Overreaching and Overtraining in Strength Sports and Resistance Exercise Training

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Overreaching and Overtraining in Strength Sports and Resistance Exercise Training

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A thesis submitted in partial fulfilment of the requirements of Sheffield Hallam University for the degree of Doctor of Philosophy

October 2024

Candidate declaration

I hereby declare that:

1. I have not been enrolled for another award of the University, or other academic or professional organisation, whilst undertaking my research degree.
2. None of the material contained in the thesis has been used in any other submission for an academic award.
3. I am aware of and understand the University's policy on plagiarism and certify that this thesis is my own work. The use of all published or other sources of material consulted have been properly and fully acknowledged.
4. The work undertaken towards the thesis has been conducted in accordance with the SHU Principles of Integrity in Research and the SHU Research Ethics Policy.
5. The word count of the thesis is 59,688 (39,223 from publications).
6. This thesis is classed as an 'article-based' submission, meaning all studies arising from this PhD have been published and have been included in the format of the journal they were submitted to as per the Doctoral Schools guidance.

Name	Lee Bell
Date	October 2024
Award	Doctor of philosophy
Submission type	Article-based
Faculty	Health, Wellbeing, and Life Sciences
Director of studies	Dr David Rogerson

Abstract

Overtraining (OT) is both a *process* and an *outcome.* As a verb, OT describes the imbalance between training demand and recovery that could result in diminished performance or an improvement above the baseline. In this sense, OT can be intentional (e.g., a prescribed period of planned overreaching (OR), training camps) or unintentional (e.g., through poor programming decisions, miscalculation of training and recovery, training hard during periods of high non-training stress). As a noun, OT (known as the overtraining syndrome; OTS) is defined as an accumulation of training and/or non-training stress resulting in a decrement in performance capacity in which restoration of performance capacity may take several weeks or months. Before this doctoral research programme, resistance exercise OT was under-represented in the research and there was limited evidence-based information available to coaches to enhance their training decisions and avoid the deleterious effects of excessive training or inefficient recovery. This thesis has published research that has led to a more detailed understanding of the relationship between resistance exercise training and OT. Evidence collected and synthesised during the doctoral programme indicates that OTS is an unlikely occurrence following resistance exercise training. Indeed, this thesis has demonstrated that when appropriately implemented, a short-term period of highly demanding resistance exercise can result in performance improvements relative to baseline. However, caution must be taken when undertaking such training as there is still a possible risk of a maladaptive response if the balance between the training stimulus and recovery is miscalculated.

Acknowledgements

I would not be at this stage of my academic journey if it were not for a great number of people. I hope the below words go some way to reflect the gratitude I have for you all.

Firstly, I would like to thank my wife, Heather, and my son, George for their endless support. You have both sacrificed so much to give me the time and space to complete this thesis, especially during the last few months. This would not have been possible without you. I can't begin to explain how much I love you both.

To my parents, Michael and Alana, and my brother, Ross, thank you for everything you have done to get me to this stage of my career. You've always been there for me and supported me in everything that I do. You've believed in me all the way and pushed me to be the best that I can be.

To Dr Dave Rogerson, thank you for your guidance as my Director of Studies. It has been a privilege to be guided through my doctoral programme by you and I truly could not have wished for a better mentor. To my supervisors, Associate Professor Alan Ruddock and Associate Professor Tom Maden-Wilkinson, thank you for pushing me to be a better researcher. Your guidance has been invaluable. I am a better thinker, writer, and researcher because of your support.

To my friends and colleagues. Dr Ben Strafford and Jonny Fraser for your words of encouragement and guidance throughout. To Dr David Nolan and Dr Arthur Lynch, in the few years I have known you both you have given me endless motivation to complete this thesis. I cannot thank you enough.

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PhD Research Outputs

Peer reviewed journal articles arising from this doctoral thesis

Bell, L., Ruddock, A., Maden-Wilkinson ,T., Rogerson, D. Overreaching and overtraining in strength sports and resistance training: A scoping review. J Sports Sci. 2020 Aug;38(16):1897-1912. doi: 10.1080/02640414.2020.1763077.

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Conference Proceedings and Presentations arising from this doctoral thesis

Bell, L., Ruddock, A., Maden-Wilkinson ,T., Rogerson, D. Overreaching and overtraining in strength sports and resistance training: A scoping review. Poster presentation at the European Powerlifting Conference, London, UK. 3rd August 2019.

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Chapter 1: Introduction

1.1 Philosophical approach

Whilst there is an ever-increasing number of empirical studies dedicated to enhancing athlete training practices, there is relatively limited research exploring practices used by coaches in the practical coaching environment (Haugen, 2021; Haugen et al., 2021). This is certainly the case within the resistance exercise overreaching (OR) and overtraining (OT) domain, where the landscape of evidence appears fragmented and heterogenous. Practitioners are often ahead of sport science research when it comes to exercise programming (e.g., planning, individualisation, monitoring, supervision of training) (Haugen, 2021; Storey & Smith, 2012). However, the practices of high-performance coaches rarely receive attention within the sport science literature (Haugen, 2021). Experienced coaches apply holistic, athlete-centred decisions when designing training, taking into account not only the underpinning principles of training but also environmental factors, accessibility, and individual athlete needs (Haugen, 2021, 2024). The experiential, tacit knowledge that accomplished coaches possess is developed through trial and error, even in the absence of in-depth mechanistic knowledge. Conversely, sport scientists are typically interested in investigating isolated variables in highly standardised research environments. Thereby, sport scientists might have to disregard the dynamics by which coaches make informed training decisions.

Current models of athlete development (e.g., programming, monitoring) are often guided by isolated ways of thinking and do not necessarily fully acknowledge the advantages of integrating experiential and empirical knowledge that practitioners possess (Rothwell et al., 2020). Consequently, this doctoral programme sought to explore bidirectional collaboration (mutual transfer of knowledge) between the high-performance strength coach and sports science to better understand OR/OT as well as when seeking to replicate the complex, chaotic interacting constraints that are representative of high-performance training environments (Otte et al., 2019).

Scientific research is guided by philosophical positions that are governed by both epistemological (the theory and nature of knowledge) and ontological (the theory and nature of reality) positions (Ryba et al., 2022). Research paradigms are philosophical positions that provide a framework, a common set of beliefs, and a worldview shared between scientists about how problems should be understood and addressed (Brown & Dueñas, 2019; Patton, 2014). Perhaps the most common paradigm by which researchers address scientific problems (Brown & Dueñas, 2019; Patton, 2014) is *positivism*; an objective approach that assumes knowledge is constructed through verifiable facts (i.e., quantitative methods). The positivist researcher seeks to verify theories through controlled research and focuses strongly on standardisation, validation, reliability, and deductive reasoning (Creswell & Poth, 2016). Conversely, *constructivism* is a subjective learning theory that recognises multiple realities (i.e., two individuals can experience the same event differently based on their own reality). The constructivist approach is primarily interested in describing human nature or how an individual's world view is shaped by social construct (Brown & Dueñas, 2019; Ponterotto, 2005). Constructivism, therefore, typically utilises qualitative research methods where data are collected through collaboration between the investigator and participant (Ciampolini et al., 2019). Finally, pragmatism is an approach that is not dedicated to a specific philosophical stance per se but adopts a mixed approach to research where both quantitative and qualitative approaches to research are employed. Therefore, pragmatism exists between the two extremes of positivism and constructivism (Neupane, 2024). Pragmatism provides the researcher with a set of loose philosophical tools to address complex problems in a variety of different ways (Morgan, 2014). Moreover, pragmatism aims to solve real world, practical problems by bridging the gap between data driven scientific inquiry and subjective truth and perceptions (Goles & Hirschheim, 2000). Pragmatism, therefore, is an appropriate paradigm for practicalminded researchers (Kaushik & Walsh, 2019), particularly when research questions require a pluralistic approach to best derive knowledge about the problem (Giacobbi et al., 2005).

Synergy between theory and real world practice is central to effective sport science research (Collins & Collins, 2019). To solve complex scientific problems in a practical way, bidirectional communication between researcher and practitioner is essential (Haugen, 2021; Rothwell et al., 2023). Whilst there is an ever-increasing number of empirical research studies dedicated to elucidating the underpinning mechanisms by which sports performance can be enhanced, there still remains a gap between how such information is communicated to coaches and athletes (Haugen et al., 2021). This is certainly the case within the OR/OT domain where the current research body appears conflicting, and with little acknowledgement of strength coaches' beliefs or experiences of the strategies employed in practice to avoid long-term maladaptation or to enhance strength performance.

This thesis adopted a pragmatic philosophy that acknowledged the practical problems faced by sport scientists and practitioners in a pluralistic way (Giacobbi et al., 2005). In line with pragmatism, a mixed methods approach was undertaken to 'fit together' (Kay & Kucera, 2018) the insights gained through quantitative and qualitative research techniques, therefore, providing novel solutions to address real problems faced by high-performance strength coaches. Specifically, this thesis adopted a sequential explorative mixed methods approach that enabled findings from qualitative research (undertaken earlier in the doctoral programme) to guide the development of subsequent quantitative experimentation (Doyle et al., 2016). A sequential explorative approach is appropriate for novel research topics where there are several unknown or under-investigated variables (Edmonds & Kennedy, 2017), therefore providing the researcher with a conceptual framework to inform (or *build*) findings from one study to the next (Onwuegbuzie et al., 2010). This approach is particularly useful when qualitative research is necessary for the design of complex interventions (e.g., training interventions or protocols, measures and assessments) during subsequent quantitative investigations (Munce et al., 2021). Given the many unknown aspects of OR/OT in strength sports and resistance exercise training, and the emphasis on synergising theory and real-world practice, a sequential explorative mixed methods approach was deemed suitable for this thesis. Moreover, it facilitated a flexible and iterative way of working, where each research question was approached using the most appropriate methodologies and tools whilst remaining systematic and rigorous (Ruddock et al., 2019). A sequential explorative approach also encouraged clear interlinkage of findings that developed organically, culminating in several novel and practically meaningful findings (Figure 1).

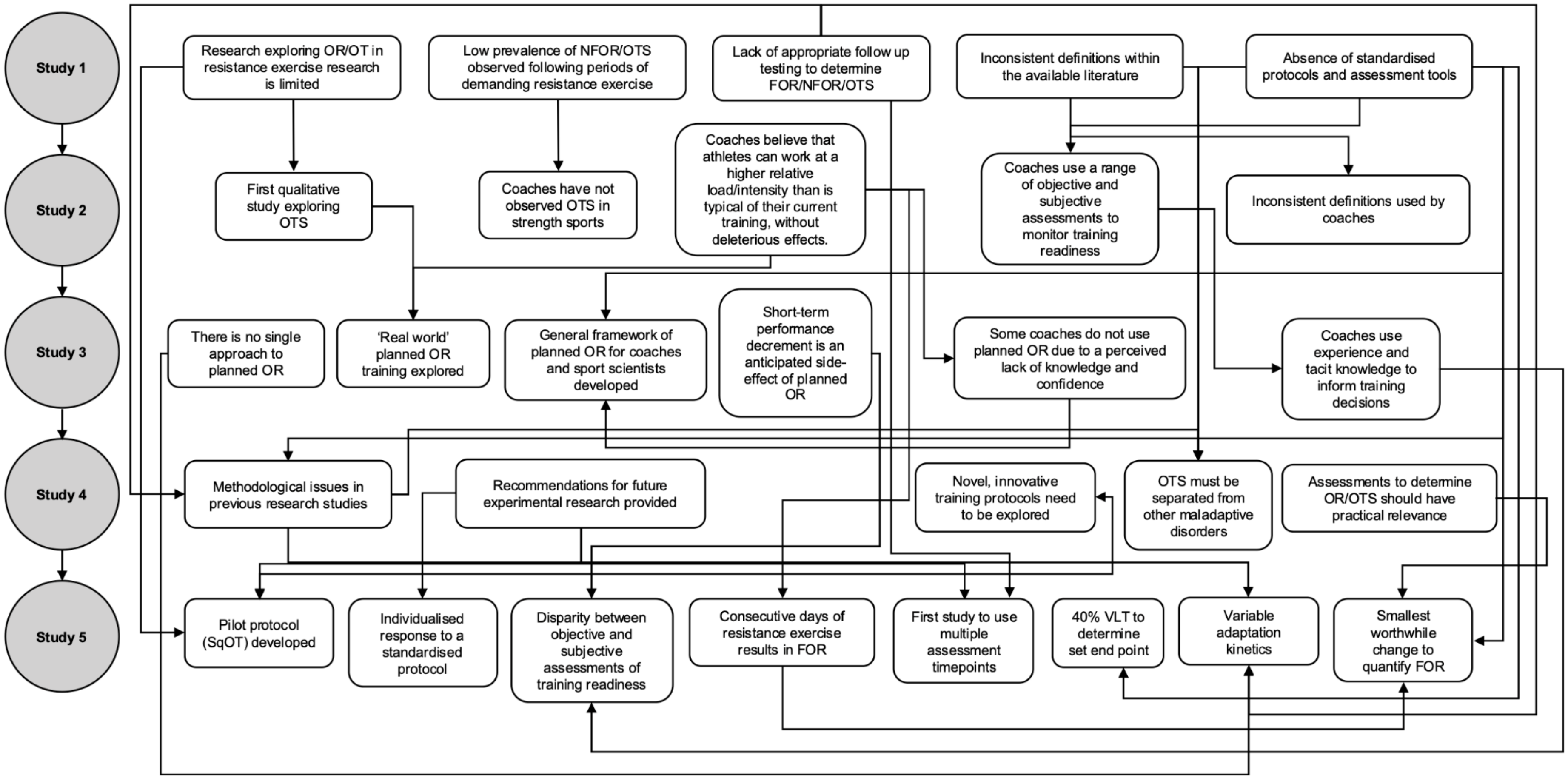

Figure 1. A schematic representation of the golden thread of this doctoral thesis

1.2 An applied research model for sport sciences

To guide the overall direction of this doctoral programme aspects of the applied research model for sport sciences (ARMSS) were utilised (Bishop, 2008). Adopting the ARMSS framework within a pragmatic paradigm facilitated a logical sequence of research studies based on cumulative knowledge, but also offered solutions to real world problems in the OR/OT domain through creation of novel (but practically meaningful) findings (Table 1). Utilising this model ensures that a programme of research is focused and integrative, enhancing the applicability and cohesiveness of findings by avoiding stand-alone studies with minimal impact for sport science researcher or practitioner (Kirk et al., 2020).

The ARMSS model should be approached flexibly, acknowledging the iterative and unexpected nature of scientific inquiry (Bishop, 2008). The model supposes that researchers consider the specific barriers to research within the context of the research topic both before and during implementation of research ideas. Therefore, researchers might not need to perform all stages of the ARMSS model in a specific sequence (Bishop, 2008).

As mentioned, the current body of research exploring OR/OT in strength sports and resistance exercise training is under-represented, displaying a fragmented landscape of individual studies with no clear or cohesive findings (Fry & Kraemer, 1997; Halson & Jeukendrup, 2004; Meeusen et al., 2013). Therefore, a pragmatic approach allowed this thesis to develop organically as new findings emerged and the ARMSS provided a framework to synthesise new findings using a logical progression, but to also develop a rationale for future research directions upon completion of the research programme. In this sense, this thesis sought to not only contribute new (and impactful) knowledge to the field but also to identify additional research directions by highlighting remaining gaps in understanding.

The first stage of the ARMSS model is to *define the problem*. Here, it is recommended that researchers identify relevant problems faced by practitioners. In this stage, coaches and athletes might be consulted in illuminating broad research questions requiring solutions that have not yet been identified in the existing literature. However, because practitioners do not rely on academic sources of information to inform their coaching practice (Shaw & McNamara, 2021), it is unlikely that coaches possess sufficient scientific knowledge to fully direct the most appropriate choice of research methodology (Stober et al., 2006). Consequently, at this initial stage, formal reviews or meta-analyses should also be undertaken to determine the current state of knowledge for the specific research problem. If potential research problems are not properly identified at the *defining the problem* stage of the ARMSS, experiments are less likely to be relevant, appropriate, and practically-meaningful (Bishop, 2008).

The first two studies of this doctoral programme were conducted to develop a thorough understanding of the topic in line with the first stage of the ARMSS model (Table 1). In study one, a scoping review was undertaken to 1) to map the current literature related to OR/OT in strength sports and resistance exercise populations, and 2) to identify gaps in knowledge that need to be further investigated. Scoping reviews not only afford the mapping of existing literature within a given field, but to also assist identification of knowledge gaps for future research (Arksey & O'Malley, 2005; Peters et al., 2015). Due to a lack of precise lines of questioning and a limited body of literature, a systematic review approach was not deemed appropriate at this stage (Munn et al., 2018).

Table 1. Applied research model for sport sciences (ARMSS) applied to this doctoral research programme (Bishop, 2008)

Category	Stage	PhD study	Overview/objective	Research skills developed
Description	Defining the problem	Scoping review (study one)	To map the current literature related to OR and OT in strength sports and resistance exercise populations, and to identify gaps in knowledge that could be further investigated in subsequent research studies.	• Data retrieval and management • Critical appraisal of research • Synthesis of findings • Identification of research gaps
		Thematic analysis (study two)	To explore high-performance strength coaches' perceptions of OT and to provide a new way of understanding and conceptualising training maladaptation from the perspective of the practitioner. An additional objective was to reveal potential lines of enquiry for future research not revealed through study one.	• Collaboration • Identification of patterns and themes within large data sets • Qualitative interpretation and analysis • Ability to be reflexive
	Descriptive research	Thematic analysis (study three)	To explore how high-performance coaches plan periods of highly demanding resistance exercise training to induce performance improvements whilst mitigating the risk of maladaptation.	• Collaboration • Data analysis software management skills • Assimilation of key findings into a framework
		Recommendations (study four)	To reveal conceptual and methodological limitations within some of the current OT literature and to propose directions for future research to advance current understanding from the perspective of the sport scientist.	• Triangulation and assimilation of key findings • Evaluation of current methodologies • Recommendations for future research
Experimentation	Predictors of performance	Experimental study (study five)	To investigate a novel resistance exercise protocol designed to induce. The aims and objectives of the pilot study were informed by findings from the previous four studies. The protocol implemented in this study was designed using the recommendations proposed in study four.	• Collaboration • Organisation and planning • Project management Leadership • Data collection and analysis

To further enhance understanding of the topic (and to compliment findings from study one), study two was conducted in collaboration with high-performance strength coaches using a reflexive thematic analysis approach (Braun & Clarke, 2006). As recommended by the ARMSS, formal reviews of the published literature should be combined with methodologies that illuminate problems faced by coaches in the real world (Bishop, 2008). As such, understanding coaches' perceptions of OR/OT would provide a new way of understanding and conceptualising training maladaptation from the perspective of the practitioner, therefore revealing potential additional lines of enquiry not revealed through study one. For study two, a reflexive thematic analysis approach was chosen as it provides a robust method for identifying, organising, analysing, and reporting qualitative data sets into compressed meaningful patterns, especially when the focus is on lived experiences (Attia & Edge, 2017; Braun & Clarke, 2006; Nowell et al., 2017). Thematic analysis is becoming an increasingly common tool for qualitative research within sport and exercise science (Clarke, 2016), especially when the focus of the research is to elucidate coaches' experiences of working in a high-performance sport environment (Brown et al., 2018).

The second stage of the ARMSS model is *descriptive research.* This stage is important as it seeks to address the gap between highly controlled laboratory research and applied real world practices (Bishop, 2008). Once a series of problems have been identified, research at this stage might focus on describing phenomena occurring in a specific field. Studies in this phase typically focus on understanding specific training practices, psychophysiological characteristics, and other factors that might influence optimal sports performance (Bishop, 2008). Moreover, methodological studies that focus on standardising terminology, develop testing interventions/protocols, and/or determine factors associated with elucidating predictors of performance can also be implemented at this stage of the ARMSS model.

In line with the second phase of the ARMSS model, the primary objective of study three was to explore how high-performance coaches plan periods of highly demanding resistance exercise training to induce performance improvements but avoid maladaptation. This was seen as an important step in informing future experimental research where there is a lack of standardised training interventions. As with study two, reflexive thematic analysis (Braun & Clarke, 2006) was used to ascertain important contextual information regarding real world training practices used by high-performance strength coaches.

Study four utilised a narrative approach to critically discuss concerns with the existing body of evidence relating to OT, and to propose potential solutions for future research. These recommendations were deemed necessary due to the lack of standardised terminology and methodological limitations highlighted in previous chapters of this doctoral thesis. The recommendations from study four communicated/promoted the findings from this doctoral programme so far (by scaffolding previous findings from this thesis) and sought to develop an action plan for the final study of the thesis (as well as to provide recommendations that other researchers intending to undertake rigorous research exploring OT in strength sports and resistance exercise training could utilise).

The third stage of the ARMSS model involves exploring the factors that are likely to affect performance (Bishop, 2008). This *predictors of performance* stage should not begin until potential solutions to the research problem have been identified using the previous two stages of the model (which had been achieved through publication of studies one to four of this doctoral programme). Research at stage three of the ARMSS model should use an experimental approach to explore relationships between predictor variables and their influence on sports performance (Kirk et al., 2020). Whilst replication studies are generally performed at stage three (Bishop, 2008), novel experimental protocols might need to be developed if no suitable existing interventions exist.

In congruence with stage three of the ARMSS model, study five of this doctoral programme sought to explore possible predictors that might influence training outcomes following a period of planned OR (specifically, factors that influence performance change (i.e., performance improvement or decline) and was the culmination of the body of work presented in this doctoral programme. Due to the novel nature of the research, study five utilised a pilot trial approach that was in line with current good practice recommendations (Brown et al., 2018; Horne et al., 2018; Thabane et al., 2010). During pilot research, analysis should be mainly descriptive avoiding statistical inferences due to the increased risk of type I statistical error. Using a descriptive pilot approach complied with stage three of the ARMSS model but also reflected the several remaining unknown aspects of OR/OT which had been highlighted in studies one to four. In this sense, a pilot trial permitted a proof-of-concept assessment (Leon et al., 2011) focusing not only on exploring predictors of performance but also on the feasibility of the training protocol itself. The development of a 'successful' training protocol (one that could successfully induce OT) would act as a starting point for ARMSS studies at stage four (*experimental testing of predictors*) which involves a more robust assessment of performance predictors and typically involves randomised control trials (Bishop, 2008).

Study five utilised a highly standardised training protocol, implementing an autoregulatory approach to determine daily load lifted, as well as a 40% velocity loss threshold (VLT) to determine set end points. This novel approach to exercise prescription during planned OR was undertaken to accurately and objectively prescribe external loads (Weakley et al., 2021b), as a way of ensuring that all participants trained close to muscular failure for all sets (Jukic, Castilla, et al., 2023; Myrholt et al., 2023; Pareja-Blanco et al., 2017), and to dynamically standardise the degree of effort between participants (as well as for the same participants on different training days).

1.3 Thesis aim and objectives

The principal research aim of this doctoral research programme was to investigate OR/OT within strength sports and resistance exercise training populations. The objectives were to:

- Map the current research landscape to enhance understanding of OR/OT within strength sports and resistance exercise training populations.
- Explore strength sport coaches' experiences and perceptions of OT and to provide a novel method of conceptualising OT from the perspective of the practitioner.
- Investigate how strength sport coaches develop, prescribe, and monitor periods of planned OR to facilitate performance improvements whilst simultaneously mitigating the risk of training maladaptation.
- Provide evidence-based recommendations for sports scientists undertaking resistance exercise OT research and to propose directions for future research.
- To develop and assess the feasibility and safety of a resistance exercise protocol (SqOR) designed to induce OT for the purpose of scientific inquiry.

Chapter 2: Literature Review

2.1 Muscular strength

Muscular strength is broadly defined as the ability to exert force upon an external resistance (Schoenfeld et al., 2021; Stone, 1993). As a physical attribute, muscular strength is considered a cornerstone of athleticism, underpinning several sporting activities such as sprinting, jumping, and throwing (Haff & Stone, 2015). Dependent on the specific demands of the sport, an athlete might be required to produce large amounts of force by manipulating an implement (e.g., powerlifting and weightlifting, throwing sports) or their own body mass (e.g., climbing, sprinting, gymnastics) plus an opponent (e.g., rugby, American football) (Suchomel et al., 2016). Therefore, different types of strength muscular strength represents specific and independent characteristics that can influence athletic performance in different ways (Stone et al., 2022).

Strength diagnosis is the process of determining which type of strength quality is necessary within a specific sporting context (James et al., 2023; Newton & Dugan, 2002; Sheppard et al., 2021). The prescription and testing of each strength-based quality must be made based on the requirement of the sport itself as well as the distinct physiological adaptations that are required to prepare athletes for competition (Newton & Dugan, 2002). Previous commentary has elucidated five distinct strength qualities: heavy maximal dynamic strength, light maximal dynamic strength, maximal isometric strength, fast dynamic strength, and reactive strength (James et al., 2023).

2.2 Strength sports

Strength sports are characterised by maximal single efforts and primarily focus on the development of maximal strength and power relative to body weight, often for a single repetition (Slater & Phillips, 2011; Winwood et al., 2018). Examples of these sports include powerlifting, weightlifting and strongman/woman (Rogerson et al., 2024). Additional to the high degree of maximal strength required to succeed, many strength sports also demand enhanced anaerobic capacity, rate of force development, and strength endurance (Steele et al., 2022). Consequently, sports such as maximal effort throws (e.g., shot putt, hammer), jumps (e.g., long jump, high jump), sprints (e.g., 100m, 200m), CrossFit and Highland games can also be categorised as strength sports. A common feature of strength sports is that resistance exercise is the primary (and sometimes only) method of training, whereas in other sports, resistance exercise is generally used in conjunction with other training methods to develop athletic performance (Slater & Phillips, 2011). Moreover, strength sport athletes often re-enact the highly-specific competition lifts in training and not just during competition (Merson, 2021).

