Monitoring exercise-induced stress and adaptation prior to and during the playing season in rugby league

Thesis submitted by

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Declaration on Ethics

The studies as part of this doctoral degree were conducted in accordance with the research ethics guidelines of the WORLD MEDICAL ASSOCIATION DECLERATION OF HELINSKI – Ethical Principles for Medical Research Involving Human Subjects (2008), the Joint NHMRC/AVCC Statement and Guidelines on Research Practice (1997) and the James Cook University Statement and Guidelines on Research Practice (2001). The research methodology and protocols of each study in the thesis received clearance from the James Cook University Experimentation Ethics Review Committee (H7918, H9175).

October 2024

Ryan Simmons Date

Statement of Contribution of Others

1. Dr Kenji Doma (James Cook University, Townsville, Australia; Principal Supervisor);
2. Professor Anthony Leicht, PhD (James Cook University, Townsville, Australia; Co-Supervisor);
3. Mr. Wade Sinclair, BSpExSc (Hons) (James Cook University, Co-Supervisor);
4. North Queensland Cowboys Rugby League Football Club, Townsville, Australia;
5. Australian Government (via Research Training Program Stipend Scholarship);

Nature of Assistance	Contribution	Names, Titles and Affiliations of Co-Contributors
Intellectual support	Proposal writing	1,2,3
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	Data Analysis	1
	Editorial assistance	1,2,3
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	Data Access/Collation	1,2,3,4
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Publications Contributing to This Thesis

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- Simmons, R. G., Leicht, A., Sinclair, W. H., Bowman, P., Dobbin, M., & Doma, K. (2024). Acute Response to Training after Returning from the Off-Season in Elite Rugby League Athletes. *Journal of Human Kinetics*, *92*, 133-146.

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List of Abbreviations

1RM	1 repetition maximum
AF	Australian football
API	Application programming interface
ARFD	Average rate of force development
AU	Arbitrary units
BMI	Body mass index
CK	Creatine kinase
CMJ	Countermovement jump
CRP	C-reactive protein
CT	Contraction time
DOMS	Delayed onset muscle soreness
EIMD	Exercise-induced muscle damage
FT	Flight time
GPS	Global positioning system
HSR	High-speed running
HVD	High-velocity distance
IIMD	Impact induced muscle damage
IL	Interleukin
LDH	Lactate dehydrogenase
MPB	Metabolic power band
MSFT	Multi-stage fitness test
N	Newtons
NMF	Neuromuscular function

NRL	National Rugby League
PICO	Population, intervention/exposure, comparison and outcome
PL	Player load
PM	Perceptual measures
PP	Peak power
PRFD	Peak rate of force development
PS	Preseason
RBE	Repeated bout effect
RHIE	Repeat high-intensity effort
RL	Rugby league
RT	Resistance training
SMD	Standardised mean differences
sRPE	Session rating of perceived exertion
TD	Total distance
TNF	Tumour necrosis factor
TRIMP	Training impulse
VHSR	Very high-speed running
VJ	Vertical jump
W	Watts

Abstract

Introduction: Numerous studies have investigated the chronic training adaptations throughout a rugby league season. However, limited research has examined the acute daily and weekly physiological responses that occur during transitions between key phases of the National Rugby League (NRL) season, particularly when training-induced stress is systematically adjusted according to periodisation principles. The prominent transitions that occur in NRL typically occurs at commencement of the pre-season, midway through the pre-season and the commencement of the competition season. The intention of introducing a new training phase is to elicit heightened acute responses due to novel or intensified training stimuli, often resulting in increased muscle damage and impaired muscle function. These responses are expected to dampen with repeated exposure, a phenomenon known as the repeated bout effect (RBE), commonly observed in semi-elite and elite athletes following highly structured periodised programs. A more comprehensive understanding of the acute physiological responses during transitions between major training phases, while accounting for the RBE, could inform strategies for optimising training load management, enhancing monitoring systems, and refining recovery protocols, especially in preparation for the competitive season. Therefore, the current thesis aimed to: 1) investigate acute physiological, perceptual and physical performance responses during the first two micro-cycles of the pre-season in athletes returning from the off-season (study 1); 2) examine the acute physiological, perceptual and physical performance responses during the transition period of two meso-cycles within the pre-season (study 2); 3) investigate the acute physiological, perceptual and physical performance responses of physical match and training demands during the initial six weeks of the competition season (study 3).

Methods: For study 1, 21 elite male rugby league athletes were monitored across the initial 2 weeks of the preseason phase after returning from the off-season. Blood creatine kinase (CK) activity and perceptual measures of fatigue and muscle soreness were recorded on each training day, whilst neuromuscular function was assessed via a countermovement jump (CMJ) on the first and last training day of each week. External (global positioning system [GPS] measures, tonnage) and internal (heart rate, session rating of perceived exertion [sRPE]) training load measures were recorded for each field and resistance-based training session. An identical methodology was applied for study 2, which took place across the final week of the first preseason mesocycle and the first week of the second preseason mesocycle. The two training weeks were separated by a two-week period of leave in which the 20 participants did not participate in any supervised training over the Christmas and New Year holidays. For study 3, 29 elite male rugby league athletes were observed across the initial six rounds of the NRL competition season. Blood CK activity, perceptual measures of fatigue and muscle soreness and neuromuscular function (via a CMJ), were measured in the week leading up to the first competitive match (baseline) and on the first training day after (48-72 hours) competition matches. External (GPS measures, tonnage) and internal (heart rate) training load measures were recorded for each field and resistance-based training session, whilst the external load (GPS measures) of each competition match were also recorded.

Results: In study 1, there was a significant increase in capillary CK activity from baseline to week 1 ($p<0.01$) but no change from week 1 to week 2 ($p>0.05$) of the initial preseason mesocycle. Numerous external training load measures (e.g. total, high-velocity and sprint distance) significantly increased in week 2 ($p<0.05$), whilst neuromuscular function declined ($p<0.05$). In study 2, there was a significant increase in CK ($p<0.05$) and numerous external ($p<0.05$) and internal ($p<0.001$) training load measures upon the commencement of the second preseason mesocycle after a two-week period of leave. However, neuromuscular function was greater ($p<0.05$) after the period of leave when compared to prior to the period of leave. Upon commencement of the competition season in study 3, there was a significant

increase ($p<0.05$) in CK activity after five of the first six competition matches when compared to baseline. However, there was no change ($p>0.05$) in perceptual measures of fatigue and muscle soreness or neuromuscular function.

Conclusion: Although there was a significant increase in indirect muscle damage markers upon commencement of the preseason phase in study 1, there was no change from week 1 to week 2, suggesting athletes adapted to the commencement of the preseason phase. In study 2, although indirect muscle damage markers remained high in response to an increase in external training load (e.g. total distance, high-velocity distance, sprint distance) upon returning from a period of leave, improvements in neuromuscular function were identified, suggesting athletes were 'coping' with the load and that the prior mesocycle may have provided a protective effect. Upon the commencement of the competition season (study 3), there was a significant increase in CK 48-72 hours after competition matches, suggesting that competition matches pose a new stimulus. However, neuromuscular function and perceptual measures did not change relative to baseline, providing further evidence that athletes develop appropriate tolerance to match-induced stress, possibly due to adaptations from strenuous training during the pre-season.

Practical applications: Although indirect muscle damage markers were high at the commencement of each mesocycle, repeated exposure to periodised training can increase the tolerance of elite male rugby league athletes. The following recommendations were suggested for practitioners to effectively prescribe training prior to and during the playing season in elite rugby league:

1. Coaches and practitioners should consider the magnitude of change of external and internal training load measures and performance measures relative to each other,

during and across microcycles. This will provide greater insight around physiological training adaptations.

2. During the preseason phase, prescribe the most neurologically demanding activities (e.g. sprinting) at the beginning of each training microcycle, as this is when athletes presented with the greatest neuromuscular function.
3. Allow a minimum of 48 hours after competition matches before reintroducing elite male rugby league athletes to training stimuli.

Chapter 1

Introduction

Rugby league is a high intensity, intermittent, collision-based team sport comprising two 40-minute halves. Players are exposed to periods of high intensity activity (running, tackling) interspersed with periods of low intensity activity (jogging, walking and standing) (Twist & Highton, 2013). Thus, competitive rugby league players are expected to undertake various modes of training at high intensities to meet the physical demands of the sport. However, such an intensified style of training causes high levels of exercise-induced muscle damage (EIMD) in competitive rugby league players (Coutts et al., 2007b; Coutts et al., 2007c). The signs and symptoms of EIMD include an increased appearance of intramuscular enzymes in circulation (e.g. creatine kinase [CK] being the most commonly reported biomarker), delayed onset of muscle soreness (DOMS) and impaired muscular contractility for up to 72 hours post-exercise (Hyldahl & Hubal, 2014). Whilst symptoms are typically more pronounced in untrained individuals unfamiliar with exercises involving eccentric contractions (Newton et al., 2008), elevated levels of CK, DOMS and impaired muscular contractility can still occur in individuals highly accustomed to eccentric, resistive exercises (Meneghel et al., 2014; Soares et al., 2015).

Elite rugby league athletes are susceptible to extended periods of EIMD given they undertake strenuous training in preparation for their competitive season. Of particular interest is the influence of this training and the number of collisions involved in the sport of rugby league, in which athletes are susceptible to impact induced muscle damage (IIMD). Impact with opposing players or the playing surface results in blunt force trauma causing IIMD, which has similar signs and symptoms to EIMD (Naughton et al., 2018). As a result of the conjoint influences of EIMD and IIMD, the quality of training for RL athletes may be compromised, possibly attenuating overall adaptation if not monitored appropriately (Doma et al., 2017).

The National Rugby League (NRL) is a competition in Australia and New Zealand, which includes 16 teams and involves 24 regular season games and a 4-week finals series (the competition was expanded to 17 teams in the years after this research was conducted). The configuration of the rugby league season is analogous for all competing clubs, often split into three primary macrocycles, including; off-season phase, preseason phase and in-season or competition phase (Gamble, 2006). Each of these phases have separate goals related to an athletes' physical fitness and wellbeing. For example, the off-season phase typically occurs between the end of the competition phase (September-October) and beginning of the preseason phase (November). The off-season phase is an opportunity for athletes to recuperate from the preceding season and prepare for the preseason ahead. Any training completed by athletes during this six to nine-week off-season period is rarely structured and is low in volume relative to the structured preseason phase (Clemente et al., 2021; Mujika & Padilla, 2000a). Conversely, the initial weeks of the preseason phase involve a sharp increase in acute training load (Miloski et al., 2016; Walker et al., 2019) and EIMD with continued elevations in CK and inflammatory markers (e.g. Interleukin [IL] -1, IL-6, IL-8, Tumour Necrosis Factor alpha [TNF-alpha] and C-reactive protein [CRP]) from baseline to the end of the preseason phase (Miloski et al., 2016; Silva et al., 2014; Walker et al., 2019). However, completing successive sessions, with similar weekly training loads, can result in a decline in EIMD symptoms due to physiological adaptations (Concepcion-Huertas et al., 2013; Kraemer et al., 2013; Miloski et al., 2016), a phenomena known as the repeated bout effect (RBE) (McHugh et al., 1999). There are three primary mechanisms that reportedly contribute to the RBE including cellular, mechanical and neural adaptations (Hyldahl & Hubal, 2014; McHugh et al., 1999). Whilst studies have reported the occurrence of RBE during the preseason in amateur handball, American football and futsal (Concepcion-Huertas et al., 2013; Kraemer et al., 2013; Miloski et al., 2016), this is yet to be identified in rugby league, particularly at the elite level. Given that there are clear differences in the method of training between team sports (Gamble, 2006) and playing level (e.g., amateur versus professional) (Gamble, 2006; Kiely, 2012), the duration and level of EIMD responses in elite rugby league players may be distinct to those reported by other team sports playing at the sub-elite or social level. Gaining an understanding of EIMD and the effects of a possible RBE in NRL athletes would inform training prescription and optimise physical preparation for each training session of the pre-season.

The primary goal of the preseason phase in any sport is to prepare athletes physically and technically for the approaching competition season (Buchheit et al., 2013). In the NRL, the preseason typically comprises two meso-cycles with a transition occurring prior to and following a 2-week holiday period (Christmas and New Year). During the first meso-cycle of the preseason, training is primarily focused on building foundational skill and running-based conditioning for seven to eight weeks (pre-holiday period). As the preseason progresses (post-holiday period), training prescription evolves to a greater focus on game simulation with deliberate skill's training under fatigue as the demand for skill becomes more advanced (Farrow & Robertson, 2017). Although load and volume may not vary greatly between the two meso-cycles, given the change in training activities foci, athletes are exposed to an unfamiliar type of stimuli at the commencement of the second meso-cycle of the preseason. However, the acute response to these transitions in meso-cycles within the NRL preseason has not yet been investigated. Determining whether acute physiological responses to training is altered prior to, and following, a holiday period will assist in implementing training programs during the second meso-cycle of the pre-season for a better transition between meso-cycles in NRL and preparation for the forthcoming competitive season.

The NRL competition season commences in March with teams competing on a weekly basis with a minimum of five days between competition matches. The physical match demands of rugby league have previously been reported (Cummins & Orr, 2015; Johnston et al., 2014) and vary depending on a number of contextual variables including the playing position of an individual. For example, elite rugby league athletes are known to cover 90-100 $m.min^{-1}$ (Johnston et al., 2014), with backs covering the greatest distance at high-velocities (>15 $km.h^{-1}$) (Johnston et al., 2014), whilst forwards are exposed to a greater number of collisions (Cummins & Orr, 2015). To the author's knowledge, two groups (McLean et al., 2010; McLellan et al., 2011) have assessed the physiological, perceptual and neuromuscular response to elite rugby league match play. It was reported that perceptual and neuromuscular measures are reduced for at least 48 hours after competition matches (McLean et al., 2010), whist blood CK activity can remain above pre-match values for up to 5 days and were strongly correlated with exposure to repeated high-intensity collisions (McLellan et al., 2011). Although these findings are insightful and informative for practitioners to implement effective recovery regimes and structure in-season microcycles, these studies only observed individual matches. Assessing the response to consecutive competition matches may identify changes in these responses as athletes adapt to competition demands. Furthermore, assessing these responses at the commencement of the competition season would be beneficial given the competition matches are a new acute stimulus, potentially invoking a heightened response. Understanding how athletes respond to match stimuli would inform practitioners to assist with structuring early in-season microcycles and periodising recovery in these early weeks of the competition season.

1.1 Statement of the problem

Two studies (Coutts et al., 2007b; Coutts et al., 2007c) have investigated the biochemical and performance response across a six-week intensified training period in rugby league athletes. However, they did not capture the daily responses, making it difficult to capture the daily variability in physiological status and performance as adaptations take place. Furthermore, although two studies (McLean et al., 2010; McLellan et al., 2011) assessed the effect of individual matches during NRL competition, they neglected to consider the effect of multiple matches consecutively, or when NRL athletes are initially exposed to competition matches at the commencement of the competition season. Collectively, no studies to date have examined indirect biomarkers of muscle damage, perceptual measures of exercise-induced stress and physical performance in response to external training and competition loads concurrently across the pre-season and in-season periods in elite rugby league athletes. Training and competition loads are continually varied in accordance with periodised programs and competition scheduling. Therefore, incorporating various measures in a monitoring system can help coaches and practitioners optimize training, recovery, and performance for NRL athletes during critical NRL pre-season and in-season periods when exposed to unfamiliar stimuli.

1.2 Aims of the thesis

The overall aim of this thesis was to examine the acute physiological responses, perceived levels of stress and physical performance measures during the pre-season and in-season phases in elite rugby league athletes. Specifically, three research questions and hypotheses were developed to address this aim:

1) Does a RBE occur during the first two micro-cycles of the pre-season? If so, what are the effects on physiological, perceptual and physical performance measures in athletes returning from an off-season? (chapter 3)

H_1: 1. Indirect markers of muscle damage will increase from baseline to week 1 of preseason but then plateau or decline in week 2 indicating a RBE.

2) How does the level of EIMD effect physiological, perceptual and physical performance measures during the transition period of two meso-cycles within the pre-season? (chapter 4)

   H_2: Indirect markers of muscle damage will increase at the commencement of the new mesocycle, whilst perceptual and performance measures will decline given exposure to a different stimulus.

3) Does a RBE occur during the initial six weeks of the competition season? If so, what are the effects of physical match and training demands upon physiological, perceptual and physical performance measures? (chapter 5)

   H_3: Indirect markers of muscle damage will increase, and perceptual and performance measures will decrease in the initial 2-3 weeks of the competition season due to the exposure to competitive match loads.

Chapter 2

Publication

Simmons, R., Doma, K., Sinclair, W., Connor, J., & Leicht, A. (2021). Acute Effects of Training Loads on Muscle Damage Markers and Performance in Semi-elite and Elite Athletes: A Systematic Review and Meta-analysis. Sports Medicine, 51(10), 2181-2207.

Author Contributions

R.S. contributed 75% to this chapter. He developed the chapter structure, wrote each section, collated and analysed the data. K.D. offered conceptual guidance and support (15%), while both J.C., A.L and W.S contributed to the manuscript drafting and construction of ideas within the discussion (10%).

2.1 Introduction

Professional athletes are expected to train under heavy training loads in order to meet the physical demands of their sport. Whilst this style of training is necessary to prepare athletes for competition and cope with greater training loads, intensified exercise also results in EIMD (Coutts et al., 2007b; Coutts et al., 2007c; Miloski et al., 2016). The signs and symptoms of EIMD include elevated levels of biomarkers (e.g. CK), inflammatory factors (e.g. C-reactive protein [CRP], Tumour Necrosis Factor alpha [TNF-alpha] and interleukin [IL] markers 1, 6 and 8), elevated measures of perceived muscle soreness and impaired muscular contractility (Doma et al., 2015). These signs and symptoms are typically more pronounced in untrained individuals unfamiliar with exercises involving eccentric contractions (Newton et al., 2008). However, significantly increased levels of EIMD indicators (i.e. CK, perceived muscle soreness) have also been reported in individuals highly accustomed to eccentric, resistive exercises (i.e. elite athletes) following muscle-damaging protocols (Meneghel et al., 2014). Subsequently, high levels of EIMD for extended periods may compromise physical preparedness for subsequent training sessions, impair training quality and overall adaptation (Doma et al., 2017), and increase the risk of injury in semi-elite and elite athletes (Baumert et al., 2016). Given that EIMD appears to occur irrespective of training background (Meneghel et al., 2014), regular monitoring of athletes' training loads and responses throughout their various training and competition phases can be undertaken to optimise training adaptations and performance (Halson, 2014).

Generally, the training and competition phases for semi-elite and elite athletes are split into three primary macrocycles, including the off-season phase, preseason phase and in-season or competition phase (Gamble, 2006). Each of these phases have separate goals related to an athlete's physical fitness and wellbeing. For example, the off-season provides an opportunity for athletes to recuperate from the preceding season and prepare for the preseason ahead (Miller et al., 2011). The off-season often involves a period of training cessation and/or a reduced training load (Clemente et al., 2021). This results in athletes becoming detrained with reductions in aerobic fitness, sprint speed, agility, vertical jump and flexibility reported in semi-elite team sport players in as little as two weeks (Caldwell & Peters, 2009; Miller et al., 2011; Mujika & Padilla, 2000a). Detraining can be characterised according to the amount of time the athlete ceases or reduces exposure to a training stimulus. These categories are known as short term detraining (< 4 weeks) and long term detraining (> 4 weeks) with long term detraining resulting in greater reductions in physical conditioning (Mujika & Padilla, 2000a). Subsequently, the preseason phase aims to physically and technically prepare athletes for the approaching competition season (Buchheit et al., 2013). The initial weeks of the preseason phase often include a rapid and substantial increase in acute training load (Miloski et al., 2016; Walker et al., 2019), which can result in increased levels of EIMD (e.g. CK and inflammatory factors) compared to the off-season phase (Miloski et al., 2016; Silva et al., 2014; Walker et al., 2019). Completion of successive training sessions though has been reported to ameliorate the symptoms of EIMD (i.e. impaired muscular contractility, increased perceived muscle soreness and increased intramuscular enzymes) in athletes (Concepcion-Huertas et al., 2013; Kraemer et al., 2013; Miloski et al., 2016). This reduction in symptomology has been termed the RBE (McHugh et al., 1999) and has been proposed to be a result of cellular, mechanical and neural adaptations (Hyldahl & Hubal, 2014). For semi-elite and elite athletes, an RBE may occur during the initial period of the preseason due to the repeated exposure of a new training stimulus. However, the RBE may also occur at other times as training programs are often periodised in a manner that alters training loads for optimal adaptation. This is particularly evident when transitioning between meso-cycles of a periodization program where the focus of training varies substantially in each meso-cycle (Farrow & Robertson, 2017; Gamble, 2006). For example, a significant and positive relationship between acute increases in training load and EIMD indicators (e.g. CK, myoglobin, lactate dehydrogenase [LDH] and inflammatory factors) was reported across the season for athletes undertaking European handball, rowing and soccer (Concepcion-Huertas et al., 2013; Purge et al., 2006; Walker et al., 2019). Therefore, regular monitoring throughout the season may allow practitioners to identify training adaptations and therefore better inform training prescription.

Recently, a narrative review suggested that the level of EIMD may be an effective tool for assessing athlete adaptation in response to varying training stimuli (Pedlar et al., 2019). However, training load and training stimuli can change between microcycles (several days) and between mesocycles (several weeks) within a phase and therefore it is essential to monitor frequently to assess training adaptations. Prior narrative reviews (Djaoui et al., 2017; Edwards et al., 2018) have documented the EIMD response across phases of elite basketball and soccer seasons, but were unable to elucidate the acute responses to specific microcycles/mesocycles or transitions between these cycles due to the lack of frequency in sampling. Therefore, more regular acute monitoring may therefore be required to evaluate responses to repeated exposures of a specific training stimulus and the identification of the RBE phenomena in elite athletes. Buchheit et al. (2011) assessed daily physiological and performance adaptations over an 11-day soccer camp and reported positive training adaptations throughout the camp and a RBE. The impact of changing training loads on physiological responses were only identified due to the consistent day-to-day monitoring of athletes. Developing an understanding of the EIMD response to specific microcycles and the transition between mesocycles could inform future training prescription. However, a review of the literature specifically examining the relationship between EIMD indicators and their response to variations in training load within microcycles and across mesocycles is yet be explored. Such a review will allow practitioners to develop their prescription with an informed understanding of the effect of EIMD upon an athlete’s performance.

Therefore, the purpose of the current review was threefold: 1) to systematically and critically evaluate studies of EIMD following the initial period of the preseason in semi-elite and elite athletes; 2) to examine acute physiological and performance responses in athletes exposed to consecutive specific training stimuli (i.e. occurrence of the RBE phenomena); and 3) to examine the acute physiological and performance responses to acute changes in training load (e.g. across micro/mesocycles).

2.2 Methods

This systematic review and meta-analysis was conducted in accordance with the PRISMA guidelines (Liberati et al., 2009) and followed a population, intervention/exposure, comparison and outcome (PICO) approach (Richardson et al., 1995).

2.2.1 Inclusion/exclusion criteria

Studies were included according to the following PICO criteria:

1. *Population:* healthy athletes of at least a semi-elite level in either team or individual sports following a periodised training program.

2. *Intervention or exposure:* at least 2-weeks of a structured periodised training program relevant to their sport.

3. *Comparison:* acute responses (e.g. blood biomarkers, inflammatory factors, performance measures, perceived measures of muscle soreness and fatigue) to training during the course of the season.

4. *Outcomes:* 1) blood biomarkers for muscle damage (CK, LDH and myoglobin); 2) inflammatory factors (CRP, TNF-alpha IL markers 1, 6 and 8); 3) physical performance measures (countermovement jump – CMJ, vertical jump – VJ and multi-stage fitness test – MSFT); 4) perceived measures of muscle soreness and fatigue (e.g. DOMS); and 5) internal and external measures of training load. External load referred to the work completed by an individual independent of their internal characteristics (e.g. weight lifted, distance ran) while internal load was the physiological and psychological stress that an individual experienced in response to a training stimulus (Halson, 2014).

Studies were excluded if: 1) conducted in animals; 2) published in a non-English language; or 3) results were published as a conference abstract, review or case report.

2.2.2 Search strategy

A literature search was conducted in March 2020, across four electronic databases, including: CINAHL, Pubmed, Scopus and SPORTDiscus. An updated search was conducted on the 2nd of September 2020 with the Web of Science electronic database added to the search. For the PubMed search, four MESH term classifications were utilised in combination as follows: ((((((("Adult"[Mesh]) OR "Young adult"[Mesh]) OR "Adolescent"[Mesh])) AND (((((((((((((((((((("Creatine kinase/blood"[Mesh]) OR "Biomarkers/blood"[Mesh]) OR "Inflammation/blood"[Mesh]) OR "Inflammation mediators/blood"[Mesh]) OR "Antioxidants/metabolism"[Mesh]) OR "Myoglobin/blood"[Mesh]) OR "Leukocytes/metabolism"[Mesh]) OR "Oxidative stress/physiology"[Mesh]) OR "Uric Acid"[Mesh]) OR "Creatinine/blood"[Mesh]) OR "Alanine transaminase/blood"[Mesh]) OR "Plasma/metabolism"[Mesh]) OR "Interleukin-6/blood"[Mesh]) OR "Interleukin-6/metabolism"[Mesh]) OR "L-Lactate Dehydrogenase"[Mesh]) OR "Musculoskeletal Pain"[Mesh]) OR "Myalgia"[Mesh]) OR "Muscle Fatigue"[Mesh]) OR "Troponin T/blood"[Mesh]) OR "Reactive Oxygen Species"[Mesh])) AND (((((((((((((("Physical Education and Training"[Mesh])) OR "Athletic Performance"[Mesh]) OR "Adaptation, Physiological"[Mesh]) OR "Physical conditioning, human/physiology"[Mesh]) OR "Exercise/physiology"[Mesh]) OR "Exercise test"[Mesh]) OR "Muscle, skeletal"[Mesh]) OR "Seasons "[Mesh]) OR "Seasons"[Mesh]) OR "Muscle strength"[Mesh]) OR "Physical fitness"[Mesh]) OR "Longitudinal studies"[Mesh]) OR "Isometric Contraction"[Mesh])) AND ((((((((((((((((("Football"[Mesh]) OR "Soccer "[Mesh]) OR "Sports"[Mesh]) OR "Basketball"[Mesh]) OR "Volleyball"[Mesh]) OR "Water sports"[Mesh]) OR "Racquet Sports"[Mesh]) OR "Hockey"[Mesh]) OR "Wrestling"[Mesh]) OR "Baseball"[Mesh]) OR "Running"[Mesh]) OR "Martial Arts"[Mesh]) OR "Swimming"[Mesh]) OR "Bicycling"[Mesh]) OR "Resistance Training"[Mesh]) OR "High-Intensity Interval

Training"[Mesh]) OR "Plyometric Exercise"[Mesh]). A free text search was then conducted within the CINAHL, PubMed, Scopus, SPORTDiscus and Web of Science databases using the following combinations: (creatine kinase OR muscle damage) and (season) and (sport OR football OR soccer OR sports OR basketball OR volleyball OR water sports OR racquet sports OR hockey OR wrestling OR baseball OR running OR martial arts OR swimming OR bicycling OR resistance training OR high-intensity interval training OR plyometric exercise).

