G. & IAIA, F. M. 2021. Perceptual and biochemical responses in relation to different match-day+ 2 training interventions in soccer players. *Frontiers in Physiology,* 12**,** 685804.

TUGWELL, P., BOERS, M., BROOKS, P., SIMON, L., STRAND, V. & IDZERDA, L. 2007. OMERACT: an international initiative to improve outcome measurement in rheumatology. *Trials,* 8**,** 1-6.

UYSAL, H. S., OJEDA-ARAVENA, A., ULAS, M., MARTIN, E. B. & RAMIREZ-CAMPILLO, R. 2023. Validity, Reliability, and Sensitivity of Mobile Applications to Assess Change of Direction Speed. *J Hum Kinet,* 87**,** 217-228.

VAN ROSSUM, G. & DRAKE, F. L. 1995. *Python reference manual*, Centrum voor Wiskunde en Informatica Amsterdam.

VANRENTERGHEM, J., NEDERGAARD, N. J., ROBINSON, M. A. & DRUST, B. 2017. Training Load Monitoring in Team Sports: A Novel Framework Separating Physiological and Biomechanical Load-Adaptation Pathways. *Sports Med,* 47**,** 2135-2142.

VARLEY, M. C., GABBETT, T. & AUGHEY, R. J. 2014. Activity profiles of professional soccer, rugby league and Australian football match play. *Journal of sports sciences,* 32**,** 1858-1866.

VERHEUL, J., NEDERGAARD, N. J., VANRENTERGHEM, J. & ROBINSON, M. A. 2020. Measuring biomechanical loads in team sports – from lab to field. *Science and Medicine in Football,* 4**,** 246-252.

VIRU, A. & VIRU, M. 2000. Nature of training effects. *Exercise and sport science,* 6795.

WALDRON, M., HARDING, J., BARRETT, S. & GRAY, A. 2021. A New Foot-Mounted Inertial Measurement System in Soccer: Reliability and Comparison to Global Positioning Systems for Velocity Measurements During Team Sport Actions. *J Hum Kinet,* 77**,** 37-50.

WATERMAN, H., TILLEN, D., DICKSON, R. & DE KONING, K. 2001. Action research: a systematic review and guidance for assessment. *Health technology assessment (Winchester, England),* 5**,** iii-157.

WDOWSKI, M., ROSICKA, K. & HILL, M. 2023. Influence of lower-limb muscular and tendon mechanical properties and strength on countermovement jump performance. *The Journal of sports medicine and physical fitness,* 63**,** 16-22.

WEST, S. W., CLUBB, J., TORRES-RONDA, L., HOWELLS, D., LENG, E., VESCOVI, J. D., CARMODY, S., POSTHUMUS, M., DALEN-LORENTSEN, T. & WINDT, J. 2021. More than a

Metric: How Training Load is Used in Elite Sport for Athlete Management. *Int J Sports Med,* 42**,** 300-306.

WILMES, E., DE RUITER, C. J., BEERS, L. G. M., DE KONING, L., BRINK, M. S. & SAVELSBERGH, G. J. P. 2023. New training load metrics in field hockey using inertial measurement units. *Eur J Sport Sci,* 23**,** 2191-2199.

WINDT, J. & GABBETT, T. J. 2017. How do training and competition workloads relate to injury? The workload—injury aetiology model. *British journal of sports medicine,* 51**,** 428-435.

WINDT, J., MACDONALD, K., TAYLOR, D., ZUMBO, B. D., SPORER, B. C. & MARTIN, D. T. 2020. "To Tech or Not to Tech?" A Critical Decision-Making Framework for Implementing Technology in Sport. *J Athl Train,* 55**,** 902-910.

YANG, G., LEICHT, A. S., LAGO, C. & GOMEZ, M. A. 2018. Key team physical and technical performance indicators indicative of team quality in the soccer Chinese super league. *Res Sports Med,* 26**,** 158-167.