Previous research has categorised bodybuilding as a strength sport due to resistance exercise being the primary method of training (Slater & Phillips, 2011). Physique sports, however, emphasise hypermuscularity and aesthetic condition (e.g., symmetry, proportionality, leanness) rather than strength performance (Bell, Nolan, et al., 2022; Rogerson et al., 2024). Therefore, for the purpose of this doctoral research programme, bodybuilding is not considered a strength sport.

2.3 Periodisation

Periodisation is a systematic method of long-term exercise planning where training is organised in a logical, cyclical manner to elicit either sequential or concurrent physiological adaptations (DeWeese et al., 2015a; Plisk & Stone, 2003). The primary goal of periodisation is to assist the athlete in achieving peak performance at set time points through development of specific biomotor qualities, achieved through careful manipulation of training variables (Turner, 2011). There are several ways in which periodised training can be implemented within strength sports (Evans, 2019). The most common, however, are the traditional method, undulating method, the conjugate method, and block periodisation.

2.3.1 Traditional periodisation

The origins of structured training lie in Ancient Greece and Rome, where military personnel participated in planned periods of exercise to enhance athleticism (Issurin, 2014). However, periodisation theory was first published by Leonid Matveyev in the 1960s (Kataoka et al., 2021). Matveyev's approach to periodisation, known as the classic, traditional or 'linear' model, was used by Soviet track and field athletes in the 1952 Olympic games (Marques Junior, 2020).

The traditional periodisation (TP) model organises training in a way so that volume is gradually reduced over time whilst both intensity and training specificity are increased until competition (Bradley-Popovich & Haff, 2001). This sequential approach to training was designed to help the athlete achieve "peak" performance at the time of competition (Williams et al., 2017). The ability to predict when peaking will occur is based on the theory of "supercompensation": training that balances stimulus with recovery in a logical manner results in a predictable improvement in performance relative to the baseline (Marrier et al., 2017; Plisk & Stone, 2003; Turner, 2011). The theory of supercompensation was originally described by Folbrot in 1941 (Verkhoshansky & Siff, 1999) and later classified as four distinct stages by Yakovlev (1967) (Figure 2). In stage one of the supercompensation model, the training stimulus increases fatigue, resulting in short-term performance decline) (Plisk & Stone, 2003; Turner, 2011). In stage two, recovery is implemented to reduce the impact of fatigue. In stage three, supercompensation is achieved providing the training stimulus is sufficiently challenging to induce physiological adaptations that lead to performance improvement, but sufficient recovery was provided (Buckner et al., 2020). In stage four, a loss of adaptation (known as involution or detraining) occurs if the training stimulus is not applied in a manner that is challenging or sustains performance (Mitsumune & Kayashima, 2013). The temporal aspects of supercompensation are central to the theory of TP, therefore, achieving peak performance at specific timepoints is ultimately a balance between training and recovery within the TP model.

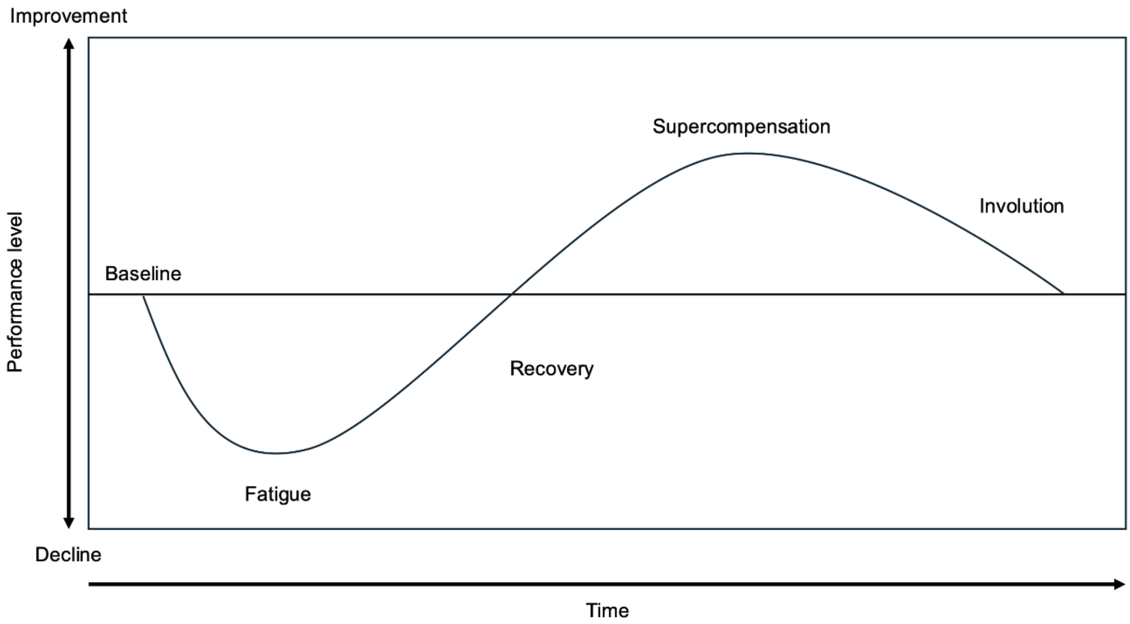

Figure 2. A hypothetical representation of supercompensation

One of the criticisms of TP was that it only accounted for a single peak per year (Lorenz & Morrison, 2015). Several sport scientists (e.g., Bonderchuk, Issurin, Verkoshansky) noted that in a TP model, peak performance could not be maintained for extended periods of time (approximately 5-8 days) making it difficult to apply in sports with multiple competitions (Issurin, 2016; Verkhoshansky, 1981).

2.3.2 Undulating periodisation

The undulating periodisation (UP) model is characterised by regular and nonlinear variations in intensity and volume (Evans, 2019; Zourdos, Jo, et al., 2016). Unlike the TP model where volume and load remain relatively constant across a training block, UP is characterised by daily or weekly alterations in exercise parameters (Rhea et al., 2002). Daily undulating periodisation (DUP) incorporates variation in exercise selection, volume or intensity on a daily basis, and weekly undulating periodisation (WUP) every 1-2 weeks (Apel et al., 2011). The frequent alteration in training stimulus induced during UP is highly advantageous for the development of muscular strength, with some research suggesting that it might be superior to TP for eliciting maximal strength and muscular hypertrophy (Hoffman et al., 2003; Rhea et al., 2002). However, some studies have reported similar improvements in strength or muscular hypertrophy between the TP and UP models, and it is likely that both models are effective for developing strength-based qualities (Baker et al., 1994; Buford et al., 2007; Grgic et al., 2017; Harries et al., 2015). It is, however, worth noting that most of the research comparing TP and UP has been conducted on untrained individuals and there is a lack of research in highly trained strength sport athletes (Grgic et al., 2017).

2.3.3 Conjugate periodisation

Strength-trained athletes are likely to experience diminishing improvements in muscular strength as training competency increases (Latella et al., 2024; Steele et al., 2023). Therefore, a greater relative magnitude of training might be required to elicit further physiological adaptations and prepare athletes for the physical demands of competition (Pistilli et al., 2008; Rhea, 2004). A limitation of the TP method is that it does not allow for variability within each training cycle, and, therefore, might lead to stagnation or accommodation as improvements begin to diminish and the athlete becomes more accustomed to the training programme (Turner, 2011). The conjugate system of training was developed by Yuri Verkoshansky to overcome the limitations of TP (Verkhoshansky, 1981). In the conjugate system, phases of *concentrated unidirectional loading* (facilitated through high-volume, high-intensity resistance exercise for a period of 1-2 weeks) are implemented into the training programme to elicit targeted physiological adaptations (Issurin, 2016; Verkhoshansky, 1981). The overall aim of these highly demanding training blocks is to systematically target physiological adaptation through completion of a large training stimulus compared to habitual training. This is, perhaps, why concentrated training blocks are commonly referred to as “shock microcycles” (Smith, 2003).

Due to the demanding nature of such training, concentrated loading periods are followed by *restitution blocks*, where the objective is to mitigate fatigue and promote recovery (Plisk & Stone, 2003; Turner, 2011; Verkhoshansky, 1981). During a concentrated loading phase, an increase in fatigue is expected, which likely leads to a temporary decrease in performance (Plisk & Stone, 2003; Turner, 2011; Verkhoshansky, 1981). However, during the restitution block, a reduction in fatigue coupled with a delayed training effect results in an improvement in performance relative to baseline (Plisk & Stone, 2003; Turner, 2011). It is worth noting though, that whilst undertaking short-term periods of concentrated loading might result in improved performance relative to baseline (Fry et al., 1994a; Pistilli et al., 2008; Ratamess et al., 2003), such training might also result in long-term performance decrement if miscalculated (Foster, 1998; Meeusen et al., 2013; Turner, 2011).

2.3.4 Block periodisation

The block periodisation (BP) model was designed to enhance multiple physical attributes across the competition period in a sequential manner. Developed by Vladimir Issurin (Issurin, 2008; Issurin, 2016) and considered to be an evolution of the conjugate system, BP focuses on two distinct elements; the *cumulative training effect* and the *residual training effect* (Issurin, 2010). During BP, athletes undertake a phase of concentrated training that has one primary emphasis (e.g., hypertrophy, strength) to induce a cumulative (concentrated) training stimulus (Abbott, 2016). To prevent stagnation and excessive fatigue during these phases, other training emphases are de-prioritised (Haff et al., 2004; Stone et al., 2021; Verkhoshansky, 1981). BP assumes that there is a delayed 'lag' time between the initiation of the concentrated loading stimulus and when adaptation is achieved (Verkhoshansky, 1985). Adaptations can then be retained beyond a certain time after cessation of training based on the residual training effect or delayed training effect (Issurin, 2008; Issurin, 2010).

The BP model is divided into three distinct phases (Issurin, 2008). The *accumulation* phase emphasises general abilities (e.g., muscular hypertrophy, general muscular strength), the *transmutation* phase focuses on sport-specific development (technique, maximal strength), and the *realisation* phase prioritises speed strength, rate of force development and prepares the athlete for competition (Suarez et al., 2019). Compared to the TP approach where training blocks are typically >4 weeks in duration, BP training blocks are usually 2-4 weeks in duration, allowing regular dosing of strength, hypertrophy, rate of force development etc. and therefore (at least hypothetically) reduces the risk of detraining (Lorenz & Morrison, 2015).

Whilst The BP model was designed primarily for sports with multiple fitness and technical qualities (Issurin, 2008), it also appears to be beneficial for strength sports (Hartmann et al., 2009; Issurin, 2016; Suarez et al., 2019). BP might be more efficient than DUP for the development of muscular strength (Painter et al., 2012). However, not all studies have reported superiority between BP programmes and TP for lower body strength development (Bartolomei et al., 2014). Consequently, more research is needed to fully elucidate BP as a system to induce strength gains in high-performance strength sport populations (Lorenz & Morrison, 2015).

2.4 General adaptation syndrome

The philosophy of TP is based largely on the fundamental principles of Hans Selye's general adaptation syndrome (GAS) (Selye, 1936). Indeed, Matveyev's development of the TP model can be traced back to the GAS principles and the assumption that all physiological systems adapt to stress in a predictable way (Haff et al., 2004; Lorenz & Morrison, 2015). Selye conceptualised the GAS as a triad of distinct stress responses (Figure 3). In this sense, the initial (alarm) phase represents the immediate acute physiological response to a stressor. The second phase (resistance) refers to the body's attempt to return to homeostasis by reversing the biological changes that occurred during the alarm phase. The third phase (exhaustion) represents the effects of prolonged or chronic stress where the body struggles to return to homeostasis (Haff et al., 2004). Selye proposed that *stressors* could be subdivided into somatic (e.g., changes in temperature, exposure to noise, toxic amounts of drugs) or psychosocial (e.g., low mood caused by frustration, fear, isolation) (Szabo et al., 2012). However, the physiological *response* to all stressors was considered non-specific and predictable (Selye, 1976).

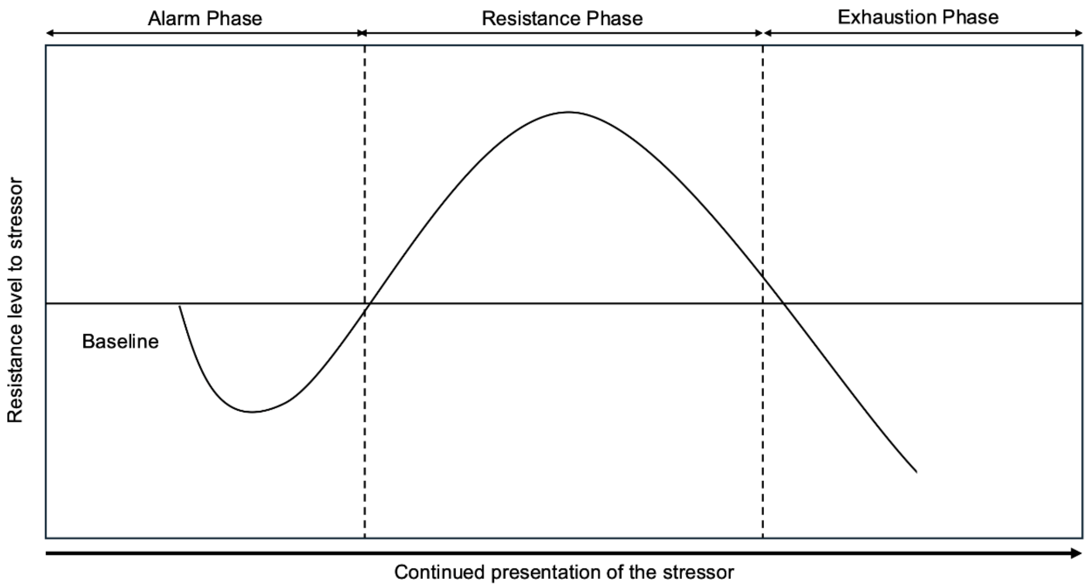

Figure 3. Schematic representation of the general adaptation syndrome (GAS)

According to the GAS model, when presented with a stressor (alarm phase), there is a rapid response initiated by the sympathetic-adreno-medullar (SAM) system resulting in an increased release of catecholamines (adrenaline and noradrenaline) into the bloodstream. The resultant neurobiological response causes increased heart rate, blood pressure, blood glucose, oxygen consumption, and lipolysis (Chu et al., 2024). Increased SAM activity also enhances alertness, arousal, and attention. During the resistance stage, the hypothalamic-pituitary-adrenal (HPA) system releases corticotropin-releasing hormone (CRH) from the hypothalamus, which, in turn, stimulates the anterior pituitary gland to release adrenocorticotropic hormone (ACTH) into the bloodstream. This increase in ACTH triggers the adrenal cortex to release glucocorticoid hormones (i.e., cortisol) into the circulation. Cortisol has several physiological effects, such as insulin suppression, liberation of energy stores and catecholamine release, and, in the context of GAS, helps to restore homeostasis by redistributing metabolic fuel and enhancing cardiovascular responsiveness (Meeusen et al., 2013). During the resistance phase of GAS, cortisol assists in the normalisation of physiological responses (i.e., those initiated during the alarm phase). Moreover, the body's resistance to the stressor would peak and adaptation would occur, given the body had sufficient "adaptation energy" (Buckner et al., 2017; Selye, 1976). Finally, if presentation of the stressor persists and the body is unable to adapt, a total breakdown of the organism occurs, leading to "disease of adaptation" (exhaustion phase). During this phase, a "triad of stress" occurs; enlargement of the adrenal glands, atrophy of the thymus (which is responsible for the production of some types of immune cells) and, in some cases, gastroduodenal ulcers (Szewczyk et al., 2018). During the exhaustion phase, there is an insufficient glucocorticoid response to increasing demands caused by persistent stress (Hackney, 2006).

The GAS was not designed to inform exercise training practices (the seminal research was performed on rodents with the purpose to test sub-lethal doses of drugs and effects of extreme environments). However, innovative strength sport practitioners such as Matveyev, Fred Wilt and John Garhammer realised the similarities between the triphasic nature of GAS and the way that athletes respond to the acute and chronic stressors of strength exercise (Garhammer, 1979; Matveyev, 1981; Stone et al., 2021). For example, Stone et al., (1982) published a theoretical model of strength training suggesting that the alarm phase corresponds to the first few days of a new training programme, the resistance phase corresponded to the physiological adaptations that occur during a period of resistance exercise, and exhaustion occurred if the athlete is not given sufficient rest and summative stress (imposed through a combination of training and non-training factors) was too great.

Several articles have described the similarities between GAS and an athlete's response to resistance exercise training (Bourne, 2008; Cunanan et al., 2018; Issurin, 2014). Indeed, Selye's work continues to be advocated as a mechanistic model by which the relationship between stress and adaptation can be explained (Cunanan et al., 2018; Fry & Kraemer, 1997; Issurin, 2014; Stone et al., 2021; Turner, 2011). Further, some commentators has suggested that the alarm stage of GAS can be likened to stiffness, soreness and a temporary decrease in performance following a bout of resistance exercise (Lorenz & Morrison, 2015). The resistance phase is where the athlete adapts to the training programme, leading to lower levels of soreness, a greater tolerance to training, and performance supercompensation (Lorenz & Morrison, 2015). Finally, during the exhaustion phase (which occurs when training continues for longer than the athlete can adapt), the athlete experiences a decline in performance or "staleness" (Lorenz & Morrison, 2015). Stone et al., (1982) referred to this stage as the "overtraining" phase and proposed that it is at this point that the athlete would experience a rapid decline in adaptation, leading to long-term performance decrement.

Whilst GAS might be firmly positioned within periodisation theory, Selye's model has been criticised by some commentators for failing to address specific aspects of the adaptive process. For example, Buckner and colleagues (2017) suggest that GAS has limited applicability to sports training and that the processes that underpin the stress (and adaptive) response to exercise does not explain the complex adaptations that occur following resistance exercise training (i.e., different types of training trigger specific responses). The authors argue that this is especially relevant to more contemporary approaches to periodisation (e.g., UP, conjugate, BP) that are far removed from the traditional model. Additionally, GAS assumes that undertaking periodised resistance exercise training will result in a predictable pattern of adaptation (Lorenz & Morrison, 2015). Moreover, that all stressors trigger similar physiological responses (Chiu & Barnes, 2003). However, a fundamental aspect of high-performance training is training *specificity*, where the human body develops highly-specific, not generalised adaptations based on the distinct stimulus (Reilly et al., 2009). Kiely (2018) has criticised the application of GAS, suggesting that periodisation is based on an implicit assumption that training parameters directly dictate biological training adaptations. Further, that the point where an athlete transitions from a "normal" (resistance phase) to "abnormal" (exhaustion, overtraining) response is not known, and appears to be highly individualised (Hackney, 2006). Indeed, when the physiological response to structured resistance exercise is analysed at an inter-individual level, athletes typically exhibit variability in training adaptations, making it difficult to predict a dose of training that is optimal from a dose that will lead to exhaustion. Such variability is likely to be modulated by genetic and epigenetic factors (Bagley et al., 2020; Bellinger et al., 2020; Carpinelli, 2017; Hubal, Gordish-Dressman, et al., 2005; Jones et al., 2016; Peltonen et al., 2018). However, additional variables such as the level of competition/training status and the individual's "stress capacity" (Kenttä & Hassmén, 1998; Kreher & Schwartz, 2012b; Stults-Kolehmainen & Bartholomew, 2012) are also likely to influence performance outcomes.

Whilst GAS is a foundational model by which periodisation theory is based upon, there is limited empirical evidence to support its application in modern resistance exercise programming. Consequently, additional research might be required to fully substantiate its application in strength sports and better understand how athletes respond to stressful periods of strength training.

2.5 Fitness-fatigue model

In contrast to Selye's GAS, the impulse-response model (more commonly known as the fitness-fatigue model; FFM), proposed by Bannister in 1982 (Bannister, 1991; Calvert et al., 1976), views an athlete's level of performance as the summation of adaptation and fatigue (Lorenz & Morrison, 2015; Plisk & Stone, 2003). In the FFM, Bannister acknowledged that distinct training stimuli result in *specific* adaptations, not just a series of generalised responses as described by the GAS. The FFM proposes two exercise training after-effects, both of which affect performance. The *fitness* (adaptation) after effect enhances performance relative to baseline, whilst the *fatigue* effect will lead to performance decline (Bannister, 1991; Chiu & Barnes, 2003).

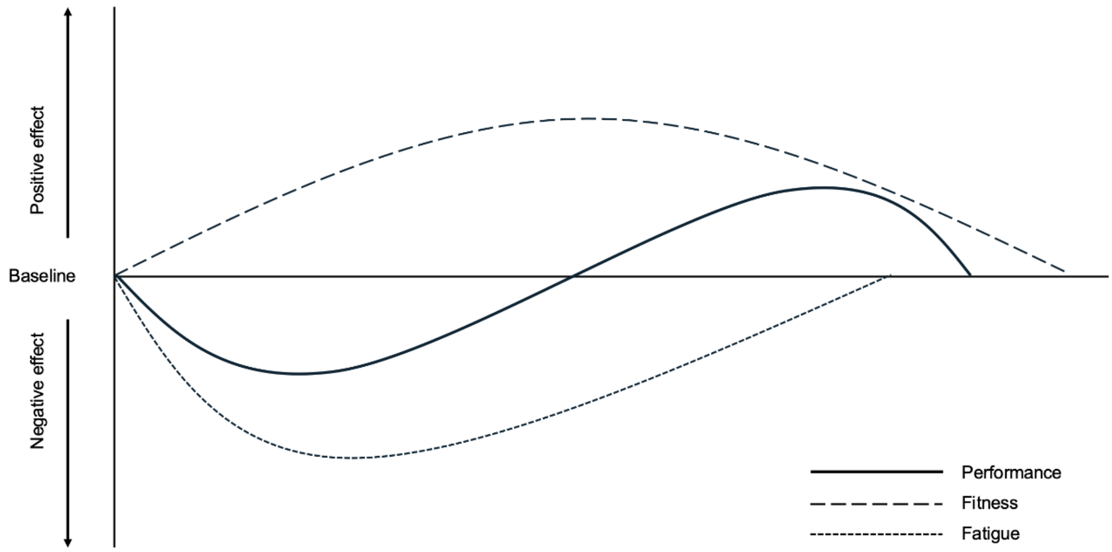

Figure 4. The fitness-fatigue model that describes an athlete's current level of performance (relative to baseline) as the combined effects of fatigue and fitness (adaptation)

According to the FFM, fatigue is a negative, high-magnitude and short-lasting training effect, whilst fitness is a positive, low-magnitude long-lasting (relative to fatigue) training effect (Figure 4). It is the net effect of these two factors that asserts an athlete's level of performance at any given time (Bannister, 1991; Calvert et al., 1976). Whilst the FFM has been refined since its original iteration, the most common mathematical formula used to predict performance is:

$$\hat{p}_n = p^* + k_1 \sum_{i=1}^{n-1} w_i e^{-(n-i)/\tau_1} - k_2 \sum_{i=1}^{n-1} w_i e^{-(n-i)/\tau_2}.$$

(Bannister, 1991; Vermeire et al., 2022)

Based on this formula, performance ($\hat{P}_n$) is estimated from training load (w_i) which can be scored from 1 to -1. Baseline performance is p^* and τ_1 (fitness) and τ_2 (fatigue) are exponential time constants (days). The magnitude of effect (referring to the size of change in both fitness and fatigue) is expressed as k_1 and k_2 respectively (Vermeire et al., 2022).

The fitness-fatigue model is considered a more accurate representation of the relationship between stimulus, adaptation and response compared to the GAS (Chiu & Barnes, 2003) because it can distinguish between different types of stressors/stimuli (e.g., neuromuscular, metabolic). A greater understanding of how fitness and fatigue interact during training (and their effect on performance) assists the coach in maximising performance whilst mitigating the risk of suboptimal performance response, exhaustion and overtraining (Busso, 2003; Morton, 1997; Stone et al., 1982). However, the mathematical formula used to predict performance is greatly impacted by univariate modelling, and, consequently, might not fully acknowledge the complexity of physiological processes underpinning human physiology (Imbach et al., 2022). Moreover, the fitness-fatigue model might not fully account for inter-individual differences between athletes (or the same athlete at different time points) and, therefore, coaches should also trust their expert/tacit knowledge and experience when interpreting information obtained from the FFM (Vermeire et al., 2022). Further, little is known about how undertaking a concentrated loading phase (e.g., during conjugate or BP where fatigue is proposed to accumulate due to concomitant effects of increased demand and impaired recovery) might affect performance and further research is required to fully elucidate the response to intentionally demanding phases of resistance exercise. Moreover, the FFM appears to assume a relatively stable state of factors and therefore might not fully acknowledge the transient factors that can influence performance such as sleep, non-training stress, psychological state, illness, or nutrition (Greig et al., 2020; Kiely, 2018).

2.6 Overreaching and overtraining

2.6.1 Definitions

According to both classic and contemporary periodisation theory, successful athletic training programmes must balance the training stimulus with adequate recovery to develop a meaningful improvement in performance. Intermittent periods of recovery, therefore, are often encouraged following (and during) phases of challenging resistance exercise to optimise the adaptive response (Raeder et al., 2016; Sousa et al., 2024). According to the FFM, it is inevitable that both during, and in the hours to days following phases of highly demanding resistance exercise, athletes will experience an acute reduction in performance due to an increase in fatigue. However, when adequate recovery is applied, physiological adaptations induced from training will result in a net positive performance change relative to baseline (Chiu & Barnes, 2003; Imbach et al., 2022). If, however, a balance between the training stimulus and recovery is not achieved, the following abnormal responses might eventually develop (Cadegiani et al., 2020; Halson & Jeukendrup, 2004; Kreider et al., 1998; Meeusen et al., 2013):

- Overreaching (OR): an accumulation of training and/or non-training stress resulting in *short-term* decrement in performance capacity with or without related physiological and psychological signs and symptoms of maladaptation in which restoration of performance capacity may take from *several days to several weeks*.