2.2.3 Screening process

The search strategy and screening process for studies are outlined in Figure 1. The literature search was completed by the lead author (RS). Abstracts were initially reviewed and classified by two authors/reviewers (RS and JC), as either meeting the criteria (i.e. 'yes'), potentially meeting the criteria (i.e. 'maybe') or not meeting the criteria (i.e. 'no'). Those studies potentially meeting the criteria were further discussed between the reviewers with consensus achieved. Based on the Weighted Kappa statistic, a value of 0.83 (95% confidence interval: 0.74-0.90) was calculated for excellent inter-rater reliability between reviewers (Cicchetti, 1994). Once the abstract screening process was complete, full text articles of studies were accessed and further screened for eligibility based upon the selection criteria.

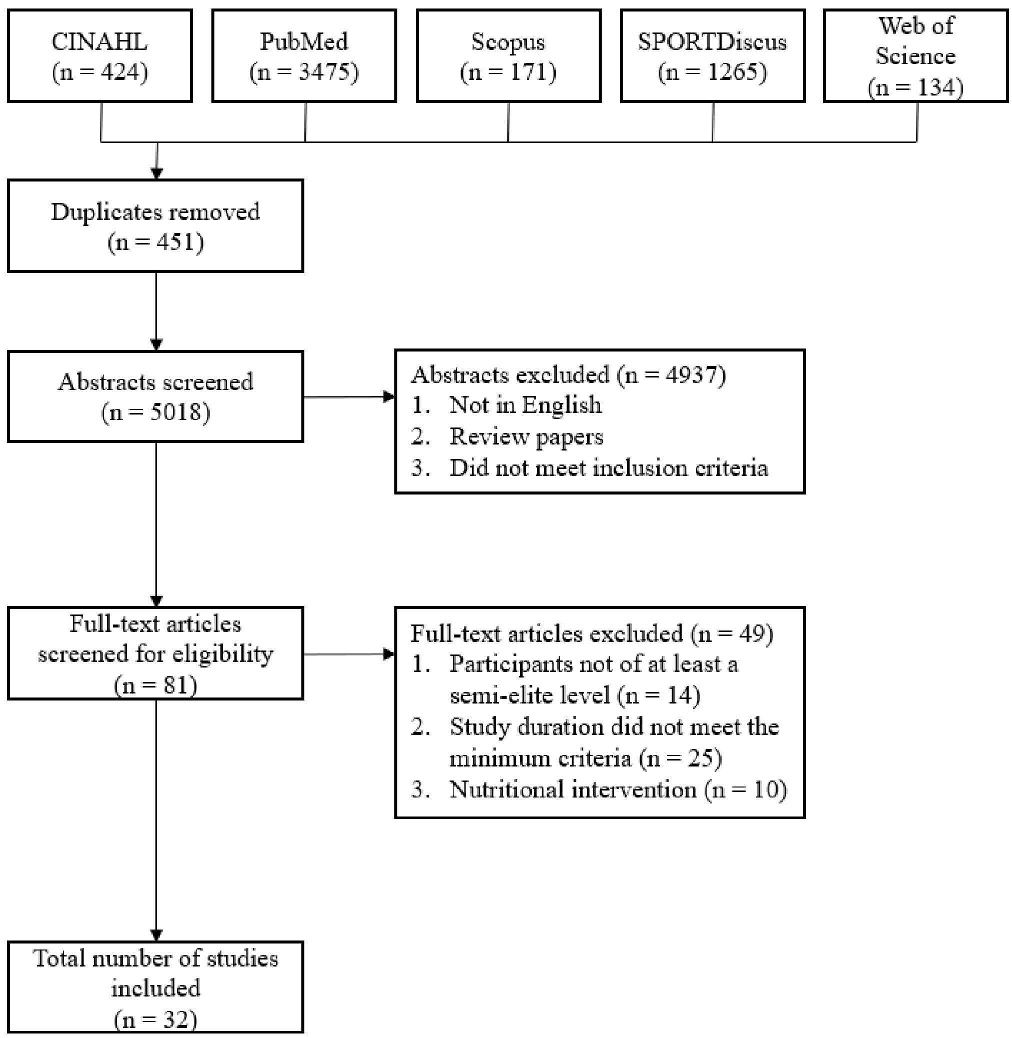


Figure 1: Flowchart of the search strategy.

2.2.4 Data extraction, quality assessment and risk of bias

Following the completion of article screening and identification of all eligible articles, participant details (e.g. age, height, mass, body fat percentage, Body Mass Index - BMI, maximal oxygen uptake - VO_2max), sample size, sport, training experience/playing level, type of EIMD measures (i.e. blood biomarkers and physical performance measures) and timing of data collection were extracted. Outcome measures were extracted as mean ± standard deviation at various time points to address each aim. Firstly, to determine the response to the initial phase of the preseason/intensified training period, data were extracted prior to the commencement of an intensified training period (T1) and at the first data collection point after the commencement of the intensified training period (T2). Secondly, to determine the response to training following exposure to consecutive bouts of a similar absolute training load within the same training phase, data were extracted at the conclusion of the first bout/period of training (RBE1) and then at the conclusion of the second bout/period of training (RBE2). Finally, to determine the response to acute changes in training load within the same training phase, data were extracted at the conclusion of two training bouts/periods of different loading. The first time point was identified as C1 and the second as C2.

All included studies were critically appraised using the Kmet Quality Scoring of Quantitative Studies tool (Kmet et al., 2004). Each criterion was rated as yes (2 points), partial (1 point), no (0 points) or not assessed (NA). The 'total sum' was determined as follows: (number of "yes" x 2) + (number of "partials" x 1). The 'total possible sum' was calculated as: 28 – (number of "NA" x 2). The final 'summary score' was equal to 'total sum' divided by 'total possible sum'. The final 'summary score' classified the quality of each article as follows: 0-0.49 (poor), 0.50-0.59 (fair), 0.60-0.79 (good), 0.80-1.00 (excellent) (Cordier et al., 2018). All included articles were appraised by two independent reviewers, who also completed the abstract screening process (RS, JC). According to the weighted Kappa statistic, the inter-rater reliability of the Kmet score was 0.88 (95% confidence interval: 0.77-0.95) and 'excellent' (Cicchetti, 1994).

The reporting bias was minimised by incorporating strict inclusion/exclusion criteria with excellent agreement between the independent reviewers from the abstract screening and critical appraisal process. Potential publication bias was determined by identifying data points within the funnel plots that were skewed to one side and demonstrating asymmetry. Funnel plots were generated by Reviewer Manager Software 5 (RevMan, Version 5.3, Copenhagen:

The Nordic Cochrane Centre, 2014). In order to address the aims of the current review, we were unable to completely avoid participation bias given studies that only examined competitive athletes at certain periods of the sporting season were strictly included.

2.2.5 Statistical methods

A meta-analysis was conducted using a statistical software package (RevMan, Version 5.3, Copenhagen: The Nordic Cochrane Centre, 2014). The CK measures were included in the meta-analysis to examine the level of indirect markers of muscle damage, whilst all other outcome measures (i.e., inflammation, perceptual measures and physical performance) were reported qualitatively as there were an insufficient number of studies for a meta-analysis (Jackson & Turner, 2017). Therefore, CK levels were compared between T1 and T2, RBE1 and RBE2, and C1 and C2. The heterogeneity of the included studies was examined using the I^2 statistic in conjunction with the associated level of statistical significance. The I^2 values of 25%, 50% and 75% were classified as low, moderate, and high thresholds, respectively (Higgins et al., 2003). The data from the CK measures were pooled and reported via forest plots using a random effects model to control for inter-study heterogeneity, and to report on standardised mean differences (SMD). Given that all included studies employed a repeated measures design, the effect estimate and its associated confidence interval across time points were calculated using the equation recommended previously (Uanhoro, 2017).

As most studies with a repeated measures design did not report the standard deviation of the change across time points, the correlation coefficient for determining confidence intervals was imputed as 0.5, which has been recommended as a relatively conservative value when dealing with missing data (Batson & Burton, 2016). The SMD and associated standard error were subsequently included in the statistical software using the generic inverse-variance method (Higgins et al., 2008). The Z-value was reported for the combined effect of all included studies between each time point with the alpha level set at 0.05.

2.3 Results

2.3.1 Systematic literature search

As displayed in Figure 1, the database search returned 5469 results, reflective of 5018 studies. After screening, this was reduced to a total of 32 studies for final evaluation.

2.3.2 Participants

The 32 included studies involved a total of 493 participants (male = 419, female = 74) with a mean sample size of 15.4 ± 6.3. Participants' mean age, height, mass and VO_{2max} were 22.6 ± 3.8 (13 – 28) years, 1.82 ± 0.08 (1.66 – 1.96) metres, 82.5 ± 13.5 (61.9 – 115.8) kilograms, and 54.1 ± 6.6 (45.9 – 66.0) ml/kg/min, respectively (Table 1).

Table 1: Physical characteristics of participants, inclusion criteria, limitations and methodological quality of included studies

Study	**Sample size (n)**	**Sport**	**Competition Level**	**Physical characteristics (mean ± SD)**	**Inclusion**	**Limitations**
(Alaphilippe et al., 2012)	Male: 12	Rugby League	Senior elite	Height 1.82 ± 5.8 m Mass 100.1 ± 11.4 kg Age 20.5 ± 0.9 years	NA	Did not report an inclusion/exclusion criteria for recruitment. Did not report all important physical characteristics. Sample size reasoning not explained.
(Alves et al., 2015)	Male: 17	Soccer	Senior elite	Mass 77.8 ± 5.6 kg Age 26.6 ± 3.7 years Fat % 9.5 ± 1.4 Aerobic capacity 55.5 ± 3.6 $ml.kg^{-1}.min^{-1}$	At least one CK activity evaluation per period (minimum 4 across the season). Must not have missed 20 consecutive days without training. Data from each game was only included if the participant played greater than 75 minutes, did not sustain any muscle strain injury and did not consume medication.	Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.

(Anđelković et al., 2015)	Male: 19	Soccer	Junior elite	Height 1.80 ± 1.4 m Mass 72.3 ± 1.8 kg Age 17.62 ± 0.14 years Fat % 9.72 ± 0.81 Aerobic capacity 52.9 ± 0.7 $ml.kg^{-1}.min^{-1}$	NA	Did not report an inclusion/exclusion criteria for recruitment. Sample size reasoning not explained.
(Aquino et al., 2016)	Male: 15	Soccer	Junior elite	Height 1.73 ± 3.6 m Mass 61.9 ± 2.9 kg Age 15.4 ± 0.2 years Fat % 11.7 ± 1.6 Aerobic capacity 48.67 ± 3.24 $ml.kg^{-1}.min^{-1}$	NA	Did not report an inclusion/exclusion criteria for recruitment. Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.
(Coelho et al., 2014)	Male: 31	Soccer	Senior elite	Height 1.81 ± 7 m Age 24.3 ± 3.9 years Fat % 9.1 ± 1.3	Attend all preseason training sessions. No injuries. Did not use medication.	Did not report all important physical characteristics. Sample size reasoning not explained.
(Becatti et al., 2017)	Male: 27	Soccer	Senior elite	Height 1.83 m Mass 79 kg Age 28 years BMI 24.2 $kg.m^2$	NA	Did not report an inclusion/exclusion criteria for recruitment. Did not report all important physical characteristics. Sample size reasoning not explained.

(Brunelli et al., 2014)	Male: 11	Basketball	Junior semi-elite	Height 1.72 ± 4.7 m Mass 62.96 ± 9.7 kg Age 13.3 ± 0.6 years	Did not use medication that could effect immune parameters, diseases or joint/muscle problems. Greater than 80% frequency during the training period.	Did not report all important physical characteristics. Sample size reasoning not explained.
(Buchheit et al., 2011)	Male: 15	Soccer	Senior elite and semi-elite	Height 1.83 ± 6 m Mass 79.6 ± 7.3 kg Age 26.2 ± 5 years	Complete all training sessions. Complete the post intervention physical performance test.	Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for. All outcome measures not considered in the conclusion.
(Coelho et al., 2016)	Male: 12	Soccer	Senior elite	Height 1.81 ± 7 m Mass 77.6 ± 3.8 kg Age 24 ± 4 years Fat % 9.1 ± 1.3 Aerobic capacity 66 ± 4.5 $ml.kg^{-1}.min^{-1}$	Participation in all CK collections. Participation in >60% of all training activities. No injuries.	Did not report all important physical characteristics. Sample size reasoning not explained. Estimate of variance not reported for all outcome measures. All confounding factors not accounted for.

(Concepcion-Huertas et al., 2013)	Male: 16	Handball	Senior elite	Height 1.87 ± 5.6 m Mass 86.8 ± 5.5 kg Age 22.7 ± 3.1 years BMI 24.57 ± 2.66 $kg.m^2$	NA	Did not report an inclusion/exclusion criteria for recruitment. Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.
(Coutts et al., 2007b)	Intensified training: 9 Normal training: 9	Rugby League	Senior semi-elite	Intensified Training: Age 24.4 ± 2.6 years Aerobic capacity 50.4 ± 4 $ml.kg^{-1}.min^{-1}$ BMI 27.7 ± 2 $kg.m^2$ Normal Training Age 22.4 ± 2.6 years Aerobic capacity 50.6 ± 3.2 $ml.kg^{-1}.min^{-1}$ BMI 27.2 ± 1.7 $kg.m^2$	NA	Did not report an inclusion/exclusion criteria for recruitment. Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.
(Coutts et al., 2007c)	Male: 7	Rugby League	Senior semi-elite	Age 25.7 ± 2.6 years VO2max 56.1 ± 1.7 mlO2/kg/min BMI 27.6 ± 2 $kg.m^2$	NA	Did not report an inclusion/exclusion criteria for recruitment. Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.

(Dubois et al., 2017)	Male: 8	Rugby Union	Senior elite	Mass 88.4 ± 3.1 kg Age 25.8 ± 4.2 years Fat % 12.7 ± 2.3	NA	Did not report an inclusion/exclusion criteria for recruitment. Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for. All outcome measures not considered in the conclusion.
(Freitas et al., 2014)	Intensified training: 8 Normal training: 8	Volleyball	Senior elite	Intensified Training: Height 1.95 ± 0.06 m Mass 88.18 ± 5.26 kg Age 23.37 ± 2.94 years Fat % 7.8 ± 2.13 Normal Training: Height 1.88 ± 0.07 m Mass 77.52 ± 11.51 kg Age 19.75 ± 1.48 years Fat % 9.07 ± 2.71	No myoarticular limitation causing withdrawal from training.	Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.

(Garatachea et al., 2011)	Male: 5 Female: 3	Sprint Kayak	Junior elite	Age 16.8 ± 2.1 years	NA	Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.
(Halson et al., 2003)	Male: 8	Cycling	Senior semi-elite	Height 1.8 ± 1.9 m Mass 73.7 ± 2.5 kg Age 27.1 ± 3 years Fat % 14.6 ± 1.1 Aerobic capacity 58 ± 1.7 $ml.kg^{-1}.min^{-1}$	NA	Did not report an inclusion/exclusion criteria for recruitment. Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.
(Hoffman et al., 1999)	Male: 10	Basketball	Senior elite	Height 1.96 ± 8 m Mass 100.7 ± 12.3 kg Age 26.4 ± 4.3 years	NA	Did not report an inclusion/exclusion criteria for recruitment. Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.

(Hoffman et al., 2005)	Starters: 11 Non-starters: 10	American Football	Junior semi-elite	Starters: Height 1.83 ± 5.4 m Mass 101 ± 16.6 kg Age 20.6 ± 1 years Non-Starters: Height 1.77 ± 5.3 m Mass 90.5 ± 12 kg Age 20.4 ± 1.6 years	NA	Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.
(Horta et al., 2019)	Male: 12	Volleyball	Senior elite	Height 1.95 ± 0.08 m Mass 94.9 ± 11.6 kg Age 26.9 ± 4.6 years Fat % 14.3 ± 4.8	No injury or infectious disease	Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.
(Huggins et al., 2019)	Male: 20	Soccer	Junior elite	Height 1.80 ± 0.1 m Mass 78.2 ± 6.3 kg Age 21 ± 1 years Fat % 12 ± 2.6 Aerobic capacity 51.5 ± 5.1 $ml.kg^{-1}.min^{-1}$	NA	Did not report an inclusion/exclusion criteria for recruitment. Sample size reasoning not explained. All confounding factors not accounted for.
(Kraemer et al., 2013)	Male: 22	American Football	Junior elite	Height 1.88 ± 8.3 m Mass 115.8 ± 29.7 kg Age 20.4 ± 1.1 years	NA	Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.

(Kurgan et al., 2018)	Female: 15	Rowing	Senior elite	Height 1.79 ± 1.4 m Mass 80.9 ± 1.3 kg Age 27 ± 0.8 years Fat % 20.8 ± 0.6	NA	Did not report an inclusion/exclusion criteria for recruitment. Did not report all important physical characteristics. Sample size reasoning not explained.
(Lacome et al., 2018)	High exposure: 13 Low exposure: 11	Rugby Union	Junior elite	Height 1.85 ± 7 m Mass 99.1 ± 9.1 kg Age 19.8 ± 0.5 years	Selected in National team	Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.
(Main et al., 2010)	Male: 8	Rowing	Senior elite	Mass 73.08 ± 0.7 kg Age 26.56 ± 4.1 years Skinfolds (sum 7) 33.87 ± 4 Aerobic capacity 65 ± 3.4 $ml.kg^{-1}.min^{-1}$	NA	Clear question/objective not clearly described. Did not report all important physical characteristics. All confounding factors not accounted for.
(Marin et al., 2013)	Male: 10	Handball	Senior elite	Height 1.87 ± 6.6 m Mass 95.3 ± 9.8 kg Age 25 ± 4.5 years Fat % 11.3 ± 3.1 Aerobic capacity 51.9 ± 2.1 $ml.kg^{-1}.min^{-1}$	NA	Did not report an inclusion/exclusion criteria for recruitment. Sample size reasoning not explained. All confounding factors not accounted for.

(Miloski et al., 2016)	Male: 12	Futsal	Senior elite	Height 1.73 ± 4.5 m Mass 75.5 ± 7.7 kg Age 24.3 ± 4.7 years	NA	Did not report all important physical characteristics. All confounding factors not accounted for.
(Purge et al., 2006)	Male: 11	Rowing	Senior elite	Height 1.93 ± 0.05 m Age 20.2 ± 2.9 years	NA	Did not report an inclusion/exclusion criteria for recruitment. Sample size reasoning not explained. Estimate of variance not reported for all outcome measures.
(Roth et al., 2019)	Male: 7	Wrestling	Junior elite	Height 1.77 ± 9.35 m Mass 82.3 ± 17.6 kg Age 20 ± 1.27 years Fat % 13 ± 0.05	NA	Did not report an inclusion/exclusion criteria for recruitment. Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.
(Silva et al., 2014)	Male: 14	Soccer	Senior elite	Height 1.78 ± 5.7 m Mass 76.5 ± 9.2 kg Age 25.7 ± 4.6 years Fat % 9.8 ± 3.7	NA	Did not report an inclusion/exclusion criteria for recruitment. Did not report all important physical characteristics. Sample size reasoning not explained.

(Stone et al., 2019)	Male: 11 Female: 9	American Football	Junior elite	Age 20 ± 1 years	NA	Did not report all important physical characteristics. Sample size reasoning not explained.
(Walker et al., 2019)	Female: 25	Soccer	Senior elite	Mass 63.42 ± 6.11 kg Age 20 ± 1.1 years Fat % 22.07 ± 4.17 Aerobic capacity 48.36 ± 3.51 $ml.kg^{-1}.min^{-1}$	NA	Did not report an inclusion/exclusion criteria for recruitment. Did not report all important physical characteristics. Sample size reasoning not explained. All confounding factors not accounted for.
(Walker et al., 2020)	Female: 22	Hockey	Senior elite	Height 1.66 ± 3.4 m Mass 64.3 ± 7.4 kg Age 19.7 ± 1.1 Fat % 26.1 ± 6.7 Aerobic capacity 45.9 ± 5.7 $ml.kg^{-1}.min^{-1}$	No major injuries or known metabolic conditions	Sample size reasoning not explained. All confounding factors not accounted for.

NA – not applicable, CK – creatine kinase.

2.3.3 Methodological descriptions

Details of the methodology and findings of all studies are provided in Table 2. Furthermore, for the purpose of this systematic review and meta-analysis, EIMD encompassed biomarkers of muscle damage (CK, LDH, myoglobin), inflammatory factors, perceptual measures and physical performance measures featured within prior studies. Of the 32 included studies, 19 investigated EIMD in the initial stage of a preseason or intensified training period, 13 investigated the potential occurrence of the RBE and 22 assessed the physiological response to changes in workload (note: studies may have had more than one purpose). For those studies investigating EIMD in the initial stages of the preseason, the duration between baseline and the next data collection point varied from four days to eight weeks. There was a range of six days to three months between data collection points for those assessing a potential RBE, and a range of one day to four months for studies identifying physiological response to changes in training load. Of the 32 included studies, 29 included a biomarker (CK, LDH, myoglobin) of muscle damage as an outcome measure, 12 included inflammatory factors while six included a physical performance measure. Of the 32 included studies, 26 reported either daily or weekly training loads that participants were exposed to throughout the training program. These training loads were expressed in a variety of ways including session duration, number of sessions, rating of perceived exertion (RPE), total distance, training volume and session RPE (sRPE = RPE x duration). Perceived exertion (n = 6), session duration (n = 10) and sRPE (n = 12) were the most consistently used measures while only five studies combined the use of internal (e.g. heart rate) and external (e.g. session duration) measures of training load.