ZAGO, M., SFORZA, C., DOLCI, C., TARABINI, M. & GALLI, M. 2019. Use of Machine Learning and Wearable Sensors to Predict Energetics and Kinematics of Cutting Maneuvers. *Sensors (Basel),* 19.

CHAPTER 10

APPENDICES

Appendix 1 – Information and Consent Form

orreco

ATHLETE INFORMATION & CONSENT FORM

BIOMARKER & LAB ANALYSIS

Orreco reviews blood biomarker and physiology data to help keep athletes in peak performance, improve recovery, optimise training response, and protect against excessive fatigue and overtraining.

Our sports performance blood panels have been developed over 20 years working with high performance athletes and professional teams. By keeping athletes in their peak performance zone, we aim to reduce injury risk and extend playing careers.

BLOOD TESTING - WHAT TO EXPECT

Participation in Redox and Inflammation Testing is completely voluntary: A skilled professional will take a small capillary blood sample from your earlobe or fingertip, using a lancet (pin prick test). This will be a small sample, the equivalent to a few drops of blood and will take a minute or two.

Venous Biomarker Testing (where applicable): A skilled professional will take a blood sample from your arm using a needle. This will be a small sample, the equivalent of a few teaspoons and will take no longer than 5 minutes.

There may be some minor discomfort, which may leave slight bruising at the point of puncture.

HOW TO PREPARE

- Do not exercise or practise or eat any food (including drinking tea/coffee) on the morning of testing.
- Drink water according to your thirst when you wake up, but limit to a maximum of 300ml.
- Show up on time. After the blood test, you'll be able to eat your usual breakfast and practise as normal.

INFORMED CONSENT

Orreco has a policy of acquiring the informed consent from participants in its programs. This is especially important given the sensitive nature of the data that will be collected and processed (including data concerning health). It is Orreco policy that you, as a participant, are given time to read and digest the content of this Athlete Information & Consent Form and our Privacy Policy before signing. You are also encouraged to read our Privacy Policy to inform you of our data processing activities at https://www.orreco.com/privacy-policy or by requesting a copy from us.
This contains important information about how we process your data and your rights. Under no circumstances are you required to participate and testing is entirely voluntary – should you wish to opt out of testing.

By signing below, you explicitly consent to Orreco collecting venous and/or capillary blood samples, physiology and performance data and processing, viewing and storing any such personal data provided by you or on your behalf, in accordance with our Privacy Policy (including your name, date of birth and sensitive personal data such as blood results) ("Your Consent") for the specific purposes set out below:

- To better understand your performance needs to optimise your training and recovery
- To provide statistical information to improve your performance
- To carry out further analyses on anonymised data for general research purposes to enhance Orreco services

There is some risk that the testing may highlight results outside the normal reference range. Should this be the case, we will advise you to see your physician/GP. We cannot liaise with your physician/GP in relation to any test results in compliance with our obligations under Data Protection Legislation. We do not provide medical advice in relation to any of the tests we carry out; our focus is solely on improving athlete performance based on the results of the tests.

This consent is provided with the understanding that the blood testing procedure involves some risks and hazards. For any questions or further information regarding this procedure, please contact info@orreco.com.

You may withdraw from the blood testing program at any time. You may also withdraw your consent to the processing of your data at any time. To do so, please email privacy@orreco.com.

CONFIDENTIALITY

We will apply all required procedures to ensure your data is held securely and that your personal privacy is upheld. All information that is collected about you will be kept strictly confidential, and we will take all reasonable steps to protect information about you from unauthorised disclosure, tampering, or damage. Your participation is conditional on you agreeing to non-clinical and non-scientific individuals having access to your data for the purposes described above. Should you have any questions or require more information about our data processing activities please see our privacy policy at https://www.orreco.com/privacy-policy or contact us at privacy@orreco.com.

CONSENT

I confirm that I have read and understand these procedures and that I have reviewed the Privacy Policy. I hereby consent to blood samples being taken and the further processing and viewing of my personal data for the purposes set out above.

NAME:____________________________________

SIGNATURE:________________________________ Date:____________________