- Overtraining syndrome (OTS): an accumulation of training and/or non-training stress resulting in *long-term* decrement in performance capacity with or without related physiological and psychological signs and symptoms of maladaptation in which restoration of performance capacity may take *several weeks or months*.

Based on these definitions, there is an implication that OR and OTS share the same pathophysiology (i.e., related physiological and psychological signs and symptoms of maladaptation). Moreover, that OR can only be distinguished from OTS by retrospective time course to recovery rather than by magnitude or type of symptoms. According to current consensus, OR is defined as a temporary performance decrement lasting <4 weeks, whilst OTS is considered a more long-term disorder characterised by "persistent fatigue or exhaustion" lasting >4 weeks (Meeusen et al., 2013). An athlete suffering from the OTS does not experience performance improvements, even following a period of rest (Meeusen et al., 2013). This is likely because all positive adaptations are lost due to the extended duration of recovery time required to restore physiological function.

OR can divided into two distinct sub-classifications. Short-term periods of training above the habitual level followed by subsequent recovery can lead to a supercompensation effect or "rebound" known as functional overreaching (FOR). Importantly, FOR only occurs following an initial period of relative performance decline (Aubry et al., 2014; Borszcz et al., 2022; Pistilli et al., 2008). Coaches often aim to induce FOR through the implementation of intensified training phases (e.g., concentrated training blocks or training camp) with the intent that the temporary decline in performance is followed by performance supercompensation, but only once a period of recovery (e.g., deload or taper) is undertaken (Aubry et al., 2014; Pistilli et al., 2008).

If a balance between training and recovery is not achieved, there is a risk that a diminished adaptive response can occur, resulting in medium-term performance decrement. This is known as non-functional overreaching (NFOR). During NFOR, no performance improvements are observed and it can take days to weeks for performance to return to baseline (Halson & Jeukendrup, 2004). Like OTS, the absence of performance improvement is likely due to a loss of adaptations during the recovery period. According to expert consensus (Meeusen et al., 2013), FOR and NFOR are defined as follows:

- Functional overreaching (FOR): A short-term decrease in performance lasting days to weeks with subsequent performance supercompensation after a period of recovery.
- Non-functional overreaching (NFOR): Performance decrement is observed over a period of weeks and while full recovery is achieved (although not always), no supercompensation effects are achieved.

Figure 5 provides a hypothetical model to illustrate how an athlete might progress between the different stages of performance change following a period of resistance exercise training. In this model, undertaking a short-term period of demanding training will result in temporary reduction in performance, but improvement above baseline if recovery is correctly applied (FOR). However, if training persists and/or insufficient recovery is applied, the athlete will experience an abnormal response, that (based on retrospective time course to restitution) can be determined as NFOR or OTS.

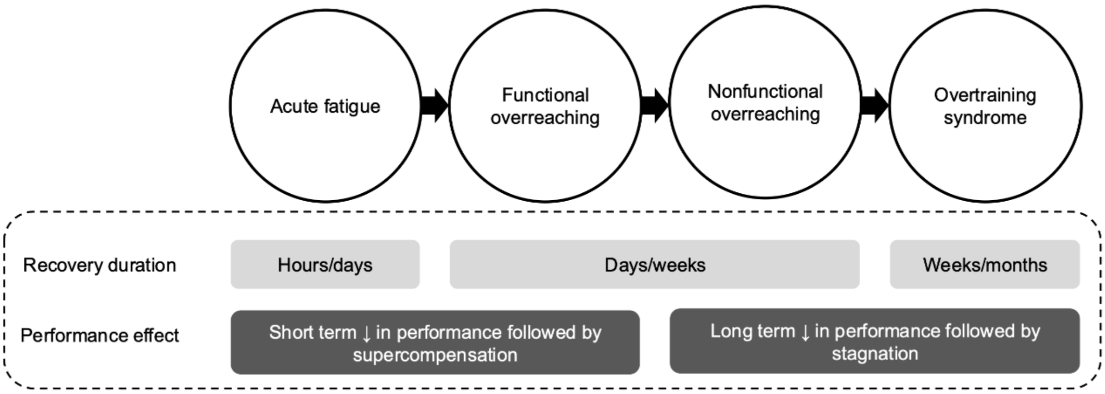

Figure 5. A hypothetical representation of the different stages of OR/OTS. Adapted from Meeusen et al., (2013)

Whilst expert consensus was developed, in part, to resolve misconceptions relating to FOR, NFOR and OTS (Meeusen et al., 2013), terminology is still misinterpreted in the literature. For example, OTS is considered a complex and multifactorial disorder that is a *result* of prolonged or excessive stress (Kreher, 2016; Kreher & Schwartz, 2012b). The more colloquial term "*overtraining*" (OT) is often used as a verb to describe the imbalance between training demand and recovery that could result in either diminished performance (e.g., NFOR/OTS) or an improvement above baseline (Meeusen et al., 2013). In this sense, OT is a *process* whilst OTS is an *outcome* (Table 2). However, previous literature has used the two terms interchangeably, resulting in confusion and misinterpretation (Budgett et al., 2000; Clarkson et al., 2005; Meeusen et al., 2010, 2013). An example of interchangeability used in the literature is provided here: "for the purpose of this study, non-functional overreaching and overtraining syndrome will be referred to as "overtraining" (Lemyre et al., 2007). Moreover, terms such as "staleness" (Haff et al., 2004; Hooper et al., 1995; Konttä et al., 2001), "burnout" (Kuipers & Keizer, 1988) "fatigue syndrome", "chronic fatigue in athletes", "sports fatigue syndrome", "failure to adapt", "physical overstrain", "underrecovery syndrome" have also been used interchangeably with OTS (Fry & Kraemer, 1997), leading to confusion as to whether athletes are truly experiencing

OTS or not (Budgett et al., 2000; Cadegiani & Kater, 2019a). In an expert roundtable discussion between strength and conditioning academics (Haff et al., 2004), OT was divided into "acute OT" and "chronic OT". Here, chronic OT was described as a syndrome characterised by long-term performance decrement lasting a few weeks (which is effectively the consensus definition of OTS). Conversely, acute OT was defined as a lack of performance improvement following a phase of training which is perhaps more indicative of NFOR.

Attempts have been made to redefine the OTS to enhance understanding. For example, the "unexplained underperformance syndrome" was proposed by Budgett et al., (2000) and the "paradoxical deconditioning syndrome" was proposed by Cadegiani & Kater (2019b). However, these alternative terms have failed to gain traction within the field. Such attempts do acknowledge the lack of standard nomenclature in this domain though.

Whilst the term "overreaching" is defined in expert consensus as short-term decrement lasting days to weeks, it has also been used to describe the *process* of undertaking a concentrated loading phase as part of a strength training periodisation plan e.g., during conjugate or block periodisation phases (Table 2) (Haff et al., 2004; Pistilli et al., 2008; Stone et al., 1999, 2021; Turner, 2011). When used intentionally, "planned OR" is implemented into the athlete's training programme through a deliberate and often dramatic increase in training volume, facilitated via multiple weekly training sessions and/or training intensity (Pistilli et al., 2008; Storey & Smith, 2012; Travis et al., 2020). Planned OR is generally undertaken during competition and/or peaking phases of a training schedule for ~7 days. Importantly, phases of planned OR are separated by longer periods of normal training or tapering to reduce the risk of maladaptation (Pistilli et al., 2008; Stone et al., 2021; Travis et al., 2020).

Table 2. Interchangeability of definitions based on current literature

	Process (verb)	Outcome (noun)
Overreaching (OR)	OR: undertaking a concentrated loading phase as part of a strength training periodisation plan e.g., during conjugate or block periodisation (Haff et al., 2004; Pistilli et al., 2008; Stone et al., 1999, p. 2, 2021; Turner, 2011).	OR: an accumulation of training and/or non-training stress resulting in *short-term* decrement in performance capacity with or without related physiological and psychological signs and symptoms of maladaptation in which restoration of performance capacity may take from *several days to several weeks* (Meeusen et al., 2013) FOR: A short-term decrease in performance lasting days to weeks with subsequent performance supercompensation after a period of recovery (Meeusen et al., 2013) NFOR: Performance decrement is observed over a period of weeks and while full recovery is achieved (although not always), no supercompensation effects are achieved (Meeusen et al., 2013)
Overtraining (OT)/Overtraining syndrome (OTS)	OT: A process of intensified training with possible outcomes of short-term OR (FOR), extreme OR NFOR), or OTS (Meeusen et al., 2013)	OTS: an accumulation of training and/or non-training stress resulting in *long-term* decrement in performance capacity with or without related physiological and psychological signs and symptoms of maladaptation in which restoration of performance capacity may take *several weeks or months* (Meeusen et al., 2013) OT: operationally defined as an increase in training volume and/or intensity that results in long-term performance decrements (Fry et al., 2006; Fry & Kraemer, 1997) OT: a non-deliberate long-term decrement in performance capacity resulting from a failure to recover adequately from an accumulation of training and non-training stress (Lemyre et al., 2007)

The precise manner by which planned OR is implemented depends on several factors including the competition schedule, level of competition, previous exposure to planned OR and the model of periodisation that the athlete is undertaking (Aubry et al., 2014; Bellinger, 2020; Pistilli et al., 2008; Turner, 2011). It is worth noting that due to the highly demanding nature of planned OR, the athlete is at an increased risk of developing NFOR/OTS (Bellinger, 2020; Meeusen et al., 2013; Roy, 2015), therefore whilst planned OR can induce performance gains, it can also lead to performance decrement if miscalculated. To date, little is known about how strength sport coaches develop planned OR to achieve FOR whilst mitigating the risk of maladaptation. There is also a lack of consensus in the literature regarding the risk-reward of planned OR. Nevertheless, a greater understanding of the process and planning that underpins concentrated training such as planned OR is important to develop a framework of good practice for strength sport coaches. Moreover, an improved understanding of how high-performance practitioners develop "real world" OR would also assist sport scientists in the creation of robust and ecologically valid training interventions to act as a model by which FOR and NFOR/OTS could be studied.

Advances in theoretical sport science knowledge means there is more pressure on strength coaches to stay up to date with advancements in research (Balagué et al., 2017). However, there is a clear lack of consistency regarding definitions of OT/OTS and more consistent communication between researcher and practitioner is needed. Traditionally, the value of coaches' experiential knowledge has been neglected in sports science and sport coaching research, resulting in a considerable gap between science and good practice (Haugen, 2021). However, the pedagogical relationship between coach and scientist should not be approached in a unidirectional or top-down manner (Rothwell et al., 2023). Instead, utilising the knowledge of expert coaches as key informants (considered an "untapped resource" sport science (Sandbakk et al., 2022)), would provide a valid line of inquiry to better understand the critical features of OR/OTS from the perspective of those on the 'front line' of coaching. Ultimately, expert consensus in the field of OTS is designed to inform and enhance coaching practice, therefore, it is important that future research is bidirectional to ensure that recommendations derived from the published literature are being effectively communicated with practitioners. Moreover, that such communication is both understood and engaged with by practitioners.

2.6.2 Diagnosis and assessment

The consensus definition of OTS dictates that an unexplained decrease in performance coupled with persistent fatigue or exhaustion must be observed for >4 weeks before a diagnosis can be considered (Meeusen et al., 2013). If such symptoms are resolved in <4 weeks, it is likely that FOR or NFOR occurred dependant on resulting performance change. Nevertheless, the >4-week threshold is rarely observed in the resistance exercise literature. For example, some studies have applied a threshold duration of >2 weeks to indicate OTS (Cadegiani et al., 2019b; Fry et al., 2006). Elsewhere, a period of 6-8 weeks of observable performance suppression was set as the threshold duration of performance decline before OTS could be determined (Roy, 2015; Tian et al., 2015). Many studies have reported incidence of OTS but failed to provide information relating to the duration of performance decline (Cadegiani et al., 2020; Cadegiani & Kater, 2018, 2019c; Hedelin et al., 2000), therefore, findings from these studies must be interpreted with caution. Some studies have completed follow-up performance testing immediately upon completion of the training protocol and not at the >4 week post-training period, but still concluded that participants were "overtrained" (Fry et al., 1998, 1994b, 1994c). Due to the immediacy of post-intervention testing, is plausible that individuals in these studies were experiencing a pattern of normal restorative processes that could have resulted in FOR given adequate recovery. However, without appropriately timed testing, neither FOR nor NFOR/OTS can be substantiated. Lastly, some studies have used participant interviews ("how long did it take you before you could resume normal training?") instead of objective performance assessment to indicate OTS (Fry et al., 2006). Clearly, diagnosis of a complex disorder as severe as OTS based on subjective self-reporting should be taken with caution due to response and recency bias, as well as the potential for athletes to over- or under-estimate the demands of training (Halson, 2014). To date, there is only one study that has implemented follow-up performance assessments after a period of intensified resistance exercise training (Margonis et al., 2007). In this study, participants completed a 12-week full-body resistance exercise training programme consisting of four 3-week training blocks followed by a 3-week training cessation period. Training blocks one and four were low volume (2-days-per-week, 2 sets of 10-12 repetitions at 70% 1-RM), and training blocks two (4-days per week, 4 sets of 6–10 repetitions at 75–85% 1RM) and three (6-days-per-week, 6 sets of 1-6 repetitions at 85-100% 1-RM) were high-volume. Performance assessments (power clean 1-RM and jump height) were undertaken at baseline, 96-hours after each training block, and following the 3-week cessation period. Improvements in jump height were observed (relative to baseline) following training block two but significantly decreased at block three (-9.6%; p = .002). Jump height remained lower than block two at block four (-6.1%) but had returned to baseline values by the end of the training cessation period. Maximal strength was significantly greater than the baseline scores at all post-testing timepoints but was significantly lower (-6.4%; p = .000) at block three compared to block two. The reduction in maximal strength continued after the training cessation period (-5.9%). Based on these findings, a reduction maximal strength and jump height was observed for > 4 weeks.

Consensus denotes that as well as performance decrement being observed for >4 weeks, a >10% decrease in the magnitude of performance is also required before OTS can be considered likely (Meeusen et al., 2013). However, few studies have reported the magnitude of performance change when NFOR or OTS have been reported. In the previously discussed study by Margonis et al., (2007), a reduction in maximal strength and jump height was likely observed for >4 weeks following high-volume resistance exercise training. However, performance reductions did not surpass >10% (maximal strength = -6.4%; jump performance = -9.6%) In a study by (Cadegiani et al., 2019b), OTS was diagnosed due to prolonged underperformance (classified as ≥10% decrease from previous sport-specific CrossFit performance). However, a 5% decrease in back squat one repetition maximum was used to indicate OTS elsewhere (Fry et al., 2006). Due to a lack of gold standard diagnostic assessment (Meeusen et al., 2013), accurately assessing OTS is a challenge, as performance decrement might vary widely based on the specific test being used. For example, one repetition maximum (1-RM) ability (which is considered the gold standard performance test for strength assessment outside of laboratory conditions) (Seo et al., 2012) can fluctuate on a daily basis, even in healthy individuals (Larsen et al., 2021). Given that the magnitude of performance decrement is rarely reported in resistance exercise OTS literature, future research should accurately report both the degree and duration of performance changes and attempt to standardise the parameters by which OTS is determined.

In resistance exercise studies, it is common for the back squat to be the training-specific criterion measure used to determine performance change (Fry et al., 1998, 2006, 1994a, 1994c, 1994b; Nicoll et al., 2016; Sterczala et al., 2017). Studies from strength sports have relied primarily on sport-specific performance i.e., weightlifting (Bazyler et al., 2018; Fry et al., 1993, 2000a; Häkkinen et al., 1987, 1989) and throwing performance (Bazyler et al., 2017a) to indicate NFOR/OTS, as well as general measures of performance (e.g., isometric and dynamic mid-thigh pull force characteristics, countermovement jump performance) (Bazyler et al., 2017; Haff et al., 2008; Suarez et al., 2019). Findings from these studies have been inconsistent though and a lack of standardised follow-up testing has prevented consistent and accurate diagnostic information. Based on the available literature, neither the magnitude nor the duration of performance decrement are consistently reported, further questioning the prevalence of NFOR/OTS in strength sports.

Due to a lack of gold standard diagnostic assessment, OTS remains a disorder of exclusion (i.e., diagnosis can only be made after ruling out all other possible causes that might lead to the same symptoms). Expert consensus has provided a flowchart to assist clinicians in a diagnosis of OTS. The stages of the diagnostic tool were developed based on the existing evidence but also the experience of the authors (Meeusen et al., 2013). Once the duration and magnitude of performance decrement have been verified, several confounding factors must be excluded (Meeusen et al., 2013). A definitive diagnosis of OTS can only be made once organic/infectious diseases (e.g., Epstein-Barr, cytomegalovirus, hepatitis), inflammatory diseases (e.g., myocarditis) and dysfunctional feeding behaviours (e.g., anorexia nervosa, bulimia) have been excluded. This is because symptoms of such disorders can mimic those of OTS, leading to misdiagnosis (Meeusen et al., 2013). Other confounding variables such as nutritional disturbance (e.g., negative energy balance caused by dietary caloric restriction, insufficient nutrient intake) must also be considered due to their influence on training and recovery (Meeusen et al., 2013).

At the time of writing, there have been several comprehensive reviews published in NFOR/OTS within endurance sports (Bell & Ingle, 2013; Bosquet et al., 2008; Cadegiani & Kater, 2017; Halson & Jeukendrup, 2004; Meeusen et al., 2010). In these reviews, several symptoms have been proposed as possible markers of NFOR/OTS and can be loosely categorised into cardiovascular, musculoskeletal, neuromuscular, and autonomic systems. However, findings from these reviews (and the individual studies included in them) have been inconsistent, and to date, no single marker or assessment has been able to reliably or consistently detect NFOR/OTS (Cadegiani & Kater, 2017; Halson & Jeukendrup, 2004; Meeusen et al., 2013). In the resistance exercise literature, there is a clear under-representation of evidence, with only one published review at the time of writing (Fry & Kraemer, 1997). In this review, the authors argued that chronic exposure to resistance exercise might lead to altered hormonal responses (amongst other physiological disturbances), with high-volume resistance exercise training following a similar pathology to endurance training, whereas high-intensity resistance exercise appears to result in a differential response. However, to date, no research has confirmed this hypothesis empirically and there is still much to learn about the possible markers of NFOR/OTS related to excessive or prolonged resistance exercise.

2.6.3 Prevalence

Data outlining the prevalence of the OTS derive mostly from endurance sports (Halson & Jeukendrup, 2004; Kreher & Schwartz, 2012b; Meeusen et al., 2013). Based on current literature, the incidence of OTS is speculated to be high, with as many as 20-60% of athletes experiencing OTS at some point in their competitive career (Halson & Jeukendrup, 2004; Meeusen et al., 2013). Moreover, 7-21% of swimmers have experienced OTS across a competitive season (Halson & Jeukendrup, 2004). Based on the relatively sparse data, those involved in individual sports (e.g., endurance running, swimming, cycling) appear to be at a greater risk of developing OTS compared to team sport athletes (e.g., intermittent, invasion sports), with as many as 64% of individual athletes and 50% of team sport athletes indicating OTS via survey (Halson & Jeukendrup, 2004; Senttä et al., 2001; Meeusen et al., 2013). Koutedakis & Sharp (1998) reported that in a group of 257 male and female elite athletes, 38 (14.7%) cases of OTS occurred. The athletes represented 8 sports, including endurance sports (e.g., cycling, swimming) and intermittent sports (e.g., basketball, volleyball) but no strength sports were represented. Findings indicated that OTS was most likely to occur during the competitive phase of the periodisation plan, and endurance athletes were most likely to develop OTS (Koutedakis & Sharp, 1998). This is most likely due to the high training volume undertaken by endurance athletes across the competition season (Bentley et al., 2008).

Similarly, in a group of 376 young British athletes ranging from club to international standard, the prevalence of NFOR/OTS was 29%, with the primary risk factors being participation in individual sports and the level of competition (with the greatest risk being at elite level) (Matos et al., 2011). Interestingly, training load was not a predictor of OTS, suggesting that individual load tolerance or non-training factors might also increase the risk of maladaptation. In a group of 272 young athletes competing across 16 different sports, an OTS prevalence of 37% was reported (Kenttä et al., 2001). The incidence rate was highest (48%) in individual sports (e.g., figure skating, cycling) and lowest in low-intensity sports (18%; e.g., sailing, golf). The prevalence of OTS was 30% in team sports (e.g., soccer, ice hockey, basketball). However, not all individual sports have a high prevalence of OTS. In a sample of 114 wrestlers, only 0.6% reported OTS, with 6.4% indicating NFOR (Tian et al., 2015). Finally, 34.6% of young swimmers have reported symptoms of OTS (Raglin et al., 2000). However, the mean duration of symptoms reported was 3.6 weeks suggesting some athletes were experiencing NFOR and not OTS. Interestingly, the prevalence of OTS was higher in those with faster personal best times, suggesting that higher-standard athletes might be at a greater risk of maladaptation compared to those at lower levels of competition.

Several studies reporting incidence of OTS have not used proper diagnostic tools and did not distinguish OTS from NFOR. Therefore, prevalence rates are likely to be inflated (Meeusen et al., 2013). Whilst OTS appears prevalent (based on the incidence rates reported in the literature) in both individual and team sports; to date, no studies have mapped the incidence of OTS in strength sports or resistance training populations. Given that the general adaptations to endurance and strength training (as well as the methods by which training is prescribed) varies between endurance and strength sports, relying on prevalence statistics from the endurance domain to assume an incidence rate in strength sports is problematic (Lambert, 2016). Given that strength sports are individual and have elite-level categories of competition, these athletes might be at a greater risk of OTS compared to those involved in team sports.

2.6.4 Related maladaptive disorders

When the adaptive response to an exercise stimulus becomes dysfunctional, it is referred to as maladaptation (Cadegiani, 2020). A key word in the recognition of OTS is "prolonged maladaptation" (Meeusen et al., 2013), however, OTS, is not the only maladaptive disorder associated with long-term performance decrement.

OTS and *athlete burnout* are often discussed in the literature synonymously, with definitions used interchangeably (Fry & Kraemer, 1997; Kuipers & Keizer, 1988). OTS and athlete burnout (also known as "burnout syndrome in athletes" or just "burnout") share similar symptomatic profiles and pathophysiology, however, they are not the same condition. Whilst OTS is primarily associated with performance decline, athlete burnout is a multifaceted disorder characterised by three central aspects: emotional and physical exhaustion, sport devaluation, and a reduced sense of accomplishment (Gustafsson et al., 2011; Nixdorf et al., 2020; Raedeke, 1997). Nevertheless, there are several risk factors associated with athlete burnout that are common to OTS, such as prolonged or excessive high training volumes, demanding performance structure, frequent competition/coaching schedules, and non-training factors (e.g., high levels of daily stress) (DiFiori et al., 2014; Meeusen et al., 2013). Like OTS, athletes involved in individual sports, as well as those competing at the highest level of sport are at a greater risk of athlete burnout compared to team sport athletes (Hanrahan & Cerin, 2009; Matos et al., 2011). However, athlete burnout appears to be more prevalent in younger athletes, perhaps due to the negative effects of early sport specialisation (Wilczyńska et al., 2022).

According to a position statement published by the American Medical Society for Sports Medicine (DiFiori et al., 2014), athlete burnout is a collective and broad spectrum of disorders that actually includes NFOR and OTS. The authors state that both OTS and athlete burnout are conditions characterised by the same central symptoms; persistent fatigue, heavy or sore muscles, decreased athletic performance, and low mood. However, factors that place an athlete at a greater risk of burnout include perfectionism, negative thinking, a need to please others, low self-esteem, and non-assertiveness (Fagundes et al., 2021). Indeed, an athlete suffering from OTS does not necessarily lose motivation to train, whereas an athlete with burnout will present signs of training apathy and amotivation (Fagundes et al., 2021). Importantly, athletes with combined symptoms of OTS and high levels of self-determined motivation appear to be most likely to develop athlete burnout (Lemyre et al., 2007), therefore the risk of burnout appears to be amplified when OTS is combined with feelings of perfectionism, pressure to succeed and prioritisation of short-term goals (Brenner et al., 2024).

Whilst there are clear areas of overlap between OTS and burnout (e.g., multifaceted condition, symptoms) (Figure 6), it is important to recognise the distinct differences between each disorder from a treatment perspective. For example, the proposed treatment pathway for an athlete diagnosed with OTS focuses primarily on a reduction in training (Meeusen et al., 2013). Secondary to this is an evaluation of the emotional state of the athlete (e.g., profile of mood state questionnaire, recovery-stress questionnaire for athletes). Conversely, the primary treatment for burnout is psychological; encouragement of athlete autonomy, modification of causative factors (e.g., interventions to address negative thoughts) and prioritisation of mental health (e.g., mindfulness interventions) which might involve referral to a mental health expert (Brenner et al., 2024; DiFiori et al., 2014; Wilczyńska et al., 2022). Indeed, there appears to be more of a psychological component to burnout, focusing on addressing the factors that can lead to sporting attrition (DiFiori et al., 2014). A secondary treatment plan focusing on reducing training demand is also likely necessary to promote recovery and combat symptoms of physical exhaustion.