Table 2: Descriptive information and findings of each included study

Study purpose	Study	Study duration	Time points	Workload parameters recorded	Outcome	Results
Changes to workloads	(Alaphilippe et al., 2012)	8 months	Week 22 to week 24	Game duration, number of strenuous training sessions	CK	Increase from week 22 to week 24
	(Aquino et al., 2016)	26 weeks	T2 to T3	RPE, training duration, training load (RPE x duration)	CK, LDH	Increase in CK from week 17 to week 26
						Decrease in LDH from week 17 to week 26
	(Coelho et al., 2014)	15 days	Day 4 to day 10	Training duration	CK	Decrease from day 4 to day 10 [a]
	(Becatti et al., 2017)	10 months	Start of in-season to middle of the season (January)	RPE	CK	Decrease from September to January [a]
			Middle of the season to the end of the season (May)			Increase from January to May [a]
	(Brunelli et al., 2014)	20 weeks	Preparatory phase to competitive phase	Training load (RPE x duration)	IL-6, TNF-alpha, CRP, CMJ	CRP, TNF-alpha & IL-6 increased from preparatory phase to

						competitive phase[a]
						CMJ increased from preparatory phase to competitive phase
	(Buchheit et al., 2011)	11 days	Day 3 to day 4	RPE	CK	Increase from day 3 to day 4
	(Coelho et al., 2016)	4 months	End of mesocycle 1 to end of mesocycle 2	Total distance	CK	Decrease from mesocycle 1 to 2
			End of mesocycle 2 to end of mesocycle 3			Increase from mesocycle 2 to 3
	(Concepcion-Huertas et al., 2013)	8 months	29/10 to 3/12	RPE	CK, LDH, Myoglobin, IL-1, IL-6, TNF-alpha	CK, myoglobin, IL-6 increase from 29/10 to 3/12
						IL-1, TNF-alpha decrease from 29/10 to 3/12
			3/12 to 28/1			CK, LDH, myoglobin decrease from 3/12 to 28/1
	(Dubois et al., 2017)	47 weeks	Middle of the season (week 32) to last part (week 44)	Total distance, high-speed distance, training duration, RPE,	CK	CK decreased from middle of

				training load (RPE x duration)		the season to last part
	(Freitas et al., 2014)	25 days	1st period to 2nd period	Training load (RPE x duration)	CK, CMJ	CK declined from the 1st period to the 2nd period in the IT group [a]
						CMJ increased from the first period to the 2nd period in the IT group
	(Garatachea et al., 2011)	42 weeks	T1 (November 12) to T2 (March 12)	Total distance	CK, CRP, Perceived fatigue	Increased from T1 to T2
			T2 to T3 (June 17)			Decreased from T2 to T3
	(Halson et al., 2003)	6 weeks	Week 2 to week 4	Not reported	CK, IL-6, TNF-alpha	CK inceased from week 2 to week 4 [a]
						IL-6 increased and TNF-alpha increased from week 2 to week 4
			Week 4 to week 6			All measures decreased from week 4 to week 6
	(Hoffman et al., 1999)	4 weeks	Day 9 to day 17	Training duration	CK, Perceived	Decreased from day 9 to day 17

			Day 17 to day 28		muscle soreness	Decreased from day 17 to day 28
	(Horta et al., 2019)	6 weeks	M3 (week 4) to M4 (week 6)	Training load (RPE x duration)	CK, CMJ	CK increased from M3 to M4 [a]
						No change in CMJ from M3 to M4
	(Kraemer et al., 2013)	32 weeks	T1 (start of preseason) to T2 (week 2)	Training volume (sets x reps x 1RM%)	CK	Increased from T1 to T2
	(Kurgan et al., 2018)	42 weeks	Week 21 to week 28	Training volume (hours/week)	IL-6, TNF-alpha	TNF-alpha increased from week 21 to week 28 [a]
						IL-6 increased from week 21 to week 28
	(Lacome et al., 2018)	19 days	Match 2 to match 3	RPE, total distance, high-speed distance	CK, CMJ	Increased for both groups from match 2 to match 3
			Match 3 to match 4	RPE, total distance, high-speed distance	CK, CMJ	Both measures increased from match 3 to match 4 for HEG

						CK decreased but CMJ increased from match 3 to match 4 for LEG
	(Miloski et al., 2016)	22 weeks	BS2 to BS3	Training load (RPE x duration)	CK, CMJ	CK decreased from BS2 to BS3
			BS5 (end of week 10) to BS6 (end of week 13)			CK increased from BS5 to BS6
			BS6 to BS7 (end of week 22)			CK increased from BS6 to BS7
						CMJ increased from BS6 to BS7 [a]
	(Purge et al., 2006)	24 weeks	Week 20 to week 24	Training volume (min/week)	CK	Decreased from week 20 to week 24 [a]
	(Roth et al., 2019)	Entire wrestling season	T2 (week 6-7) to T3 (week 9-10)	Training duration (hours)	CK, IL-1, IL-6, IL-8, TNF-alpha, Perceived muscle soreness, Perceived fatigue	All measures except muscle soreness decreased from T2 to T3
	(Silva et al., 2014)	Entire soccer season	E3 (end of season) to E4 (end of recovery period)	Not reported	CK, CRP, CMJ	All measures decreased from E3 to E4

	(Walker et al., 2019)	16 weeks	T2 to T3 (week 8)	Training load (RPE x duration)	CK, IL-6	CK decreased from T2 to T3 [a]
						IL-6 increased from T2 to T3
Identification of RBE	(Alves et al., 2015)	6 months	Initial period to Intermediate period	Training duration, training intensity (% heart rate max)	CK	Decrease from initial period to intermediate period [a]
	(Anđelković et al., 2015)	3 months	Day 45 to day 90	Training duration	CK, CRP	CK decreased from day 45 to day 90 [a]
						CRP increased from day 45 to day 90
	(Aquino et al., 2016)	26 weeks	T1 to T2	RPE, training duration, training load (RPE x duration)	CK, LDH	CK and LDH decreased from T1 to T2 [a]
	(Buchheit et al., 2011)	11 days	Day 4 to day 10	RPE	CK	Decrease from day 4 to day 10 [a]
	(Concepcion-Huertas et al., 2013)	8 months	29/10 to 28/1	RPE	CK, LDH, Myoglobin, IL-1, IL-6, TNF-alpha	CK, LDH, myoglobin, TNF-alpha decrease from 29/10 to 28/1

						IL-6 increased from 29/10 to 28/1
	(Halson et al., 2003)	6 weeks	Week 3 to week 4	Not reported	CK, IL-6, TNF-alpha	CK increased from week 3 to week 4
						IL-6 and TNF-alpha decreased from week 3 to week 4
	(Huggins et al., 2019)	12 weeks	Week 8 to week 12	Training duration, training load (RPE x duration), total distance, average heart rate	CK, LDH, Myoglobin, IL-1, IL-6	CK decreased from week 8 to week 12
						LDH & IL-6 increased from week 8 to week 12
						There was no change in Myoglobin and IL-1 from week 8 to week 12
	(Kraemer et al., 2013)	32 weeks	T4 (post game 4) to T5 (post game 6)	Training volume (sets x reps x 1RM%)	CK	Decreased from T4 to T5
			T5 to T6 (post game 9)			Increased from T5 to T6

	(Main et al., 2010)	8 weeks	Session 1 to session 3	Not reported	IL-1, IL-6, IL-8	IL-1, IL-6, IL-8 all decreased from session 1 to session 3
						TNF-alpha increased from session 1 to session 3
	(Miloski et al., 2016)	22 weeks	BS3 (end of week 4) to BS4 (end of week 6)	Training load (RPE x duration)	CK, CMJ	CK decreased from BS3 to BS4
	(Purge et al., 2006)	24 weeks	Week 4 to week 12	Training volume (min/week)	CK	Increased from week 4 to week 12[a]
	(Roth et al., 2019)	Entire wrestling season	T1 (week 3-4) to T2 (week 6-7)	Training duration (hours)	CK, IL-1, IL-6, IL-8, TNF-alpha, Perceived muscle soreness, Perceived fatigue	CK, IL-1, IL-6, IL-8, TNF-alpha and perceived fatigue increased from T1 to T2
						Perceived muscle soreness decreased from T1 to T2
	(Silva et al., 2014)	Entire soccer season	E2 (midseason) to E3 (end of season)	Not reported	CK, CRP, CMJ	All measures decreased from E2 to E3
	(Stone et al., 2019)	189 days	T4 (start of competition) to T5 (end of pre-conference)	Not reported	CK	Increased from T4 to T5

Initial EIMD	(Alaphilippe et al., 2012)	8 months	Baseline to week 1	Game duration, number of strenuous training sessions	CK	Increase from baseline to week 1 [a]
	(Anđelković et al., 2015)	3 months	Baseline to day 45	Training duration	CK, CRP	Increase from baseline to day 45
	(Coelho et al., 2014)	15 days	Offseason to day 4	Training duration	CK	Increase from off-season to day 4 [a]
	(Becatti et al., 2017)	10 months	Start of preseason (August) to start of in-season (September)	RPE	CK	Increase from August to September [a]
	(Brunelli et al., 2014)	20 weeks	Preseason to preparatory phase	Training load (RPE x duration)	IL-6, TNF-alpha, CRP, CMJ	CRP & CMJ increased from preseason to preparatory phase
						TNF-alpha & IL-6 decreased from preseason to preparatory phase
	(Concepcion-Huertas et al., 2013)	8 months	Pre (18/8) to 8/10	RPE	CK, LDH, Myoglobin, IL-1, IL-6, TNF-alpha	All measures remained steady from Pre to 8/10
	(Coutts et al., 2007c)	7 weeks	Pre training to post training	Training load (RPE x	CK, MSFT	CK increased from pre training to post training

				duration), training duration		MSFT decreased from pre training to post training
	(Coutts et al., 2007b)	6 weeks	Week 1 to week 2	Training load (RPE x duration), training duration	CK, MSFT	Increase from week 1 to week 2
	(Hoffman et al., 1999)	4 weeks	Day 1 to day 9	Training duration	CK, Perceived muscle soreness	Increased day 1 to day 9
	(Hoffman et al., 2005)	12 weeks	T1 (day before preseason) to T2 (day 10)	Not reported	CK, Myoglobin	CK increased from T1 to T2 [a]
						Myoglobin increased from T1 to T2
	(Horta et al., 2019)	6 weeks	Baseline to M2 (end of week 2)	Training load (RPE x duration)	CK, CMJ	CK and CMJ decreased from baseline to M2
	(Huggins et al., 2019)	12 weeks	PS to week 1	Training duration, training load (RPE x duration), total distance, average heart rate	CK, LDH, Myoglobin, IL-1, IL-6	CK, LDH, Myoglobin increased from PS to week 1
						IL-6 decreased from PS to week 1
						No change in IL-1 from PS to week 1

	(Marin et al., 2013)	6 months	T1 (week 0) to T2 (week 8)	Not reported	CK, IL-1, IL-6, TNF-alpha	CK, IL-6 and TNF-alpha increased from T1 to T2
						IL-1 decreased from T1 to T2 [a]
	(Miloski et al., 2016)	22 weeks	BS1 (start of preseason) to BS2 (end of week 2)	Training load (RPE x duration)	CK, CMJ	CK increased from BS1 to BS2 [a]
	(Purge et al., 2006)	24 weeks	Week 0 to week 4	Training volume (min/week)	CK	Increased from week 0 to week 4 [a]
	(Roth et al., 2019)	Entire wrestling season	Preseason to T1 (week 3-4)	Training duration (hours)	CK, IL-1, IL-6, IL-8, TNF-alpha, Perceived muscle soreness, Perceived fatigue	CK, TNF-alpha, IL-6, muscle soreness, fatigue increased from preseason to T1
						IL-1 and IL-8 decreased from preseason to T1
	(Silva et al., 2014)	Entire soccer season	E1 (start preseason) to E2 (midseason)	Not reported	CK, CRP, CMJ	CK and CRP increased from E1 to E2 [a]
						CMJ increased from E1 to E2
	(Stone et al., 2019)	189 days	T1 (start of preseason) to T2 (end of preseason)	Not reported	CK	Increased from T1 to T2 [a]

	(Walker et al., 2019)	16 weeks	T1 (start of preseason) to T2 (week 4)	Training load (RPE x duration)	CK, IL-6	CK increased from T1 to T2 [a]
						IL-6 increased from T1 to T2
	(Walker et al., 2020)	4 weeks	A1 (start of preseason) to A2 (week 4)	Training load (RPE x duration)	CK, IL-6	CK increased from A1 to A2[a]
						IL-6 increased from A1 to A2

[a] Significant change between time points ($p<0.05$). CK – creatine kinase; LDH – lactate dehydrogenase, CRP – C-reactive Protein; TNF-alpha – tumor necrosis factor alpha; IL – interleukin; CMJ – countermovement jump; MSFT – multi-stage fitness test; RPE – rating of perceived exertion; PS - preseason.

2.3.4 Methodological quality

The Kmet scores for included studies were high and indicated excellent (n = 31) and good (n = 1) quality studies (Table 3). Almost all authors provided a clear purpose addressing the population, protocol details and outcome measures included in their study. All included studies followed a repeated measures design with appropriate statistical analysis, appropriate outcome measures relevant to the purpose of the study and reported results for all outcome measures. Kmet criteria points 5, 6 and 7 were not applicable to any study due to the methodological nature of the included studies. Only one study reported a sample size calculation for the main outcome measure of CK (Anđelković et al., 2015).

Table 3: Kmet ratings of all included studies

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	Total Sum	Total Possible Sum	Summary Score	Interpretation
(Alaphilippe et al., 2012)	2	2	1	1	NA	NA	NA	2	1	2	2	2	2	2	19	22	0.86	Excellent
(Alves et al., 2015)	2	2	2	1	NA	NA	NA	2	1	2	2	1	2	2	19	22	0.86	Excellent
(Anđelković et al., 2015)	2	2	1	2	NA	NA	NA	2	1	2	2	2	2	2	20	22	0.91	Excellent
(Aquino et al., 2016)	2	2	1	1	NA	NA	NA	2	1	2	2	1	2	2	18	22	0.82	Excellent
(Coelho et al., 2014)	2	2	2	1	NA	NA	NA	2	1	2	2	2	2	2	20	22	0.91	Excellent
(Becatti et al., 2017)	2	2	1	1	NA	NA	NA	2	1	2	2	2	2	2	19	22	0.86	Excellent
(Brunelli et al., 2014)	2	2	2	1	NA	NA	NA	2	1	2	2	2	2	2	20	22	0.91	Excellent

(Buchheit et al., 2011)	2	2	2	1	NA	NA	NA	2	1	2	2	1	2	1	18	22	0.82	Excellent
(Coelho et al., 2016)	2	2	2	1	NA	NA	NA	2	1	2	1	1	2	2	18	22	0.82	Excellent
(Concepcion-Huertas et al., 2013)	2	2	1	1	NA	NA	NA	2	1	2	2	1	2	2	18	22	0.82	Excellent
(Coutts et al., 2007b)	2	2	1	1	NA	NA	NA	2	1	2	2	1	2	2	18	22	0.82	Excellent
(Coutts et al., 2007c)	2	2	1	1	NA	NA	NA	2	1	2	2	1	2	2	18	22	0.82	Excellent
(Dubois et al., 2017)	2	2	1	1	NA	NA	NA	2	1	2	2	1	2	1	17	22	0.77	Good
(Freitas et al., 2014)	2	2	2	1	NA	NA	NA	2	1	2	2	1	2	2	19	22	0.86	Excellent
(Garatachea et al., 2011)	2	2	2	1	NA	NA	NA	2	1	2	2	1	2	2	19	22	0.86	Excellent
(Halson et al., 2003)	2	2	1	1	NA	NA	NA	2	1	2	2	1	2	2	18	22	0.82	Excellent

(Hoffman et al., 1999)	2	2	1	1	NA	NA	NA	2	1	2	2	1	2	2	18	22	0.82	Excellent
(Hoffman et al., 2005)	2	2	2	1	NA	NA	NA	2	1	2	2	1	2	2	19	22	0.86	Excellent
(Horta et al., 2019)	2	2	2	1	NA	NA	NA	2	1	2	2	1	2	2	19	22	0.86	Excellent
(Huggins et al., 2019)	2	2	1	2	NA	NA	NA	2	1	2	2	1	2	2	19	22	0.86	Excellent
(Kraemer et al., 2013)	2	2	2	1	NA	NA	NA	2	1	2	2	1	2	2	19	22	0.86	Excellent
(Kurgan et al., 2018)	2	2	1	1	NA	NA	NA	2	1	2	2	2	2	2	19	22	0.86	Excellent
(Lacome et al., 2018)	2	2	2	1	NA	NA	NA	2	1	2	2	1	2	2	19	22	0.86	Excellent
(Main et al., 2010)	1	2	2	1	NA	NA	NA	2	2	2	2	1	2	2	19	22	0.86	Excellent
(Marin et al., 2013)	2	2	1	2	NA	NA	NA	2	1	2	2	1	2	2	19	22	0.86	Excellent

(Miloski et al., 2016)	2	2	2	1	NA	NA	NA	2	1	2	2	2	2	2	20	22	0.91	Excellent
(Purge et al., 2006)	2	2	1	2	NA	NA	NA	2	1	2	1	2	2	2	19	22	0.86	Excellent
(Roth et al., 2019)	2	2	1	1	NA	NA	NA	2	1	2	2	1	2	2	18	22	0.82	Excellent
(Silva et al., 2014)	2	2	1	1	NA	NA	NA	2	1	2	2	2	2	2	19	22	0.86	Excellent
(Stone et al., 2019)	2	2	2	1	NA	NA	NA	2	1	2	2	2	2	2	20	22	0.91	Excellent
(Walker et al., 2019)	2	2	1	1	NA	NA	NA	2	1	2	2	1	2	2	18	22	0.82	Excellent
(Walker et al., 2020)	2	2	2	2	NA	NA	NA	2	1	2	2	1	2	2	20	22	0.91	Excellent

C1 – C14 representative of Kmet criteria point one through to 14, NA – not applicable. All criteria have been previously defined (Kmet et al., 2004)

2.3.5 Quantitative analysis

For the analysis of the CK response to the initial stages of the preseason phase, a total of 19 data sets were incorporated from the included studies. As shown in Figure 2, CK was significantly greater at T2 when compared to T1 ($p<0.00001$; $I^2 = 74\%$). Data from 13 studies were utilised to identify a potential RBE with no significant difference in CK levels across two time points with similar training loads ($p = 0.15$; $I^2 = 74\%$, Figure 3). Activity of CK decreased significantly ($p<0.0001$; $I^2 = 79\%$, Figure 4a) with a significant decrease in training load between C1 and C2 ($p<0.00001$; $I^2 = 85\%$, Figure 4b). Figure 5 displays how CK activity reacted to an increase in workload. CK activity significantly increased ($p<0.0001$; $I^2 = 36\%$, Figure 5a) as workload increased from C1 to C2 ($p<0.0001$; $I^2 = 73\%$, Figure 5b).

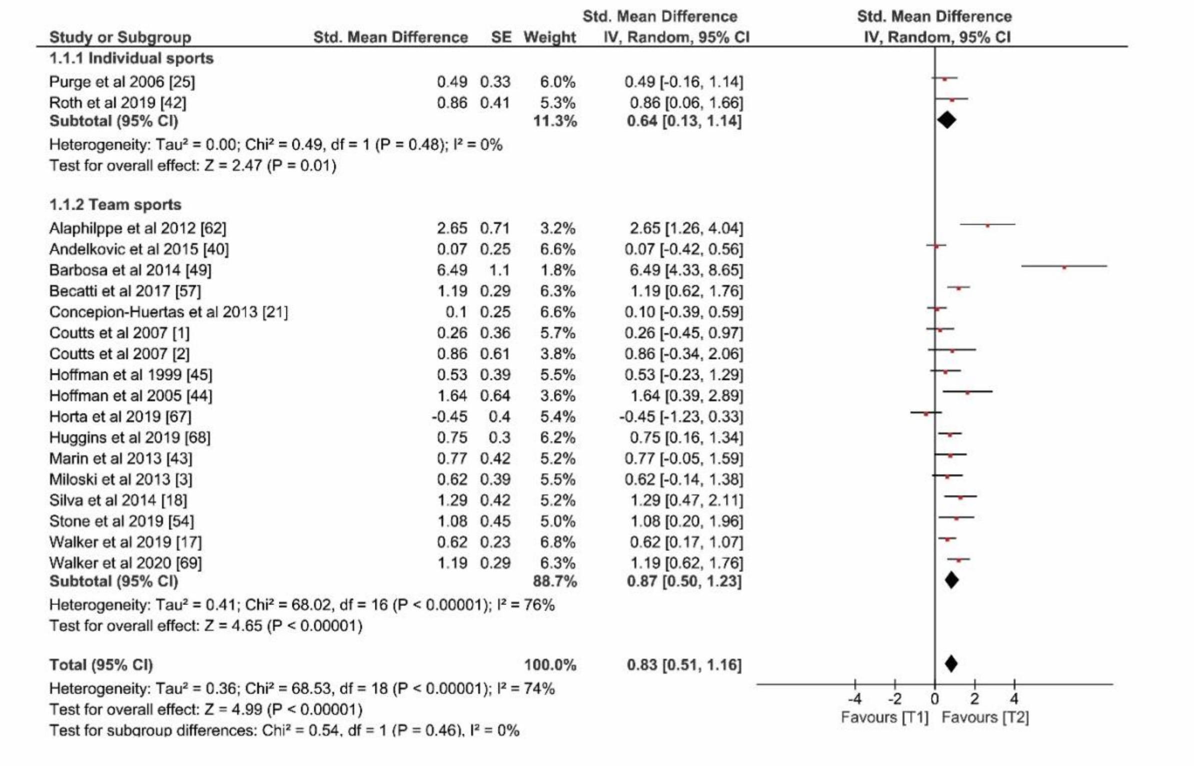


Figure 2: Forest plot of Creatine Kinase (CK) measures prior to (T1 – data collection point prior to the commencement of an intensified training period) and following (T2 – first data collection point following the commencement of an intensified training period) the initial exposure to training during the preseason period with standardised (Std.) mean differences and 95% confidence intervals (CI).

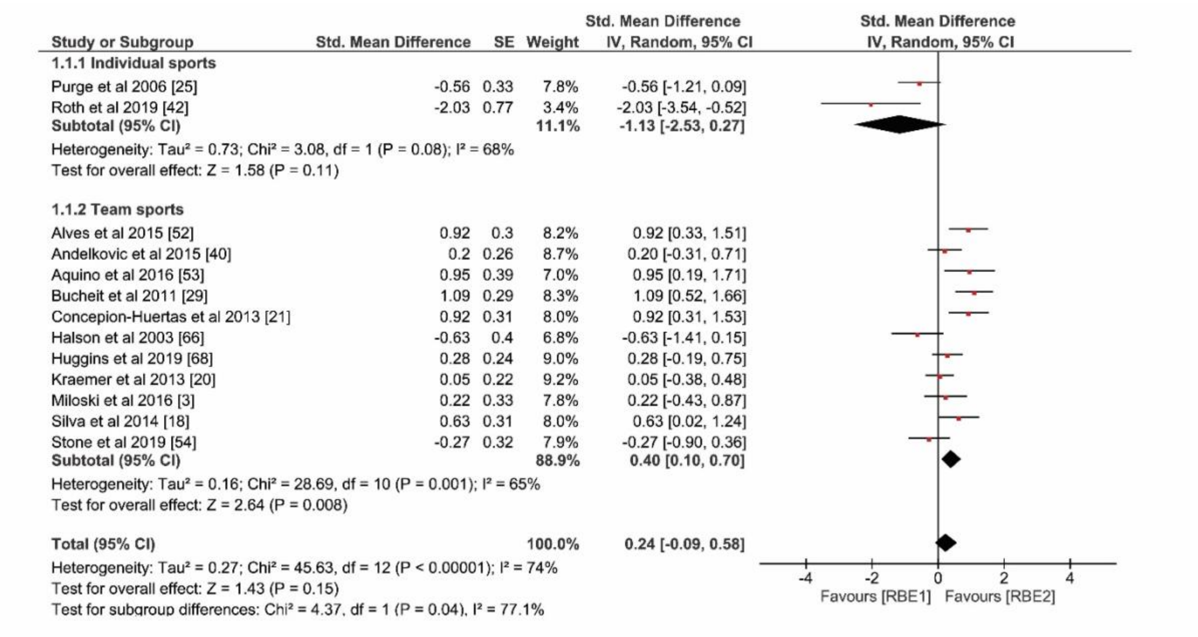


Figure 3: Forest plot of Creatine Kinase (CK) measures prior to (RBE1 – conclusion of the first bout of training) and following (RBE2 – conclusion of the second bout of training) two time points of similar training loads with standardised (Std.) mean differences and 95% confidence intervals (CI).

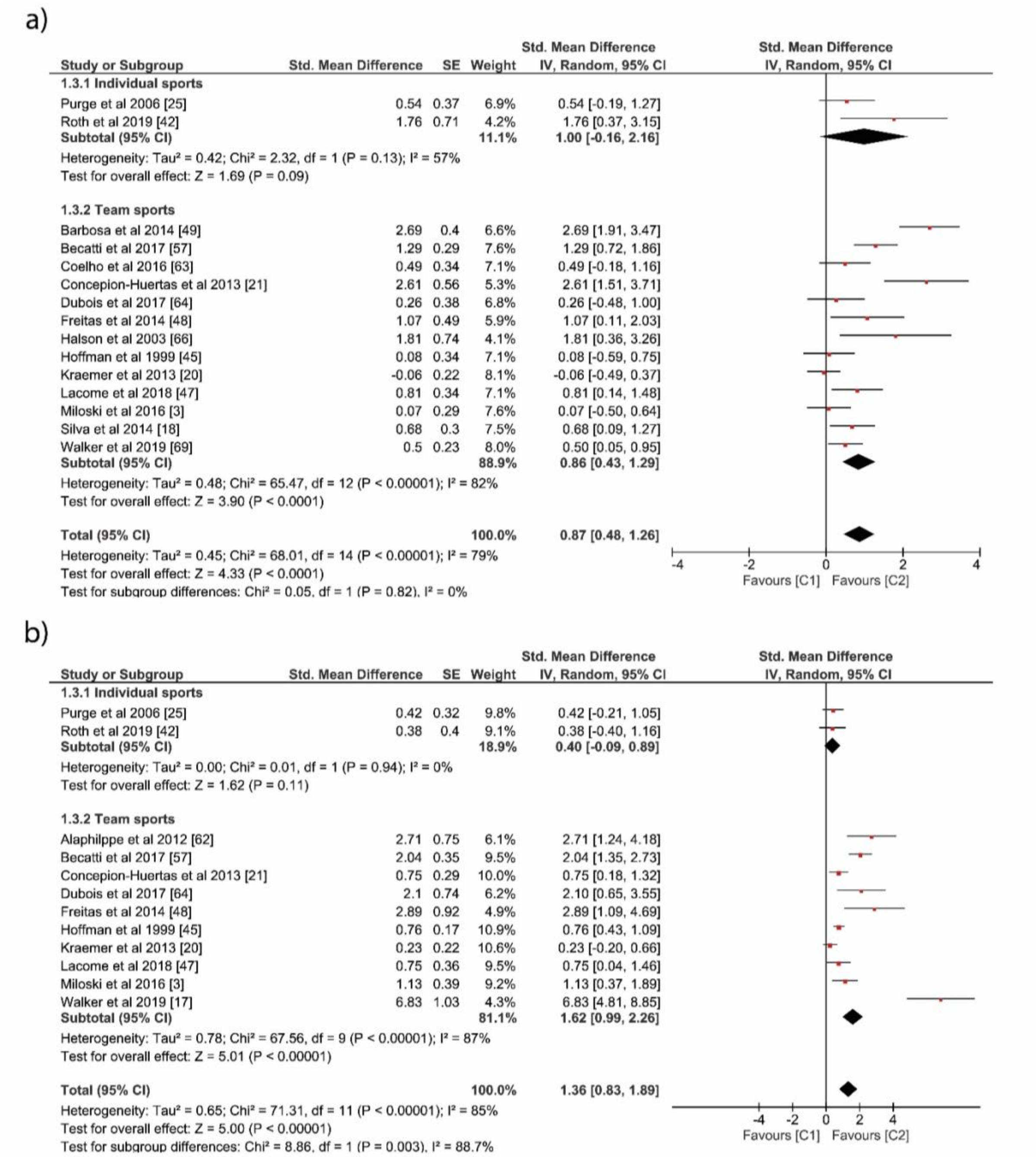


Figure 4: a) Forest plot of Creatine Kinase (CK) measures prior to (C1 – the end of a training period preceding a change in load) and following (C2 – the end of a training period of different loading to that of C1) a decline in training load with standardised (Std.) mean differences and 95% confidence intervals (CI); b) Forest plot of training loads across two time points (C1 and C2) with standardised (Std.) mean differences and 95% confidence intervals (CI).