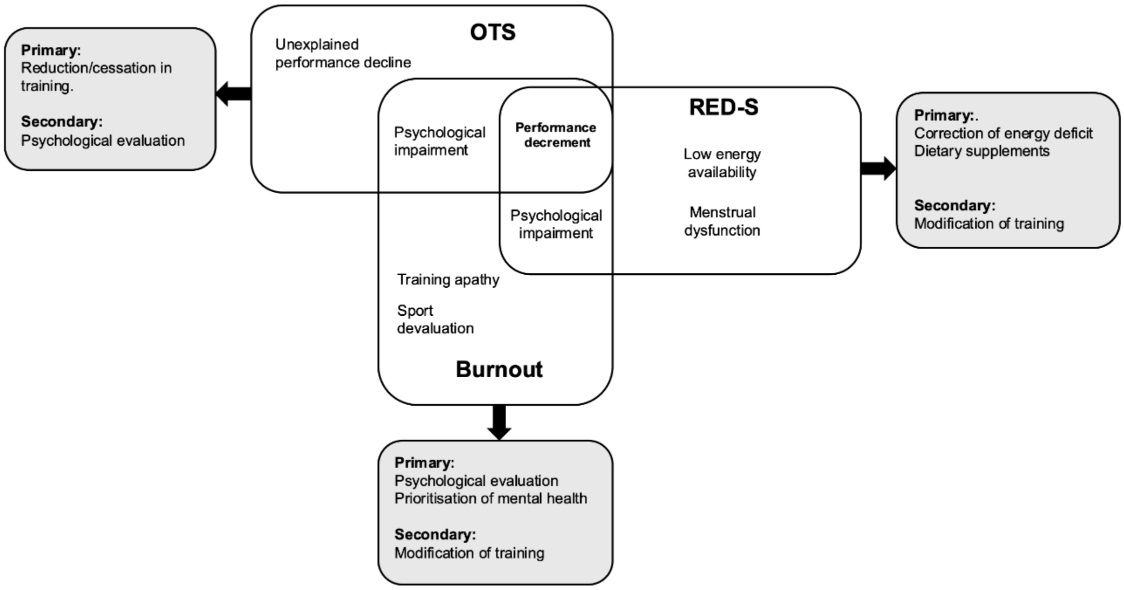

Figure 6. A simplified schematic representing the main similarities and differences between OTS, athlete burnout and relative energy deficiency in sport (REDs). The grey boxes denote the proposed primary and secondary treatment and recovery plans.

Relative energy deficiency in sport (REDs) is a maladaptive disorder that was first described in the 2014 International Olympic Committee (IOC) expert consensus statement (Mountjoy et al., 2014). An updated statement was subsequently released in 2018 to address gaps in knowledge and provide more robust clinical application (Mountjoy et al., 2018). REDs is a maladaptive condition characterised by impaired physiological function and caused by low energy availability (insufficient energy intake relative to the balance between dietary energy intake and energy expenditure required for health and daily physical activity and exercise) (Mountjoy et al., 2014; Statuta et al., 2017). Like OTS, symptoms of REDs include (but are not limited to) decreased athletic performance, blunted response to training, increased risk of injury, and psychological impairment (e.g., depression, irritability, anxiety) (Mountjoy et al., 2018; Statuta et al., 2017) (Figure 6).

REDs is characterised by menstrual cycle dysfunction, caused by changes in reproductive hormones initiated by low energy availability (Mountjoy et al., 2014). More specifically, a reduction in luteinising hormone suppresses estrogen production leading to functional hypothalamic amenorrhea (FHA); anovulation caused by inadequate stimulation of the hypothalamic-pituitary-ovarian axis (Gordon et al., 2017). The risk of FHA increases in the presence of excessive exercise training, disordered eating and psychological stress (Shufelt et al., 2017). A consequence of FHA is that estrogen is, in part, responsible for maintaining bone mineral density, therefore, reduced energy availability can have both short term (e.g., reduced bone formation and accelerated bone reabsorption) and long-term (e.g., fractures and osteoporosis) consequences (Papageorgiou et al., 2018). It is worth noting that whilst menstrual cycle dysfunction is a central tenet of REDs, the disorder can also affect male athletes; with a relative decline in testosterone being a primary symptom (Stenqvist et al., 2020). Like female athletes, a consequence of hormone disturbance caused by low energy availability in male athletes is a loss of bone mineral content resulting in impaired bone health (Tenforde et al., 2016).

Like OTS, identification and diagnosis of REDs is based on exclusion. The REDs Clinical Assessment Tool (RED-S CAT) is a clinical practice diagnostic tool developed to screen and manage athletes at risk of REDs (Mountjoy et al., 2015). The RED-S CAT provides a 'return to play' framework that guides clinicians in their decision making. In this sense, REDs differs from OTS as clinical assessment can be undertaken as a preventative measure and not just when an athlete is at risk of maladaptation. Upon completion of RED-S CAT, athletes at risk of REDs are given one of the following classifications: a 'green light' assessment means that an athlete is considered low risk and clear to train and compete as normal. A 'yellow' light assessment is a moderate risk athlete who can undertake competition but only with a supervised training and medical plan. Athletes considered high risk (a 'red' light assessment) are not cleared for sport participation (Mountjoy et al., 2015). In the event of a yellow or red light assessment, the athlete is advised to seek evaluation and treatment from a registered medical professional (e.g., sports medicine physician, dietician, strength and conditioning coach, sports psychologist) (Mountjoy et al., 2015). The primary treatment following a REDs diagnosis is to correct the energy deficit through increased caloric intake and/or reduced exercise training, as well as a nutrition/supplement plan (e.g., vitamin D, iron) to correct any nutrient deficiencies (Kuikman et al., 2021). In most cases, athletes are required to complete a written treatment contract outlining those who are to be involved in the intervention plan, specific signposting and referral details, and the athlete targets (e.g., target recovery body fat percentages, frequency of weigh-ins) (Mountjoy et al., 2015).

Based on the available evidence, athletes involved in endurance sports (e.g., cycling, running) and/or sports that emphasise low body mass or body fat (e.g., combat sports, aesthetic sports) are at greater risk of developing REDs, likely due to the combination of impaired energy intake and high training loads (Lane et al., 2019). However, there is little research investigating the prevalence of REDs in strength sports. Nevertheless, strength sports competitions are generally organised by weight class and the prevalence of REDs in these sports *might* be high due to constraints related to weight cutting (Marzuki et al., 2023). In strength sport research where NFOR/OTS has been identified, dietary intake is rarely recorded (Fry et al., 1998, 1994c, 1994b; Sterczala et al., 2017). It is, therefore, feasible that performance decrement reported in these studies was due to low energy availability and was not OTS. To date, only one study has controlled for dietary intake during a period of intentional OT (Margonis et al., 2007). However, the details of the diet (including energy intake) were not revealed.

There are clear similarities between OTS and REDS. Both conditions are characterised by physiological disturbance resulting in performance decrement, neither condition has one single marker by which diagnosis can be made, and there are several symptoms that appear to overlap between conditions. What distinguishes REDs from OTS is low energy availability (Figure 6). During diagnosis of OTS, confounding variables such as nutritional disturbance (e.g., negative energy balance caused by dietary caloric restriction, insufficient nutrient intake) must be excluded before a diagnosis can be considered (Meeusen et al., 2013). Consequently, REDs and OTS should be separated by presentation of low energy availability. However, this is extremely challenging for the clinician, both logistically and practically, as techniques to assess energy intake and expenditure are not always accurate and cutoffs to determine low energy availability are yet to be standardised (Logue et al., 2018).

Chapter 3: Study 1 - Overreaching and overtraining in strength sports and resistance training: A scoping review

This chapter is based on the following peer-reviewed publication: Bell, L., Ruddock, A., Maden-Wilkinson ,T., Rogerson, D. Overreaching and overtraining in strength sports and resistance training: A scoping review. J Sports Sci. 2020 Aug;38(16):1897-1912. doi: 10.1080/02640414.2020.1763077.

3.1 Rationale

The first study in this doctoral programme is a scoping review that has two main aims: 1) to map the current literature related to OR and OTS in strength sports and resistance exercise populations, and 2) identify gaps in knowledge that could be investigated in subsequent studies. The overall objectives of this research study are summarised in Table 3 using the framework for conducting scoping reviews according to the Joanna Briggs Institute (JBI) (Peters et al., 2015). A Scoping review was chosen as it affords a robust and transparent methodological tool to synthesise a landscape of literature where precise lines of questioning are undetermined, or where the literature appears heterogenous. Importantly, scoping reviews not only afford the mapping of existing literature within a given field, but also assists identification of knowledge gaps for future research that inform practice in the field (Arksey & O'Malley, 2005; Peters et al., 2015).

3.2 Abstract

To date, little is known about overreaching (OR) and the overtraining syndrome (OTS) in strength sports and resistance training (RT) populations. However, the available literature may elucidate the occurrence of both conditions in these populations. A scoping review was conducted. SPORTDiscus, Scopus and Web of Science were searched in a robust and systematic manner, with relevant articles analysed. 1,170 records were retrieved during an initial search, with a total of 47 included in the review. Two broad themes were identified during data extraction: (1) overreaching in strength sports; (2) overreaching and overtraining syndrome in resistance exercise training. Short-term periods of OR achieved with either high-volume or high-intensity resistance exercise training can elicit functional OR (FOR) but there is also evidence that chronic high-volume and/or intensity resistance exercise training can lead to non-functional overreaching (NFOR). There is minimal evidence to suggest that true OTS has occurred in strength sports or resistance exercise training based on the studies entered

during this review. More research is needed to develop robust guiding principles for practitioners. Additionally, due to the heterogeneous nature of the existing literature, future research would benefit from the development of practical tools to identify and diagnose the transition from FOR to NFOR, and subsequently OTS in strength athletes and resistance exercise training populations.

Table 3. Reasons to conduct a scoping review according to JBI with specific examples related to this doctoral programme

Reasons to conduct a scoping review according to JBI (Peters et al., 2015)	Objectives of the scoping review linked to this doctoral programme
To identify the types of available evidence within a given field	To summarise the methodological approaches taken when investigating OR/OTS, including research the designs and methods used, types of interventions developed, and appropriateness of performance-specific measures to determine or diagnose OR/OTS.
To clarify key concepts/ definitions in the literature	To understand how OR and OTS are conceptualised, defined, measured, and diagnosed.
To identify key characteristics or factors related to a concept	To highlight which markers and assessments are used in the literature to determine, detect, or diagnose OR and OTS.
To identify and analyse knowledge gaps	To highlight gaps within the literature and to guide the direction of this doctoral programme by identifying relevant lines of scientific inquiry

3.3 Introduction

Resistance exercise training can induce acute fatigue due to reduction in neuromuscular activation and sequencing (Raastad & Hallén, 2000), manifested as short-term (seconds to hours) decrease in performance, occurring due to impairment of central and/or peripheral mechanisms (Todd et al., 2003). Recovery from resistance exercise training varies based on the magnitude, duration and mode of training (Triscott et al., 2008), with typical mechanical and biochemical restoration occurring within 3 hours of moderate-intensity resistance exercise training using loads at 70% of 1-RM or 24-96 hours during intense resistance exercise training where muscular failure is achieved and/or muscle damage has occurred. (Morán-Navarro et al., 2017; Raastad & Hallén, 2000; Soares et al., 2015). Whilst a single overloading resistance exercise training bout results in acute fatigue and relative decrease in performance, short-term periods of accumulated training above the habitual level followed by subsequent recovery can lead to a supercompensation "rebound" effect known as functional overreaching (FOR), or a diminished adaptive response and long-term performance decrement, known as non-functional overreaching (NFOR). Prolonged exposure to such training may lead to overtraining syndrome (OTS) (Meeusen et al., 2013). Large-scale reviews and joint expert statements (Cadegiani & Kater, 2017; Halson & Jeukendrup, 2004; Meeusen et al., 2013) have defined these terms as such:

- Functional overreaching (FOR): A short-term decrease in performance lasting days to weeks with subsequent performance supercompensation after a period of recovery.
- Non-functional overreaching (NFOR): Performance decrement is observed over a period of weeks to months, and while full recovery is achieved (although not always), no supercompensation effects are achieved.
- Overtraining syndrome (OTS): Long-term reductions in performance capacity observed over a period of several months.

In strength sports such as weightlifting, it is common for athletes and coaches to utilize periods of purposeful increased volume and/or intensity resistance exercise training within a competition cycle to achieve FOR (Pistilli et al., 2008; Stone et al., 2006). This may also be the case in other resistance exercise training populations such as bodybuilding and high-intensity conditioning (e.g. CrossFit) where athletes participate in repeated high volume/intensity resistance exercise training sessions/blocks in order to achieve a supercompensation effect (Szewczyk et al., 2018). To date, there is a lack of research into OR practices and the implications for non-functional outcomes (Kreher, 2016; Meeusen et al., 2013). As such, athletes may be at risk of maladaptation and performance decrement due to NFOR and/or OTS.

3.3.1 Objectives

Scoping reviews are an ideal "reconnaissance" tool to evaluate a body of literature not comprehensively reviewed, or that exhibits a heterogeneous nature not amenable to a more systematic approach (Peters et al., 2015). Scoping reviews provide the flexibility to map out broad narratives within a limited literature base, allowing researchers to examine emerging evidence where precise lines of questioning are undetermined (Arksey & O'Malley, 2005; Munn et al., 2018). Additionally, such reviews help develop key definitions and conceptual boundaries as well as identify gaps for future research (Arksey & O'Malley, 2005). The available OR/OTS literature in strength-sports and resistance exercise training contexts appears to be broad, disparate and heterogeneous. After careful investigation and consultation with the appropriate guidance (Munn et al., 2018), a scoping review was chosen ahead of a systematic review. Not only is a scoping review a relevant tool to synthesize the cross-disciplinary landscape of available evidence, but it also offers a robust but transparent approach, navigating multiple nuanced themes and identifying areas for further exploration where a systematic review is inappropriate. A PCC framework (population, concept, context) (Peters et al., 2017) was used to develop the research question: "what is known about overreaching and overtraining in strength sports and resistance training populations?"

3.4 Methods

3.4.1 Protocol and registration

This scoping review was developed using guidance from the Joanna Briggs Institute (Peters et al., 2017) and PRISMA-ScR (Tricco et al., 2018) together with the methodological framework proposed by Arksey and O'Malley (2005) and subsequent recommendations from Levac et al. (2010) The protocol was registered with Open Science Framework on 5th July 2019 [https://osf.io/vhp68/].

3.4.2 Eligibility criteria and definitions

A strength sport is defined here as a competitive sport where resistance exercise training provides the primary overloading stimulus and where maximal strength or high force output is a primary determinant of performance, with limited or no additional overloading from endurance training. Weightlifting, powerlifting, strongman, explosive throwing sports and sprinting met these guidelines. The term resistance training refers to any study where participants were required to complete a short or long-term resistance exercise training-based OR protocol without additional, concurrent endurance or technical training. This included studies where both recreational resistance exercise training subjects and/or competitive athletes were used, or review papers that discussed resistance exercise training in the context of OR/OTS. Research was not limited by geographical location or year and was incorporated in the review if it included: 1) human subjects of either sex and at all age groups; 2) OR/OTS in the context of either strength sports or resistance exercise training, and 3) peer reviewed data including quantitative/qualitative research, prospective cohort studies, mixed-methods, systematic/scoping/narrative reviews/meta-analyses or case reports. Conference proceedings and poster presentations were not included due to potential limitations in reporting quality and/or duplication.

3.4.3 Information sources and search strategy

The search was conducted using three electronic databases: SPORTDiscus, Scopus and Web of Science during June 2019. These databases were selected to provide relevant literature and were identified by the research team in consultation with an expert information scientist, who assisted with the development of the search strategy and database search. Boolean search terms AND/OR were used to identify relevant studies: "overreaching" OR "overtraining" AND "resistance training" OR "strength training" OR "weight training" OR "weightlifting" OR "weight lifting" OR "powerlifting" in all databases. Titles, abstracts, key words, and data sources were searched, with relevant articles entered for full paper review. Upon completion, an investigation of additional citations from each reference list was conducted.

3.4.4 Data charting and synthesis

Data charting was carried out by the principal investigator using a charting tool designed for this study, developed to capture key information. The charting tool was independently assessed by the research team to determine robustness. Participant characteristics (trained/untrained, elite/non-elite, age, gender, number), and article characteristics (author, publication date, OR/OT protocols, measures, and outcomes) were extracted during data charting. For comprehensive study breakdown see Table 4 and 5.

Table 4. Summary of data extraction for theme A: overreaching in strength sports

Author/publication date/location	Participants	Study design	Purpose	Protocol	Measures	Study findings
Bazyler et al., 2017, USA	n = 6 National Collegiate Athletic Association (NCAA) Division I track and field athletes (M: n = 4; F: n = 2; age = 20.6 ± 0.93 years)	Prospective cohort study	OR and taper on measures of muscle architecture, jumping, and throwing performance in collegiate throwers	12-wk block-periodization model consisting of throwing training and RET culminating in a 1-wk OR followed by a 3-wk taper	Throwing performance, performance measures, muscle architecture	↑ throwing performance and unloaded jump performance after OR. ↑ muscle thickness in vastus lateralis observed during in-season training but not after OR. ↓ in RET volume load multiplied by bar displacement. ↓ RPETL between in-season and OR
Bazyler et al., 2018, USA	n = 1 elite F weightlifter (age = 21.82 yrs; body mass = 70.7 kg)	Case study	Physiological and performance changes of a national-level 69 kg female weightlifter after 3 competition phases over a 28-wk training period	Observation of physiological adaptations over a 28-day period, consisting of 3 competition phases	WP, serum biomarkers, mCSA	Biomarkers of stress, inflammation and muscle hypertrophy were sensitive to training load. Performance measures indicated competition preparedness during competitions 1 and 2 (regional/local), but not competition 3 (national). Rapid ↓ body mass/mCSA observed during competition 3
Fry et al., 1993, USA	n = 28 elite-level M junior weightlifters (age = 17.3 ± 0.3 yrs)	Double-blind, prospective cohort study	1-wk high volume weightlifting and amino acid supplementation	High-volume weightlifting exercise	WP, performance measures, serum hormones	↑ WP. ↓ vertical jump height and T concentrations in both groups. ↓ in T/C ratio was observed in placebo only
Fry et al., 1994a, USA	n = 9 elite M junior weightlifters (age = 17.6 ± 0.3 yrs)	Longitudinal observational study	Effects of 1-wk of ↑training volume on strength and serum hormones after 1-year of weightlifting	Performance testing administered before and after 1-wk OR stimulus performed at year intervals.	Performance measures, serum hormones	↑ strength by Year 2 but « during either week of OR. ↓ T in year 2, but ↑ in year 2. ↑ C in year 1 and 2. « T/C ratio
Fry et al., 2000a, USA	n = 22 junior weightlifters (non-elite: n = 14; age = 17.2 ± 0.4 yrs; elite: n = 8;	Prospective cohort study	The relationship between serum testosterone and cortisol on weightlifting performance	Identical 4-wk protocol performed by subjects in each group consisting of 1) 1-wk	WP, serum hormones	↑ WP by the end of wk 4. Non-elite group pre-exercise T/C alterations negatively correlated to weightlifting performance during high-volume training, with positive

	age = 18.4 ± 0.4 yrs: sex undisclosed)			high-volume training of 3-4 training sessions/day; 2) 3-wk normal volume phase of 1-2 training sessions/day		correlations observed during reduced volume training between T/C and performance during high-volume training in the elite group and a positive relationship during normal volume training
Haff et al., 2008, USA	n = 6 elite F weightlifters (age = 21.5 ± 3.1 yrs)	Observational study	11-wk training period performed by female weightlifters	11-wk protocol consisting of weightlifting-specific and supplemental exercises of varying volume and intensity	Performance measures, serum hormones	↑ volume load corresponded to ↓ in T/C ratio as well as concomitant ↓ in peak force during isometric peak force, dynamic pull with 30% isometric peak force and dynamic 100 kg pull trials
Häkkinen et al., 1987, Finland	n = 11 elite M weightlifters (age = 23.0 ± 2.8 yrs)	Longitudinal observational study	Training volume during prolonged training on physical performance capacity and serum hormone concentrations	Weightlifting-specific training for a mean average of 5.0 (±0.8) times/wk (1.7 ± 0.4 hrs per training session, 5,200 ± 1,500 kg training volume, 80.5% ± 2.5% intensity) over the course of a competitive season (1-year)	WP, serum hormones	↓ T, T/C and T/SHBG ratio. ↑ LH during 2-wk OR period that did not return to baseline until 2-wk period of normal training and subsequent 2-wk taper had been completed. Alterations in T/SHBG correlated with weightlifting performance in the clean and jerk. Subsequent ↓in C and LH, as well as ↑ T/SHBG during normal training/taper
Häkkinen et al., 1989, Finland	n = 8 elite M weightlifters (age = 24.3 ± 1.5 yrs)	Longitudinal observational study	Endocrine responses and on physical performance capacity	Weightlifting-specific training ranging from 4-10 sessions/wk (mean = 7) over the course of a competitive season (1-year)	Performance measures, serum hormones	↓T during periods of highest training load. « for serum hormones over 1 year
Hartman et al., 2007, USA	n = 10 elite M weightlifters (once-daily RT: n = 5; age = 20.2 ± 1.4 yrs; twice-	Prospective cohort study	Physiological responses to twice- and once-daily training	Twice- (8 sessions/wk) or once-daily (4 sessions/wk)	Performance measures, serum hormones, mCSA, neuromuscular activation	Main effects between groups reported. ↑ %change observed in the twice-daily group for maximal isometric

	daily RT: n = 5; age 20.9 ± 0.9 yrs)		sessions with similar training volumes	weightlifting training sessions over a 3-wk period		knee extension strength, neuromuscular activation, T and T/C ratio
Khlif et al., 2019, Tunisia	n = 16 elite weightlifters (M: n = 8; age = 19.46 ± 1.2 yrs; F: n = ; age = 18.25 ± 1.2 yrs)	Prospective cohort study	↑weightlifting training load on plasma iron status	3 intensive wks consisting of 10 training sessions/wk followed by 1 mod-intensity wk of 6 sessions/wk. Loads varied between 70-100 1-RM,	Serum biomarkers	Pre- to post-OR ↑ was observed in plasma ferritin, while a significant ↓ in transferrin was also observed. Plasma CK levels were ↑ pre-to post-OR. No statistically significant changes to CRP were observed
Pistilli et al., 2008, USA	Undisclosed	Observational study	1-wk weightlifting camp designed to promote a short-term period of OR; and to compare the training variables from a normal training wk to what is recommended during a short-term OR period and a taper wk	1-wk OR consisting of a 94% ↑ volume (compared to normal training), with a total ↑ of 55% (reps), 200% (sets) and 300% (number of training sessions/wk) followed by subsequent return to normal training	WP	↑ WP after 2-5 wks of normal training resumed
Suarez et al., 2019, USA	n = 9 collegiate weightlifters (M: n = 4; age = 22.4 ± 1.6 yrs; F: n = 5; age = 20.5 ± 2.6 yrs)	Prospective cohort study	Kinetic and morphological adaptations that occur during distinct phases of a block periodized training cycle in weightlifters	4 training sessions/wk split into push-pull: 1) 4-wk strength-endurance phase (high volume and low-mod intensity); 2) 4-wk strength-power phase (mod volume at higher intensity); 3) 1-wk OR phase (high volume) followed	Performance measures, mCSA, muscle architecture	Small ↑ in mCSA and RFD observed across the block of training. Significant ↑ for mCSA observed during high-volume strength-endurance phase, with small ↓ in RFD. ↑ in RFD above pre-test baseline was reported during the higher-intensity strength-power phase despite significant ↓ in mCSA. Small to moderate ↑ in RFD reported during peak/taper (<150 m.s time band only), with « to mCSA

				by a 3-wk taper (low volume at mod intensity)		
Warren et al., 1992, USA	n = 28 elite junior weightlifters (17.3 ± 1.4 yrs)	Prospective cohort study	Short-term overwork (OR) on performance measures, blood lactate, and plasma ammonia concentrations	2-3 training sessions/day for 7-days. Training consisted of weightlifting-specific testing conducted before and after OR training protocol	WP, performance measures, serum biomarkers	↓ jump height from pre- to post OR but « snatch test performance. ↑ resting ammonia at post-test, as well as ↓ lactate and ammonia at 5-min post-exercise after OR protocol

Variations denoted as ↑ (increase) ↓ (decrease) or « (no change). RET = resistance training; OR = overreaching; WL = Weightlifting performance; RPETL = session rating of perceived exertion training load; RM = repetition maximum; mCSA = muscle cross-sectional area; T = testosterone; C = cortisol; SHBG = sex hormone binding globulin; LH = luteinizing hormone; RFD = rate of force development

Table 5. Summary of data extraction for theme B: overreaching and overtraining syndrome in resistance training

Author/publication date/location	Participants	Study design	Purpose	Protocol	Measures	Study findings
Berning et al., 2007, USA	n = 6 resistance-trained M (age = 29 ± 5 yrs)	Prospective cohort study	Metabolic demands of pushing and pulling a 1,960 kg motor vehicle 400 m in an all-out maximal effort	1) single session pushing a motor vehicle 400 m; 2) single session pulling a motor vehicle 400 m	Performance measures	BLa response reached 131%, $\dot{V}O_2$ reached 65% and HR reached 95% of values obtained from pre- $\dot{V}O_2$ max test. Jump height ↓ pre- to post- in both pushing and pulling conditions
Cadegiani et al., 2017, Brazil	N/A	Systematic review	Role of hormones in OTS/FOR/NFOR	N/A	Serum hormones and biomarkers	Basal hormones are unable to predict FOR/NFOR/OTS
Cadegiani et al., 2019, Brazil	N/A	Post-hoc analysis	CrossFit in healthy athletes and OTS athletes	Data extracted from EROS-HPA, EROS-STRESS, EROS-BASAL, EROS-PROFILE	Serum hormones and biomarkers	90% of adaptive changes were lost in CrossFit athletes under OTS including ↓ T and ↑ E2. Long-term low CHO intake may act as a trigger for OTS
Davies et al., 2016, Australia	N/A	Systematic review	Failure versus non-failure training on muscular strength	N/A	Failure vs. non-failure on muscular strength	Similar ↑ in muscular strength are observed with failure and non-failure RT, however failure should be used sparingly to ↓ the risk of NFOR/OTS
Drake et al., 2017, USA	n = 6 recreationally active M (age = 25.0 ± 5.4 yrs)	Prospective within-subjects pre-post intervention	Short-term CF participation on measures of health and fitness	4-wks of CF training consisting of 5 training sessions/wk of either "traditional" or "real world" CrossFit	Performance measures, serum biomarkers, mood state	↑ CRP/CK and ↓ mood state observed alongside small ↑ in performance measures/fitness-based outcomes that may be indicative of FOR
Fahey et al., 1998, USA	n = 11 trained M (age = 22.8 ± 3.4 yrs)	Double-blind, cross-over design prospective cohort study	PS supplementation during 2-wks of resistance exercise-induced OT	5 x 10-RM for 13 exercises, 4 times/wk, for two 2-wk periods separated by a 3-wk recovery	Serum hormones	Muscle soreness ↑ in placebo group compared to PS. C concentrations were ↓ in PS compared to placebo
Fatouros et al., 2006, Greece	17 resistance-trained M (age = 21.6 ± 2.6 yrs)	Prospective cohort study	cf-DNA as a potential indicator of OTS during resistance training	12-wk RET programme consisting of four 3-wk protocols: 1 and 4) low-volume exercise training 2-days/wk, 2 x 10-12 reps, 70%	Serum biomarkers	cf-DNA ↑ proportionate to training load and may be a reliable marker of NFOR/OTS. Concomitant ↑ in CRP/UA after high- and very-high volume were also observed, with CK increasing only after very high-volume training

				1-RM; 2) high-volume exercise training 4-days/wk, 4 x 6-10 reps, 75-85% 1-RM; 3) very high-volume exercise training 6-days/wk, 6 x 6 reps, 85-100% 1-RM.		
Fry et al., 1994b, USA	n = 17 resistance-trained M (age = 22.0 ± 0.9 yrs)	Prospective cohort study	The effects of a high-intensity resistance exercise OT protocol on muscular strength decrements.	Daily 10 x 1-RM (100% 1-RM) squat machine for 2-wk period	Performance measures, serum biomarkers	↓ 1-RM performance compared to control group, with subsequent ↓ in isokinetic and stimulated isometric muscle force indices. Concomitant ↑ in CK with declining performance indicative of OR
Fry et al., 1994c, USA	n = 9 recreationally trained M (age = 22.9 ± 1.3 yrs)	Prospective cohort study	Efficacy of a 3-wk, high-intensity resistance OT exercise protocol	3 weeks of 5 days/wk low-volume, high-intensity machine squats consisting of 8 single reps using 95% 1-RM with 2-min recovery between attempts. If a rep was unsuccessful, 5% of 1-RM ↓ on the subsequent attempt.	Performance measures	↓ in sprint and vertical jump performance as well as leg extension torque were observed, but 1-RM ↑. Based on ↑ strength, NFOR/OTS was not induced but results suggest FOR did occur
Fry et al., 1994d, USA	n = 17 resistance-trained M (age = 22.0 ± 0.9 yrs)	Prospective cohort study	Catecholamine response to high-intensity RET OT	Daily 10 x 1-RM (100% 1-RM) squat machine for 2-wk period	Performance measures, serum biomarkers	↑ exercise-induced catecholamine concentrations, as well as ↓ responsivity of skeletal muscle to sympathetic nervous system activity reported during OT but not in control group
Fry et al., 1997, USA	N/A	Systematic review	Neuroendocrine responses to RET OT and OR	N/A	Serum hormones and biomarkers	RET can provide differential responses to OR/OTS during chronic exposure. Hormonal disturbances during high-volume RET may follow a pattern similar to endurance training OR/OTS, whereas during high-intensity RT, OR/OTS may result in an alternate pattern of response
Fry et al., 1998, USA	n = 11 resistance-trained M (age = 22.0 ± 0.9 yrs)	Prospective cohort study	Pituitary-adrenal-gonadal responses to high-intensity RET OTS	Daily 10 x 1-RM (100% 1-RM) squat machine for 2-wk period	Performance measures, serum hormones and biomarkers	↓ in strength observed after 2-wk protocol with slight ↑ in exercise-induced T, T/C ratio as well as ↓ C. GH and plasma peptide F were unchanged.

Fry et al., 2000b, USA	n = 6 resistance-trained M (age = 27.5 ± 5.4 yrs)	Prospective cohort study	3-wk high relative intensity RET resulted in OTS and to investigate what types of performance would be affected	2-days/wk for 4-wks of normal training, followed by 3-wk high-intensity RET consisting of 3 training sessions/wk of 2 x 1 95% 1-RM, 3 x 1 90% 1-RM, 3 x 10 RM	Performance measures	↑ 1-RM observed during normal training but not during high-intensity training. No change in self-reported indices of muscle soreness, vertical jump and other performance measures, but high-intensity training led to ↑ 9.1 m sprint times but ↓ peak isokinetic squat force suggesting high-intensity training may negatively impact performance measures but augment others
Fry et al., 2001, USA	n = 1 resistance-trained M (age = 21 yrs)	Case study	Joint-centered mechanism of performance decrement caused by OTS	Daily 10 x 1-RM (100% 1-RM) squat machine for 2-wk period	Performance measures	↓ 1-RM and isokinetic knee-extension strength. ↑ voluntary isometric knee-extension and stimulated isometric knee-extension strength. Joint-centered overload injury of the knees as assessed by anterior/posterior drawer and Lachman tests
Fry et al., 2006, USA	n = 16 resistance-trained M (age = 20.2 ± 0.1 yrs)	Prospective cohort study	Cellular and molecular responses of skeletal muscle to performance decrements due to high-relative-intensity RET OT	Daily 10 x 1-RM (100% 1-RM) squat machine for 2-wk period	Performance measures, serum biomarkers	↓ 1-RM/mean power at 100% 1-RM. ↓ in muscle β2AR density, ↑ (but insignificant) nocturnal urinary epinephrine was also observed in OTS group, as well as ↓ β2AR sensitivity. Normal training could only be resumed 2-8 wks after training cessation and may have signalled NFOR/OTS.
Jakubowski et al., 2019, Canada	n = 26 trained M (age = 23 ± 2 yrs)	Randomized, double-blind repeated-measures design	HMB-FA versus leucine, added to whey protein and muscle hypertrophy and strength gains	Phase 1 consisted of 3 training sessions/wk undulating periodization for an 8-wk period, followed by phase 2; a 2-wk OR phase consisting of 5 training sessions/wk and phase 3; a subsequent 2-wk taper consisting of 3 training sessions/wk	Performance measures, serum biomarkers, mCSA	Between groups for measures of mCSA or 1-RM at any phase. A small ↑ in 1-RM was observed in both groups during OR, however a subsequent ↑ during the taper was indicative of FOR.
Kraemer et al., 2005, USA	N/A	Literature review	Hormonal responses and adaptations to RT	N/A	Serum hormones	OR may not result in T or C alterations, and any observed change may be specific to exercise volume and/or intensity. During OT, high-intensity exercise training does not appear to alter resting T/C concentrations, whereas

						high-volume exercise training may result in adverse changes
Kraemer et al., 2006, USA	n = 17 trained M (age = 19.7 ± 1.4 yrs)	Double-blind, placebo-controlled, randomized study	AA supplementation on muscular performance and resting hormone concentrations during resistance training OR	4-wk OR training consisting of 4 pw resistance training. The first 2-wk were higher-volume (3 x 8-12-RM) and the last 2-wk were high-intensity (5 x 3-5-RM)	Performance measures, serum hormones and biomarkers, hemodynamic measures	Significant elevation in CK was highly correlated to a ↓ in 1-RM strength during OR. ↑ SHBG was observed in the placebo group but not in the AA group, likewise, ↓ in T were observed in placebo but not in AA
Lowery et al., 2016, USA	n = 17 trained men (age = 21.7 ± 0.4 yrs)	Double-blind, placebo-controlled, randomized study	12-wk HMB-FA and ATP supplementation on lean body mass, strength and power	12-wk protocol consisting of three phases: 1) 8-wk daily undulating periodization; 2) 2-wk OR; 3) 2-wk taper	Performance measures, serum hormones and biomarkers, mCSA	During OR, both strength and power ↓ in the placebo group compared to a small ↑ in the HMB-FA/ATP group. Lean mass, strength and performance improved similarly in both groups after taper
Nicoll et al., 2016, USA	n = 14 resistance-trained M (age = 19.8 ± 1.8 yrs)	Prospective cohort study	ERK1/2, JNK and p38-MAPK following a period of RET OR/OT	HPOR consisting of 2-wk normal training followed by a 2-wk OR phase of twice-daily workouts for 7.5 days (15 total workouts), or HIOR protocol consisting of 4-wk normal training followed by daily 10 x 1-RM (100% 1-RM) squat machine for 2-wk period	Serum biomarkers	Total-ERK ↑ after HPOR but ↓ with HIOT. Additionally, the HIOT group also experienced a ↓ in p-p38-MAPK, and the HPOR group reported a ↓ in the ratio of p-JNK/total-JNK and p-ERK1/2/total-ERK, suggesting that β2AR expression may be altered during periods of OR/OT
Raastad et al., 2001, Norway	n = 18 resistance-trained M (heavy training group: age = 25.9 ± 1.3 yrs; control: age = 25.4 ± 1.3 yrs)	Prospective cohort study	Neuromuscular and hormone changes during 2 wks of heavy strength training	2-wk heavy lower body training consisting of 6-days/wk leg press/hack squat and squat/front squat on the 7th. All exercises were 3 x 6-RM	Performance measures, serum hormones and biomarkers, electrical stimulation	↓ T coincided with ↑ maximal strength. ↑ in urinary catecholamine levels during heavy training was also reported.
Raeder et al., 2016, Germany	n = 23 athletes (M: n = 14; age = 24.1 ± 2.0 yrs.; F: n = 9; age = 25.4 ± 1.9)	Prospective cohort study	Neuromuscular, physiological, and perceptual markers for routine assessment of fatigue	6-day intensified strength training microcycle consisting of twice-daily RT	Performance measures, muscle contractile properties, serum	Maximal strength ↓ during intensified training, however, performance returned to baseline after 3-days of recovery. Other performance measures remained ↓ beyond this point. Measures of stress-recovery, muscle damage,

			and recovery in high-intensity RT		biomarkers, psychometric measures	soreness and neuromuscular function may have detected the onset of NFOR
Ratamess et al., 2003, USA	n = 17 trained M (AA: n = 9; age = 19.7 ± 1.4 yrs; placebo: n = 8; age = 21.3 ± 3.0 yrs)	Double-blind, placebo-controlled, randomized study	AA supplementation on muscular strength, power, and high-intensity endurance during short-term RET OR	4-wk OR consisting of 2-wk mod-intensity/high-volume (3 x 8-12-RM, 8 exercises) and 2-wk high-int, low volume (5 x 3-5-RM, 5 exercises), followed by 2-wk taper	Performance measures	Initial ↓ 1-RM strength and peak power was observed during OR in the placebo group only, however, ↑ 1-RM strength in both groups was observed after taper
Robbins et al., 2012, Australia	n = 43 resistance-trained M (1-set: n = 11; age = 25.5 ± 1.4 yrs; 4-set: n = 11; age = 31.0 ± 3.2 yrs; 8-set: n = 10; age = 26.0 ± 1.5 yrs)	Prospective cohort study	Lower-body strength in RET men after performing varying training volumes (1, 4, 8 sets)	2-wk standardization phase, 3-wk volume-manipulated (VM) phase, 4-wk post-manipulation phase. During VM, subjects completed either 1, 4 or 8-sets of back squat at 80%-1-RM additional to other exercises.	Performance measures	All groups ↑ 1-RM at wk-6, however the magnitude of change was largest in the 8-set group, suggesting a potential FOR dose-response over short-term periods
Sharp et al., 2010, USA	n = 8 trained M (age = 22.9 ± 2.0 yrs)	Balanced, cross-over, placebo-controlled, double-blind, repeated measures design,	Short-term amino acid supplementation on anabolic hormonal profile and muscle cell damage during a period of high-intensity RET OR	1-wk high-intensity OR (4 training sessions/wk) consisting of 3 x 6-RM, 8 exercises)	Serum hormones and biomarkers	Serum T was significantly higher in the AA group compared to placebo, and C and CK were ↓
Sikorski et al., 2013, USA	n = 35 resistance-trained subjects (undisclosed sex) (age = 21.3 ± 1.9 yrs)	Prospective cohort study	High-volume muscle damaging training session on perceived recovery	A single exercise session consisting of 3 x 10-12-RM involving upper and lower body RT	Perceived recovery scale (PRS), serum hormones and biomarkers	PRS ↓ and ratings of soreness/CK concentrations ↑ pre- to post-training. Free T may have a positive relationship with PRS
Sterczala et al., 2017, USA	n = 17 trained M (supplement: n = 8; age = 22.6 ± 2.1 yrs; placebo: n = 3; age = 20.3 ± 1.3 yrs; control: n = 6; age = 24.2 ± 4.6 yrs)	Randomized, double blind, group × time experimental design	Multi-ingredient recovery drink on OR induced by high-frequency, high-power RT	1-wk OR protocol consisting of 10 x 5 reps speed squats (submaximal repetitions performed at maximal speed) twice-daily for a total of 15 sessions	Performance measures, serum biomarkers	↓ mean squat velocity and power using 70%-1RM observed in both groups after OR, but 1-RM was unaffected. ↓ β2-AR expression also observed (61% in the supplement group, 81% in the placebo group)

Stone et al., 2000, USA	n = 21 resistance-trained M (age not reported)	Prospective cohort study	Different weight training approaches on maximal strength over 12-wks	3 groups: 1) non-periodized training (5 x 6-RM); 2) stepwise periodization group (↓ volume in steps) ; and 3) OR group (fewer reps)	Performance measures	Stepwise and OR periodization led to ↑ 1-RM compared to the non-periodized group. The OR group reported the greatest relative training intensity of 1-RM at 72%, compared to 67% in the non-periodized group and 61% for the stepwise group
Taylor et al., 2016, Australia	n = 6 strength-trained athletes (M: n = 3; age = 28.0 ± 5.9 yrs; F: n = 3; age = 28.0 ± 0.7 yrs)	Prospective cohort study	Within-athlete variability exist in countermovement jump performance	12 wk: baseline (4-wk), OR (4-wk) and taper (4-wk). During the OR phase, training volume ↑ by approximately 10% each wk	Performance measures	Within-subject variability in jump performance was observed during all phases of training, but was highest during OR
Tibana et al., 2018, Brazil	n = 9 trained M (age = 26.7 ± 6.6 yrs)	Prospective cohort study	Two different extreme conditioning sessions on neuromuscular responses and biomarkers in trained men	2 training sessions (24-hrs apart) using a variety of RET exercises, intensities and volumes	Performance measures, serum biomarkers	A single bout of exercise led to ↑ BLa and cytokine (IL-6, IL-10 and OST) concentrations from workout one to two, « for muscle power
Volek et al., 2004, USA	n = 17 trained M (CrM: n = 9; age = 20.7 ± 1.9 yrs; placebo: n = 8; age = 21.3 ± 3.0 yrs)	Double-blind, placebo-controlled, randomized study	Creatine monohydrate (CrM) supplementation during short-term RET OR	4-wk OR consisting of 2-wk mod-intensity/high-volume (3 x 8-12-RM, 8 exercises) and 2-wk high-int, low volume (5 x 3-5-RM, 5 exercises), followed by 2-wk taper	Performance measures, serum hormones	↓ maximal and explosive power during OR in the placebo group but not CrM. A tendency for improvement in CrM following subsequent 2-wk taper was also observed. T and T/SHBG both ↓ during OR, with ↑ C in CrM at wk-1 but return to baseline at wk 2
Willardson, 2007, USA	N/A	Literature review	The application of training to failure	N/A	Failure vs. non-failure effect on muscular strength	Chronic exposure to failure training may result in OTS and/or overuse injury
Willardson et al., 2010, USA	N/A	Literature review	Application of training to failure in mainstream RET programmes	N/A	Failure vs. non-failure effect on muscular strength	Chronic exposure to failure training may result in OTS and/or overuse injury
Wilson et al., 2013, USA	n = 21 trained M (age = 23.4 ± 0.7 yrs)	Double-blind, placebo-controlled, randomized study	Oral ATP supplementation on muscular adaptations in trained individuals during OR training	12-wk protocol consisting of three phases: 1) 8-wk daily undulating periodization; 2) 2-wk OR; 3) 2-wk taper	Performance measures, serum hormones and biomarkers, mCSA	ATP and placebo both ↑ maximal strength, muscle power and LBM, with ATP resulting in significant improvements when compared to placebo. During OR, both groups experienced ↓ maximal strength and muscle power, however placebo was significantly ↓ than ATP. ↑ in CK in both groups during OR were observed, but ↑ performance suggests FOR occurred in both groups

Variations denoted as ↑ (increase) ↓ (decrease) or « (no change). RET = resistance training; OR = overreaching; FOR = functional overreaching; NFOR = non-functional overreaching; OTS = overtraining syndrome; CHO = carbohydrate; T = testosterone; E2 = oestradiol; C = cortisol; BLA = blood lactate; $\dot{V}O_2$ = oxygen uptake; CF = CrossFit; CK = creatine kinase; CRP = C-reactive protein; PS = phosphatidylserine; cf-DNA = cell-free deoxyribonucleic acid; UA = uric acid; RM = repetition maximum; β2AR = beta-2-adrenergic receptor; AA = amino acid; SHBG = sex hormone binding globulin; HMB = β-Hydroxy β-methylbutyric-free acid; ATP = adenosine-5'-triphosphate; ERK = extracellular signal-regulated kinase; JNK = c-Jun NH2-terminal kinase; HPOR = high-power overreaching; HIOR = high-intensity overreaching; MAPK = mitogen-activated protein kinase; PRS = perceived recovery scale; IL = interleukin; OST = osteoprotegerin = CrM = creatine monohydrate; LBM = lean body mass

3.5 Results

3.5.1 Selection of sources of evidence

Initial search yielded 1,170 results. After duplicates were removed, 832 studies were entered for title, abstract, key word, and data source review. Subsequently, 137 items were selected for full-text review, with 90 full texts excluded for the following reasons: 7 were symposia or poster presentations and 83 were not relevant to the central review question. 47 studies were included in this scoping review (see Figure 7). There were two broad investment themes extracted during data charting. These were developed a priori and agreed on by the research team:

A. Overreaching in strength sports (Theme A) (27.7% total)
B. Overreaching and overtraining in resistance exercise (Theme B) (72.3% total)

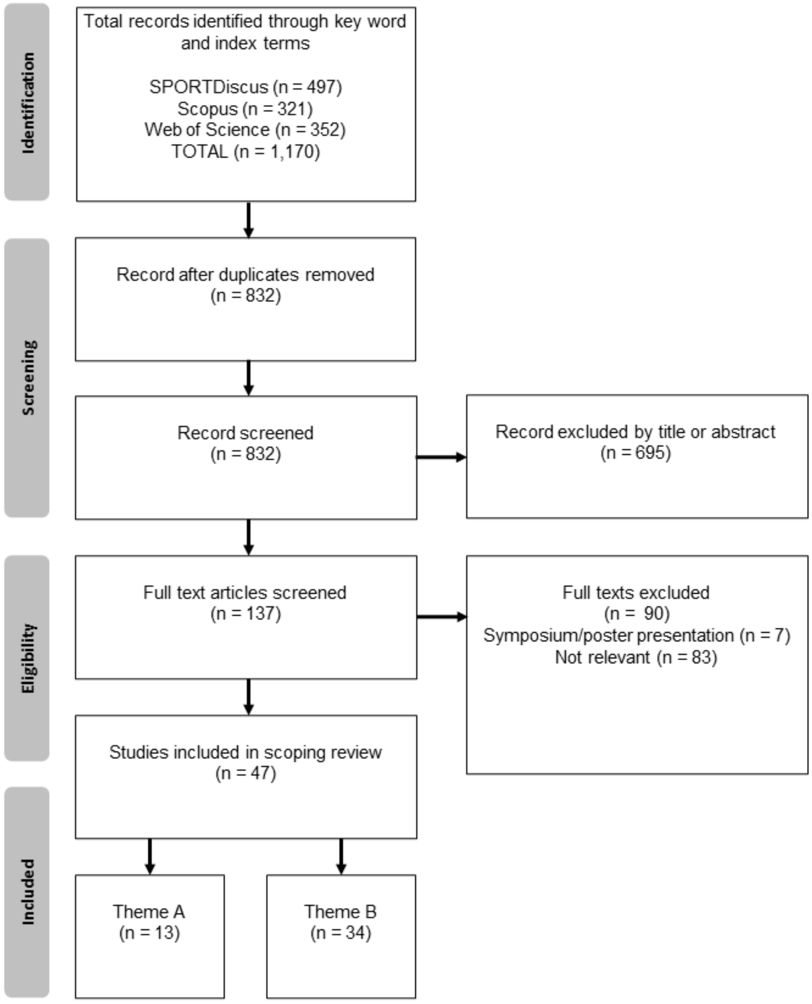

Figure 7. PRISMA-ScR Flow chart of extracted, included, and excluded studies

3.5.2 Synthesis of results

Publication dates ranged from 1987-2019. 20 studies (42.6%) were published between 2010-2019. From those 20 studies, 16 (80.0%) are in theme B. Unlike many areas of sport science research, no obvious global increase in publications was observed, especially for theme A, further illustrating the need for future research in this area. Figure 8 highlights publications by date and theme.

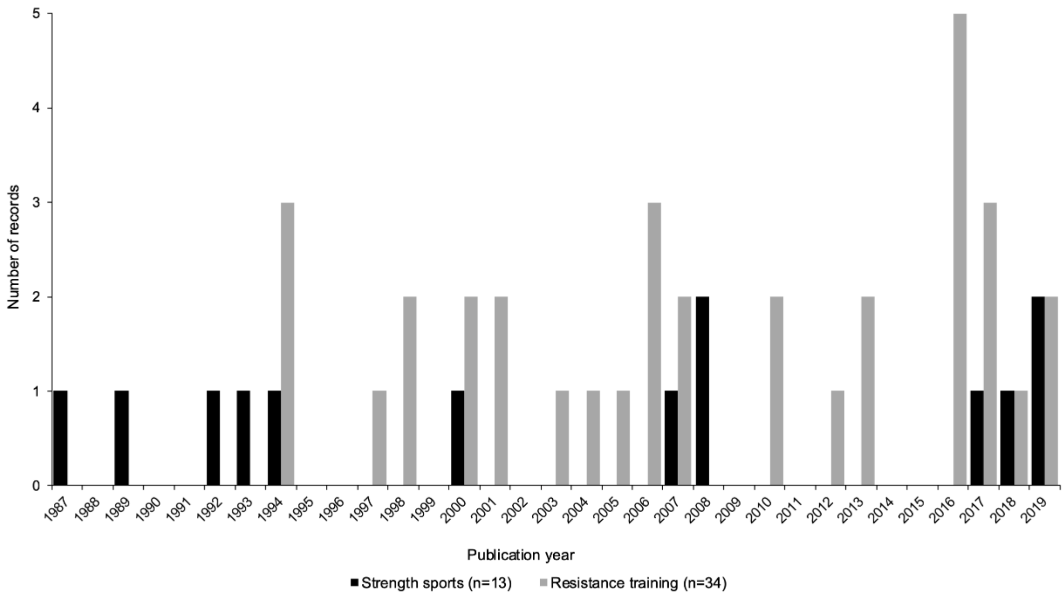

Figure 8. Publications for strength sports (Theme A, n=13; Black) and resistance training (Theme B, n=34; Grey) meeting search criteria for overreaching and/or overtraining

Overall, 85.1% (n=40) studies included in the review were observation/intervention studies with timelines ranging from a single training session to a ~1-year competition schedule. Participant cohort sizes ranged from 1-28 in theme A and 1-43 in theme B. 2 studies used female only subjects (1 was a single subject case study) and 5 included both males and females. 4 studies did not disclose the sex of participants. 29 used only male subjects. 4 studies involved junior weightlifters. In theme A, 92.3% (n=12) of studies involved weightlifters, with a single study (7.7%) involving throwing athletes. No studies included powerlifting, strongman or sprinting athletes.

There were 6 systematic/literature reviews included in data extraction, with 1 post-hoc data analysis also included (all located within theme B). 23.5% of studies for Theme B (n=8) were conducted by the same first author; Andrew C. Fry, published between 1994-2006. In theme A, the same author published 2 studies (15.4%) as first author between 1993-1994. Several measures and tools were used across both themes to identify the onset of OR/OTS and fell under the following broad categories: "weightlifting performance (WP)," "performance measures", "serum hormones" or "serum biomarkers" (see Table 1 and Table 2). These are discussed in detail in the discussion.

Despite the ongoing risk of NFOR, our review considers this area to be under-investigated based on a lack of studies investigating OR/OTS in strength sports and RT, as well as insufficient data relating to diagnoses and guidelines for coaches.