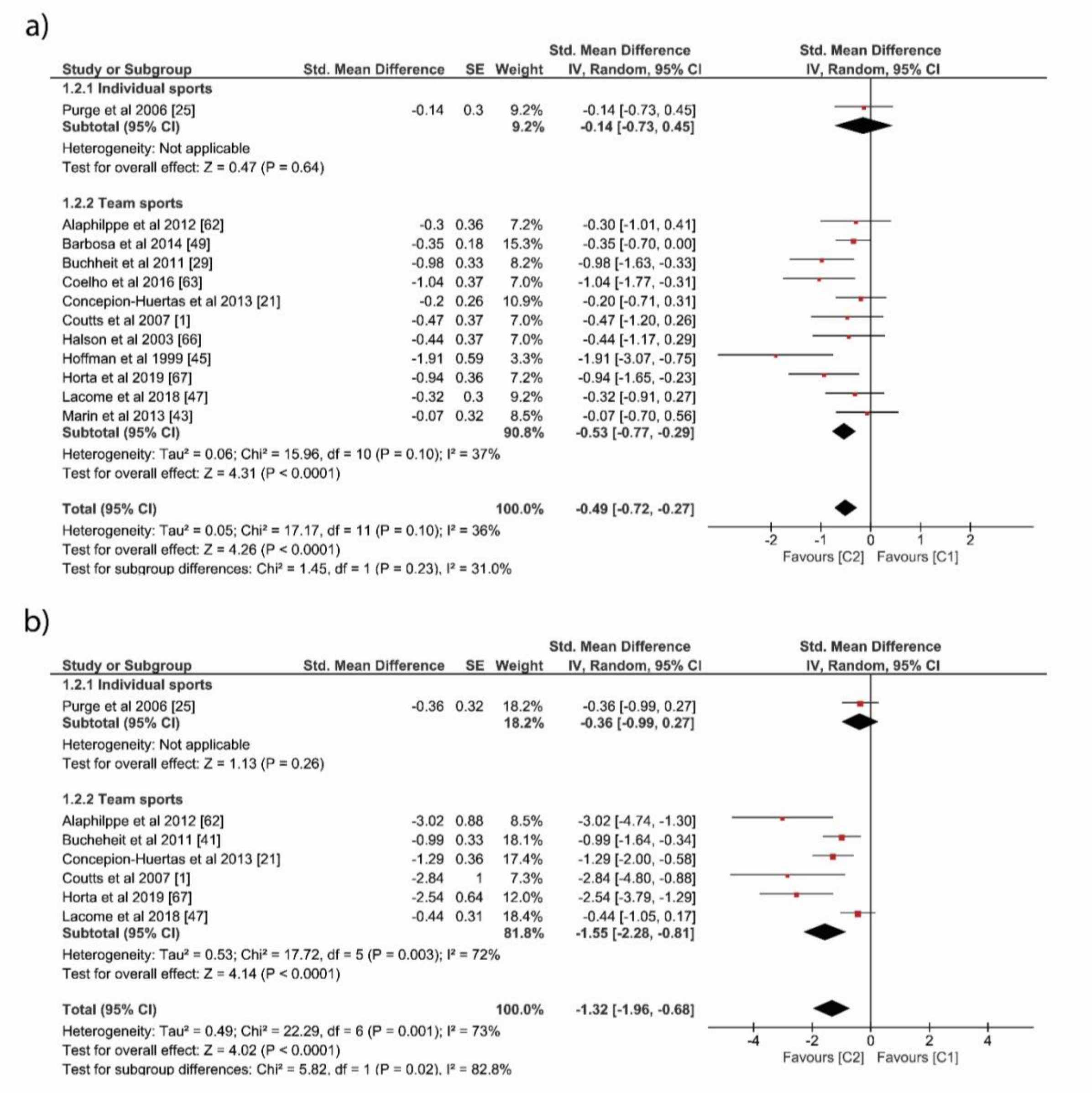


Figure 5: a) Forest plot of Creatine Kinase (CK) measures prior to (C1) and following (C2) an increase in workload with standardised (Std.) mean differences and 95% confidence intervals (CI); b) Forest plot of workloads across two time points (C1 and C2) with standardised (Std.) mean differences and 95% confidence intervals (CI).

2.3.6 Qualitative analysis

All qualitative results from the included studies are reported in Table 2. In comparison to CK, few studies reported the effect of training load upon inflammatory factors, physical performance measures and perceptual measures. Most studies reported increases in inflammatory factors (Anđelković et al., 2015; Brunelli et al., 2014; Marin et al., 2013; Roth et al., 2019; Silva et al., 2014; Walker et al., 2019), other indirect markers of muscle damage (Hoffman et al., 2005) and perceptual measures (Hoffman et al., 1999; Roth et al., 2019) upon commencement of the preseason period. In contrast, only one study by Concepcion-Huertas et al. (2013) reported no changes in indirect markers of muscle damage or inflammatory factors from baseline to the first data collection point within the preseason period. Only three of 19 studies (Brunelli et al., 2014; Coutts et al., 2007b; Silva et al., 2014) reported an improvement in physical performance measures (CMJ and MSFT) in the early stages of the preseason period.

Numerous studies reported that inflammatory factors and blood biomarkers (LDH and myoglobin) were altered in response to changes in training load. Brunelli et al. (2014) and Kurgan et al. (2018) reported a significant increase in inflammatory factors (IL-6, TNF-alpha and CRP) in response to an increase in workload, whilst Concepcion-Huertas et al. (2013) reported a decrease in LDH and myoglobin in response to a decrease in load. Additionally, two studies (Brunelli et al., 2014; Miloski et al., 2016) reported improvements in performance (CMJ) in response to an increase in load whilst contrastingly, Silva et al. (2014) reported improvements in performance in response to a decrease in load. Lacome et al. (2018) and Freitas et al. (2014) reported an improvement in CMJ in response to a decrease in load.

2.4 Discussion

This systematic review demonstrated that: 1) in the initial phase of the preseason period, athletes experienced high levels of EIMD; 2) the RBE phenomenon was non-existent for semi-elite and elite athletes; and 3) changes in training load and blood biomarkers of EIMD occurred concurrently, and in a positive and linear manner, throughout the training and competition phases. Using blood biomarkers as a monitoring tool for EIMD, when acute changes to training load and/ or stimulus are implemented, can be an effective tool for training prescription of both individual and team sport athletes.

2.4.1 Commencement of intensified training workloads

Several studies have reported high levels of CK in professional athletes during the initial phase of the preseason period (Coelho et al., 2014; Hoffman et al., 2005). The current meta-analysis confirmed these findings, whilst the qualitative analysis identified an increase in inflammatory factors (IL-1, IL-6, IL-8, TNF-alpha, CRP) and perceived measures of muscle soreness and fatigue. Elevated levels of EIMD markers have been identified in resistance trained men for several days following eccentric, resistance exercises despite being accustomed to this type of training (Meneghel et al., 2014). Likewise, team-sport athletes experienced similar EIMD responses in the early phases of the preseason period due to greater training loads compared to the offseason (Coutts et al., 2007a; Coutts et al., 2007d; Miloski et al., 2016). High training loads are typically prescribed to ensure athletes are physically prepared for the approaching competition season (Buchheit et al., 2013; Murray et al., 2017; Windt et al., 2017) and 'protect' athletes by reducing the likelihood of injury during the competitive phase of the season (Murray et al., 2017). Therefore, coaches should be aware that an acute and substantial increase in training load upon returning from the off-season will result in EIMD for athletes, which may impact upon subsequent training and adaptations in the pre-season period.

2.4.2 Similar absolute workloads within the same training phase

The RBE phenomenon has been reported to result from cellular, mechanical and neural adaptations that neutralise symptoms of EIMD such as increases in CK and muscle soreness (Hyldahl & Hubal, 2014; McHugh et al., 1999). Despite an overall increase in CK during the pre-season, our quantitative analysis identified no significant differences in CK across time points with similar training loads, whilst contrasting results were reported in the qualitative analysis. For example, some authors (Alves et al., 2015; Anđelković et al., 2015; Aquino et al., 2016) reported a decline in CK activity across time points of similar training loads, whereas others (Roth et al., 2019; Stone et al., 2019) reported an increase in CK activity. Similarly, contradictory changes in inflammatory factors (IL-1, IL-6, IL-8, TNF-alpha) were reported in the qualitative analysis. One study reported a decline in TNF-alpha across periods of similar training loads but an increase in IL-6 (Concepcion-Huertas et al., 2013), whilst another (Main et al., 2010) reported an increase in IL-1, IL-6 and IL-8 but a decrease in TNF-alpha. Of the nine studies that reported a decline in CK activity, and therefore a potential occurrence of the RBE, all involved athletes participating in non-contact/collision-based sports. Involvement in collision-based sports has been suggested to expose athletes to EIMD as well as IIMD (Naughton et al., 2018). Actions such as tackling, running into others and contact with the ground have been reported to cause potential damage to the muscle tissue at or adjacent to the contact site resulting in outcomes similar to those of EIMD (Naughton et al., 2018). Although muscle damage markers related to EIMD may begin to reduce across two time points of similar training loads, exposure to collisions may inflate these markers. As such, IIMD may potentially inhibit the occurrence of the RBE phenomenon in team sport athletes as collisions with opposing players and the playing surface are unpredictable and unavoidable in some sports.

The reporting of training load can also affect how data is interpreted and may explain why the RBE results were trivial in the current review. Both external and internal measures of training load were recommended for practitioners to understand an athlete's physiological and psychological well-being (Halson, 2014). However, only three of the 13 studies that investigated a potential RBE reported both external and internal load measures, further complicating comparisons between studies, as similar training loads could not be clearly confirmed at the comparative time-points. To further elucidate the existence of the RBE in athletes, external and internal load measures should be included in all future studies involving athlete monitoring regimes.

2.4.3 Different workloads within the same training phase

The data presented in the current meta-analysis clearly identified that, after the initial phase of the preseason period, markers of muscle damage were responsive to changes in training load. For example, Becatti et al. (2017) and Coelho et al. (2014) reported significant decreases in CK levels in elite level soccer players whilst Brunelli et al. (2014) reported decreases in IL-6, CRP and TNF-alpha in response to a decrease in training load in semi-elite basketball players. Perceptual measures of muscle soreness and fatigue were also reported to respond concurrently with changes in external training load (Hoffman et al., 1999; Roth et al., 2019). These findings support a review by Pedlar et al. (2019) who suggested that markers of EIMD (e.g. CK) were directly proportionate to the amount of stress imposed upon the athlete. Therefore, CK may be a sensitive tool to detect changes in training load. Practitioners could use CK as a monitoring tool during transitions between mesocycles or at times when training and/or competition load is expected to change.

Whilst it is important to understand the physiological effects of changes in training load upon EIMD, an understanding of how EIMD effects physical performance measures is also important to ensure athletes are acutely responding, and chronically adapting to the training stimuli. Attenuation in muscular contractility has been suggested as one the most valid measures of EIMD (Warren et al., 1999), and as such, physical performance testing should be considered to monitor acute responses to training in athletes (Doma et al., 2017). Several studies included in the current systematic review (Brunelli et al., 2014; Coutts et al., 2007b; Lacome et al., 2018; Miloski et al., 2016; Silva et al., 2014) reported improvements in physical performance outcomes in response to an increase in training load and muscle damage markers. Improvements in performance outcomes may have been observed during the season as these outcomes were compared to baseline measures taken prior to the commencement of the season. Thus, any potential stress-induced decrement in performance at particular time points during the season could have been masked by positive adaptations to training (Hyldahl & Hubal, 2014). Conducting more regular performance testing may better exemplify the acute response to training and should be considered for future research.

2.4.4 Limitations of the study

This systematic review has clearly identified the effect of training and competition upon EIMD however, it should be noted that there are some limitations that should be acknowledged. Firstly, this review included athletes of varying competition levels, age, sex and sports, which may have directly influenced responses. Practitioners should take into consideration the specific demands of the sport they are working with and the effect that these demands have upon EIMD. For example, collision sports may be influenced by IIMD as well as EIMD, which may affect adaptations and potentially inhibit any potential RBE phenomenon. Further, the included studies all analysed athletes via a group analysis. The effects and magnitude of EIMD may vary considerably dependant on an individual playing position within a team sport (Oxendale et al., 2016). It is also important to consider differences in the training and performance demands as a result of age or competition level of the athlete (de Alcaraz et al., 2017; Scanlan et al., 2011). For example, competition intensity may increase as an athlete moves from an elite youth level of competition to an elite senior level changing the physiological demands experienced by the athlete. Finally, a number of I^2 values in the meta-analyses were large (>75%), which was indicative of large variation in results between studies. Every effort was made to standardise the outcome measures and experimental approach of each study based on strict inclusion criteria however, this review included elite and semi-elite athlete populations involving individual and team sport athletes of both female and male sexes. Of the athletes within the included studies, 15% were female which highlights an area for further research. These factors may have contributed to the large heterogeneity of results with future studies needed to clearly delineate the impact of these on athlete's training and competition performances.

2.5 Conclusion

Elite and sub-elite athletes were exposed to significantly greater levels of blood biomarkers of EIMD in the early phases of the preseason. Changes in blood biomarkers also responded concurrently with acute changes in training loads. Despite these changes, the current review was unable to confirm the RBE phenomena in athletes with the potential influence of IIMD associated with collision sports requiring further clarification. The quantification of blood biomarkers is a sensitive tool to assess the physiological response to changes in training load with practitioners encouraged to utilise indirect markers of muscle damage, such as CK, as a monitoring tool when transitioning between phases of the season or mesocycles to support prescription and adaptations. Further investigations should strive to determine the impact of

EIMD upon physical performance measures and utilise a holistic approach to the reporting of training loads to ensure practitioners gain a greater understanding of the physiological stress their athletes are experiencing, enabling more informed decision making.

Chapter 3

Publication

Simmons, R. G., Leicht, A., Sinclair, W. H., Bowman, P., Dobbin, M., & Doma, K. (2024). Acute Response to Training after Returning from the Off-Season in Elite Rugby League Athletes. Journal of Human Kinetics, 92, 133-146.

Author Contributions

R.G.S contributed 70% to this chapter. He developed the chapter structure, wrote each section, collated and analysed the data. K.D offered conceptual guidance and support (15%), both W.H.S and A.L contributed to the manuscript drafting and construction of ideas within the discussion (10%), while P.B and M.D assisted with the collation of data and offered conceptual guidance (5%).

3.1 Introduction

Rugby league (RL) is a collision-based intermittent team sport played at amateur, semi-elite and elite levels. Players are exposed to periods of high intensity activity interspersed with periods of low intensity activity (Johnston et al., 2014). Thus, RL players are required to complete various modes of training at high intensities to physically prepare them for the demands of competition. The elite competition in Australia and New Zealand is the NRL. Like many team sports, the NRL season comprises of three macro-cycles in the following order: the off-season, preseason and the competition season (Gamble, 2006). Each of these phases have separate goals related directly to a player's physical fitness and wellbeing

(Buchheit et al., 2013). For example, the off-season occurs between the end of the competition season (September-October) and the beginning of the preseason (November) and is an opportunity for players to recuperate from the preceding competition season. Conversely, the preseason phase aims to optimise physical and technical qualities of players, whilst the focus of the competition phase is to maintain these qualities (Jeong et al., 2011). Of these phases, athletes are exposed to the greatest training loads in the preseason (Jeong et al., 2011), which has been known to cause EIMD (Simmons et al., 2021).

The signs and symptoms of EIMD include increased intramuscular enzymes in the blood (e.g. CK) and perceived muscle soreness (Doma et al., 2015). The EIMD symptoms are also known to impair muscle force-producing capabilities for several days after a training stimulus (Hyldahl & Hubal, 2014), potentially impacting the athletes ability to perform at the required capacity. However, repeated exposure to a training stimulus was reported to ameliorate markers of EIMD and is termed the RBE (Hyldahl & Hubal, 2014; McHugh et al., 1999). Declines in CK across two time points of similar training load indicative of an RBE have been reported for athletes in team sports such as handball (Concepcion-Huertas et al., 2013), American football (Kraemer et al., 2013) and futsal (Miloski et al., 2016). However, these RBE effects were observed across the final weeks of the preseason (Miloski et al., 2016) and competition (Concepcion-Huertas et al., 2013; Kraemer et al., 2013) periods with the duration between data collection varying from two to 12 weeks. Collecting data sporadically makes it challenging to determine the acute physiological response to a specific training stimulus in a single macro-cycle such as the preseason. Furthermore, only one of the aforementioned studies (Concepcion-Huertas et al., 2013; Kraemer et al., 2013; Miloski et al., 2016) involved participants from a contact sport. Athletes participating in contact sports experience significant IIMD as a result of physical collisions with the ground and opposition players (Naughton et al., 2018), which exhibits similar symptoms to those of EIMD and may affect the occurrence of the RBE phenomenon. Thus, athletes in contact sports should have their physical impact monitored in both training and competition to gain a more holistic understanding of the external training load.

The optimisation of training loads in the preseason can have a significant impact on the availability of team sport athletes to train and compete throughout the competition phase of the year. For example, higher preseason training loads were associated with an increased training and match availability during the competitive season (Gabbett, 2016; Windt et al., 2017). A greater understanding of the physiological responses to training during the initial preseason period may assist in optimising readiness for each training session, reduce the risk of overtraining and enhance training quality throughout the remainder of the preseason period. To the authors' knowledge, no studies have investigated the physiological response to training during a NRL preseason. Given the unique physical demands of elite RL, it is important to understand the physiological response to the initial weeks or micro-cycles of the preseason period to ensure training loads can be optimised and enhance athlete preparation for the latter preseason and upcoming competition season. Therefore, the purpose of this study was to: 1) quantify the EIMD response experienced during the initial two weeks of the preseason phase in elite male RL athletes; and 2) determine if a RBE occurs during the study period.

3.2 Methods

3.2.1 Participants

A group of 21 elite, male, RL players from the same NRL club participated during the preseason leading into the 2020 NRL competition season. Prior to the commencement of the study, players received comprehensive explanations of the study and provided voluntary written informed consent. Players reported no illness, injury or medication that would contraindicate any of the testing and training protocols and were familiar with testing protocols and wearable technologies as part of their normal training and monitoring routines. To minimise biological variation, players refrained from strenuous activity for at least 48 hours prior to the initial or baseline testing session and maintained their dietary habits throughout the study period. Institutional ethics approval (H7918) was obtained prior to the recruitment of players in line with the Declaration of Helsinki.

3.2.2 Methodology

3.2.2.1 Design

A repeated measures design was used to assess the acute responses (i.e. muscle damage marker, perceptual measures, neuromuscular power, heart rate) to the initial period of the preseason phase. The players participated in eight field-based skill/conditioning sessions and six resistance-based gym sessions (Figure 6). Capillary blood samples were collected on day 1 (D1), 2 (D2), 4 (D4), 5 (D5), 8 (D8), 9 (D9), 11 (D11) and 12 (D12) at the same time each morning prior to the commencement of training. Upper and lower body neuromuscular performance was assessed on D1, D5, D8 and D12. Lower body neuromuscular performance was assessed in the morning prior to the field-based session, whilst upper body neuromuscular performance was assessed in the afternoon prior to the resistance-based gym session. All data was entered into an athlete management system (Smartabase, Fusion Sport, Brisbane, Australia) either manually or via an application programming interface for collation and subsequent analysis.

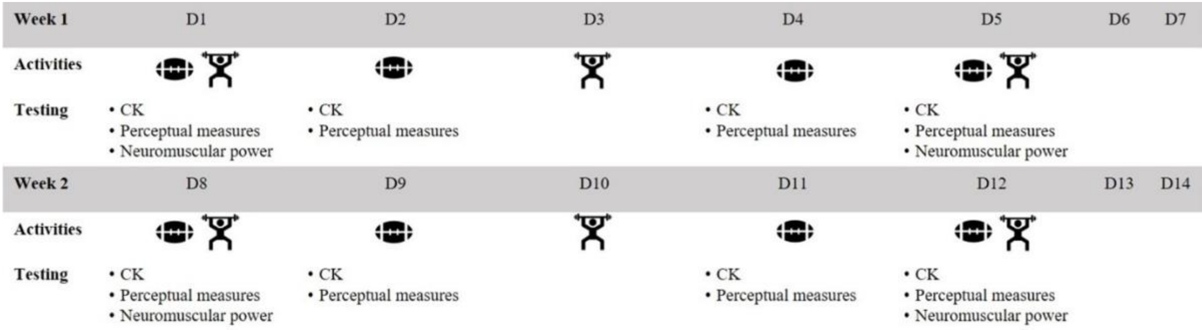


Figure 6: Schematic outlining the schedule of training and testing throughout the study period. CK - creatine kinase, D – day (i.e. day 1).

 = field-based skill/conditioning session

 = resistance-based gym session

3.2.2.2 Muscle damage marker

Fingertip capillary blood samples (30 µL) were collected from each player for analysis of CK and stored in a heparinised microtube in a cool environment (i.e. foam container with ice blocks). Within 30 minutes after collection, each blood sample was placed on a measurement strip using a pipette, and analysed via a Reflotron Plus system (Roche Diagnostics, Grenzacherstrasse, Switzerland), which has previously been reported as a valid and reliable tool for CK assessment (Horder et al., 1991).

3.2.2.3 Internal training load

Perceptual measures of fatigue and muscle soreness were assessed on each training day morning prior to or upon arriving at the training facility (Figure 1). Players were asked to rate each measure on a Likert scale from 1 to 10 with 10 being the best possible score (i.e. no fatigue or muscle soreness). Players completed questionnaires via an athlete management system mobile application (Smartabase Athlete, Fusion Sport, Brisbane, Australia). The internal load of field-based sessions was quantified via fitted heart rate monitors (Firstbeat Sports, Firstbeat, Finland) that recorded training impulse (TRIMP) (Bogdány et al., 2016; Stagno et al., 2007). Each player wore the same monitor throughout the duration of the study to minimise between-monitor error (Bogdány et al., 2016). Internal load for all field-based sessions was also quantified via a session rating of perceived exertion (sRPE) as previously defined (Foster et al., 2001).

3.2.2.4 External training load

External load was quantified during each field-based skill/conditioning session using a 10 Hz global positioning system (GPS). The GPS device (Vector S7, Catapult, Melbourne, Australia) also consisted of an accelerometer and was worn in a fitted harness between the scapulae of the player. Scott and colleagues (Scott et al., 2016) have reported strong validity and reliability of 10 Hz GPS devices in measuring distances covered at both low and high velocities and each player wore the same device for each training session to minimise interunit error (Scott et al., 2016). At the conclusion of each session, data was downloaded and analysed using the proprietary software (Openfield, Catapult, Melbourne, Australia). The cumulative session totals for the following metrics per player were then exported into a customised Microsoft Excel spreadsheet (Microsoft, Redmond, USA): total distance (m), high velocity (>15 km/h) distance (m), sprint (>22 $km.h^{-1}$) distance, PlayerLoad^{TM} (arbitrary units, AU), repeat high-intensity efforts (RHIE), metabolic power (W) in three bands (B4 = 35-45 W, B5 = 45-60 W, B6 = >60 W) and count of body impacts in three bands (B4 = 7-8 G, B5 = 8-10 G, B6 = >10 G). External load during resistance-based gym sessions was quantified using the following equation: total repetitions x weight lifted = total resistance volume (Hiscock et al., 2015).

3.2.2.5 Neuromuscular function

Lower body neuromuscular performance was assessed via a CMJ on a dual force platform (ForceDecks FD4000, Vald Performance, Australia). Prior to testing, players completed a 10-minute dynamic warm up consisting of foam rolling, active mobility, and practice jumps. For a successful test, players were required to keep their hands in contact with their hips for the duration of the movement and land whist maintaining balance. Players were instructed to jump as high as they could for three repetitions separated by a short pause of ~3 seconds to maintain balance and preparation to jump again. The average peak power, flight time:contraction time ratio (FT:CT) and peak rate of force development (PRFD) were then identified for further analysis. These CMJ variables have previously been shown to be reliable (Cormack et al., 2008b; Lombard et al., 2017). Upper body neuromuscular performance was assessed via a bench throw test on a Smith machine. Prior to testing, players completed a 10-minute warm-up consisting of active mobility and muscle activation exercises. To complete the test, players laid supine on a bench and were instructed to push a loaded barbell (total weight = 30kg) as high as possible with two hands for three consecutive attempts separated by a short pause of at least 2 seconds. Average peak power was calculated using a linear position transducer (GymAware PowerTool, GymAware, Canberra, Australia) attached to the barbell.

3.2.3 Statistical analysis

The SPSS statistical software package (SPSS inc., Chicago, IL, USA) was used to complete a two-way (week x day) repeated measures analysis of variance for all variables. Where appropriate, a Bonferroni corrected, pairwise comparison, post-hoc test was completed to identify statistical differences between factors and a p value of less than 0.05 was considered statistically significant.

3.3 Results

3.3.1 EIMD marker

A significant interaction effect was identified for CK levels (p=0.00). Post-hoc analysis showed that CK levels were significantly greater during D2-D5 compared to D1 in week 1, with the same trends observed in week 2 (Table 4). There were no differences in CK levels between weeks (i.e. no main effect of week). However, a main effect of day was evident (p=0.00) with significantly lower levels on the first day (p=0.00) compared to all other testing days (Table 5).

Table 4: The mean ± standard deviation of EIMD, internal and external training loads, and neuromuscular function metrics during each day and week of the study.

	Week 1					**Week 2**				
	D1	**D2**	**D3**	**D4**	**D5**	**D8**	**D9**	**D10**	**D11**	**D12**
EIMD										
Creatine Kinase (U/L)	149.8±94.6	878.5±560.3[a]		710.6±446.6[a]	829.6±453.7[a]	266.1±133.8[a]	656.0±263.2[b]		911.9±572.0[b]	870.1±502.5[b]
Internal Training Load										
Fatigue (au)	8.6±1.0	7.3±1.3	7.5±1.3	7.0±1.3	7.1±1.2	8.1±1.3	7.4±1.0	7.3±1.0	7.1±1.0	6.9±1.0
Muscle Soreness (au)	8.6±1.4	6.8±1.7	6.5±1.6	6.6±1.3	6.7±1.2	7.9±1.2	7.1±0.9	6.9±1.3	6.7±0.9	6.5±1.2
TRIMP (au)	149.6±50.8	123.3±29.5		138.5±35.9	123.7±32.9	154.6±47.8	154.0±76.7		153.2±43.6	121.4±26.0[c]
sRPE (au)	7.2±2.6	7.2±2.6		5.6±1.3	6.1±1.3	5.5±1.9	8.2±1.0[bd]		5.8±2.4	4.9±1.3
External Training Load										
Total Distance (m)	4,277.4±1,098.3	4,364.9±152.5		4,925.1±250.1[ce]	4,671.4±273.4[e]	4,816.9±264.1	5,691.7±377.1[bcde]		5,402.0±217.5[bd]	4,739.1±208.0

High-Velocity Distance (m)	510.9±331.8	817.2±188.8^{a}		433.2±103.8^{e}	816.2±256.1^{df}	524.2±133.9	1,105.9±119.9^{bcde}		630.5±81.8^{df}	380.1±122.1^{b}
Sprint Distance (m)	11.2±18.8	22.9±12.4		173.1±83.7^{ae}	23.3±19.9^{f}	190.9±139.4^{a}	8.8±5.5^{cde}		156.8±104.1^{d}	41.1±40.4^{b}
Metabolic Power – Band 4 (W)	38.6±0.4	39.6±0.4^{a}		39.2±0.4^{a}	39.2±0.2^{a}	39.1±0.3	39.3±0.2^{c}		38.8±0.3	39.1±0.4
Metabolic Power – Band 5 (W)	49.2±0.9	51.6±1.1^{a}		51.0±0.5^{a}	50.9±0.5^{a}	51.0±0.6^{a}	51.2±0.3		51.0±0.5	51.0±0.4
Metabolic Power – Band 6 (W)	61.7±21.8	65.4±2.0		66.9±2.7	65.8±1.5	68.6±3.1	65.9±1.4		66.8±1.8	68.2±1.9
RHIE (au)	11.1±4.0	8.5±3.4		14.4±3.9^{e}	15.3±4.0^{ed}	16.0±4.2	26.2±5.5^{bcde}		17.4±4.7	21.0±2.8^{b}
Player Load (au)	466.8±117.2	469.7±50.1		570.3±51.9^{e}	536.6±57.5^{e}	549.5±57.0	687.9±62.7^{bcde}		595.0±68.5	543.4±59.8^{c}
Impacts – Band 4 (n)	2.1±1.7	1.6±2.9		2.2±2.4	6.6±4.9^{ae}	0.8±1.0	6.9±4.8^{be}		3.4±1.6^{b}	5.2±3.1^{b}
Impacts – Band 5 (n)	2.6±1.8	0.2±0.5^{a}		1.3±2.2	6.6±5.5^{def}	0.4±0.8^{a}	3.5±4.6		1.5±1.5	2.6±3.2

Impacts – Band 6 (n)	1.0±1.4	0.1±0.4		0.2±0.5	2.4±2.5	0.1±0.3	1.3±1.5		1.0±1.4	0.4±1.0
Strength Volume (kg)	22,499.4±10,161.5		6,186.1±1,827.5		17,423.6±9,381.6	19,585.4±8,229.1		7,782.0±1,936.2		7,424.3±2,077.5
Neuromuscular Function										
CMJ Peak Power (W.kg-1)	57.3±8.8				54.3±8.6	55.9±8.4				53.4±8.4
CMJ FT:CT	0.8±0.1				0.7±0.1	0.8±0.1				0.7±0.2
CMJ PRFD (N.s-1)	2,423.4±2,794.6				2,334.1±2,061.8	1,649.5±1,248.3				1,694.4±1,126.5
Bench Throw Peak Power (W.kg-1)	11.7±1.6				12.0±1.5	12.5±1.6				12.3±1.8

Values reported as mean ± SD. Where EIMD = exercise induced muscle damage; TRIMP = training impulse; sRPE = session rating of perceived exertion; RHIE = repeat high-intensity efforts; CMJ = countermovement jump; FT = flight time; CT = contraction time; PRFD = peak rate of force development; U/L = units per litre; au = arbitrary units; W = watts; n = count; m = meters; kg = kilograms; N = newtons; s = seconds: [a] <0.01 vs D1; [b] <0.05 vs D8; [c] <0.05 vs D11; [d] <0.05 vs D12; [e] <0.05 vs D2; [f] <0.05 vs D4.

Table 5: The mean ± standard deviation of EIMD, internal and external training loads, and neuromuscular function metrics for each day of the week.

	First day of week (D1 and D8)	Second day of week (D2 and D9)	Third day of week (D3 and D10)	Fourth day of week (D4 and D11)	Fifth day of week (D5 and D12)
EIMD					
Creatine Kinase (U/L)	207.9 ± 99.4	767.2 ± 388.6^{a}	-	811.2 ± 438.6^{a}	849.9 ± 435.3^{a}
Internal Training Load					
Fatigue (au)	8.3 ± 0.9	7.3 ± 0.9^{a}	7.4 ± 0.9^{ab}	7.0 ± 0.9^{ac}	7.0 ± 0.9^{abc}
Muscle Soreness (au)	8.3 ± 0.9	7 ± 0.9^{a}	6.7 ± 1.4^{a}	6.7 ± 0.9^{a}	6.6 ± 0.9^{a}
TRIMP (au)	152.1 ± 39.4	138.6 ± 38.5	-	145.9 ± 36.2	122.6 ± 26.6^{abd}
sRPE (au)	6.3 ± 1.8	7.7 ± 1.4^{a}	-	5.7 ± 0.9^{b}	5.5 ± 0.9^{ab}
External Training Load					
Total Distance (m)	4547.0 ± 550.8	5028.0 ± 236.5^{a}	-	5164.0 ± 180.6^{ab}	4705.0 ± 187.9^{bd}
High-Velocity Distance (m)	517.5 ± 203.5	961.5 ± 126.9^{a}	-	531.8 ± 81.6^{b}	598.1 ± 141.1^{b}
Sprint Distance (m)	101.0 ± 74.7	15.9 ± 6.9^{a}	-	165.0 ± 77.9^{ab}	32.2 ± 23.4^{abd}
Metabolic Power – Band 4 (W)	38.9 ± 0.5	39.5 ± 0.5^{a}	-	39.0 ± 0.5^{ab}	39.2 ± 0.5^{ab}
Metabolic Power – Band 5 (W)	50.1 ± 0.5	51.4 ± 0.5^{a}	-	51.0 ± 0.5^{ab}	50.9 ± 0.5^{ab}
Metabolic Power – Band 6 (W)	65.1 ± 11.5	65.7 ± 1.8	-	66.9 ± 1.8^{b}	67.0 ± 1.4^{b}
RHIE (au)	13.6 ± 2.7	17.4 ± 3.2^{a}	-	15.9 ± 2.7^{a}	18.1 ± 2.7^{ae}
Player Load (au)	508.2 ± 56.8	578.8 ± 45.8^{a}	-	582.7 ± 52.7^{a}	540.0 ± 52.7^{bd}
Impacts – B4 (n)	1.5 ± 0.9	4.3 ± 2.7^{a}	-	2.8 ± 1.4^{ab}	5.9 ± 3.2^{abd}
Impacts – B5 (n)	1.5 ± 0.9	1.9 ± 2.3	-	1.4 ± 1.4	4.6 ± 0.9^{abd}

Impacts – B6 (n)	0.5 ± 0.9	0.7 ± 0.9	-	0.6 ± 0.9	1.4 ± 0.3[ad]
Strength Volume (kg)	21042.0 ± 6866.5	-	6984.0 ± 1627.3[a]	-	12424.0 ± 4608.7[ac]
Neuromuscular Function					
CMJ Peak Power ($W.kg^{-1}$)	56.6 ± 8.7	-	-	-	53.9 ± 8.2[a]
CMJ FT:CT	0.8 ± 0.0	-	-	-	0.7 ± 0.0[a]
CMJ PRFD ($N.s^{-1}$)	2036.0 ± 1845.9	-	-	-	2014.0 ± 1481.1
Bench Throw Peak Power ($W.kg^{-1}$)	12.1 ± 1.4	-	-	-	12.1 ± 1.4

Values reported as mean ± SD. Where EIMD = exercise induced muscle damage; TRIMP = training impulse; sRPE = session rating of perceived exertion; RHIE = repeat high-intensity efforts; CMJ = countermovement jump; FT = flight time; CT = contraction time; PRFD = peak rate of force development; U/L = units per litre; au = arbitrary units; W = watts; n = count; m = meters; kg = kilograms; N = newtons; s = seconds: [a] = $p<0.05$ vs First day of week; [b] = $p<0.05$ vs Second day of week; [c] = $p<0.05$ vs Third day of week; and [d] = $p<0.05$ vs Fourth day of week.

3.3.2 Internal training load

There was a significant interaction effect for TRIMP (p=0.03) and sRPE (p=0.00) but not for perceived fatigue (p=0.27) or muscle soreness (p=0.12). TRIMP on D12 was significantly (p=0.00) lower than D11, whilst sRPE on D9 was significantly (p=0.00) greater than D8 and D12. There was no main effect of week (TRIMP, p=0.51; sRPE, p=0.35), but a main effect of day was found for all variables (p=0.00; Table 5). As displayed in Table 5, post-hoc analysis revealed significantly reduced perceived fatigue (i.e. greater score) on the first day of the week (p=0.00) compared to all other testing days. TRIMP was significantly reduced on the last day of the week (p=0.04) whilst sRPE was greatest on the second day of the week (p=0.03) compared to all other days.

3.3.3 External training load

A significant interaction effect was found for all external training load measures (p=0.00), except for metabolic power B6 and strength volume. Post-hoc analysis identified a significant increase for numerous measures (total distance, high-velocity distance, sprint distance, RHIE, player load and impacts B4) on D9 compared to D2 (Table 4). There was a main effect of week (p=0.03) for most external training load measures with significantly greater values for total, high-velocity and sprint distances, metabolic power B5 and B6, RHIE, PlayerLoad™ and impacts B4 during week 2 compared to week 1 (Table 6). In contrast, strength volume was lower in week 2 compared to week 1 (Table 6). Other than metabolic power B6 and impacts B6, there was a main effect of day (p=0.00; Table 5) for all external training load measures. As identified in Table 5, impacts B4 (p=0.04), B5 (p=0.05), strength volume (p=0.00) and RHIE (p=0.00) were all greatest on the last day of the week. Absolute total distance and absolute sprint distance (p=0.01) were greatest on the fourth day of the week whilst, absolute high-velocity distance (p=0.00) was greatest on the second day of the week (Table 5). PlayerLoad^{TM} (p=0.00) and metabolic power B4 (p=0.04) and B5 (p=0.00) were significantly lower on the first day of the week compared to the rest of the days (Table 5).

Table 6: The mean ± standard deviation of EIMD, internal and external training loads, and neuromuscular function metrics for each week of the study.

	Week 1	Week 2
EIMD		
Creatine Kinase (U/L)	642.1 ± 313.9	676.0 ± 322.2
Internal Training Load		
Fatigue (au)	7.5 ± 0.9	7.4 ± 0.9
Muscle Soreness (au)	7.0 ± 0.9	7.0 ± 0.9
TRIMP (au)	123.8 ± 27.5	127.8 ± 32.1
sRPE (au)	6.0 ± 1.4	5.7 ± 0.9
External Training Load		
Total Distance (m)	4138.1 ± 244.3	4530.2 ± 203.5 [a]
High-Velocity Distance (m)	591.8 ± 107.7	558.4 ± 61.9 [a]
Sprint Distance (m)	49.9 ± 22.9	82.6 ± 43.5 [a]
Metabolic Power – Band 4 (W)	39.2 ± 0.0	39.2 ± 0.0
Metabolic Power – Band 5 (W)	50.8 ± 0.5	51.1 ± 0.5 [a]
Metabolic Power – Band 6 (W)	65.4 ± 5.0	67.8 ± 1.4 [a]
RHIE (n)	12.7 ± 0.5	17.7 ± 0.5 [a]
Player Load (au)	466.8 ± 34.8	526.3 ± 54.5 [a]
Impacts – Band 4 (n)	2.8 ± 1.8	4.0 ± 1.8 [a]
Impacts – Band 5 (n)	2.2 ± 1.4	2.3 ± 1.4
Impacts – Band 6 (n)	0.8 ± 0.5	0.8 ± 0.9
Strength Volume (kg)	15369.7 ± 5276.8	11597.3 ± 2803.2 [a]

Neuromuscular Function		
CMJ Peak Power ($W.kg^{-1}$)	55.8 ± 8.7	54.6 ± 8.2[a]
CMJ FT:CT	0.8 ± 0.0	0.7 ± 0.0[a]
CMJ PRFD ($N.s^{-1}$)	2378.8 ± 2322.9	1671.9 ± 1073.2
Bench Throw Peak Power ($W.kg^{-1}$)	11.8 ± 1.4	12.4 ± 1.4[a]

Values reported as mean ± SD. Where EIMD = exercise induced muscle damage; TRIMP = training impulse; sRPE = session rating of perceived exertion; RHIE = repeat high-intensity efforts; CMJ = countermovement jump; FT = flight time; CT = contraction time; PRFD = peak rate of force development; U/L = units per litre; au = arbitrary units; W = watts; n = count; m = meters; kg = kilograms; N = newtons; s = seconds: [a] = $p<0.05$ vs Week 1.

3.3.4 Neuromuscular function

None of the neuromuscular function measures showed significant interaction effects (p=0.40; Table 4). However, there was a main effect of week (p=0.02; Table 6) for all neuromuscular function measures other than CMJ PRFD. Table 6 highlights a significant decline in lower body neuromuscular function (i.e. CMJ relative peak power, p=0.00 and FT:CT, p=0.00) in week 2, whilst there was an increase in upper body neuromuscular power output (i.e. bench throw relative peak power, p=0.03) compared to week 1. There was a main effect of day (p=0.00) with lower body outputs (i.e. CMJ relative peak power, p=0.00 and FT:CT, p=0.00) reduced on the fifth day of the week relative to the first day of the week (Table 5).

3.4 Discussion

The aims of this study were to identify the physiological responses to the initial two weeks of the preseason phase in elite male RL athletes and determine if there was an occurrence of a RBE. The present findings identified similar levels of EIMD and internal training load across the initial two weeks of the preseason in elite male RL athletes. A significant increase in numerous external training load variables was identified in the second week of the study while there was a decline in lower body neuromuscular function. Despite a significant increase in external training load from week 1 to week 2, similar EIMD and internal training loads were exhibited suggesting the existence of a RBE. These findings can be used by practitioners to inform training prescription in the initial weeks of the preseason.

The key finding of the current study was the lack of change in EIMD markers and internal training load, concurrently with a significant increase in external training load during early preseason. These findings support a recent review(Simmons et al., 2021), which identified no change in markers of EIMD in response to repeated bouts of a given training stimulus in elite and semi-elite athletes. The theoretical construct of the RBE suggests that the levels of EIMD markers will reduce following repeated exposure to the same training stimulus (McHugh et al., 1999; Simmons et al., 2021). Although the mechanisms resulting in this attenuation of EIMD markers are not fully understood, it has been suggested that neural, cellular and connective tissue adaptations may all contribute to this RBE (McHugh et al., 1999). It could be concluded that the athletes within the current study did not demonstrate the typical responses associated with the theoretical RBE as there were no significant reductions in EIMD markers from week 1 to week 2. Whilst the current findings do not support this traditional definition of the RBE, the work of Burt and colleagues (Burt et al., 2015) provides an alternate suggestion for a RBE. They identified an identical EIMD response concurrently with an increase in training load as well as a maintenance of training load across two microcycles (Burt et al., 2015). These authors indicated that EIMD attenuations were not dependent upon external training load (Burt et al., 2015). Similarly, the athletes in the current study were exposed to a significant increase in external training load in week 2 yet, maintained a similar EIMD response to that of week 1. Potentially, the current athletes exhibited similar levels of EIMD for both weeks due to neural, cellular and connective tissue adaptations underpinning the RBE (McHugh et al., 1999). Although the theoretical construct of the RBE requires repeated micro-cycles of a similar training load, athletes rarely undertake identical micro-cycles during the preseason, given the importance of applying progressive overload and limiting the possibility of diminishing returns (Jeong et al., 2011). Thus, the acute responses reported in the current study reflects 'real world' training situations in elite male RL players during the early weeks of the preseason. These results, along with previous work (Burt et al., 2015) could provide the foundation for an alternate view of the RBE.

An important and novel element of the current study was the inclusion of physical performance testing throughout the two training micro-cycles of the preseason. A previous systematic review (Simmons et al., 2021) identified a lack of regular physical performance testing in prior work, which is essential in identifying training-induced physical performance changes. Multiple studies (Brunelli et al., 2014; Coutts et al., 2007b; Lacome et al., 2018; Miloski et al., 2016; Silva et al., 2014) have included inconsistent physical performance testing regimes within micro-cycles with testing completed every couple of weeks or months. Conducting physical performance tests over extended periods does not capture the acute changes in physical performance capabilities due to training-induced stress (e.g. EIMD). Several studies (Brunelli et al., 2014; Coutts et al., 2007b; Lacome et al., 2018; Miloski et al., 2016; Silva et al., 2014) reported improvement in physical performance measures (e.g. CMJ) across several weeks and months, indicating chronic rather than acute adaptations. To our knowledge, the current study was the first to examine acute responses in physical performance capabilities across two successive micro-cycles of a preseason in elite RL players with increasing external training loads reflecting authentic periodisation. This regular assessment may provide a less invasive method of monitoring EIMD in elite team sport athletes.

The findings of this study identified a significant decline in two of the lower body neuromuscular function metrics across the weeks. The significant reduction in CMJ performance in week two highlighted a negative acute response with attenuation of muscle contractility a common symptom of EIMD (Warren et al., 1999). Both resistance training and field-based sessions involved numerous eccentric contractions, which are known to induce greater EIMD and chronic muscular adaptations (Hedayatpour & Falla, 2015). Although the biweekly testing of neuromuscular function in this study demonstrated an acute reduction in physical performance capabilities, this decrement in neuromuscular function may be required for the achievement of positive chronic adaptations. Future research could longitudinally observe these weekly responses to modify training prescription and further promote physiological adaptations.

The current increases in EIMD (CK) and internal training load measures (fatigue and muscle soreness) confirmed previous findings observed in the initial phase of the preseason period in semi-elite populations (Coutts et al., 2007b; Coutts et al., 2007c; Miloski et al., 2016). To our knowledge, the current study is the first to assess EIMD repetitively throughout the initial micro-cycles of the preseason phase in team sport athletes. This consistent monitoring was able to detect a sustained increase in internal response across the two micro-cycles at a time of an external training load increase relative to the preceding off-season period (Simmons et al., 2021). Further, this regular monitoring was able to identify a decline in lower body neuromuscular function on the fifth day of the week indicating a potential compromise in muscular contractility (Doma et al., 2015). Practitioners should be aware of the heightened physiological response in this early phase of the preseason macro-cycle and ensure training programs are promoting adaptation without exposing athletes to the risk of overtraining. Incorporating effective recovery regimes may adequately prepare athletes for future training stimuli, enhance training quality and optimise adaptation (Doma et al., 2017).

Given the sharp increase in external training load from the off-season to the initial weeks of the preseason period, practitioners should complete daily monitoring of external and internal training loads as well as EIMD in collision sport athletes. Understanding each athletes' off-season training load would also aid in prescribing training with the goal of gaining maximum training adaptations. Although practitioners may not observe an initial preseason reduction in internal training load and EIMD markers in response to an increase in external training load, athletes may still be adapting to the training stimulus. This study provided a 'real world' example of how elite RL athletes respond to the early phase of the preseason period.

Although this study identified key findings concerning the initial phase of the preseason, there were some limitations relevant for practitioners. Firstly, due to economic feasibility and the invasive nature of CK collection, this study investigated the initial two weeks of the preseason only. Although this is an important period for practitioners to monitor, future research could potentially investigate the entire preseason and validate other non-invasive markers of EIMD (e.g. delayed onset muscle soreness) for greater monitoring. Secondly, the external training load of athletes in the weeks preceding the study period were unknown. Due to the unstructured nature of the off-season phase, it is possible that athletes participated in varying types and volumes of training. Although it did not affect baseline levels, this may have impacted the magnitude of EIMD and adaptation to the structured training stimuli. Although quantifying training load in the off-season phase is not a common practice in elite RL, practitioners should be aware of any off-season training undertaken by athletes and potentially alter training prescription in the initial micro-cycles of the preseason to optimise adaptations.

3.5 Conclusion

Internal training load and markers of EIMD did not change in response to an increase in external training load across the initial two weeks of the preseason period in elite male RL athletes. Although these findings do not support the traditional definition of the RBE, they may provide a foundation for a ‘real world’ perspective of the phenomenon that may be more applicable for team sport practitioners.

Chapter 4

Acute response to transitioning between a two-week holiday period during the pre-season in elite rugby league athletes.

4.1 Introduction

Rugby League is an intermittent team sport played by both males and females at the amateur, semi-elite and elite level (Johnston et al., 2014). The elite level men's competition in Australia and New Zealand is the NRL, which is played between the months of March and October. Prior to the competition season, players are exposed to a period of high-volume training known as the preseason. The preseason begins as early as November and concludes in February. During this four-month period, coaching and high-performance staff aim to optimise the physical and technical capabilities required by players to compete in the NRL competition (Jeong et al., 2011).

High training volumes in the preseason period have been associated with increased training and competition availability in the competition phase (Gabbett, 2016; Windt et al., 2017). Therefore, understanding how players physically respond to training stimuli in the preseason can aid in the optimisation of training intensity and volume in this phase of the year. An earlier review (Simmons et al., 2021) (Chapter 2), identified that markers of EIMD were sensitive to changes in training load, especially during periods of intensified training load, such as the preseason. However, the EIMD responses were reported across multiple mesocycles and macrocycles that did not consider week-to-week or within microcycle responses. Given the aforementioned importance of the preseason period, monitoring acute responses to training stimuli within microcycles provides practitioners with information that may alter the daily prescription of training and recovery to ensure athletes are optimally adapting. To the author's knowledge, only one study (Simmons et al., 2024) (Chapter 3) has investigated the acute physiological response of elite rugby league players to training stimuli in the preseason period. This study observed a significant increase in indirect markers of muscle damage within the first week of the preseason that plateaued during the second week despite an increase in external training load (Simmons et al., 2024). It was suggested that this response was a 'real world' RBE that could aid practitioners in prescribing appropriate training load in the early weeks of a preseason. However, prescription for the remainder of the preseason requires a greater understanding of the EIMD responses during the transitions between mesocycles.

An elite rugby league preseason consists of two mesocycles, separated by two-weeks to celebrate the Christmas and New Year holidays. Although this holiday duration is unlikely to have a detraining effect (Gavanda et al., 2020; Mujika & Padilla, 2000a), it is important to understand how players physiologically respond to structured training following this period of leave. While previous work (Mujika & Padilla, 2000b) has reported that strength performance is not affected by short-term rest, muscular mitochondrial enzyme activity in elite athletes can decline to pre-training levels during a two-week break from structured training (Mujika & Padilla, 2000b). This reduction may alter the EIMD response to training and therefore, impact upon the training adaptations of athletes that need to be considered within training prescription during these transitional periods. Therefore, this study aimed to quantify the changes in indirect markers of muscle damage, external and internal training load measures and measures of neuromuscular function in elite male rugby league players due to a two-week period of leave. This information will aid practitioners in the optimisation of training intensity during the preseason that involves two mesocycles and a short-term period of leave.

4.2 Methods

4.2.1 Participants

A group of 20 elite, male rugby league players from the same NRL club provided voluntary written, informed consent to participate in the study held during the preseason of the 2020 competition season. Players were familiar with all testing protocols and wearable technologies as part of their usual training and monitoring regimes. All players were screened for any injury, illness or medication that would influence the results of the study. Players refrained from participating in strenuous physical activity for 48 hours prior to baseline testing in both training weeks and were instructed to maintain their usual dietary habits throughout both training weeks. Institutional ethics approval (H7918) was obtained for this study which was conducted in line with the Declaration of Helsinki.

4.2.2 Methodology

4.2.2.1 Design

A repeated measures design was utilised to assess the acute responses to training in the week prior to and following the Christmas holidays. During this two-week period of leave, players were provided with a training program to complete at their own leisure. It consisted of six gym-based resistance training sessions focusing on upper and lower body strength, and six field-based running sessions focused on maximal aerobic speed conditioning. Players participated in ten field-based skill/conditioning sessions and six gym-based resistance training sessions across the two active weeks of the study (Table 7). Capillary blood samples were collected at the same time each morning prior to the field-based skill/conditioning session on day 1 (D1), 2 (D2), 4 (D4), 5 (D5), 22 (D22), 23 (D23), 25 (D25) and 26 (D26). Lower body neuromuscular function was assessed following the collection of blood samples.

All data was entered manually or via an application programming interface (API) into an athlete management system (Smartabase, Brisbane, Australia) for collection and subsequent analysis.

Table 7: Schematic of the research design.

Week 1	D1	D2	D3	D4	D5	D6	D7
Assessment type	• CK • PM • NMF	• CK • PM		• CK • PM	• CK • PM • NMF		
Training type	• RT • FT	• FT	• RT	• FT	• RT • FT		
Week 2	D8	D9	D10	D11	D12	D13	D14
Assessment type	• CK • PM • NMF	• CK • PM		• CK • PM	• CK • PM NMF		
Training type	• RT • FT	• FT	• RT	• FT	• RT • FT		

CK – creatine kinase; PM – perceptual measures; NMF – neuromuscular function; RT – resistance training; FT – field-based training; D – day (i.e., Day 1)

4.2.2.2 Indirect muscle damage marker

Each player provided a fingertip capillary blood sample (30 µL) for analysis of CK, which was stored in a cool environment in a heparinised microtube. Within 30 minutes of collection, each sample was placed onto a measurement strip using a pipette and analysed using a Reflotron Plus system (Roche Diagnostics, Grenzacherstrasse, Switzerland). This system has been previously identified as a valid and reliable tool for the assessment of CK (Horder et al., 1991).