3.6 Discussion

Theme A: Overreaching in strength sports

3.6.1 Endocrinological measures and biomarkers

Studies have investigated the effects of purposeful OR on serum hormones and biomarkers with conflicting results (Bazyler et al., 2018; Fahey & Pearl, 1998; Fry et al., 1993, 2000a, 1994d; Haff et al., 2008; Häkkinen et al., 1987, 1989; Hartman et al., 2007; Khlif et al., 2019; Warren et al., 1992). Most studies involved elite-level weightlifters, with a single study comparing the effects of OR in elite- and non-elite subjects (Fry et al., 2000a). Two studies involved a female only cohort (Bazyler et al., 2018; Haff et al., 2008) and 4 studies recruited junior-level individuals (Fry et al., 1993, 2000a, 1994d; Warren et al., 1992). Collectively, the data indicates that endocrinological markers can detect acute changes in training state, which could be useful for monitoring purposes in practice. However, these studies also indicate that such hormonal alterations can occur independent of performance changes, and therefore may not be reliable when identifying NFOR. Testosterone (T), cortisol (C) and T/C ratio were investigated in several short- and long-term studies (Bazyler et al., 2018; Fry et al., 1993, 2000a, 1994d; Haff et al., 2008; Häkkinen et al., 1987, 1989; Hartman et al., 2007), with additional measures of T and sex hormone binding globulin (SHBG) assessed during a single study (Häkkinen et al., 1987). Overall, results indicated that training state and anabolic-catabolic response to RET were somewhat related to T/C changes (Bazyler et al., 2018; Haff et al., 2008; Häkkinen et al., 1987), however, disturbances were independent of performance in others (Fry et al., 1993, 2000a; Häkkinen et al., 1989; Hartman et al., 2007). Such effects might indicate that these biomarkers are not appropriate for the identification of NFOR. Lifting experience was found to influence both acute (Fry et al., 2000a) and chronic (Fry et al., 1994d) hormonal responses to OR. Attenuation of T/C was observed after 1-week of purposeful OR in year 1, however was augmented in year 2 during a longitudinal observation of male junior weightlifters (Fry et al., 1994d). Endocrinological responses differed between elite- and non-elite weightlifters during short-term OR, with elite subjects experiencing no relationship between T/C ratio and OR, however, a negative correlation between T/C and OR training in non-elite subjects was observed suggesting training competence and/or experience might affect the hormonal response to overload training. Other potential biomarkers have been assessed during purposeful OR, including lactate and ammonia (Warren et al., 1992), creatine kinase (CK) and plasma iron status (Khlif et al., 2019). Short-term OR resulted in altered lactate and ammonia concentrations coinciding with reductions in maximum effort jump performance (Warren et al., 1992). However, no decrease in performance during a weightlifting-specific snatch test was observed, suggesting alterations in such biomarkers can occur without performance decrement. A single study assessed the effects of short-term OR on plasma iron status and selective inflammatory markers (Khlif et al., 2019). OR resulted in altered iron-status-balance parameters (especially in female weightlifters), with concomitant increases in CK. Whilst altered iron status coincided with RT-based OR, performance was not measured, therefore the relationship between iron status and performance is unknown. However, such alterations might indicate acute adaptation rather than detection of NFOR with more research is needed to investigate further. In summary, endocrinological responses to resistance exercise training may help coaches identify acute training state, trainability, and long-term adaptive responses to exercise. However, endocrinological alterations can occur independent of performance, and whilst T/C may identify acute hormonal disturbance in strength athletes, does not appear to be a determinant of FOR/NFOR. Changes in iron metabolism and selective biomarkers caused by short-term changes in resistance exercise training may provide a novel method for identifying FOR/NFOR in elite level weightlifters during intensified training protocols; current evidence, however, is limited and requires further investigation.

3.6.2 Performance measures

Several studies have assessed the effects of short-term, purposeful OR on performance outcomes in weightlifters, including weightlifting-specific testing (Bazyler et al., 2018; Fry et al., 2000a; Häkkinen et al., 1987; Pistilli et al., 2008; Warren et al., 1992) and/or general measures of performance (Fry et al., 1994d; Haff et al., 2008; Häkkinen et al., 1989; Hartman et al., 2007; Suarez et al., 2019; Warren et al., 1992). A single study examined throwing performance parameters in Collegiate-level throwers (Bazyler et al., 2017a). Overall, changes in maximal force (MF), rate of force development (RFD) and relative peak power output (PPO) through maximal effort jumping (Bazyler et al., 2017a, 2018; Hartman et al., 2007; Warren et al., 1992) and isometric- and/or dynamic mid-thigh pull (IMTP/DMTP) testing (Haff et al., 2008; Suarez et al., 2019) are able to identify changes in training load and fatigue which may occur prior to performance decrement, however no performance test can currently determine the onset of NFOR. Periods of increased resistance exercise training volume have resulted in weightlifting-specific performance improvement in elite/non-elite-level weightlifters (Fry et al., 2000a; Häkkinen et al., 1989; Pistilli et al., 2008; Suarez et al., 2019) and throwers (Bazyler et al., 2017a), suggesting that FOR can be achieved through manipulation of training and can be successfully monitored using performance measures. Some studies found that high-volume resistance exercise training did not lead to changes in weightlifting-specific performance but did result in reduced maximal jump height during purposeful OR (Fry et al., 1993; Warren et al., 1992), suggesting that coaches could use some performance measures to guide successful programming and avoid NFOR. Measures of RFD and MF appear to be sensitive to changes in training load and may provide a viable method to determine changes in neuromuscular characteristics prior to performance decrement, especially with tests that mirror the technical constraints of weightlifting and throwing-specific performance. Further research will elucidate whether such testing can differentiate between typical fatigue associated with increased training load indicative of FOR, or the onset of NFOR.

3.6.3 Changes in body mass and muscle cross-sectional area

Reductions in body mass (-6.0 kg) and very likely reduction in muscle cross-sectional area of the vastus lateralis (precision = 99%, effect size = 2.08) were observed in a female athlete during an OR phase in preparation for a national weightlifting competition (Bazyler et al., 2018).Nonsignificant increases in cross-sectional area of the vastus lateralis ($p > .05$) were observed in male weightlifters training once- or twice-daily for 3-weeks, with researchers speculating that multiple daily training sessions may be more beneficial to muscle hypertrophy and may also offer a more effective neuromuscular training stimulus (Hartman et al., 2007). There is limited literature available in OR and muscle hypertrophy in strength sports, and it is unwise to offer a generalised consensus based on the available literature, but investigation into the effects of weight cutting through caloric restriction during OR is needed to expand current understanding in this area.

Theme B: Overreaching and overtraining in resistance exercise

3.6.4 The effects of high-volume and high-intensity resistance training on performance measures

Studies have examined the effects of high-volume and/or high-intensity resistance exercise training (Berning et al., 2007; Fry et al., 1998, 2001, 2006, 1994a, 1994c, 1994b, 2000b; Nicoll et al., 2016; Raastad et al., 2001; Raeder et al., 2016; Robbins et al., 2012; Sharp & Pearson, 2010; Sikorski et al., 2013; Sterczala et al., 2017; Taylor et al., 2016; Tibana et al., 2016) as well as phasic, periodized approaches to OR (Fatouros et al., 2006; Jakubowski et al., 2019; Kraemer et al., 2006; Lowery et al., 2016; Stone et al., 2000; Volek et al., 2004; Wilson et al., 2013). Overall, both short-term increased resistance exercise training volume and intensity can result in FOR, but excessive exposure in terms of magnitude and/or duration can also result in NFOR – especially during prolonged high-intensity resistance exercise training. Identifying the transitional threshold from FOR to NFOR is difficult to determine based on the limited, heterogenous studies available within the literature and practitioners need to be aware that optimising performance is reliant on the prescription of appropriate volume and intensity during purposeful OR. Increases in resistance exercise training volume designed to induce fatigue over a 4-week period have resulted in performance improvement indicative of FOR (Taylor et al., 2016). Similarly, increases in intensity-matched lower body resistance exercise training volume over a 6-week period have resulted in improved maximal strength, with higher volumes superior to moderate or low volume (Robbins et al., 2012). Reductions in mean power (MP) jumping performance have illustrated greater within-subject variability during periodized overload training, which was greatest during OR, suggesting that whilst jump performance can be used to assess temporal changes to MF, MP, RFD and fatigue in resistance exercise training populations during OR, practitioners need to be aware of typical error scores when interpreting change from subject to subject (Taylor et al., 2016). Differing definitions of “high-volume” training makes inferencing from the existing data challenging. For example, a single upper/lower body resistance exercise training workout of 3 x 10-12 repetition maximum was defined as "high volume, muscle damaging training" in one study (Sikorski et al., 2013), which was notably lower in magnitude and duration (of volume) compared to other high-volume resistance exercise training studies (Nicoll et al., 2016; Raeder et al., 2016; Robbins et al., 2012; Taylor et al., 2016). Such ambiguity raises questions around the thresholds used to determine high volume OR in the resistance exercise training literature, which appear to be poorly defined. A lack of consistent findings exists within high-intensity OR literature, with short-term, purposeful high-intensity OR of similar duration resulting in FOR in some studies (Fry et al., 1994a), but performance plateau (Fry et al., 1998) and NFOR in others (Fry et al., 1998, 2006, 1994c; Raeder et al., 2016). Although designed to invoke OTS, an increase in maximal strength was observed after a 2-week high-intensity OR protocol in 9 recreationally trained men, even in the presence of reduced jumping and sprint performance (Fry et al., 1994a). Conversely, maximal strength plateaued during a purposeful 3-week OR period (after a period of strength improvement in a preceding 4-week period of normal resistance exercise training), with associated reduction in peak isokinetic squat force at 0.20 $m.s^{-1}$ (Fry et al., 2000b). However, several other performance parameters including vertical jump height, 36.6-m sprints, lateral agility, and isokinetic squat force at 0.82 and 1.43 $m.s^{-1}$ were unchanged. Maximal strength decline with concomitant reductions in isokinetic and stimulated isometric muscle force has been observed during periods of high-intensity OR (Fry et al., 1994c). Similarly, short-term decreases in maximal strength have been observed after 2-3 week purposeful OR (Fry et al., 1998), and a decrease in maximal strength/mean power at 1-RM after 2 week OR (Fry et al., 2006). A decrease in maximal strength and isokinetic knee-extension strength, as well as joint-centred overload injury of the knee occurred in a male subject after high-intensity OR has been observed in one study, suggesting indices of NFOR could place athletes at a higher risk of injury (Fry et al., 2001). Interestingly, voluntary isometric knee-extension and stimulated isometric knee-extension strength increased, suggesting a reduction in performance only affected dynamic strength indices. Whilst a variety of high-intensity protocols have been observed in the literature, several studies utilised the same protocol, consisting of daily 10 x 1-RM (Fry et al., 1998, 2001, 2006, 1994c), resulting in performance decrements indicative of NFOR and/or OTS. Such an extreme protocol is unlikely to reflect resistance exercise training practice but suggests that a dose-response "threshold" might exist by demonstrating that periods of high-intensity resistance exercise training can result in NFOR even over short periods of time. One study stated that after completing the 10 x 1-RM protocol, normal training could only be resumed after 2-8 weeks of cessation and may be one of the only available studies in the literature where OTS occurred, based on current definitions (Fry et al., 1994c). Overall, high-volume and high-intensity resistance exercise training programming can result in FOR, however, in the presence of excessive magnitude or duration of resistance exercise training can also result in NFOR. Whilst evidence might suggest a dose-response to both volume and intensity exists, currently there is minimal literature to support at what point that might occur. Further research to determine when FOR capacity is maximized and non-functional effects begin to take place will help coaches programme optimal resistance exercise training and avoid unnecessary performance decline.

3.6.5 Extreme conditioning practices

Studies have investigated the high-volume, high-intensity and multi-adaptive nature of CrossFit (CF) and other extreme resistance exercise training -based conditioning practices (Cadegiani et al., 2019b; Drake et al., 2017; Tibana et al., 2016). Findings suggest that such resistance exercise training practices can lead to endocrinological alteration, (Cadegiani et al., 2019b) increased inflammatory response (Tibana et al., 2016), performance decline, increased risk of NFOR and possibly OTS if the balance between training and recovery is not adhered to (Cadegiani et al., 2019b; Drake et al., 2017).

Participation in two consecutive "extreme conditioning" workouts resulted in increased anti-inflammatory cytokines without impacting muscle function (Tibana et al., 2016) suggesting that acute disturbances in some biomarkers are sensitive to short-term increases during high-intensity, high-volume resistance exercise training prior to performance changes being observed. Whilst short-term CF-based resistance exercise training can result in FOR, increased acute inflammatory markers and measures of mood state may suggest that prolonged exposure could lead to a NFOR state (Drake et al., 2017). In a post-hoc analysis of data, those who participated in high-intensity CF training and displayed OTS (defined as fulfilling diagnostic criteria outlined by Meeusen et al., (2013)) reported hormonal and biochemical disturbances including attenuated T and elevated oestradiol (E2) (Cadegiani et al., 2019b). Interestingly, performance decline associated with OTS may have been accelerated by insufficient carbohydrate (CHO) intakes, which were 3 times lower in the OTS CF group compared to healthy CF athletes. The author suggested that compensatory high-CHO meals may offer a protective role against OTS, and that CHO intakes of <5.0 g/kg/day for 8-weeks or more may be a contributing cause of OTS in CF athletes.

Literature in CF populations appears to be limited, however based on existing evidence, the risk of NFOR/appears to be high in these athletes - especially in the presence of restricted CHO intake. In high-intensity, extreme RT-based exercise such as CF, a robust series of systemic markers should be developed to help coaches optimize training (Drake et al., 2017).

3.6.6 Training to muscular failure

Three review papers have discussed the potential effects of muscular failure on OR/OTS (Davies et al., 2016; Willardson, 2007; Willardson et al., 2010), however no studies appear to have tested this hypothesis in practice. Whilst regular failure training can stimulate increases in strength and athletic performance, it might also result in NFOR/OTS when used to excess (Davies et al., 2016; Willardson, 2007; Willardson et al., 2010). Consequently, future research should investigate the effects of training to muscular failure on NFOR/OTS to inform the scientific community (Davies et al., 2016), and to provide coaches and athletes with much needed guidance in this area – particularly in experienced recreational bodybuilders where training to failure may be more widely used (Willardson et al., 2010).

3.6.7 Endocrinological measures and biomarkers

The effects of chronic resistance exercise training exposure on hormonal and biochemical systems has been investigated in several cohort studies (Drake et al., 2017; Fatouros et al., 2006; Fry et al., 1998, 2006, 1994c, 1994b; Nicoll et al., 2016; Raastad et al., 2001; Raeder et al., 2016; Sikorski et al., 2013; Tibana et al., 2016), with two systematic reviews investigating the hormonal response to OR (Cadegiani & Kater, 2017; Davies et al., 2016), a post-hoc analysis (Cadegiani et al., 2019b) and a single review referencing OTS within the broader theme of resistance exercise training (Fry & Kraemer, 1997). Overall, chronic exposure to resistance exercise training can lead to altered hormonal responses, with high-volume resistance exercise training following similar patterns to endurance training, whereas high-intensity resistance exercise training appears to result in a differential response (Fry & Kraemer, 1997). It is unlikely that endocrinological measures can predict NFOR/OTS due to a lack of reliable supporting literature but may be useful to identify acute changes in training state. The heterogeneous nature of the literature coupled with inconsistent findings makes it difficult to corroborate the effects of purposeful OR on hormonal systems and it is likely that serum hormones such as T, C and T/C ratio are able to predict the onset of NFOR/OTS (Cadegiani & Kater, 2017; Kraemer & Ratamess, 2005; Sikorski et al., 2013). A recent systematic review suggested basal hormone levels are not a reliable predictor of NFOR/OTS and that excessive endurance and/or resistance exercise training practices could lead to neuroendocrine fluctuations indicative of NFOR (Cadegiani & Kater, 2017). From 38 studies included in this review, only 3 (7.9%) investigated RT, therefore only limited literature relevant to this review was included. A small increase in T and T/C ratio was observed during 2-weeks of daily high-intensity resistance exercise training (Fry et al., 1998), and whilst 1-RM performance decreased over the training period, measures of anabolic status were unable to detect such strength loss. Conversely, reductions in T coincided with an increase in maximal strength during 2-weeks of heavy training (Raastad et al., 2001) and in CF subjects classified as suffering OTS (Cadegiani et al., 2019b), illustrating a lack of consistency in hormonal responses to high-intensity resistance exercise training. Increases in C-reactive protein (CRP) and CK have been reported during periods of short-term OR (Drake et al., 2017; Fatouros et al., 2006; Sikorski et al., 2013). CK appears to be correlated with perceived recovery after a single resistance exercise training session (Sikorski et al., 2013), and maximal squat strength (Kraemer et al., 2006). However, increased CRP/CK has been reported after a period of high-intensity, high-volume resistance exercise training resulting in performance gain (Drake et al., 2017), and therefore may be a part of the adaptive process that underpins FOR rather than an indicator of NFOR or OTS. A slight but insignificant increase in nocturnal urinary epinephrine activity during high-intensity resistance exercise training has been observed, as well as significant downregulation in β2- adrenergic receptors concurrently with decreased 1-RM strength (Fry et al., 2006). Interestingly, OTS was diagnosed through a reduction in maximal strength as well as mean power at 100% 1-RM loads, which is conflicting with current diagnostic criteria (Meeusen et al., 2013) based on retrospective recovery time course. That said, normal training could be resumed only after 2-8 week suggesting NFOR was more likely to have occurred in some participants, but OTS could have occurred in others. Changes in skeletal muscle signal transduction downstream to β2-adrenergic receptors have been observed in trained males during 2-4 weeks of high-intensity and high-power OR (Nicoll et al., 2016). Similar reductions in β2-adrenergic expression and increased nocturnal urinary epinephrine have also been observed during high-intensity OR (Sterczala et al., 2017), and as such, resistance exercise training subjects may experience alterations in epinephrine-β2-ERK signalling axis during periods of OR. A novel marker of cell-free plasma DNA (cf-DNA) has been proposed as a possible tool to detect OTS during intensified resistance exercise training (Fatouros et al., 2006). cf-DNA increased proportionate to training load during a 12-week period of undulating resistance exercise training volume, with highest concentrations reported during a high-volume, high-intensity phase. cf-DNA may be sensitive enough to detect short-term response to OR, with transient increases in cf-DNA possibly due to increased muscle fibre damage caused by prolonged overloading resistance exercise training. Hormonal and biochemical measures may help coaches identify acute training state, but inconsistent findings in the literature suggest these measures are not sufficiently robust to identify or predict NFOR/OTS; particularly when used in isolation rather than in combination with performance measures.

3.6.8 Supplement use during periods of overreaching periods

The effects of various supplements have been examined during purposeful OR periods, including amino acids (AA) (Kraemer et al., 2006; Ratamess et al., 2003; Sharp & Pearson, 2010), β-Hydroxy β-methylbutyric-free acid (HMB-FA) (Jakubowski et al., 2019), adenosine-5'-triphosphate (ATP) (Wilson et al., 2013), creatine monohydrate (CrM) (Volek et al., 2004), phosphatidylserine (Ps) (Fahey & Pearl, 1998) and multi-ingredient supplementation (Lowery et al., 2016; Sterczala et al., 2017). Overall, supplementation during purposeful OR may help to offset the deleterious effects of NFOR, however some studies have observed no change. The overall literature to support supplementation during OR resistance exercise training is less than conclusive.

High volume OR initially leads to a decrease in muscle strength and power, with subsequent rebound effect (FOR) after low volume training in both AA supplementation and placebo (Ratamess et al., 2003). Similarly, a small decrease in 1-RM was observed during high-volume OR in both whey and HMB-FA and whey and leucine groups. However, increased maximal strength was observed during a subsequent taper, indicative of FOR (Jakubowski et al., 2019). No differences were observed at any point between groups, suggesting the OR training stimulus and not supplementation was the main driver of FOR outcomes. AA supplementation was found to preserve T and attenuate CK levels during high-volume resistance exercise training and was highly correlated to reductions in squat 1-RM but a subsequent increase in maximal strength suggests the protocol resulted in FOR (Kraemer et al., 2006). High-power resistance exercise training OR led to a reduction in mean squat velocity and concurrent increase in the ratio between serum epinephrine/ β2-adrenergic receptor expression (β2-AR), without reduction in maximal strength in both a multi-ingredient supplementation group and control (Sterczala et al., 2017). Whilst these results further illustrate the attenuation in force and velocity prior to maximal strength decay during periods of intensified RT, it is worth noting that maximal strength did begin to plateau, and further stressful resistance exercise training could have resulted in NFOR. The group receiving supplementation demonstrated a smaller decrease in β2-AR expression and a lower epinephrine/β2-AR ratio, suggesting the recovery drink reduced the detrimental effects of OR on sympathetic activity, however had no effect on performance outcome compared to placebo. Interestingly, the authors of this study referred to the 1-wk training phase as an "overtraining" phase, however no incidence of OTS occurred, although some subjects were overreached based on time-course to recovery. Exploration into differences between high power OR and high intensity/volume OR may provide further understanding in this area.

3.9.9 Changes in body mass and muscle cross-sectional area

A small number of studies have investigated the effects of dietary supplementation on alterations to lean body mass (LBM) and mCSA during strength training programmes that included short-term OR (Jakubowski et al., 2019; Lowery et al., 2016; Wilson et al., 2013). An increase in mCSA of the vastus lateralis was observed in male subjects administered either whey protein with HMB-FA or with leucine during a 12- week resistance exercise training programme comprising a 2-week OR phase (Jakubowski et al., 2019). No differences in mCSA were reported between groups at any phase, suggesting neither supplement was superior in invoking resistance exercise training -induced muscle hypertrophy, and that OR itself had an impact on mCSA during periodized strength training. Combined HMB-FA plus ATP supplementation led to increased LBM (8.5 ± 0.8 kg vs. 2.1 ± 0.5 kg; $p<.05$) and thickness of the quadriceps muscle (7.8 ± 0.4 mm vs. 2.4 ± 0.7; $p<0.01$) when compared to placebo during a 12-week strength training programme with 2-week OR (Lowery et al., 2016). Whilst this may appear to illustrate short-term OR could have a positive impact on muscle hypertrophy, is worth noting that an increase in LBM of this magnitude in trained subjects across 12-weeks of resistance exercise training appears to be somewhat questionable and these results should be taken with caution. In another study, ATP supplementation was reported to enhance LBM (4.0 ± 0.4 kg vs, 2.1 ± 0.5 kg; $p<.009$) and quadriceps muscle thickness (4.9 ± 1.0 mm vs. 2.5 ± 0.6; $p<.02$) compared to placebo during a 12-week periodized strength training programme consisting of three phases of varied intensity and volume (Wilson et al., 2013). Concerns have since been raised regarding the methodological robustness of the data presented in the studies by Lowery et al., and Wilson et al., (2016; 2013), with inconsistencies in data suggested by other researchers (Gentles & Phillips, 2017). To date, there is little evidence suggesting that purposeful OR during resistance exercise training results in negative alterations in mCSA. However, this is likely due to a significant lack of literature looking specifically at markers of muscle hypertrophy during periods of resistance exercise training resulting in NFOR or OTS. This provides an interesting gap for future research.

3.10 Conclusion

Implementing short-term OR is a common practice in some strength sports where the training stimulus is presented typically through high-volume/high-intensity resistance exercise training over a 2-4-week period and often leads to FOR due to improved performance. There is a lack of representation in the research from strength sports such as powerlifting, strongman and explosive throwing and sprinting sports, with only a single study assessing the effects of purposeful OR in throwing athletes. Several performances, neuroendocrine, neuromuscular, and biochemical markers have been proposed as markers to determine NFOR/OTS in both strength sports and RT, but no single test or method has been able to identify the exact point at which FOR becomes NFOR or OTS. A dose-response transition from FOR to NFOR that is identifiable through perturbations in physiological markers or performance testing might exist, however this has not been identified in the current literature. There is no evidence that planned FOR protocols used in strength sport research have led to true OTS based on current definitions (Meeusen et al., 2013). Studies have demonstrated short-term performance loss indicative of NFOR, however, in these cases, diminished performance has typically been resolved within days to weeks and is therefore not indicative of OTS. Many studies located for this review were published prior to the latest guidelines and definitions proposed by the ACSM/ECSS joint statement (Meeusen et al., 2013) and it appears that the definition of “overtraining” is poorly interpreted in the research. Reductions in performance lasting weeks to months, generalised performance reductions, and short-term high-volume/high-intensity training protocols have all been described as "overtraining", adding to confusion around the true meaning of the term. That said, OTS may have occurred during prolonged exposure to high-intensity or combined high-intensity/high-volume resistance exercise training. Evidence suggests that NFOR is a real consequence of excessive and chronic training in the absence of sufficient recovery from RT, especially in practices involving extreme conditioning. Coaches and athletes must be cognisant to the deleterious effects of excessive training loads, and there is sufficient justification that a robust testing battery to identify when FOR becomes NFOR is now needed. Specific areas of interest for further investigation include the effects of muscular failure training, weight cutting during periods of OR (which is a tool often used in weight category strength sports as well as bodybuilding) and the reliability of performance-specific measures and biomarker sensitivity to resistance exercise training OTS.

Chapter 4: Study 2 - "Is It Overtraining or Just Work Ethic?": Coaches' Perceptions of Overtraining in High-Performance Strength Sports

This chapter is based on the following peer-reviewed publication: Bell, L., Ruddock, A., Maden-Wilkinson ,T., Hembrough, D., Rogerson, D. "Is It Overtraining or Just Work Ethic?": Coaches' Perceptions of Overtraining in High-Performance Strength Sports. Sports (Basel). 2021 Jun 7;9(6):85. doi: 10.3390/sports9060085.

4.1 Rationale

Study one revealed that short-term periods of highly demanding resistance exercise training can elicit FOR when appropriately planned. However, if the balance between training and recovery is not adhered to, such training might also result in NFOR. Importantly, study one highlighted that the precise point where the training stimulus transitions from FOR to NFOR was unknown. This was likely due to the disparate and heterogeneous landscape of the available research, a lack of practical tools sensitive enough to detect the onset of training maladaptation, and an absence of standardised training interventions to assess the physiological response to undertaking highly demanding resistance exercise training. Study one also highlighted minimal evidence that true OTS has occurred following a period of resistance exercise training; even after intentional attempts to induce training maladaptation. However, this assumption was based on a limited number of studies, and definitions of "overtraining" were poorly defined and interpreted within the research.

Strength and conditioning coaches often solve problems through experience, intelligence and tacit knowledge (Dorgo, 2009). Study one highlighted a noticeable lack of research examining strength coaches' experiences of OT, and that there had been no qualitative research undertaken to capture high-performance strength sport coaches' perceptions of long-term performance decline or maladaptation. Therefore, the primary aim of study two was to explore high-performance strength coaches' perceptions of OT and OTS, and to provide a new way of understanding and conceptualising training maladaptation from the perspective of the practitioner. An additional objective was to reveal potential lines of enquiry for future research not revealed through study one (as recommended by the ARMSS).