4.2.2.3 Perceptual measures and internal training load

Upon waking on each training day, players provided ratings of perceived muscle soreness and fatigue via an athlete management system mobile application (Smartabase Athlete, Brisbane, Australia). Each measure was rated on a Likert scale from 1-10 with 10 being the best possible score. This was a customised questionnaire based on the recommendations of Hooper and Mackinnon (1995). Training impulse (TRIMP) was recorded via fitted heart rate monitors (Firstbeat Sports, Firstbeat, Finland) to quantify the internal training load of field-based sessions (Bogdány et al., 2016; Stagno et al., 2007). Players wore the same monitor throughout the study period to minimise inter-unit error (Bogdány et al., 2016). Session rating of perceived exertion (sRPE) was also used to quantify the internal training load of field-based sessions as previously defined (Foster et al., 2001).

4.2.2.4 External training load

External training load of each field-based session was quantified using a 10 Hz global positioning system (GPS) device. The device (Vector S7, Catapult Sports, Melbourne, Australia) was worn medially to the scapulae in a fitted vest to reduce movement. These GPS devices have been identified as a valid and reliable tool to measure distance at both low and high velocities (Scott et al., 2016). Each player wore the same device for the duration of the study to minimise interunit error (Scott et al., 2016). At the conclusion of each session, data was downloaded, cleaned and analysed using the proprietary software (Openfield, Catapult Sports, Melbourne, Australia). Cumulative session totals per each player for the following were included for further analysis: total distance (m), high velocity (>15 km/h) distance (m), sprint (>22 km.h-1) distance, PlayerLoad™ (arbitrary units, AU), repeat high-intensity efforts (RHIE), metabolic power (W) in three bands (B4 = 35-45 W, B5 = 45-60 W, B6 = >60 W) and count of body impacts in three bands (B4 = 7-8 G, B5 = 8-10 G, B6 = >10 G). The following equation was used to quantify the external training load of gym-based resistance training sessions: repetitions completed x weight lifted (Hiscock et al., 2015).

4.2.2.5 Neuromuscular function

The assessment of lower body neuromuscular function was completed via a CMJ, which has been identified as a valid and reliable method (Alba-Jiménez et al., 2022). The players completed each jump on an AMTI force plate (Watertown, MA, USA) which was connected to a computer running the proprietary software. Data was sampled at 200 Hertz and the vertical force-time curve filtered using a fourth-order Butterworth low-pass filter with a cutoff frequency of 17 Hz. Players completed a dynamic warm up prior to each test, consisting of foam rolling, active mobility, and practice jumps. Players were informed to keep their hands on their hips throughout the duration of the movement and maintain balance upon landing. They were instructed to perform three repetitions separated by a short pause (~3 seconds) to assist in maintaining balance. Average peak power (W), time-to-peak force (s) and average rate of force development ($N.s^{-1}$) were recorded for further analysis. Time based metrics have been shown to correspond with acute neuromuscular function (Bishop et al., 2023), whilst average values have been reported to have greater sensitivity than maximum values (Claudino et al., 2017).

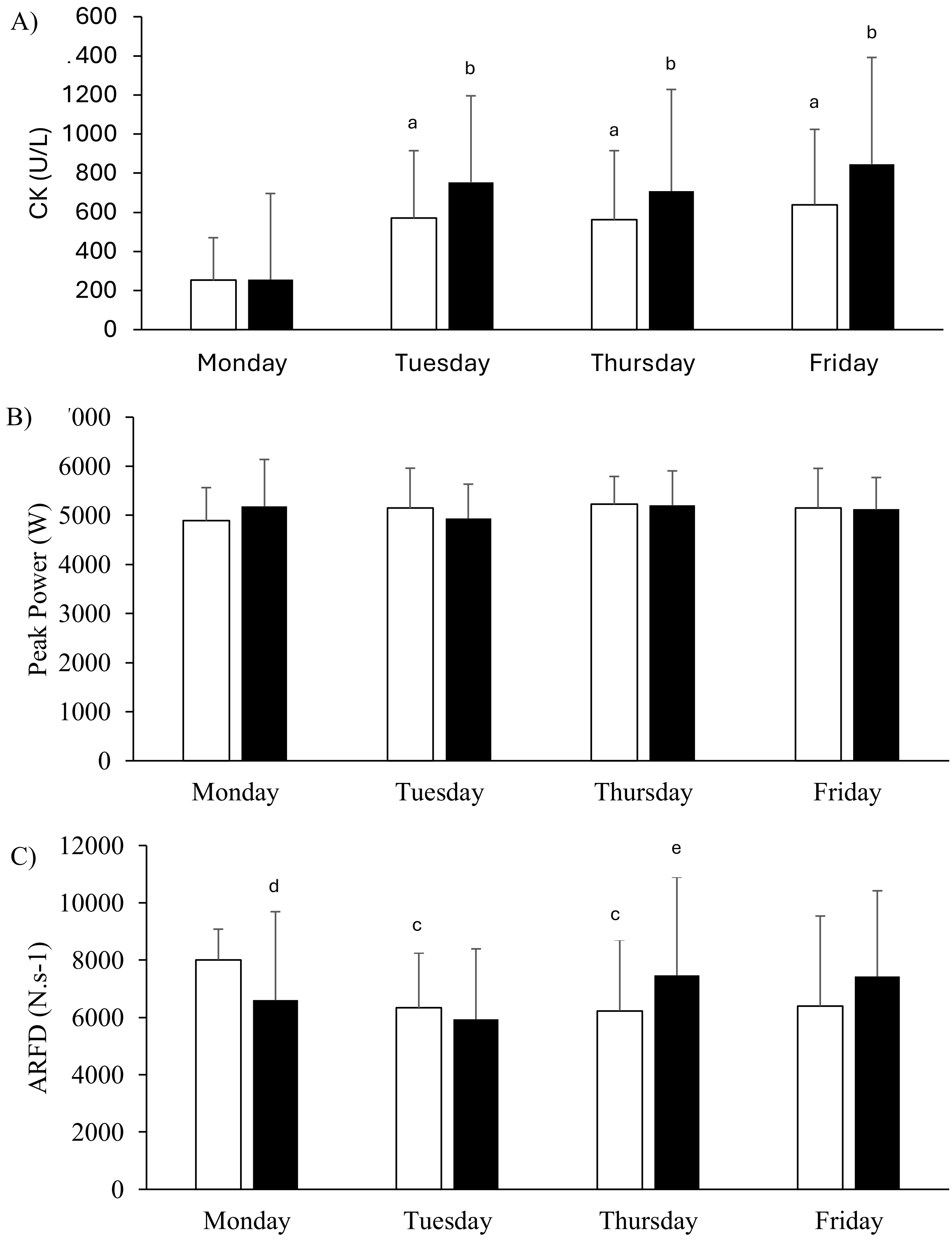
4.2.3 Statistical analysis

A two-way (week x day) repeated measures analysis of variance was completed for all variables using the statistical software package SPSS v29.0.0.0 (SPSS inc., Chicago, IL, USA). Where appropriate, a Bonferroni corrected, pairwise comparison, post-hoc test was utilised to identify statistical differences between factors. A p-value of less than 0.05 was considered statistically significant.

4.3 Results

4.3.1 Indirect muscle damage marker

A significant interaction effect was identified for blood CK activity ($p=0.03$; Figure 7A). CK activity was greater on Tuesday (D23), Thursday (D25) and Friday (D26) of week 2 compared to the same days in week one (i.e. D2, D4, D5), whilst activity on Monday of week 1 (D1) was lower than all other days in that week (D2-5). There was a main effect of week ($p=0.02$) with CK activity significantly greater in week 2 (641±448 UL) compared to week 1 (506±295 UL). There was also a main effect of day, with significantly lower CK activity on Monday than the other days of the week ($p<0.001$; Figure 8A).



A)
CK (U/L)
600
.400
1200
1000
800
600
400
200
0
a
b
Monday
Tuesday
Thursday
Friday
B)
'000
6000
5000
4000
3000
2000
1000
0
Peak Power (W)
Monday
Tuesday
Thursday
Friday
C)
ARFD (N.s-1)
12000
10000
8000
6000
4000
2000
0
d
c
e
Monday
Tuesday
Thursday
Friday

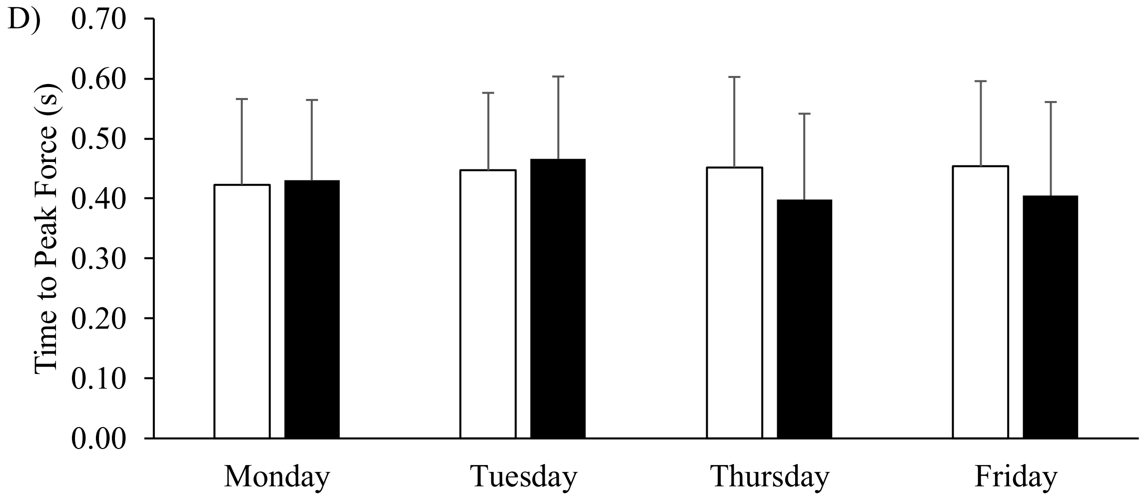
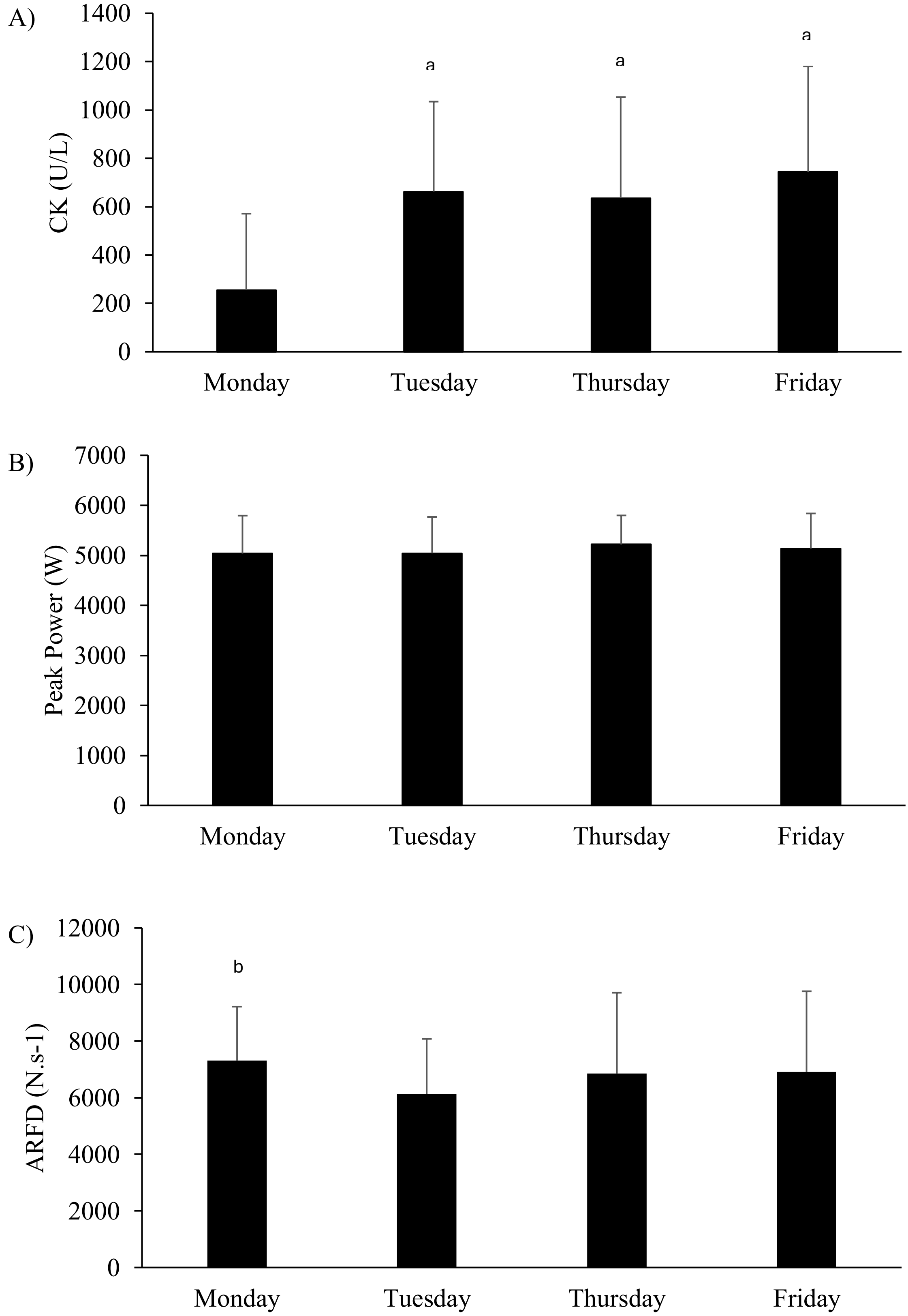


Figure 7: Mean ± standard deviation for A) creatine kinase (CK); B) countermovement jump peak power; C) countermovement jump average rate of force development (ARFD); D) countermovement jump time-to-peak force. White boxes denoting each day of week 1 (Monday – D1, Tuesday – D2, Thursday – D4 and Friday – D5) and black boxes denoting week 2 (Monday – D8, Tuesday – D9, Thursday – D11 and Friday – D12). a – significantly greater than Monday of Week 1 ($p<0.05$); b – significantly greater than same day in Week 1 ($p<0.05$); c – significantly lower than Monday of Week 1 ($p<0.05$); d – significantly lower than same day in Week 1 ($p<0.05$); e – significantly greater than same day in Week 1 ($p<0.05$).


A)
1400
1200
1000
800
600
400
200
0
CK (U/L)
a
a
a
Monday
Tuesday
Thursday
Friday
B)
7000
6000
5000
4000
3000
2000
1000
0
Peak Power (W)
Monday
Tuesday
Thursday
Friday
C)
12000
10000
8000
6000
4000
2000
0
ARFD (N.s-1)
b
Monday
Tuesday
Thursday
Friday

D)

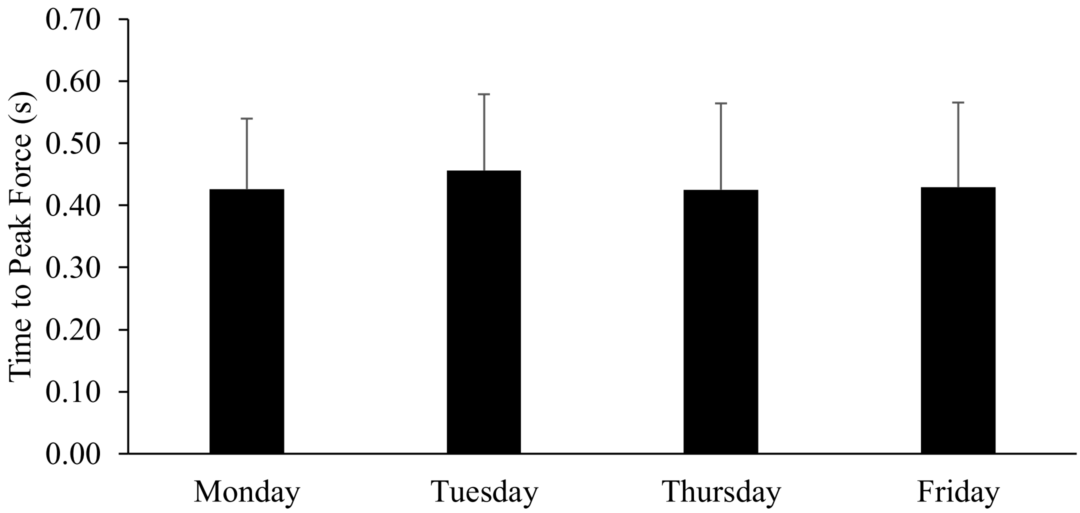


Figure 8: Mean ± standard deviation as a main effect of day for A) creatine kinase (CK); B) countermovement jump peak power; C) countermovement jump average rate of force development (ARFD); D) countermovement jump time-to-peak force. a – significantly greater than Monday ($p<0.05$); b – significantly greater than Tuesday and Thursday ($p<0.05$)

4.3.2 Perceptual measures and internal training volume

A significant interaction effect was identified for all measures of internal training volume (Table 8). Perceived fatigue was greater ($p=0.05$) on the Friday of week 2 (D26) compared to the Friday of week 1 (D5), whilst perceived muscle soreness was greater ($p=0.01$) on the Monday of week 1 (D1) compared to the Monday of week 2 (D22). sRPE was greater on the Monday ($p<0.001$) and Thursday ($p<0.001$) of week 2 (D22 and D26) compared to those days in week 1 (D1 and D4). TRIMP was greater on Monday ($p<0.001$), Tuesday ($p=0.03$) and Thursday ($p<0.001$) of week 2 (D22, D23 and D25) compared to week 1 (D1, D2 and D4) but significantly lower ($p=0.02$) on Wednesday (D24; Table 8). There was a main effect of week for TRIMP ($p<0.001$) and sRPE ($p<0.001$) with both greater in week 2. There was a main effect of day for all measures of internal training volume. Perceived levels of fatigue and muscle soreness were significantly lower ($p<0.001$) on Monday compared to all other days of the week (Table 9). The highest TRIMP and sRPE recordings were on Tuesday ($p=0.01$), whilst Wednesday was significantly lower than all other days ($p<0.001$).

Table 8: The mean ± standard deviation of internal training load metrics during each day and week of the study.

	Monday	Tuesday	Wednesday	Thursday	Friday
Fatigue (au)					
Week 1	8.05±0.94 (D1)	7.50±0.83 (D2)	7.10±0.79 (D3)	7.00±0.73 (D4)	7.30±0.86 (D5) [a]
Week 2	8.65±0.99 (D8)	7.80±0.70 (D9)	7.30±0.73 (D10)	7.05±0.83 (D11)	6.85±0.81 (D12)
Muscle soreness (au)					
Week 1	7.95±0.94 (D1)	7.00±1.08 (D2)	6.85±0.81 (D3)	6.70±1.22 (D4)	6.90±0.79 (D5)
Week 2	8.65±0.93 (D8) [b]	7.30±1.03(D9)	6.80±0.89 (D10)	6.60±0.82 (D11)	6.65±1.04 (D12)
TRIMP (au)					
Week 1	119.91±27.90 (D1)	179.80±32.79 (D2)	57.08±19.05 (D3)	112.52±32.88 (D4)	141.75±34.75 (D5)
Week 2	177.82±31.48 (D8) [b]	153.47±53.58 (D9) [d]	71.41±21.51 (D10) [e]	176.03±32.67 (D11) [c]	129.42±39.94 (D12)
sRPE (au)					
Week 1	5.00±1.02 (D1)	7.56±0.90 (D2)	4.28±1.19 (D3)	5.33±1.08 (D4)	7.06±1.33 (D5)
Week 2	6.61±1.31 (D8) [b]	7.94±0.99 (D9)	4.72±1.19 (D10)	7.28±0.87 (D11) [c]	6.61±1.03 (D12)

au – arbitrary units; TRIMP – training impulse; sRPE – session rating of perceived exertion; D1 to D5 – Day 1 to Day 5 in Week 1; D8 to D12 – Day 8 to Day 12 in Week 2. [a] – significantly greater than D12; [b] – significantly greater than D1; [c] – significantly greater than D4; [d] – significantly greater than D2; [e] – significantly lower than other days in Week 2.

Table 9: The mean ± standard deviation of internal and external training volume metrics for each day of the week as a main effect.

	Monday	Tuesday	Wednesday	Thursday	Friday
	(D1 & D8)	(D2 & D9)	(D3 & D10)	(D4 & D11)	(D5 & D12)
Internal Training Volume					
Fatigue (au)	8.35±0.67 [a]	7.65±0.65	7.20±0.70	7.03±0.70	7.08±0.69
Muscle Soreness (au)	8.30±0.77 [a]	7.15±0.95	6.83±0.77	6.65±0.84	6.78±0.80
TRIMP (au)	148.86±26.21	166.63±36.66 [a]	64.24±16.05 [b]	144.27±27.04	135.58±29.53
sRPE (au)	5.81±0.81	7.75±0.73 [a]	4.50±0.99 [b]	6.31±0.87	6.83±0.96
External Training Volume					
Total Distance (m)	4616.64±262.55	5356.72±441.07	2455.08±227.94 [b]	4942.62±464.46	4754.86±764.93
HVD (m)	621.18±124.55	990.27±201.03	209.84±69.09 [b]	691.86±155.05	570.34±152.33
Sprint Distance (m)	161.37±75.48	141.85±105.54	24.53±21.84 [b]	178.81±73.75	92.83±60.09
MPB 4 (W)	39.24±0.18	39.36±0.17	39.15±0.32	39.14±0.19	39.05±0.16
MPB 5 (W)	50.79±0.45	50.89±0.32	50.71±0.93	50.76±0.27	50.52±0.33
MPB 6 (W)	66.92±1.93	67.38±2.33	64.21±7.77	68.38±2.08	67.71±1.74
RHIE (au)	19.34±3.73	22.39±4.77	10.26±2.83 [b]	23.87±3.12	24.61±2.87
Player Load (au)	504.23±52.13	559.53±65.93	262.79±31.45 [b]	520.46±69.37	505.84±83.27
Impacts – B4 (n)	2.32±1.26	3.18±2.34	2.92±1.61	3.97±2.42	5.61±3.43
Impacts – B5 (n)	2.05±1.31	1.92±1.82	1.87±1.77	4.08±2.14	4.63±3.22

Impacts – B6 (n)	0.92±1.32	0.92±1.04	0.68±0.99	1.71±2.10	2.21±1.91
Strength Volume (kg)	10538.35±3183.48 [a]	–	5142.80±1624.34	–	4847.63±1990.63

au – arbitrary units; TRIMP – training impulse; sRPE – session rating of perceived exertion; HVD – high velocity distance; RHIE – repeated high intensity efforts; MPB – Metabolic-power band. [a] – significantly greater than all other days; [b] – significantly lower than all other days

4.3.3 External training volume

Other than metabolic power B6 and strength volume, there was an interaction effect for all measures of external training volume (Table 10). Total distance, high-velocity distance, sprint distance, PlayerLoad^{TM} and impacts B4 and B5 were significantly higher ($p<0.001$) on Monday and Thursday of week 2 (D22 and D25) compared to those days in week 1 (D1 and D4; Table 10). There was a main effect of week for total distance (week 1: 4324.39±443.51 m, week 2: 4525.98±423.09 m), high-velocity distance (week 1: 540.57±119.27 m, week 2: 692.83±131.39 m), sprint distance (week 1: 100.63±56.17 m, week 2: 139.12±75.17 m), PlayerLoad (week 1: 455.76±54.07, week 2: 485.38±63.19) and strength volume (week 1: 5774.08±1942.04 kg, week 2: 7911.77±2338.25 kg), which were all greater in week 2 compared to week one. In contrast, RHIE (week 1: 21.51±3.22, week 2: 18.68±2.46) and Metabolic power B4 (week 1: 39.24±0.12 W, week 2: 39.13±0.20 W) and B5 (week 1: 50.89±0.25 W, week 2: 50.57±0.38 W) were significantly greater ($p=0.00$) in week 1. There was a main effect of day ($p=0.00$) for most external training volume measures with running volume (i.e. total distance, high-velocity distance, sprint distance, RHIE and PlayerLoad^{TM}) lowest on Wednesday compared to all other days, whilst strength volume was greatest on Monday compared to all other days (Table 11).

Table 10: The mean ± standard deviation of external training load metrics during each day and week of the study.

	Monday (D1 & D8)	Tuesday (D2 & D9)	Wednesday (D3 & D10)	Thursday (D4 & D11)	Friday (D5 & D12)
Total Distance (m)					
Week 1	4439.50±405.88 (D1)	5429.06±581.32 (D2)	2476.32±310.21 (D3)	4451.15±518.89 (D4)	4825.91±771.95 (D5)
Week 2	4793.77±274.93 (D8) [a]	5284.39±453.32 (D9)	2433.84±377.83 (D10)	5434.09±620.03 (D11) [b]	4683.80±962.38 (D12)
HVD (m)					
Week 1	541.27±140.48 (D1)	810.18±320.67 (D2)	269.08±78.65 (D3)	429.06±164.13 (D4)	653.25±157.59 (D5)
Week 2	701.10±165.76 (D8) [a]	1170.36±146.78 (D9)	150.60±128.60 (D10)	954.66±208.96 (D11) [b]	487.44±179.50 (D12)
Sprint Distance (m)					
Week 1	238.52±83.12 (D1) [c]	84.46±115.08 (D2)	24.17±22.13 (D3)	59.93±59.92 (D4)	96.09±51.66 (D5)
Week 2	84.22±108.72 (D8)	199.24±162.95 (D9)	24.88±35.15 (D10)	297.70±92.46 (D11) [b]	89.58±82.45 (D12)
MPB 4 (W)					
Week 1	39.26±0.21 (D1)	39.33±0.12 (D2)	39.43±0.45 (D3)	39.07±0.29 (D4)	39.12±0.23 (D5)
Week 2	39.21±0.28 (D8)	39.40±0.30 (D9)	38.86±0.54 (D10)	39.22±0.22 (D11)	38.99±0.29 (D12)
MPB 5 (W)					
Week 1	50.96±0.53 (D1)	50.89±0.42 (D2)	51.30±0.57 (D3)	50.75±0.53 (D4)	50.55±0.42 (D5)
Week 2	50.61±0.58 (D8)	50.89±0.40 (D9)	50.12±1.55 (D10)	50.77±0.34 (D11)	50.49±0.45 (D12)
MPB 6 (W)					

Week 1	67.27±2.02 (D1)	66.98±2.20 (D2)	66.70±2.09 (D3)	68.16±2.36 (D4)	67.72±2.04 (D5)
Week 2	66.57±2.75 (D8)	67.78±2.80 (D9)	61.73±15.56 (D10)	68.60±2.04 (D11)	67.69±2.35 (D12)
RHIE (au)					
Week 1	18.32±4.26 (D1)	29.68±6.89 (D2)	10.00±3.81 (D3)	22.47±4.59 (D4)	27.05±3.01 (D5)
Week 2	20.37±4.37 (D8)	15.11±4.24 (D9)	10.53±4.95 (D10)	25.26±5.41 (D11)	22.16±4.49 (D12)
Player Load (au)					
Week 1	482.76±50.66 (D1)	563.93±75.89 (D2)	260.20±34.43 (D3)	459.79±64.48 (D4)	512.14±81.15 (D5)
Week 2	525.71±64.78 (D8) [a]	555.13±67.29 (D9)	265.38±51.69 (D10)	581.13±94.74 (D11) [b]	499.53±103.46 (D12)
Impacts – B4 (n)					
Week 1	1.37±1.58 (D1)	2.89±2.60 (D2)	1.95±1.11 (D3)	4.79±2.93 (D4)	7.21±6.04 (D5)
Week 2	3.26±2.08 (D8) [a]	3.47±2.66 (D9)	3.89±2.62 (D10)	3.16±2.47 (D11) [b]	4.00±1.90 (D12)
Impacts – B5 (n)					
Week 1	1.21±1.43 (D1)	1.84±1.65 (D2)	1.21±1.00 (D3)	5.21±2.89 (D4)	6.32±4.03 (D5)
Week 2	2.89±2.08 (D8) [a]	2.00±2.69 (D9)	2.53±3.21 (D10)	2.95±2.12 (D11) [b]	2.95±3.22 (D12)
Impacts – B6 (n)					
Week 1	0.16±0.38 (D1)	0.84±1.50 (D2)	0.53±0.79 (D3)	2.32±3.59 (D4)	3.16±3.25 (D5)
Week 2	1.68±2.56 (D8)	1.00±1.32 (D9)	0.84±1.42 (D10)	1.11±1.53 (D11)	1.26±1.56 (D12)
Strength Volume (kg)					

Week 1	9092.85±2721.46 (D1)		4529.60±1601.14 (D3)		3699.80±2159.63 (D5)
Week 2	11983.85±4053.29 (D8)		5756.00±1998.69 (D10)		5995.45±2022.08 (D12)

au – arbitrary units; HVD – high velocity distance; RHIE – repeated high intensity efforts; MPB – Metabolic-power band; D1 to D5 – Day 1 to Day 5 in Week 1; D8 to D12 – Day 8 to Day 12 in Week 2; m – metres; W – watts; n – newtons; MPB – Metabolic-power band. [a] – significantly greater than D1; [b] – significantly greater than D4; [c] – significantly greater than D8.

Table 11: The mean ± standard deviation of external training load metrics for each day of the week as a main effect.

	Monday	Tuesday	Wednesday	Thursday	Friday
Total Distance (m)	4616.7 ± 262.4	5356.7 ± 440.7	2455.1 ± 228.0 [a]	4942.6 ± 464.4	4754.9 ± 764.4
HVD (m)	621.1 ± 124.7	990.2 ± 201.2	209.8 ± 69.3 [a]	691.9 ± 155.1	570.3 ± 152.0
Sprint Distance (m)	161.4 ± 75.5	141.8 ± 105.5	24.5 ± 21.5 [a]	178.8 ± 73.8	92.8 ± 59.9
MPB 4 (W)	39.2 ± 0.18	39.4 ± 0.18	39.1 ± 0.31	39.1 ± 0.18	39.1 ± 0.18
MPB 5 (W)	50.8 ± 0.45	50.9 ± 0.31	50.7 ± 0.95	50.7 ± 0.27	50.5 ± 0.36
MPB 6 (W)	66.9 ± 1.9	67.4 ± 2.3	64.2 ± 7.8	68.4 ± 2.1	67.7 ± 1.7
RHIE (au)	19.3 ± 3.8	22.4 ± 4.8	10.2 ± 2.8 [a]	23.9 ± 3.1	24.6 ± 2.9
Player Load (au)	504.2 ± 52.3	559.5 ± 65.7	262.8 ± 31.3 [a]	520.5 ± 69.3	505.9 ± 83.1
Impacts – B4 (n)	2.3 ± 1.4	3.2 ± 2.3	2.9 ± 1.6	4.0 ± 2.4	5.6 ± 3.4
Impacts – B5 (n)	2.1 ± 1.4	1.9 ± 1.8	1.9 ± 1.8	4.1 ± 3.0	4.6 ± 3.2
Impacts – B6 (n)	0.9 ± 1.2	0.9 ± 1.0	0.7 ± 1.0	1.7 ± 2.1	2.2 ± 1.9
Strength Volume (kg)	10,538.4 ± 3182.2 [b]	–	5142.8 ± 1623.5	–	4847.3 ± 1989.6

au – arbitrary units; HVD – high velocity distance; MPB – Metabolic-power band; D1 to D5 – Day 1 to Day 5 in Week 1; D8 to D12 – Day 8 to Day 12 in Week 2; m – metres; W – watts; n – newtons; MPB – Metabolic-power band. [a] – significantly lower than all other days of the week; [b] – significantly greater than all other days.

4.3.4 Neuromuscular function

An interaction effect ($p<0.001$) was identified for CMJ ARFD but not for CMJ peak power ($p=0.06$; Figure 7B) or CMJ time-to-peak force ($p=0.15$; Figure 7D). Specifically, CMJ ARFD was greater on Monday of week 1 (D1) compared to Tuesday (D2) and Thursday (D4) of the same week as well as Monday of week 2 (D22), whilst Thursday of week 2 (D25) was greater than Thursday of week 1 (D4; Figure 7C). There was no main effect of week for any measure of neuromuscular function. However, there was a main effect ($p=0.04$) of day for CMJ ARFD, with greater values on Monday compared to Tuesday ($p=0.01$; Figure 8C). There was no main effect of day for CMJ peak power ($p=0.10$; Figure 8B) or CMJ time-to-peak force ($p=0.34$; Figure 8D).

4.4 Discussion

The aim of the current study was to quantify the changes in indirect markers of muscle damage, external and internal training load measures, and measures of neuromuscular function in elite male rugby league players due to a two-week period of leave. Following a 2-week period of leave, athletes exhibited increased CK activity, perceived levels of fatigue, neuromuscular function, and numerous external training load measures. Further, the improvement in neuromuscular function after the commencement of the second mesocycle suggested that improved tolerance to high training loads existed even when there was evidence of EIMD. Although the findings of this study suggest that CK activity may be a sensitive tool to detect the stress response to a training stimulus, neuromuscular function measures may be better indicators of readiness to perform.

Upon commencement of a new mesocycle (i.e., after a two-week period of leave from a structured training regime), the elite male rugby league players in this study exhibited increased CK activity with greater perceived levels of fatigue at the end of week 2 compared to the end of week 1. This increase in indirect markers of EIMD may have resulted from the increase in external training load within week 2 compared to week 1 as well as a change in the focus of the training stimuli. The second mesocycle of the preseason typically involves more team-based and game simulation activities compared to the first mesocycle, which often focuses on fundamental skill. The conditioning component also becomes more specific to the positional demands required of the player. Two previous reviews (Pedlar et al., 2019; Simmons et al., 2021) identified that capillary CK activity was directly proportionate to the amount of stress imposed upon an athlete. The findings of this study support previous work in elite youth rugby (Alaphilippe et al., 2012), where significant increases in CK activity were also identified following the Christmas holiday period. Like the findings in the current study, the young rugby athletes were also exposed to an increase in training load following the holiday period compared to prior to the holiday period. It has been identified that elite athletes will not experience significant strength losses following a period of short-term leave, however muscular mitochondrial enzyme activity can decline to pre-training levels (Mujika & Padilla, 2000a). It is possible that the decline in mitochondrial enzyme activity during the period of leave reduced the tolerance to the training loads athletes were exposed to, prior to the period of leave. To the authors knowledge, the magnitude of EIMD following a period of short-term leave in elite rugby league athletes is yet to be fully investigated. The current study along with the previous work in youth rugby (Alaphilippe et al., 2012) may provide a foundation regarding the training-stress response following a short-term period of leave in team sport athletes that remains to be followed up.

Although there was an increase in the physiological stress response after the commencement of the second mesocycle, there was also a concurrent increase in performance (CMJ ARFD). While capillary CK activity reflects exposure to external training load (Simmons et al., 2021), the response of performance measures such as neuromuscular function are not as clear (Simmons et al., 2021). Earlier (Chapter 3) (Simmons et al., 2024) we observed similar EIMD responses to an acute increase in external training load during the initial two weeks of the preseason after returning from the off-season in elite rugby league. However, in contrast to the current study, a decline in neuromuscular function was reported in the first two weeks of the preseason period (Chapter 3) (Simmons et al., 2024). This decline in neuromuscular function was expected given the intermittent high-intensity nature of the early pre-season training that induced EIMD and impaired muscular contractility (Byrne et al., 2004). The improvement in neuromuscular function after the commencement of the second mesocycle in the current study may reflect a RBE phenomenon and a resultant 'protective effect' (McHugh et al., 1999).

Prior to the two-week period of leave, the players were exposed to a seven-week mesocycle of high-volume training that may have provided a 'protective effect' to the subsequent increase in external training load and change of focus upon commencing the second mesocycle. Previously, semi-elite rugby league athletes experienced heightened CK activity at the conclusion of a 6-week intensified training period, although vertical jump performance significantly increased after a 7-day taper (Coutts et al., 2007b). Similarly, elite youth soccer athletes recorded significant increases in CMJ performance following a 26-day period of rest (Pereira et al., 2020). Furthermore, a recent systematic review and meta-analysis identified a paradoxical effect between markers of EIMD, recovery and performance (Doma et al., 2022). Notably this review identified that CK and muscular strength responses varied with acute (negative relationship) and chronic (positive relationship) resistance training and creatine monohydrate supplementation (Doma et al., 2022). The authors postulated that the increased level of CK with strength improvements was likely due to enhanced training adaptations following greater training load exposure and muscle damage in a dose-response manner. It is likely that the athletes in the current study demonstrated a similar response with enhanced ability to tolerate training as demonstrated by improved neuromuscular function in the second week, despite an increased level of CK and perceived fatigue. Collectively these results indicate that a period of short-term leave after a mesocycle of intensified training may provide adequate recovery and result in a performance benefit. Further, these findings may signify measures of neuromuscular function (e.g. CMJ) as indicators of readiness to perform.

Conventionally, capillary CK activity has been regarded a simple monitoring measure of external load exposure (Simmons et al., 2021). However, the current findings suggest that neuromuscular function may be a robust indicator of an athlete's readiness to perform. For example, there was a decline in neuromuscular function at the end of week 1, which was at the end of a seven-week mesocycle where players may have been subjected to a state of functional overreaching and unable to perform optimally (Meeusen et al., 2013). After the two-week period of leave, players had adequate time to recover from the excessive training loads of the first mesocycle and functional overreaching state (Meeusen et al., 2013) with an improvement in neuromuscular function identified during week 2. The strong relationship between neuromuscular performance and athlete 'readiness' in the current and prior (McLean et al., 2010; Pereira et al., 2020) studies indicate that simple assessments like CMJ may be beneficial for practitioners to identify athlete 'readiness' to perform during the pre- and competitive season.

Although the findings of this study will assist practitioners to understand the physiological responses during a mesocycle transition, they should be aware of a few limitations to the current findings. Due to guidelines put in place by the governing body of the sport, it was not possible to monitor athletes' training loads during periods of leave. Therefore, it was possible that training loads may have varied amongst athletes, potentially influencing indirect markers of muscle damage and neuromuscular function measures upon commencement of the second mesocycle. The training program provided to players during leave aimed to reduce external load whilst maintaining the adaptations achieved in the first mesocycle. Finally, this study did not observe the initial 6 weeks of the first mesocycle that led to players displaying symptoms of functional overreaching in the final week prior to the period of leave. Although this information would have provided a more in depth and definitive understanding of the physiological state of the playing group, it was not deemed economically feasible or possible within organisational processes.

4.5 Conclusion

Indirect markers of muscle damage and perceived levels of fatigue increased in response to an increase in external training load following a period of short-term leave in elite male rugby league athletes. Markers of neuromuscular function improved following the period of leave suggesting that players may have reached a state of functional overreaching prior to the break. Collectively, the findings of this study suggest that indirect markers of muscle damage may be a sensitive tool to detect the stress response to training stimuli whereas, neuromuscular function measures may be more indicative of readiness to perform. Practitioners can utilise this information to create a more specific monitoring regime and to enhance their understanding of how athletes may respond to a period of short-term detraining which can aid training prescription, especially in the transition between mesocycles.

Chapter 5

Acute responses to consecutive matches at the commencement of the season in elite rugby league athletes.

5.1 Introduction

The elite rugby league competition in Australia and New Zealand is the NRL and compromises of 24 regular season matches per team. These competition matches take place between the months of March and September with teams competing on a weekly basis. Rugby league match play is intermittent in nature with regular bouts of high-intensity activity (i.e. high-velocity running, accelerations, etc.) and collisions, interspersed with periods of low intensity activity (walking and jogging) (Glassbrook et al., 2019). Prior to the commencement of the competition season, technical and physical performance coaches put players through a carefully designed preseason program with the goal of optimising physical and technical qualities required for the ensuing elite rugby league match play (Jeong et al., 2011). Subsequently, the goal of players during the competition phase of the season is to perform at an optimal level through the maintenance and/or enhancement of these qualities (Jeong et al., 2011).

It is well established that the physical demands of elite rugby league match play can cause EIMD as well as IIMD, which is caused by repeated collisions with opposition players and the playing surface, eliciting similar symptoms to EIMD (McLean et al., 2010; McLellan et al., 2011; Naughton et al., 2018). Symptoms of EIMD and IIMD have been associated with reductions in the force producing capabilities of muscles, potentially limiting a player's ability to optimally perform (Hyldahl & Hubal, 2014; Naughton et al., 2018). Therefore, regular monitoring of EIMD and IIMD may help practitioners to understand how athletes are responding to physical (training and competition) stimuli, which may assist with effective training periodisation and limit performance deficits.

The signs of EIMD include elevated biomarkers (e.g. CK), elevated perceptual measures of muscle soreness and reduced muscular contractility, which have all previously been utilised to better understand the response to elite rugby league match-play (McLean et al., 2010; McLellan et al., 2011; Twist et al., 2012). For example, CK activity has been reported to remain above pre-match values for up to five days after elite rugby league match-play (McLellan et al., 2011), whilst perceived measures of muscle soreness and fatigue can remain elevated for up to 48 hours (McLean et al., 2010). Whilst there is an understanding regarding acute responses to a single competition match (McLellan et al., 2011; Twist et al., 2012) and between different match recovery periods (McLean et al., 2010), athletes' cumulative responses to consecutive competition matches in the NRL is not yet known. Depending on the NRL competition schedule, the recovery time between matches can vary from five to ten days in which players are required to complete on-field skill sessions as well as resistance training sessions (McLean et al., 2010). Although adhering to a five-day recovery period may appear optimal, its practicality is hindered by the coaches' preference to engage athletes in technical and tactical preparations for the subsequent match. Thus, the training load that players are exposed to within these training sessions is often dictated by the recovery time between matches (McLean et al., 2010). For example, weekly training load was reported to significantly increase as the number of days between competition matches increased from five, seven to nine days (McLean et al., 2010). Further, this increased training load was suggested to compromise measures of neuromuscular function and muscular contractility (McLean et al., 2010), and their readiness to train and perform. Thus, regular monitoring of performances measures and/or internal measures of training load, can provide practitioners with insights regarding athlete management for the cumulative impact of both external training and competition loads. For example, elite Australian Rules Football (AF) athletes were monitored across an entire competition season via a CMJ test with a substantial decline in neuromuscular function identified, particularly in the initial six weeks of the season (Cormack et al., 2008a). According to the findings by Cormack et al (2008), although players were prepared for the demands of elite competition throughout the preseason, it is plausible that the commencement of competitive matches provided a novel stimulus, thereby inducing greater physical stress. Similarly, elite NRL players may experience a higher level of EIMD and diminished performance at the commencement of the competition season that should be considered by coaches in long-term planning. However, this potential response conflicts with the well-known RBE where repeated exposure to a novel stimulus results in an improvement in the acute EIMD response, typically indicated by a reduction in EIMD markers and improvement in neuromuscular function (Hyldahl & Hubal, 2014). This exact in-season response for elite rugby league players remains unknown. Therefore, the purpose of this study was to quantify the EIMD, perceptual and neuromuscular response to the initial six matches of an NRL season. We hypothesised that CK response and perceptual measures of muscle soreness would be elevated, whilst neuromuscular performance would decline, after the first two-three rounds of matches (Simmons et al., 2021). Thereafter, we hypothesised that players would present with reductions in post-match CK activity and improvements in post-match perceptual and performance measures, possibly due to the RBE (Hyldahl & Hubal, 2014).

5.2 Methods

5.2.1 Participants

With institutional ethics approval (H9175), 29 players contracted with the same NRL club participated over the first six rounds of the 2021 NRL season (i.e. six weeks). The number of participants available for this study changed from round to round due to injuries and team selections. Players were familiar with all testing and monitoring regimes as they were the usual practices carried out by their club.

5.2.2 Methodology

5.2.2.1 Design

A repeated measure design was implemented to examine the acute responses to the first six (R1, R2, R3, R4, R5 and R6) competition matches for the season with successive matches separated by 6-8 days. Initial (T0) perceptual and neuromuscular function measures were recorded five days prior to R1. Baseline capillary CK activity was collected during the preseason phase after two days of no physical activity. Thereafter, capillary blood samples, and perceptual and neuromuscular function measures were recorded on the first day of training post-match which fell 48-hours after R3 and R6 (i.e. T3 and T6) and 72-hours after R1, R2, R4 and R5 (i.e. T1, T2, T4, and T5) (Figure 9). Between matches, players engaged in three to four field-based skill sessions and two to three gym-based resistance training sessions per week. Field-based sessions focused primarily on technical and tactical skill development in preparation for upcoming competition matches, whilst gym-based sessions involved lower and upper body strength- and power-focused exercises. All data was entered into an athlete management system (Smartabase, Brisbane, Australia) either manually or via an application programming interface for storage and subsequent analysis.

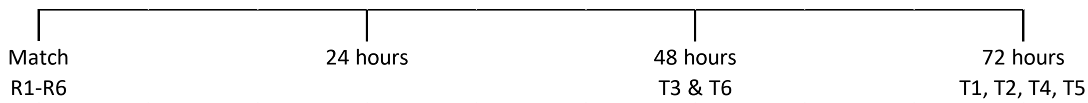


Figure 9: Outline of testing after NRL competition matches. R1-6 = the first six matches of the competition; and T1-6 = testing time points 1-6.

5.2.2.2 Indirect muscle damage marker

Fingertip capillary blood samples (30µL) were collected for the analysis of CK and then stored in a heparinised microtube in a cool environment. Within 30 minutes of collection, each sample was placed onto a measuring strip using a pipette (Simmons et al., 2024). The sample was then analysed using the Reflotron Plus system (Roche Diagnostics, Grenzacherstrasse, Switzerland), which has been previously identified as a valid and reliable tool for the assessment of CK (Horder et al., 1991).

5.2.2.3 Perceptual measures and internal training load

Prior to arriving at the training facility on each training day of the competition period, players provided ratings of perceived muscle soreness and fatigue via a mobile application (Smartabase Athlete, Smartabase, Brisbane, Australia). Ratings were provided according to a 1-10 Likert scale where 10 was the best possible score (i.e. 10 = not very sore; 10 = no fatigue). Training impulse (TRIMP) was recorded and calculated via a proprietary software to quantify the objective internal load for each field-based session using fitted heart rate monitors (Firstbeat Sports, Firstbeat, Finland) (Bogdány et al., 2016; Stagno et al., 2007). Players wore the same heart rate monitor for the duration of the study to minimise inter-unit error (Bogdány et al., 2016).

5.2.2.4 External training and competition load

The external load of all field-based training sessions and competition matches (R1-6) was quantified using global positioning system (GPS) technology. Players wore a 10Hz GPS device (Vector S7, Catapult Sports, Melbourne, Australia) medially to the scapulae in a fitted vest, which is designed to minimise movement of the device. This technology has previously been identified as a valid and reliable tool to measure locomotion at low and high velocities (Scott et al., 2016). Players wore the same GPS device for the entirety of the study to minimise inter-unit error (Scott et al., 2016). After each session and competition match, the data was downloaded and cleaned for further analysis using the proprietary software (Openfield, Catapult Sports, Melbourne, Australia). For each player, cumulative session totals of the following were analysed: total distance (training - TrainTD, matches - MatchTD, m), high velocity (>15 km/h) distance (training – TrainHSR, matches – MatchHSR, m), very-high velocity (>18 km.h^{-1}) distance (training – TrainVHSR, matches – MatchVHSR, m), sprint (>22 km.h-1) distance (training – TrainSprint, matches – MatchSprint, m), and PlayerLoad™ (training – TrainPL, matches – MatchPL, arbitrary units, AU). The external load of gym-based resistance training sessions were quantified using the following formula: repetitions completed x weight lifted (kg) (Hiscock et al., 2015). All external training and match loads included in the data analyses were totals representative of the training week leading into and the load during the competitive match for that round. For example, R2 training load data is the total for the week leading into the R2 match, which is then represented by the R2 match data. Additionally, all match competition loads were inclusive of cumulative time on the field (i.e. time off the field was not included for interchanged players), whilst all training load metrics represent weekly totals.

5.2.2.5 Neuromuscular function

Neuromuscular function was assessed via the completion of a CMJ on a dual force plate system (Forcedecks, Vald Performance, Brisbane, Australia), which sampled at 1000 Hz. The CMJ has been identified as a valid and reliable tool to determine lower body neuromuscular function (Alba-Jiménez et al., 2022). Players completed a dynamic warm up consisting of foam rolling, active mobility and practice jumps prior to each testing session. Players were instructed to perform three maximal jumps separated by a short pause (1-3 seconds) to ensure they maintained balance. For the jumps to be valid, players kept their hands in contact with their hips throughout the movement and maintained balance upon landing. Data was collected using the proprietary software (Forcedecks Jump, Vald Performance, Brisbane, Australia) and peak power (PP, $W.kg^{-1}$) and peak rate of force development (PRFD, $N.s^{-1}$) were recorded for analysis. These variables have been reported to be reliable in trained populations (Cormack et al., 2008b; Lombard et al., 2017).

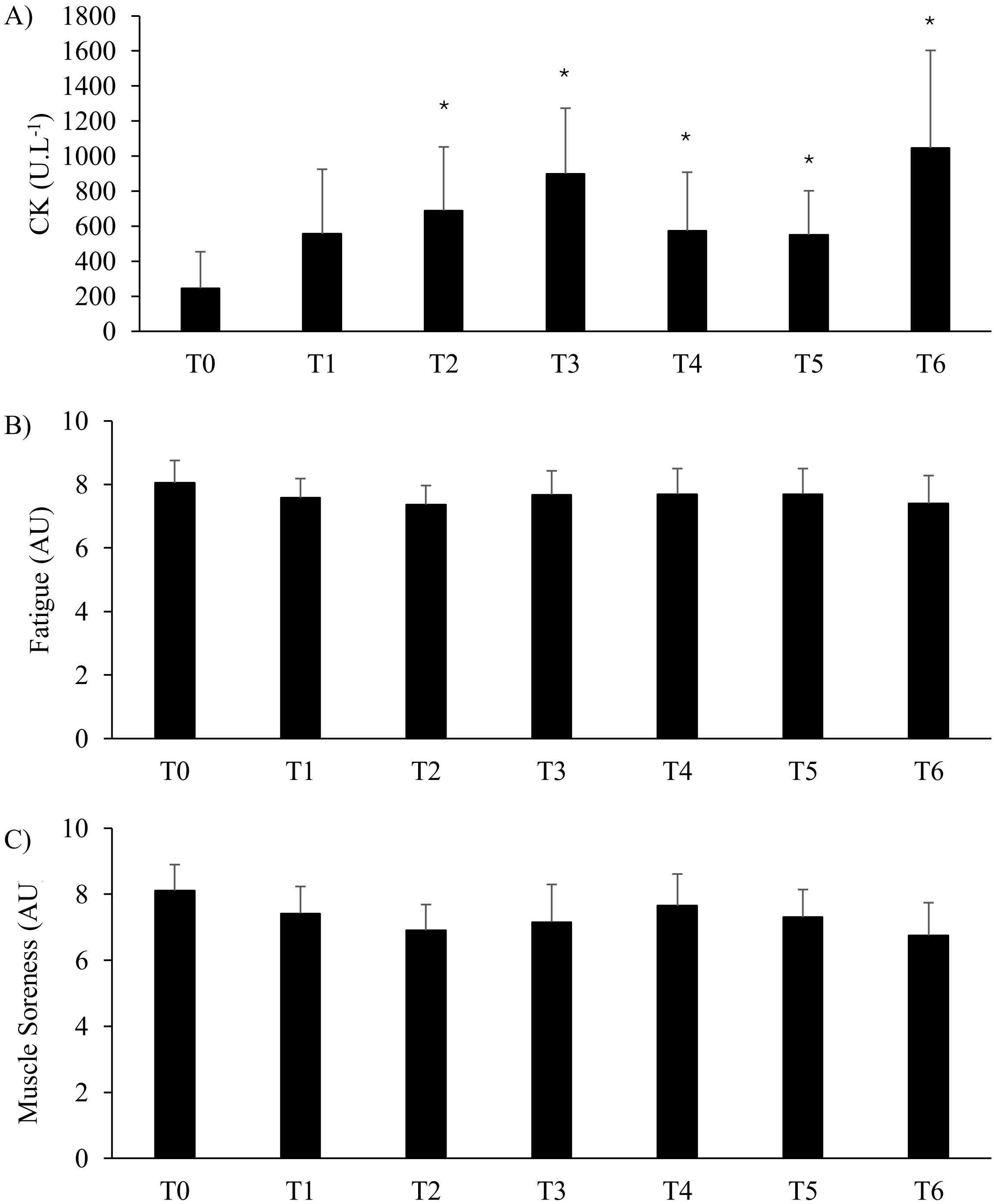
5.2.3 Statistical analysis

Data were analysed using the statistical software package for the social sciences (SPSS, version 29.0.0.0) (SPSS inc., Chicago, IL, USA). The Kolmogorov–Smirnov test was completed to assess normality for all measures at all time points. To determine the physiological response to the initial six matches of the NRL season, a linear mixed model analysis was completed, where the outcome measures were treated as the dependant variable and the testing point (e.g. T1) or competition match (e.g. R1) were treated as the repeated measures factor. Separate linear mixed models were conducted for CK, perceptual measures of soreness and fatigue, CMJ (across seven time points; T0-T6) and external load measures (across six time points; R1-R6). Where appropriate, a Bonferroni corrected, post-hoc pairwise comparison test was utilised to identify statistical differences. A p-value of less than 0.05 was considered statistically significant.