4.2 Abstract

Optimal physical performance is achieved through the careful manipulation of training and recovery. Short-term increases in training demand can induce functional overreaching (FOR) that can lead to improved physical capabilities, whereas nonfunctional overreaching (NFOR) or the overtraining syndrome (OTS) occur when high training-demand is applied for extensive periods with limited recovery. To date, little is known about the OTS in strength sports, particularly from the perspective of the strength sport coach. Fourteen high-performance strength sport coaches from a range of strength sports (weightlifting; n = 5, powerlifting; n = 4, sprinting; n = 2, throws; n = 2, jumps; n = 1) participated in semistructured interviews (mean duration 57; SD = 10 min) to discuss their experiences of the OTS. Reflexive thematic analysis resulted in the identification of four higher order themes: *definitions*, *symptoms, recovery* and *experiences and observations*. Additional subthemes were created to facilitate organisation and presentation of data, and to aid both cohesiveness of reporting and publicising of results. Participants provided varied and sometimes dichotomous perceptions of the OTS and proposed a multifactorial profile of diagnostic symptoms. Prevalence of OTS within strength sports was considered low, with the majority of participants not observing or experiencing long-term reductions in performance with their athletes.

4.3 Introduction

In sports such as weightlifting and powerlifting, the goal is to successfully lift the largest mass within a weight class (Aasa et al., 2017). Sports that involve maximal effort throwing, jumping, and sprinting are determined by mass-specific force generation and impulsiveness (Suchomel et al., 2016). Optimal performance in these sports is achieved using planned periods of strength training and recovery with the aim of inducing physiological adaptations that underpin performance (Storey & Smith, 2012). This is typically achieved by strategically organising training load to achieve peak performance at key periods within the competition schedule (Mujika et al., 2018).

Short-term, intentional periods of increased training (multiple daily training sessions, increases in volume and intensity) have been used in weightlifting (Pistilli et al., 2008; Suarez et al., 2019), powerlifting (Colquhoun et al., 2017; Zourdos, Jo, et al., 2016) and track and field sports (Bazyler et al., 2017a) to induce a performance "supercompensation" or "rebound" effect, typically observed within approximately <10 (2–5) weeks after the resumption of normal or reduced training. Importantly, this occurs after an initial relative reduction in performance (Pistilli et al., 2008). This method has been referred to as functional overreaching (FOR) (Meeusen et al., 2013). Whilst FOR might occur if the balance between training and recovery is achieved, there is a risk that prolonged training without enough recovery can impair adaptation and long-term performance and result in either nonfunctional overreaching (NFOR), which can take several weeks to recover from, or the overtraining syndrome (OTS), where recovery can take several months or longer (Meeusen et al., 2013). The terms "staleness", "fatigue syndrome" and "unexplained underperformance syndrome" have all been used interchangeably with OTS (Budgett et al., 2000). NFOR has been referred to as "overreaching" (OR) in the literature, whilst the terms "overtraining" (OT) and "underrecovery" have been used to describe the imbalance between intensified training and insufficient recovery which can lead to OTS (Budgett et al., 2000; Meeusen et al., 2013).

Evidence for the identification, diagnosis, and prevalence of OTS in strength sports or resistance training is limited (Bell et al., 2020; Budgett et al., 2000; Fry & Kraemer, 1997; Grandou et al., 2020). Whilst more than 70% of strength sport competitors have reported unexplained decreases in performance, approximately 43% of those have indicated a range of symptoms lasting one week to one month, with 13.1% lasting one to three months and only

4.7% > 4 months (Grandou et al., 2021), suggesting higher occurrence of acute fatigue or NFOR, and lower incidence of OTS.

A lack of individualised testing protocols and gold standard markers combined with multidimensional and individual symptoms make the identification of OTS difficult (Grandou et al., 2021; Meeusen et al., 2013). As such, there are a lack of reliable, prognostic tools for sport coaches to accurately judge when periods of increased training will lead to performance supercompensation or result in NFOR/OTS. Currently, OTS can only be assessed retrospectively using the diagnostic flowchart presented by the joint consensus statement of the European College of Sport Science (ECSS) and the American College of Sports Medicine (ACSM) (Meeusen et al., 2013). However, the nature of such a tool suggests it can only be utilised by those already considered to be at risk of OTS. Further, there is limited agreement on “textbook” symptoms in the overtrained athlete, with athletes either presenting a myriad of individualised symptoms, exhibiting normal symptoms of acute fatigue, or displaying an asymptomatic profile (Meeusen et al., 2013). Current guidance on management of symptoms and diagnostic assessment of OTS has been developed largely from studies from the endurance sport domain (Halson & Jeukendrup, 2004; Meeusen et al., 2013) and fewer from strength sports or resistance training populations (Bell et al., 2020; Fry & Kraemer, 1997; Grandou et al., 2020). However, the profile of endurance and strength athletes exhibiting symptoms of OTS typically elicit different responses (Fry & Kraemer, 1997), making the identification and management of NFOR/OTS difficult for the strength coach.

It is important to improve communication between laboratory research and applied experience in order to develop robust and practical coaching tools, particularly in under-investigated area such as OR/OTS, and where the existing literature suggests inconsistency between expert statements, experimental study findings and the application of such evidence to the training environment (Bell et al., 2020; Fry & Kraemer, 1997; Grandou et al., 2020, 2021; Meeusen et al., 2013). To our knowledge, there has been no previous qualitative research undertaken to capture high-performance strength sport coaches' perceptions of long-term performance decline and their experiences of OTS. Such research could elicit important information about the understanding of OTS, its impact on strength athletes, and approaches to managing the delicate balance between training and recovery. The aim of this study therefore was to explore perceptions of OT and OTS in high-performance strength coaching, and to provide a new way of understanding and conceptualising these concepts.

4.4 Materials and Methods

4.4.1 Study Design

To answer the aims of this study, semistructured interviews were analysed using reflexive thematic analysis based on guidelines provided by Braun and Clarke (Braun & Clarke, 2006, 2019). Thematic analysis is a method for identifying, organising, analysing, and reporting qualitative data sets into compressed meaningful patterns (Nowell et al., 2017), and provides a suitable design when examining lived experiences (Attia & Edge, 2017). Thematic analysis is becoming an increasingly common tool for qualitative research within sport and exercise science, however, its use within this domain has previously been criticised for misapplication of its methodological principles (Braun & Clarke, 2019). Therefore, following detailed theoretical and conceptual frameworks such as the one provided by Braun and Clarke (Braun & Clarke, 2006) is fundamental to better thematic analysis practice (Braun & Clarke, 2006, 2019).

4.4.2 Participants

Following institutional ethical approval (ER16222001), 14 high-performance strength sport coaches were recruited via opportunity sampling. All benefits and risks were explained prior to data collection, informed consent was obtained, and the study was conducted according to the principles of the Declaration of Helsinki. Inclusion criteria stated that participants had a minimum of 3 years' experience of coaching in at least one strength sport at a national level or above. For this research, *strength sports* were defined as either weightlifting, powerlifting, sprinting, jumps (e.g., long jump, triple jump) or throwing sports (e.g., hammer, discus, javelin). Sample size was determined by the principal of saturation, with participants recruited until new data failed to evolve further insight or provide novel information (Guest et al., 2006). Based on previous research guidance (Guest et al., 2006), a non-probabilistic sample size of ≥ 6 participants was expected to achieve saturation due to the participant pool being recruited from a homogenous group.

Participants comprised 12 males and 2 females (the descriptive profile of each participant is located in Table 6). Duration of experience ranged from 4 to 57 years (mean 14.4; SD = 13.4 years) and participants included a cross-section of strength sports: weightlifting (5), powerlifting (4), and track and field (5). Track and field coaches consisted of sprinting (2), jumps (1), and throws (2). Ten participants were based in the United Kingdom, 2 in Republic of Ireland, 1 in the United States and 1 in New Zealand. Education level ranged from no academic degree to Doctor of Philosophy. Coaches possessed a range of relevant governing body certifications for their respective sport, with some holding additional strength and conditioning accreditation.

Table 6. Descriptive characteristics of participants

Participant ID	Sex	Sport	Location	Experience (years)	Experience (level)
1	M	Weightlifting	UK	20	International
2	M	Powerlifting	IRE	6	International
3	M	Powerlifting	IRE	5	International
4	M	Weightlifting	UK	9	International
5	M	Powerlifting	USA	10	National
6	M	Weightlifting	UK	12	International
7	F	Weightlifting	UK	4	International
8	M	Weightlifting	UK	57	International
9	M	Powerlifting	UK	15	International
10	M	Throws	UK	15	International
11	M	Sprints	UK	10	International
12	F	Sprints	UK	4	International
13	M	Jumps	UK	13	International
14	M	Throws	NZ	21	International

To maximise the quality and range of potential candidates, initial contact was made with relevant national governing bodies via email. An information and recruitment poster was provided at initial contact, detailing the aims of the research study, as well as inclusion and exclusion criteria. After, an information and recruitment poster was shared organically across several social media platforms, and additional sharing of the poster was encouraged across social media to widen the reach of the study. The research team also shared the poster via personal and institutional social media channels. A supplementary participant information sheet was presented to potential participants after initial contact had been made to provide further details about the interview process. Each interested participant was screened by the principal investigator (L.B.) prior to the interview to ensure inclusion criteria were met.

4.4.3 Procedures

Before data collection, an interview guide was created by the principal investigator in consultation with the research team and refined through a process of pilot interviewing. Pilot interviews were conducted on two strength coaches. The interview guide was further developed after piloting to reflect the aims and objectives of this study (see Appendix 1 for a copy of the interview guide). A semistructured interview approach permitted the collection of rich data whilst remaining focused on the study objectives (B. Smith & Sparkes, 2016a), and provided a qualitative method previously used within strength and conditioning research to ascertain coaches' experiences (Tod et al., 2012). All interviews were conducted by the principal investigator. A flow diagram of the data collection procedure is presented in Figure 9.

Participants were invited to either a face-to-face or online interview based on geographical location and availability. Face-to-face interviews were conducted in a neutral, quiet, and mutually agreed environment, and data were collected using a digital voice recorder (Zoom, Hn1 digital recorder 2.0, UK). For online interviews, data were collected using European Union General Data Protection Regulation-compliant software (Skype Ltd, version 15, Luxembourg) and exported to a password-protected external hard drive (Seagate Technology PLC, Fremont, CA, USA). All data were anonymised, and only participant identification numbers were used during publication of results, assigned chronologically based on order of interview. The principal investigator sought to conduct interviews that built trust through relaxed dialogue and rapport building, and actively explored participant responses in a systematic and comprehensive way. To achieve this, the interview agenda was approached in a fluid and flexible manner; an important aspect of realist interview good practice (Jamshed, 2014).

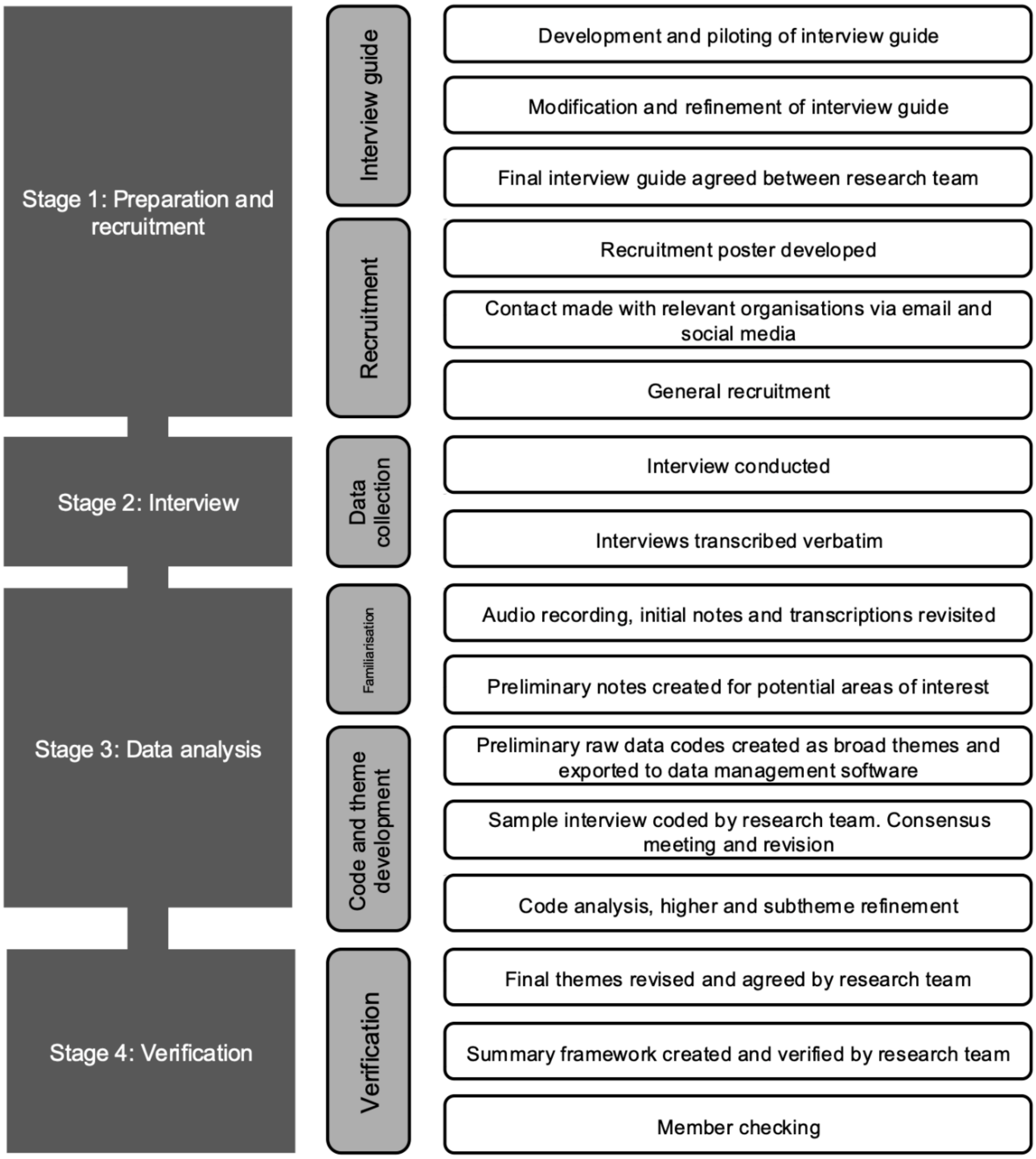

Figure 9. Flow diagram of data collection procedure

Throughout the interview, participants were encouraged to draw upon their own experiences, offer detailed and practical responses where possible, and to elaborate where appropriate to provide rich, experiential responses. Introductory questions were used to provide descriptive and contextual background information, and to act as an "ice breaker" between participant and researcher (for example, *"tell me a bit about yourself and what sport you're involved in"*).

Central questioning related to the research question (for example, *"how would you define the overtraining syndrome?"*). Closing questions provided participants with an opportunity to reflect or add anything they thought relevant to the interview that had not already been covered (*"before we finish, is there anything you'd like to elaborate on or add to the discussion?"*). The principal investigator created field notes throughout the interview to act as prompts for additional questioning and to explore lines of enquiry not contained in the interview guide.

4.4.4 Data Analysis

The initial stage of analysis involved immersion in the overall dataset by repeated listening to recordings and reading of transcripts and highlighting potential "points of interest" using Google Document highlight colour tools. During this initial phase, potential data codes were identified by extracting lines and/or paragraphs deemed relevant to the research question. Such codes presented a worldview of participants' perceptual filters and lived experiences (Christ, 2013). Codes were then organised into broad, open-ended themes which were identified inductively in order to remain true to the transcribed data (Braun & Clarke, 2006; Ward et al., 2013).

After completion of the initial coding and theme development, all transcribed data were exported to NVivo Pro (v11.4.1.1064, Flexera Software LLC; Itasca, IL, USA) where codes were placed into themes and subthemes (as nodes) to organise and index the data in preparation for analysis. A transcribed interview sample was sent to members of the research team who were also asked to code the data and develop themes. This process was completed blindly and neither the principal investigator nor members of the research team were permitted to discuss the codes or themes that emerged from the sample during this process. The whole research team then met to discuss similarities and differences between codes, themes and data patterns and challenge the overall decision-making process of the principal investigator.

Reflexive thematic analysis was used to analyse the data with reference to the aims and objectives of the research. Themes and subthemes were refined and developed throughout analysis in a reflexive and flexible manner using a process of open coding. Themes were developed, not based on prevalence across the data set or by number of participants that articulated the data item, but rather the importance of what the data revealed about coaches' experiences (Nowell et al., 2017). In the final stage of analysis, themes and subthemes were approved by the whole research team and cross-referenced with the aims and objectives of the study. A summary framework was developed for each theme and subtheme in order to manage and organise the large data set (Gale et al., 2013), and Stage 4 of the framework analysis guidelines proposed by Ward et al. (2013) helped to organise themes into a brief summary matrix.

After reflexive thematic analysis had been agreed upon and approved by the research team, member checking was conducted to provide transparency and improve overall data trustworthiness (Birt et al., 2016). During this process, each participant was sent their individual framework to verify that the synthesised data provided a true representation of their comments, to allow reflection on personal experiences or to add data where appropriate (Birt et al., 2016). Last, a report was produced to detail the main findings of the study.

4.5 Verification

Throughout the coding process and development of themes, a detailed codebook was maintained by the principal investigator to track initial ideas, changes, or modifications to the thematic analysis process, to create an audit trail of data saturation (Guest et al., 2006), and for the purpose of reflection, traceability, and dependability (Nowell et al., 2017). Themes were adapted, updated, merged, or deleted throughout analysis and during periodic verification meetings that took place at regular and/or important stages of analysis (Braun & Clarke, 2006;

Gale et al., 2013). Verification strategies enhance credibility, dependability, and trustworthiness during the qualitative process (terms analogous to reliability and validity in quantitative research) and help to reduce potential bias from the research team (Morse et al., 2002). This is important in realist approaches to thematic analysis (Braun & Clarke, 2006). Additionally, blinded sampling of data was implemented early in the analysis process to enhance dependability and interpretation of codes and themes, and final member checking was performed to help improve transparency and trustworthiness (Birt et al., 2016).

4.5 Reflexivity

To strengthen the credibility and transferability of this research from theory to practice (and to deepen the overall understanding of the research question), the principal investigator utilised the practice of *reflexivity* throughout the research process (Attia & Edge, 2017). As such, the following information should be used to contextualise and appraise the credibility of this study, as well as to assist in its transparency.

The primary research question originated as part of a wider investigation into strength sports as part of a Philosophy Doctorate and aimed to investigate the complex topic of OT/OTS from the perspective of the strength sport coach; an area of applied research that has not yet been explored to date, and as such, lacks qualitative analysis. Improved communication between laboratory research and applied experience is key for the development of optimal coaching practices, particularly in under-investigated areas such as OT/OTS where the existing literature suggests dichotomy between experimental research and the application of such evidence in the training environment (Bell et al., 2020; Fry & Kraemer, 1997; Grandou et al., 2020, 2021; Meeusen et al., 2013). The principal investigator has practical experience and a research interest in strength sports, and, as such, understands the importance of advancing knowledge by bridging the gap between research and practice. During the development of the interview guide and subsequent data collection and analysis stages, the principal investigator aimed to distinguish their own experiences and perceptions from those held by participants in order to remain objective; an aspect of qualitative research essential within realist practice (Price & Martin, 2018).

4.7 Results

Interviews were conducted between July 2019 and March 2020 and lasted between 0:39:44 and 1:17:38 min (mean 0:57:01; SD = 0:10:27 min). Audio recordings were transcribed verbatim, resulting in 276 pages of data (mean = 19.7; SD = 4.4 pages). A central concept of *overtraining* was organised into four higher order themes, with subthemes developed to further organise the large volume of data collected and to aid in the publicising of information. Figure 10 provides a schematic representation of themes and subthemes. Direct, anonymised quotes were used within the main report to illustrate discussion points and to contextualise participant experiences. Additional words were placed in parentheses to clarify intended meaning or provide further context where required. Punctuation was also added to quotations to reduce ambiguity where relevant.

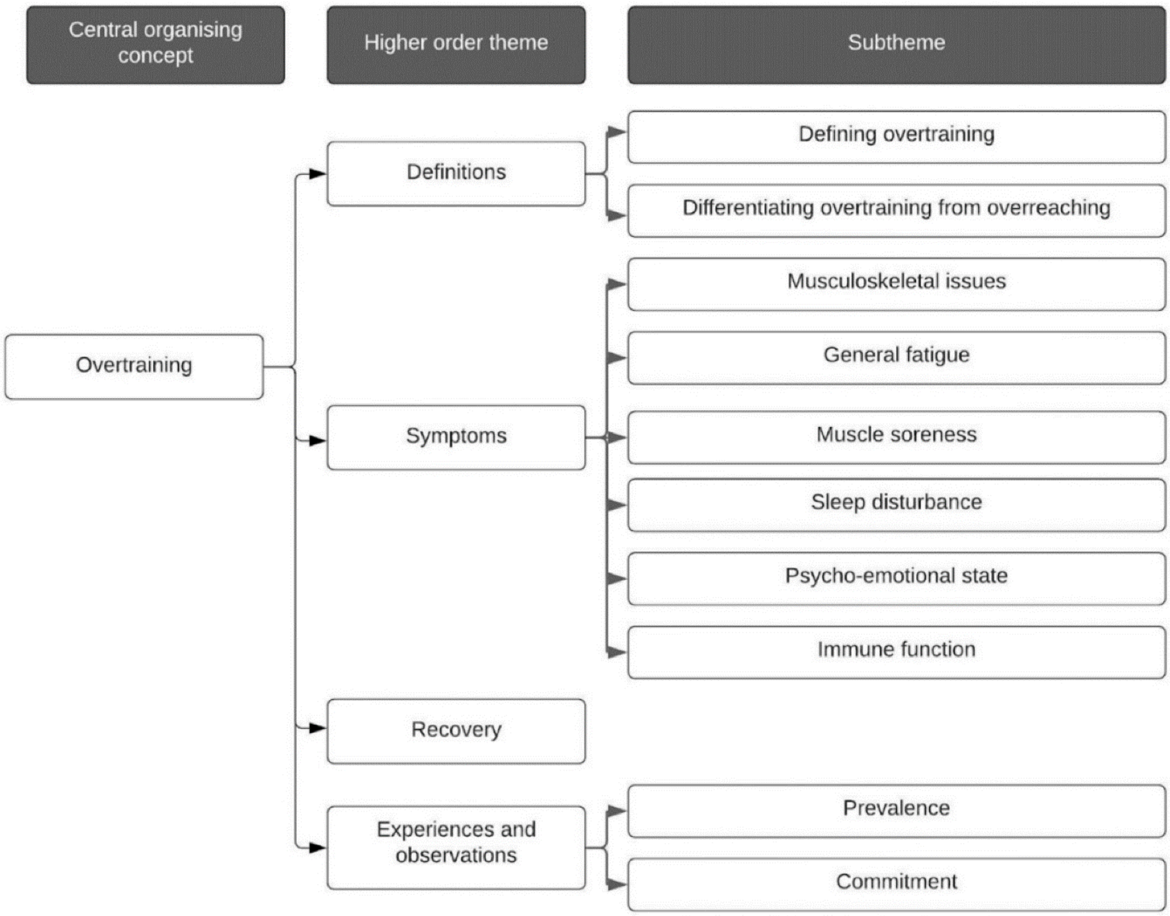

Figure 10. Schematic representation of central, higher order and subthemes

4.7.1 Definitions

4.7.1.1 Defining Overtraining

In this theme, 11 participants (1–9,11,12) characterised OT as a miscalculation of training load resulting in maladaptation and/or suboptimal response to training. OT was associated with either short- or long-term performance decline as well as loss of motivation. Synonyms were frequently used to describe the complex, multifactorial nature of OT, which included the terms *"under-recovery"* (1) and *"fatigue syndrome"* (7), however, the term *overtraining syndrome* was not used by any participants at any time.

> *"So, if as part of the rebound... as part of the recuperation week they don't rebound back to where you expect, you can term that overtraining I guess"* (1).

> *"I guess it would just be being flat-lined or turning in the opposite direction"* (4).
>
> *"I would say (overtraining) is a systematic decrease in the capacity of the athlete to either endure training... a decrease in the outcomes of desired adaptations and a decrease in performance over a period of time"* (11).
>
> *"Overtraining for me is generally not listening to your body"* (7).

For one participant (5), the term "*overtraining*" was used to define the *act* of training above a recovery threshold. Participant 11 viewed OT as the "*capacity of the athlete to endure training*" alluding to OT as a verb to describe training, rather than a multifactorial condition as observed with OTS.

> *"Feeling bad for a week or two weeks or three weeks, that's like the colloquial 'overtraining'... you're doing too much"* (5).

For some coaches (3,4,9,12) OT was an ambiguous concept and difficult to define.

> *"Honestly, that's a real difficult one"* (9).

4.7.2.1 Differentiating Overtraining from Overreaching

Overall, OT was seen as a progression from OR caused by prolonged exposure to the training stimulus. OT was considered an unwanted "*deviation*" (1) from planned programming resulting in unwanted symptoms of fatigue and performance decline, whereas OR was described as a deliberate, intentional part of the training process. For some (1,2,4), "*intention"* and "*outcome"* were what distinguished OR from OT.

> *"I guess there's a fine line between overreaching and overtraining, and the difference will be the ability to rebound and bounce back in a short period of time...if it comes to the point where it means you have to deviate from the plan... if you overreach, it's part of the plan, you overtrain you've gone too far"* (1).

4.7.2 Symptoms

In this theme, participants characterised OT by associated or indicative symptoms that either result in an overtrained state or indicated risk of OT. Overall, several symptoms were provided by participants as possible identifiers of OT. These ranged from physiological manifestations such as musculoskeletal issues, fatigue, and muscle soreness to psychological symptoms of altered mood state, loss of motivation and reduced readiness to train.

4.7.2.1 Musculoskeletal Issues

One of the most cited symptoms of OT related to musculoskeletal issues caused by *"overuse"* (1,3,6,7,10,11). Participants revealed that OT might result in musculoskeletal maladaptation specifically in muscle, joint and/or connective tissue. Terms such as *"tendinopathy injuries", "physical knocks"* and *"niggles"*, were used to describe manifestation of OT, particularly within shoulders, elbows, hips, lower back, or knees.