5.3 Results

5.3.1 EIMD, perceptual and neuromuscular function measures

As displayed in Figure 10A, capillary CK activity was significantly greater at T2 ($p=0.005$; $n = 16$), T3 ($p=0.001$; $n = 15$), T4 ($p=0.049$; $n = 16$), T5 ($p=0.009$; $n = 17$) and T6 ($p=0.001$; $n = 15$) when compared to baseline ($n = 20$). There was no significant change in perceptual measures of muscle soreness (Figure 10B), neuromuscular function (Figure 10C and 10E) or muscle fatigue (Figure 10D) between baseline (T0) and after any of the six matches.


A)
1800
1600
1400
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1000
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CK (U.L-1)
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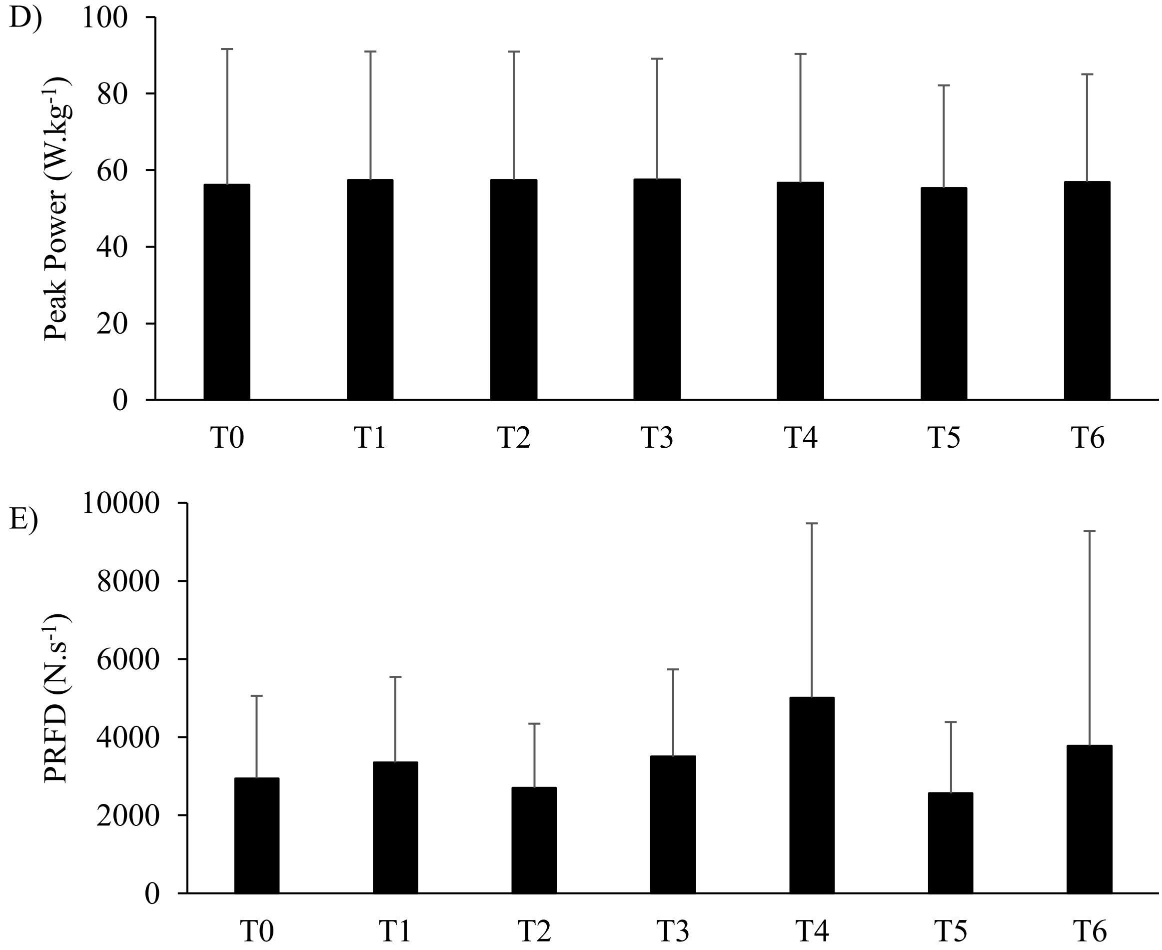

Figure 10: Mean±standard deviation of A) capillary CK activity; B) perceived muscle fatigue; C) perceived muscle soreness; D) countermovement jump peak power; E) countermovement jump peak rate of force development at baseline (T0) and after each of the initial six matches of the NRL season. *p<0.05 vs. T0.

5.3.2 Internal and external training and match loads

All training load measures, other than TrainPL that was greater (p=0.035) in the training week leading into the R2 match compared to the week leading into the R4 match, were unchanged during the study period (Table 12). Similarly, all match load measures, except MatchVHSR (p=0.047) and MatchSprint (p=0.038) that were greater at R5 compared to R6, were unchanged during the study period (Table 12).

Table 12: The mean±standard deviation of internal and external load measures leading up to and during each of the six matches.

Match	R1	R2	R3	R4	R5	R6
TRIMP (AU)	155±471	245±470	211±459	140±460	229±473	215±426
MatchTD (m)	6133±2231	5977±1809	5933±1855	6439±1981	6558±1886	6029±1878
MatchHSR (m)	694±324	684±294	656±281	862±342	880±343	592±228
MatchVHSR (m)	390±216	389±203	370±186	476±238	529±238[a]	309±141
MatchSprint (m)	132±79	161±108	150±83	197±97	220±126[a]	106±54
MatchPL	639±5037	642±5667	638±5516	688±4867	684±5361	638±5201
TrainTD (m)	12871±4370	13948±3088	13089±2251	10623±3186	13812±4477	12652±2958
TrainHSR (m)	1376±563	1736±395	1856±576	1427±572	1678±653	1574±517
TrainVHSR (m)	760±370	1036±297	1098±404	782±367	960±434	893±399
TrainSprint (m)	242±166	414±196	397±162	250±159	357±229	308±181
TrainPL (AU)	1292±458	1398±322[b]	1326±219	1060±348	1398±466	1263±301
Strength Volume (kg)	9604±6217	8610±4380	13181±5706	8205±7785	10366±5417	12126±5456

TRIMP = training impulse; MatchTD = match total distance; MatchHSR = match high-velocity distance; MatchVHSR = match very high-velocity distance; MatchSprint = match sprint distance; MatchPL = match PlayerLoad™; TrainTD = training total distance; TrainHSR = training high-velocity distance; TrainVHSR = training very high-velocity distance; TrainSprint = training sprint distance; TrainPL = training PlayerLoad^{TM}; AU = arbitrary units. [a] = significantly greater than R6; [b] = significantly greater than R4.

5.4 Discussion

The aim of this study was to quantify the EIMD, perceptual and neuromuscular response to the initial six matches of the competition season in elite rugby league athletes. Capillary CK activity significantly increased post-match for all rounds T2-T6 in comparison to baseline (T0), however, there was no change in activity between the initial six competition matches. When compared to baseline, there was no difference in perceptual measures or neuromuscular function measures following the initial six matches of the NRL season, potentially indicative of a long-term RBE as a result of preseason training. The current findings highlight minimal change in physiological response across the first six matches of the competition season. These findings could be indicative of an effective preseason training program that has physically prepared athletes for the demands of competition, as well as effective periodisation between matches.

There was a significant increase in capillary CK activity 48-72 hours after NRL matches when compared to baseline measures, which partly confirmed our hypothesis. The acute CK response identified in this study was supportive of previous work in elite male rugby league athletes (McLellan et al., 2011; Twist et al., 2012) where CK activity remained above baseline values for at least 72-hours post-match. We hypothesised that the introduction of a novel stimulus (competition matches) would induce greater stress upon the athletes following the initial matches of the competition season and decline thereafter due to the RBE. However, our findings did not support this hypothesis for a short-term RBE. Furthermore, these findings were different to that of a previous study (Simmons et al., 2024) (Chapter 3), reporting impairment in neuromuscular function with a concomitant increase in CK response and perceptual measures of muscle soreness at the commencement of the NRL preseason phase. Interestingly, the elevated CK response (~810 $U \cdot L^{-1}$) in the prior study (Simmons et al., 2024) (Chapter 3) at the commencement of the NRL preseason phase was comparable to that of this study (~719 $U \cdot L^{-1}$) at the commencement of the NRL competition phase. Therefore, NRL players at the commencement of the preseason appear susceptible to neuromuscular impairment with elevated CK levels, whereas at the commencement of the competition phase, neuromuscular function is no longer perturbed despite similar elevated CK responses. Although the results of the present investigation did not exhibit a conventional RBE trend during the initial matches of the competition phase, the absence of alterations in neuromuscular function, notwithstanding elevated CK levels, implies that the athletes may have enhanced their tolerance to a specific extent of EIMD (i.e. long-term RBE). Collectively, these findings suggest that the elite rugby league athletes in the current study were physiologically prepared for the demands of NRL competition, highlighting the importance of appropriately periodising training during the preseason phase.

When compared to baseline measures (T0), there were no differences in perceptual measures or neuromuscular function 48-72 hours after NRL competition matches confirming that players had recovered within this time frame despite elevated CK levels. The absence of any change in perceptual measures from baseline to post-match may contribute to the concurrent lack of changes observed in neuromuscular function as both measures have been related to each other in a range of athletes (Hyldahl & Hubal, 2014). Perceived muscle soreness has been identified as an indirect marker of muscle damage (Doma et al., 2015), however, the results of this study suggest that perceptual measures are not always indicative of the physiological damage to the musculature. Although perceptual measures are known to return to baseline within 48-hours after competition matches (McLean et al., 2010), measures of neuromuscular function have previously been reported to take up to 96 hours to return to baseline (McLean et al., 2010). In the current study, neuromuscular function was assessed at 48-72-hours after competition, an earlier timeframe to that examined by McLean et al (2010). This earlier return to baseline is an important finding given the preference for coaches to engage athletes in technical training in preparation for upcoming competition matches. Athletes can have as little as five days between competition matches and a 48-72 hour recovery period highlighted by the current study, provides coaches and athletes with an earlier training opportunity in comparison to the previously stated 96 hour recovery period (McLean et al., 2010).

The most striking result of the current study was that neuromuscular function was unperturbed at 48-72 hours after each of the initial six matches of the NRL season. These findings were contrary to previous work in elite AF (Cormack et al., 2008a), which identified a substantial decline in neuromuscular function across the initial weeks of the competition season. Differences between match physical demands of AF and rugby league (116-1342%) could explain the contrasting results. Elite AF players experience greater total distance (~14505m) and accelerometer load (~1436 AU) than elite rugby league players (~6694m and ~108 AU respectively) (Johnston et al., 2022). Additionally, greater eccentric contractions involved with running (particularly deceleration) during AF (Gastin et al., 2019) may have induced greater EIMD, which can inhibit muscular contractility (Hyldahl & Hubal, 2014). Furthermore, the lack of any lower body neuromuscular function differences between AF and rugby league athletes could be attributed to greater muscle damage occurring in the upper body of rugby league athletes. The mid-torso region was reported to be the most common area for contact during the tackling action in NRL competition matches (King et al., 2010) with blunt-force trauma from collisions eliciting IIMD and similar symptoms to that of EIMD (Naughton et al., 2018). Therefore, the elevated CK post-match in the current study may have been due to IIMD caused from collisions to the upper body, rather than EIMD caused from lower body locomotive activities, albeit a combination of both is most likely. Further research should consider implementing an upper body neuromuscular function test during repeated exposure to matches, to confirm the degree of upper body trauma in relation to the level of CK, especially in collision-based sports such as rugby league.

Although this study identified key findings with numerous practical applications, there are some limitations that practitioners should be aware of for their practice. Given the collision-based nature of rugby league, the quantification of physical collisions during training and competition is warranted. However, further research may first need to identify the most valid and reliable way of achieving this. To the author's knowledge, there is currently no consensus on a valid and reliable method of quantifying collisions (Naughton et al., 2020). Although it was outside of the scope of this study, the response to all competition matches throughout the season was not assessed. The current study evaluated the response to the initial six matches only to assess the acute response to the commencement of the competition phase; thus, the findings may not be applicable to later phases of the season. Finally, the quality of the opposition team, environmental conditions and travel pre- and post-game (Gonçalves et al., 2021; Lo et al., 2022) were not considered for the current study and are encouraged to be considered in future research.

5.5 Conclusion

This study identified a consistent elevation in CK activity at 48-72 hours post-match without any significant concomitant changes in perceptual or lower body neuromuscular function measures after each of the initial six matches of the NRL competition. These findings suggested that elite rugby league athletes were prepared for the physiological demands of NRL competitive matches, as represented by their tolerance to elevated levels of EIMD, with similar recovery trajectories and a long-term RBE effect during the initial weeks of the competition phase. Collectively, these findings highlight the importance of the preseason phase in preparing athletes for the demands of their sport.

Chapter 6

Thesis Summary

The aim of this project was to examine the acute physiological responses, perceived levels of stress and physical performance measures during the preseason and in-season phases for elite rugby league athletes. Acute increases in EIMD were identified at the commencement of all three mesocycles observed during this thesis. This increase in indirect markers of EIMD can be attributed to the acute increase in external training load (Chapters 3 and 4) and the introduction of new stimuli (Chapter 5). Although acute adaptations, indicative of a short term RBE are apparent in Chapters 3 and 4, the accumulation of these acute adaptations and the effect they have upon the elite rugby league population in Chapter 5 is the most important finding in this thesis. The gradual improvement in neuromuscular function across the three mesocycles is indicative of the improved ability to cope with high levels of EIMD and therefore, the chronic protective effect that training had upon the athletes. These findings emphasise the importance of constructing a well periodised training program during the preseason phase of the year as well as effectively managing in-season microcycles to ensure the optimisation of physical performance.

6.1 Preseason

The commencement of both mesocycles within the preseason phase resulted in an increase in indirect markers of EIMD, including capillary CK activity and perceptual measures of fatigue and muscle soreness. This EIMD response was concurrent with an increase in external training load when compared to the offseason (Chapter 3) and final week of the first preseason mesocycle (Chapter 4). These findings were supportive of the evidence presented in Chapter 2 (Simmons et al., 2021) as well as prior work (Coutts et al., 2007b; Coutts et al., 2007c), reporting a heightened EIMD response after the commencement of an intensified training period in semi-elite rugby league athletes. Although the EIMD response was heightened at the commencement of both preseason mesocycles, this response was sustained whilst external training load significantly increased (week 1 to week 2), which is indicative of increased training tolerance and may provide the foundation for an applied understanding of the RBE phenomenon. For example, there was a significant increase in external training load in week two after the commencement of the preseason period (Chapter 3) without changes in capillary CK activity or perceived measures of fatigue and muscle soreness. Although these findings do not support previous work of a heightened CK response to increased training loads (Simmons et al., 2021) (Chapter 2), a physiological adaptation likely occurred from the first to the second week at the commencement of the preseason, allowing athletes to maintain their EIMD response despite increased training stimulus. Furthermore, after the commencement of the second preseason mesocycle (Chapter 4), improvements in neuromuscular function were reported concurrently with increases in external training load, CK activity and perceived fatigue. The work of Burt and colleagues (2015), may explain why adaptations were identified for our rugby league athletes even with the significant increases in external training load. These authors reported (Burt et al., 2015) that exposure to a training stimulus, which invokes an EIMD response, can have a protective effect when the athlete is exposed to a repeated bout of the stimulus. Throughout the first mesocycle in the current project (both weeks in Chapter 3 and week 1 of Chapter 4), athletes were repeatedly exposed to stimuli that invoked an EIMD response. Once adequate recovery was provided (i.e. two-week period of Christmas holiday when transitioning from the last week of the first mesocycle to the first week of the second mesocycle in Chapter 4), the repeated exposure to muscle damaging stimuli could have produced a protective effect at the commencement of the second mesocycle (week 2 of Chapter 4). Collectively, these findings provide practitioners with a novel and applied understanding of the RBE phenomenon, whereby the proposed mechanisms of the traditional RBE phenomenon (i.e., enhance efficiency in neural, cellular and mechanical processes) may only partly explain the improved level of tolerance to EIMD during the preseason. In a practical setting, it is rare that an identical external training load would be prescribed in consecutive weeks as would typically be practiced in more traditional RBE studies, due to the importance of applying the progressive overload principle during the preseason phase (Jeong et al., 2011). Therefore, observing measures of external training load, markers of EIMD and performance measures collectively, could provide practitioners with a greater understanding of how their athletes are responding and potentially adapting to the alteration in prescribed stimuli.

Neuromuscular performance measures were observed throughout the first mesocycle of the preseason (Chapter 3 and week 1 of Chapter 4) and were adversely affected, with significant improvements in neuromuscular performance not observed until the commencement of the second mesocycle. It is well established that training for team sports such as rugby league, involves numerous repeat high-intensity efforts, including accelerations, decelerations, collisions and high-velocity running (Gabbett et al., 2012; Johnston et al., 2014). These activities can be neurologically demanding but need to be prescribed within the first mesocycle of the preseason to prepare athletes for the demands of competition (Crang et al., 2022; Johnston et al., 2019). This poses a challenge for practitioners as they should be strategic when planning weekly microcycles within the first mesocycle to ensure athletes will tolerate the neurological demands. It was reported in week one and two of Chapter 3, and week 1 of Chapter 4, that neuromuscular function, assessed via a CMJ, was greatest at the beginning of the week after two days of recovery. These neurologically demanding activities could be prescribed at the beginning of the training week to maximise the quality of the session and reduce the risk of injury (Baumert et al., 2016). Furthermore, tests of neuromuscular function such as the CMJ, may be utilised prior to these sessions to determine the athletes' readiness to train (Boullosa et al., 2023). Time-based metrics such as time to peak power and modified reactive strength index should be used by practitioners to assess an athlete's neuromuscular status (Bishop et al., 2023). Athletes may adjust their jump technique to produce the same force and jump height (increase time to produce the force) meaning time-based metrics are a more sensitive indicator. Average values have been reported to be more sensitive than maximum values (Claudino et al., 2017).

6.2 In-Season

Whilst baseline capillary CK activity was heightened in response to the commencement of the competition phase of the season, there were no changes in perceptual measures of fatigue and muscle soreness, nor neuromuscular function following each of the first six matches. Previous work in AF (Cormack et al., 2008a), identified a significant reduction in neuromuscular function across the initial six weeks of the in-season phase. According to these previous findings, it was hypothesised in Chapter 5 that a heightened response would occur in the initial rounds due to the introduction of a new stimulus generated by the competition matches, thereby increasing CK and perceptual measures of fatigue and muscle soreness, whilst impairing the neuromuscular response. Although this hypothesis was only partially confirmed in the current thesis based on the CK response, rugby league athletes appeared to be well prepared for the physical demands of NRL competition according to perceptual measures and neuromuscular performance (Chapter 5). The greater acceleratory loads AF athletes are exposed to during competition (Johnston et al., 2022) may explain the contrasting results between the current project and the study by Cormack and colleagues (2008a). The eccentric nature of acceleratory activities are known to induce EIMD and inhibit muscular contractility (Hyldahl & Hubal, 2014), potentially explaining why AF players experienced greater neuromuscular deficits during the initial weeks of the in-season phase. In contrast, rugby league athletes are not exposed to the same level of eccentric loading and therefore, potentially less EIMD. Thus, although NRL games are well known for its physically demanding nature, the athletes at the professional level appear to recover reasonably well within 48 hours of the match at the commencement of the competition phase.

The significant decline in external training load from the preseason to the in-season phase may also contribute to the lack of any change in perceptual measures of fatigue and neuromuscular performance reported in Chapter 5. The commencement of the in-season mesocycle is different to the commencement of the two preseason mesocycles examined earlier (Chapters 3 and 4). The commencement of both preseason mesocycles typically involves a significantly greater external training load in week one compared to that of week one of the in-season period (Cross et al., 2016; Jeong et al., 2011; Windt et al., 2017) as the in-season focus turns to recovery and preparation for competition matches. The training loads between the preseason and in-season (first 6-weeks) phases were not compared in Chapter 5 however, it is possible that the introduction of competition matches as a new stimulus was compensated by the reduction in weekly training volume, resulting in the similar perceptual measures of fatigue and neuromuscular performance during the first six matches of the competition season.

6.3 Conclusion

The current PhD project identified significant increases in capillary CK activity at the commencement of all mesocycles during the preseason and in-season phases. However, perceived levels of stress and physical performance measures improved in the latter stages of the mesocycles after repeated exposure to training stimuli. These results indicated that repeated exposure to high training loads during the preseason had a protective effect upon elite male rugby league players leading into the competition phase. A summary of the project findings are as follows:

- A systematic review (Chapter 2) in semi-elite and elite athletes identified a significant increase in indirect markers of muscle damage at the commencement of an intensified training period, as well as concurrent changes in indirect markers of muscle damage with changes in external training load (i.e. as training load increased, so too did indirect muscle damage markers). The occurrence of the RBE phenomenon was not clearly reported in semi-elite and elite athletes.
- A short-term RBE was evident in the first mesocycle of the preseason based on the lack of any significant change in capillary CK activity, despite an increase in external training load (Chapter 3).
- The tolerance of high external training loads and increased CK activity improved after chronic exposure to training stimuli in the first two mesocycles. This was evident by improvements in perceived stress and physical performance measures (Chapters 4 and 5).
- Elite male rugby league athletes can return to training 48 hours after NRL competition matches, however, muscle damage causing activities such as tackling and sprinting should be limited due to the presence of indirect markers of muscle damage.

Chapter 7

Practical Applications and Future Recommendations

7.1 An applied understanding of the RBE

The current understanding of the RBE phenomenon suggests that after repeated exposure to an identical training stimulus, physiological responses (e.g. EIMD) will be reduced. The findings in Chapters 3, 4 and 5 suggest that given the high external training and competition loads athletes are exposed to prior to and during the season, EIMD symptomology can remain high, however, physiological adaptations (e.g. improvements in neuromuscular function) still occur. Practitioners should monitor the ability to perform in the presence of high EIMD symptomology (i.e. maintenance of performance measures such as neuromuscular function) which is indicative of physiological adaptation.

7.2 Prescription of neurologically demanding activities

Based on the findings in Chapters 3 and 4 that demonstrated greater neuromuscular function at the commencement of preseason microcycles, practitioners should prescribe neurologically demanding activities such as high velocity running and high acceleration and deceleration-based movements in the early days of each microcycle (e.g. Monday or Tuesday) during the preseason phase of the year. A test of neurological function such as the CMJ can be used as an assessment of readiness for these sessions.

7.3 Return to training after competition matches

Based on the findings in Chapter 5, which demonstrated no significant change between baseline perceptual and neuromuscular measures and those taken 48-72 hours post-match, athletes recover by 48 hours after a rugby league match. Training can be reintroduced from this point; however, practitioners should be conscious of the activities they prescribe upon the return to training as the current findings identified that EIMD may still be present. Muscle damaging activities such as tackling and sprinting should be limited upon the initial return to training until approximately four days post-match. Coaches could prescribe non-contact activities such as fundamental skills practice (e.g. passing, catching) and unopposed tactical structures.

7.4 Future recommendations

- Although findings from this PhD project have provided practitioners with an applied understanding of the RBE phenomenon, further validation of this concept is required. Future research should investigate acute responses over an extended period rather than just a two-week period at the commencement of mesocycles. Such research would be more feasible with a less invasive and more financially efficient method of analysing indirect markers of EIMD. Therefore, future research could also aim to validate other markers of EIMD (e.g. perceived muscle soreness) that could be used more frequently in high performance environments. Furthermore, correlation analyses could be completed to determine which internal and external load measures are related to changes in CK activity, perceptual and performance measures.
- Due to access restrictions imposed by the NRL, participants could not be monitored during the two-week leave period in chapter 4. Monitoring participants during this period would have provided valuable insights on the level of EIMD and its impact on physiological, perceptual and physical performance measures. It may also further explain the results reported upon resumption of training after the leave period.
- When assessing the acute response to competition matches (chapter 5), this thesis did not consider the quality of the opposition team, environmental conditions or the amount of travel required. Furthermore, it was not clear if similar responses and

adaptations would be identified later in the competition season when the high training loads of the preseason were completed many months earlier. Future research should further investigate the acute responses to competition matches across the entire competition season and attempt to identify if the adaptations observed at the commencement of the competition season are maintained. Furthermore, the effect of contextual factors such as opposition quality, environmental conditions and travel should all be considered.

- This thesis only assessed one club in the NRL competition. Different clubs may have different training and recovery approaches, potentially influencing the results reported in this thesis. Future research could assess the effect of varying training and recovery methodologies across multiple clubs. Furthermore, with a larger sample size, participants could potentially be separated into positional groups to determine if different positional loads influence indirect markers of EIMD, perceptual and performance measures.

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