> *"But when you start seeing someone as overtrained, or trained particularly in a poor way, you start seeing issues with tendon, ligament and bone deformities"* (11).

> *"Well, the most common (symptoms) tend to be like the sore elbows, the sore knees, that kind of thing. And they're often just a function of people doing too much, way too soon, or when their body isn't really primed for it"* (3).

4.7.2.2 Psycho-Emotional State

Terms including *"apathy towards the sport"* (3), *"abnormal behaviour"* (6), *"irritability"* (8), *"mood swings"* and *"(lack of) compliance"* (9) were cited as OT symptoms by participants 3,6,8–10. Psycho-emotional state was associated with diminished readiness to train, and participants discussed these manifestations independent of physiological disturbances or alterations in performance parameters.

> *"The definition of overtraining really is to see somebody come in the gym with no motivation at all. It can be other reasons, but if their lifestyle hasn't changed at all, and they're coming in(to) the gym and they can't be bothered... that's overtraining I think"* (8).

4.7.2.3 General fatigue

Four coaches (7,8,10,12) considered fatigue to be an indicator of OT, suggesting signs of "*sluggishness*", *"lethargy"* (10), and "*extreme fatigue*" (6) could indicate chronic maladaptation. These were linked, albeit not explicitly in some cases, to reduced physical performance. For some coaches, multidimensional references to fatigue were contextualised either as reduced physical function (for example decreased strength) or mental capacity and/or emotional state.

> *"I think where somebody shows signs of extreme fatigue. That'll be displayed in a bit more abnormal behaviour. So, they might be a bit more sluggish in getting the weights on the bar and actually lifting the weights"* (6).
>
> *"Suddenly their bodies were like, 'I can't do this'. And so, there was a real peak in strength and then within a week, dropped massively"* (7).

4.7.2.4 Muscle Soreness

For participants 7,10,12, muscle soreness was an important indicator of OT. For coach 8, muscle soreness was expected during periods of increased training demand; but needed to be distinguished from the muscle soreness experienced during OT.

> *"I'd imagine they would talk about that soreness; their readiness would go down; they'd talk about not being able to lift the weight they were doing previously"* (10).
>
> *"Does it (overtraining) exist in strength sport?... I think in the powerlifting sport, I think it's more the DOMS and peripheral fatigue"* (8).

Differentiating between muscle and joint soreness was important for coach 12, resulting in either the continuation, or cessation of exercise training.

> *"If your muscle is sore, get over it. But if your joint is hurting... there's a difference between soreness and 'it hurts'. If it's hurting, I will stop the session or I will change to do something else... because there's always something else you can do"* (12).

4.7.2.5 Sleep Disturbance

Disturbed sleep was strongly associated with OT by participants 8 and 10, either as a direct cause of OT, or as an indirect effect. In both cases, poor sleep was related to impaired physical capacity.

"I think (it) was maybe a bit of fatigue and that messed up his sleeping pattern. He just sort of couldn't switch off because his body was... I can't remember what he said. He said he felt twitchy or something with it." (10).

4.7.2.6 Immune Function

For three participants (3,8,10) symptoms of compromised immune function (or the development of acute illness) or increased prevalence of acute upper respiratory tract infections could be used to indicate the risk of OT, presenting either concurrently with psychophysiological symptoms, or independently.

"And if a lifter's starting to get regular colds and that, it could be that the system is being overloaded too much" (8).

4.7.3 Recovery

In this theme, seven participants (1,2,4,6,9,10,13) revealed the duration they considered necessary to recover from OT. For most (1,2,6,9,10,13), a period of days to two weeks would be required, but for one (4), convalescence would require months or years.

"You know, some people can bounce back within four days, some people take two weeks, but we never see much beyond those two different extremes" (9).

"Things that they say like, "oh, yeah, I just can't be arsed today". But it's not just one day they say that, it's a couple of days or a week or something and it starts to become a bit of a pattern or they say... and then you just don't see them for a few days" (6).

"In terms of strength sports. I think overtraining is when, just by having an acute recovery period of, you know, one, two or three weeks of minimal training, it brings it back to pretty much baseline. They can go again" (2).

"I'd say probably 18 months to 2 years" (4).

4.7.4 Experiences and Observations

In this theme, all participants (1–14) discussed their experience of OT. Most (2–6,8–12,14) had not observed OT, and some considered terminology relating to OT and OTS to be overused, and hard to distinguish from *"a lot of moaning"* (6).

4.7.5 Prevalence

The majority of participants had not observed OT. One participant (12) had *"heard of people"* (12) exhibiting symptoms of OT, and another participant (7) revealed they "*possibly*" observed an athlete OT that led to a subsequent recovery period lasting 6–9 months. Interestingly, participant 7 referred to this occurrence as OR and not OT or OTS.

> *"I make it very clear that the medical overtraining I have not seen with strength sport athletes"* (5).
>
> *"I haven't seen anyone experience it"* (3).
>
> *"From a performance perspective, no"* (2).
>
> *"Overtrained? I've heard of people... I don't know of anybody directly myself"* (12).
>
> *"I don't think I've experienced overtraining… just doing too much powerlifting is very, very hard to do unless you are doing something insane with max testing all the time… because powerlifting just isn't that much work"* (6).
>
> *"It's not something I see often, or barely at all"* (14).

OTS might exist according to participant 8, but is unlikely within the strength sport domain, elaborating that some athletes could work at a greater relative load/intensity and still achieve performance improvements without the risk of OT/OTS developing.

> *"So, I think it does exist, but I don't see many lifters, my lifters, who are really overtraining to be honest… and I think some could push themselves a bit harder"* (8).

4.7.6 Commitment

Four participants (5,6,10,12) discussed the relationship between training hard and being a successful athlete. For coach 12, a blurred line between commitment and OT exists. For coach 5 though, a *"train at all costs"* attitude could be considered a risk factor for OT.

> *"We had this mentality instilled in these kids from an earlier age of you have to work hard. The hardest worker or the best. There's this, this valuation of effort over results"* (5).
>
> *"Is it overtraining or just work ethic?"* (12).

4.8 Discussion

The aim of this study was to examine high-performance strength coaches' experiences of OT/OTS and to provide a new way of understanding and conceptualising these concepts in strength sports. Results of this investigation provide important contextual evidence of training maladaptation from the perspective of the strength sport coach; an area of research not yet explored in this domain. Findings demonstrated that strength sport coaches typically revealed different experiences and understanding of OT/OTS and are unaware of expert consensus literature. Findings also note the importance of collaboration between researchers, academics and coaches when developing a holistic approach to understanding OT/OTS.

4.8.1 How Did Coaches Define Overtraining?

Definitions between OT and OTS were interchangeable. Participants described aspects of training maladaptation in a detailed but diverse way, with little to no reference to accepted terminology provided by expert consensus. Similarly, there was a lack of cognisance relating to accepted diagnostic criteria used for the objective identification or diagnosis of OTS. Moreover, participants seemed unaware that these existed. On occasion, participants did, albeit indirectly, acknowledge the difference between OT and OTS, using terms such as "physiological OT" and "fatigue syndrome" to describe training maladaptation indicative of OTS. However, the term "overtraining syndrome" was not used by any participant at any time. "Overtraining" on the other hand was used colloquially to refer to the *act* of training excessively. OT was differentiated from OR based on outcome, with OR considered a planned and intentional training tool where short-term periods of elevated training demand resulted in a positive training outcome, and OT being a training error resulting in maladaptive response. The terms FOR or NFOR were not used at all by any participant.

Short-term increases in training demand can induce functional overreaching (FOR) leading to improved physical capabilities. However, NFOR or the OTS occur when high training-demand is undertaken for extensive periods without sufficient recovery. In this case, it is the time-course to recovery from impaired performance that provides the distinction between NFOR and OTS; NFOR requires *weeks to months* of performance restoration, whilst OTS can require *several months* (Cadegiani & Kater, 2017; Halson & Jeukendrup, 2004; Meeusen et al., 2013). Previous research has accepted that a lack of consistent terminology and definitions is a major concern for understanding the aetiology of OTS, and that a lack of consistency might hinder both the ability to compare results of research studies and apply such findings in practice (Budgett et al., 2000; Grandou et al., 2021; Halson & Jeukendrup, 2004). This is illustrated in the literature by the use of the term *overtraining* when referring to both the prescription of a short-term resistance training protocol where no incidence of OTS was reported (Sterczala et al., 2017), and also to describe training protocols purposely designed to induce OTS (Fry et al., 2000b). Divergent use of terminology elucidates confusion when determining OT and OTS and can lead to potential misdiagnosis (Budgett et al., 2000). In an attempt to improve the understanding of OTS, broader, alternative terminology has been proposed, such as the "unexplained underperformance syndrome" (Budgett et al., 2000) and "paradoxical deconditioning syndrome" (Cadegiani & Kater, 2019a). These have failed to gain traction within the field but do demonstrate the multiple attempts made to address terminology of OT/OTS. Such varied terminology may be a contributing factor for the range of definitions provided by high-performance coaches in this study.

4.8.2 How Prevalent Did Coaches Consider Overtraining to Be?

Participants of this study considered prevalence of OT/OTS to be low; with few observing or encountering overtrained athletes in their respective sport. Moreover, many participants considered it unlikely that strength sport athletes would experience chronic maladaptation indicative of OTS. In most cases, participants seemed unconcerned about OT/OTS and at times suggested athletes could work at a higher relative load/intensity than is typical of their current training, without deleterious effects.

Studies from endurance sports have elucidated NFOR/OTS prevalence to be 7–21% during a training monocycle, although it is acknowledged that these figures are estimates (Halson & Jeukendrup, 2004). The evidence for prevalence of OTS within both strength sports and resistance training is very low, with only limited cases reported (Bell et al., 2020; Grandou et al., 2020). However, a lack of experimental research may be a contributing factor to such low prevalence, and further exploration will help to inform more clearly the dichotomous findings between strength and endurance populations. Cross-sectional survey research has demonstrated that symptoms of unexplained underperformance reported by competitive strength athletes typically last for only short periods of time (1 week to 1 mo = 43.8%), with fewer reporting training maladaptation indicative of NFOR (1–3 mo = 13.1%) or OTS (>4 mo = 4.7%) (Grandou et al., 2021). However, whilst this study (Grandou et al., 2021) provides important contextual information relating to training maladaptation and prognostic symptoms of OTS from the perspective of the strength sport, caution should be advised when interpreting these results. Response and recency bias may impact self-reporting of symptoms. Moreover, this study did not control for responder misinterpretations of "unexplained underperformance", and as such it is possible that conditions relating to low energy availability or incidence of acute illness may have contributed towards such symptoms. Further experimental research is needed to accurately elucidate the prevalence, symptoms, and experiences of NFOR/OTS within strength and resistance sport contexts.

4.8.3 What Symptoms Did Coaches Associate with Overtraining?

Several symptoms were perceived as indicators of OT/OTS by participants of this study. For a small number of participants, performance change was an important manifestation of OT/OTS, whereas for others, performance outcome was less important. Overall, references to performance were often not explicit; instead, performance alterations were contextualised within discussions relating to other symptoms: physiological manifestations such as overuse issues and increased muscle soreness, or psychological symptoms such as reduced readiness to train or altered psycho-emotional state. The most frequently cited symptoms provided by participants of this study related to musculoskeletal injury as a result of overuse, and symptoms of general fatigue.

NFOR and OTS present with or without physiological and psychological symptoms (Halson & Jeukendrup, 2004; Meeusen et al., 2013) and several proposed biochemical and pathophysiological markers have failed to prospectively elucidate OTS (Cadegiani & Kater, 2017; Halson & Jeukendrup, 2004). Moreover, common symptoms exhibited in overtrained endurance athletes might not be indicative of those exhibited within strength sport athletes (Fry & Kraemer, 1997; Meeusen et al., 2013). Previous research has highlighted risk factors, symptoms and mechanisms that may assist in the detection of NFOR/OTS within strength sports and resistance training, however, no single diagnostic tool has been determined, and further research is required (Bell et al., 2020; Grandou et al., 2020, 2021). It is accepted that aerobic and resistance exercise protocols can elicit different biological responses, likely due to the contrasting adaptations created by each mode of exercise. This may explain, in part, why both the symptomatic profile and response to NFOR/OTS might differ between strength and endurance athletes (Bell et al., 2020; Fry & Kraemer, 1997; Grandou et al., 2020).

Risk factors for the onset of NFOR/OTS in strength sports include the continued pursuit of high-intensity or high-volume and monotonous resistance training and/or training to muscular failure, as well as prolonged low energy availability and/or carbohydrate consumption (Bell et al., 2020; Grandou et al., 2020, 2021). Several performance, neuromuscular, and biochemical mechanisms have been proposed as markers to determine NFOR/OTS in both strength sports and resistance exercise, but no single test or method has yet been able to identify either state (Bell et al., 2020; Grandou et al., 2020). Further investigation using well-designed protocols, under both experimental conditions and within an applied context, will help to reduce the negative impact of NFOR/OTS on strength performance.

Impaired muscle recovery and dysfunctional muscle response have been suggested as predictive characteristics of OTS (Cadegiani & Kater, 2019c). However, musculoskeletal issues resulting from high training demand might be the result of acute exercise-induced tissue microtrauma leading to acute training maladaptation or the cumulative effects of OR rather than OTS (Aicale et al., 2018; Grandou et al., 2021), therefore, caution is advised when diagnosing OTS based on the presence of musculoskeletal issues alone. However, coaches should monitor training load for manifestations of musculoskeletal aches and pains regardless, to ensure optimal adaptation to resistance exercise and to reduce risk of orthopaedic injury, as this can be equally as debilitating as OTS and both would require substantial recovery time (Meeusen et al., 2013).

Whilst performance decline is considered the “gold standard” symptom of OTS, decreased performance and/or increased perceived effort at a given relative intensity are also typically observed during periods of acute fatigue and FOR (Grandou et al., 2021). Premature reductions in training based on the presence of short-term performance decrement or in the presence symptoms of general fatigue might lead to a miscalculation in training. Currently, OTS can only be diagnosed in the presence of prolonged maladaptation leading to a decrease in performance during training or competition lasting several weeks to months (Halson & Jeukendrup, 2004; Meeusen et al., 2013), and whilst a decline in performance associated with OTS is likely to be accompanied by symptoms of generalised fatigue, the presence of fatigue in itself is not necessarily synonymous with OTS (Grandou et al., 2021). Therefore, measures of generalised fatigue should only be included within a pragmatic, multidimensional diagnostic tool when used to identify OTS.

Participants in this study made occasional reference to a possible causal relationship between OT and disturbed sleep. Sleep loss can have a significant detrimental effect on readiness to train, motivation, cognition, and sports performance, and as such, monitoring of sleep has been proposed as a useful tool for early detection of performance decrement (Halson, 2014). Additionally, stress and anxiety caused by increased training demand and/or competitive schedule, as well as stress caused by underperformance, can result in sleep disturbance (Lastella et al., 2018). Furthermore, sleep is an essential component of restoration and recuperation, therefore, it is feasible that sleep loss could also accelerate symptoms of NFOR/OTS by reducing recovery capacity during periods of increased training demand (Lastella et al., 2018). However, it has also been argued that a relationship between NFOR/OTS and sleep disturbance could be coincidental (Fullagar et al., 2015). Further research in this area will elucidate the possible relationship between sleep disturbance and OTS, or the validity of sleep loss as a predictor of OTS.

4.8.4 How Long Did Coaches Consider Was Necessary to Recover from Overtraining?

Perhaps the most dichotomous thinking between participants and accepted expert consensus related to time needed for performance restoration following symptoms of OT. For many participants, recovery from OT necessitated days to ≤2 weeks of recovery, with only a single reference to longer convalescence periods. The general consensus from participants was that whilst OT was associated with under-recovery and reduced motivation to train, such symptoms lasted only for a short duration of time.

Current expert consensus suggests that OTS is characterised by the persistence of underperformance lasting several weeks to months, or in some cases even longer (Meeusen et al., 2013). Moreover, that NFOR requires several days to weeks to recover from. By this rationale, participants elucidated a restorative time-course more analogous to acute fatigue or OR, but not OTS. Of course, it has already been discussed that participants in this study identified OT more as the *act* of participating in high-demand training, and displayed little understanding of true OTS, which could in part, help to explain the reference to shorter recovery durations. This further illustrates the lack of awareness and understanding of accepted terminology.

4.9 Practical Applications

This study provides important contextual evidence relating to the understanding of training maladaptation from the perspective of the high-performance strength sport coach; an area of research not yet explored in depth. The inconsistent interpretations provided by participants demonstrates the need for the provision of accessible information in a way that allows accurate identification of NFOR and/or OT/OTS within a practical setting, thereby facilitating the successful planning and organisation of training and performance.

Previous literature has highlighted the importance of an *evidence-informed* approach to high-performance sport science where collaboration between researchers and stakeholders (including coaches and support staff), is key for the development of best practice (Coutts, 2017). This study has indicated (within the high-performance strength sport domain), that coaches are at times unfamiliar with the underpinning terminology, concepts and paradigms of

OT/OTS. Consequently, a more robust, iterative system of knowledge translation may be required to help strength sport coaches understand the nuances of OT/OTS to support decision-making and bridge the gap between research and applied practice. Whilst academics rank peer-reviewed journals highly when obtaining scientific evidence, coaches and high-performance support staff are more likely to report a greater propensity towards informal communication (Malone et al., 2019). Consequently, the development of coach educational resources, peer discussion and discussion relating to shared experience may be a viable option to improving the understanding of research to practice for OT/OTS.

4.10 Study Strengths and Limitations

Coaches provided real life insight and experiences of OT/OTS that will underpin and develop further understanding within applied practice. This study is the first to analyse information about experiences of OT/OTS within a group of strength sport coaches and highlights current understanding and worldview within this group. Moreover, this study utilises a qualitative analytical method that, whilst flexible and reflexive, allows for analysis in a systematic and precise way. The findings of this study should serve as a catalyst for further investigation in this area of research.

Whilst this study offers new insight into OT/OTS, it is recognised that limitations do exist. Inclusion criteria ensured that the sample of participants derived from high-performance strength sports, thereby creating a level of homogeneity. Future research may benefit from analysing coaches' perspectives from amateur athletic populations as well as from a broader scope of sports (intermittent, concurrent or endurance) which has not yet been performed. Recruitment followed an opportunity, snowball approach, with a heavy reliance on social media distribution. Whilst this provided a fair and unobtrusive recruitment strategy, it might also have biased participants who met all necessary criteria and were quick to respond to recruitment information. It might also have excluded those who were eligible to participate, suitably experienced and appropriately qualified, but not attached to social media communication, and therefore unaware of the opportunity.

Chapter 5: Study 3 - "I Want to Create So Much Stimulus That Adaptation Goes Through the Roof": High-Performance Strength Coaches' Perceptions of Planned Overreaching

This chapter is based on the following peer-reviewed publication: Bell, L., Ruddock, A., Maden-Wilkinson ,T., Rogerson, D. "I Want to Create So Much Stimulus That Adaptation Goes Through the Roof": High-Performance Strength Coaches' Perceptions of Planned Overreaching. Front. Sport. Act. Living 2022, 4. doi 10.3389/fspor.2022.893581

5.1 Rationale

Findings from study one revealed that NFOR is unlikely to occur in observational studies using 'real world' training approaches. Study two provided important contextual evidence relating to the understanding of training maladaptation from the perspective of the high-performance strength sport coach; an area of research that had not yet explored in depth. The main finding from study two was that high-performance strength coaches were not concerned about OT/OTS, and at times, believe that strength athletes could work at a higher relative load/intensity than is typical of their current training, without deleterious effects. Findings were in agreement with those from study one where the risk of training maladaptation appeared to be lowest in research utilising real world training programmes. Based on these findings, the primary aim of study three was to explore how high-performance coaches plan periods of highly demanding resistance to induce FOR but avoid NFOR/OTS. A greater understanding of the ways in which high-performance strength coaches programme such training would inform future experimental research where there is a lack of standardised approach. As a result, study three sought to gather information and insight from real world strength coaching to inform the development and design of training interventions that could be used in future research.

5.2 Abstract

Functional overreaching (FOR) occurs when athletes experience improved athletic capabilities in the days and weeks following short-term periods of increased training demand. However, prolonged high training demand with insufficient recovery may also lead to non-functional overreaching (NFOR) or the overtraining syndrome (OTS). The aim of this research was to explore strength coaches' perceptions and experiences of planned overreaching (POR); short-term periods of increased training demand designed to improve athletic performance. Fourteen high-performance strength coaches (weightlifting; $n = 5$, powerlifting; $n = 4$, sprinting; $n = 2$, throws; $n = 2$, jumps; $n = 1$) participated in semistructured interviews. Reflexive thematic

analysis identified 3 themes: *creating enough challenge*, *training prescription*, and *questioning the risk to reward*. POR was implemented for a 7-to-14-day training cycle and facilitated through increased daily/weekly training volume and/or training intensity. Participants implemented POR in the weeks (~5–8 weeks) preceding competition to allow sufficient time for performance restoration and improvement to occur. Short-term decreased performance capacity, both during and in the days to weeks following training, was an anticipated by-product of POR, and at times used as a benchmark to confirm that training demand was sufficiently challenging. Some participants chose not to implement POR due to a lack of knowledge, confidence, and/or perceived increased risk of athlete training maladaptation. Additionally, this research highlights the potential dichotomy between POR protocols used by strength coaches to enhance athletic performance and those used for the purpose of inducing training maladaptation for diagnostic identification.

5.3 Introduction

Optimal performance in strength sports is achieved through careful manipulation of training and recovery and facilitated through strategic resistance exercise programming relative to competition schedule (Storey & Smith, 2012). To invoke the physiological adaptations necessary to achieve a meaningful standard of performance, the training process must provide an appropriate stimulus without training maladaptation (DeWeese et al., 2015a). In strength sports such as weightlifting, powerlifting, and maximal effort throws, short-term periods of increased training demand have been reported to improve characteristics that contribute to optimal performance, such as maximal strength, impulsiveness, and rate of force development (Bazyler et al., 2017a, 2018; Pistilli et al., 2008; Travis et al., 2020b; Zourdos, Jo, et al., 2016). These short-term, concentrated "mini preparation" training cycles have been referred to as planned overreaching (POR), or simply "overreaching" in the literature (Meeusen et al., 2013; Pistilli et al., 2008; Stone et al., 2021). POR is typically implemented into the athlete's training programme through a deliberate and often dramatic increase in training volume, facilitated via multiple daily training sessions and/or training intensity (Pistilli et al., 2008; Storey & Smith, 2012; Travis et al., 2020). Moreover, POR is often undertaken during competition and/or peaking phases of a training schedule for several days (7–14 days), separated by longer periods of normal training or tapering to reduce the risk of maladaptation (Pistilli et al., 2008; Stone et al., 2021; Travis et al., 2020)

The objective of POR is to achieve functional overreaching (FOR) which is characterized by performance improvement above the initial baseline (DeWeese et al., 2015b), observed only after an initial period (2–5 weeks) of performance decline from baseline (DeWeese et al., 2015b; Kreher & Schwartz, 2012b; Meeusen et al., 2013; Pistilli et al., 2008). Non-functional overreaching (NFOR) is characterized by impaired performance lasting several days to weeks, with no performance improvement above the initial baseline (Halson & Jeukendrup, 2004; Meeusen et al., 2013). During prolonged or excessive training without sufficient recovery, the overtraining syndrome (OTS) may occur (Meeusen et al., 2013). The OTS is characterized by a long-term reduction in performance lasting several weeks to months (Meeusen et al., 2013). To date, no single test or assessment has been developed that can reliably detect the transitory point where periods of increased training demand such as POR result in either FOR or NFOR/OTS, making it difficult for coaches to identify optimal training demand to achieve FOR and avoid maladaptive states such as NFOR/OTS (Bell et al., 2020; Fry & Kraemer, 1997; Grandou et al., 2020). The latest consensus, in the scientific community, suggests that OTS and NFOR can only be differentiated by retrospective recovery time-course, and not the type of training stress, the magnitude of impairment, or profile of symptoms (Meeusen et al., 2013).

Previous research exploring the effects of POR in strength athlete populations has focused largely on prospective cohort (Bazyler et al., 2017; Fry et al., 1993, 2000a; Haff et al., 2008;

Hartman et al., 2007; Khlif et al., 2019; Suarez et al., 2019; Warren et al., 1992) and longitudinal observational studies involving weightlifting athletes (Fry et al., 1994d; Häkkinen et al., 1987, 1989), as well as case studies involving both weightlifting (Bazyler et al., 2018; Travis et al., 2020b) and maximal effort throws athletes (Bazyler et al., 2017a). These study designs facilitate the assessment of exposure to tailored POR protocols, as well as the analysis of baseline data at different time points with or without manipulation of the training environment. However, it can be difficult to ensure consistent assessment of participants at each time point during the research, especially during observational research. Moreover, the control of confounding variables can also be a challenge. Therefore, whilst these studies provide evidence for the potential causative inference between undertaking POR and the resulting performance, they cannot prove causality (Sedgwick, 2013).

Improved sport-specific performance (i.e., weightlifting, throws) and/or general measures of athletic performance indicative of FOR (i.e., maximal strength) has been reported in some studies utilizing POR (Bazyler et al., 2017a; Fry et al., 1993, 2000a; Häkkinen et al., 1989; Pistilli et al., 2008; Suarez et al., 2019; Warren et al., 1992). However, performance plateau or NFOR has been reported in others (Fry et al., 1998, 2006, 1994c, 1994b; Purdom et al., 2021). Overall, the number of studies reporting performance improvement after a period of high training demand (i.e., FOR) outweigh those that have observed NFOR (Bell et al., 2020; Grandou et al., 2020). There is only minimal evidence that true OTS has occurred in either competitive strength athletes or in athletes undertaking resistance-based exercise (Bell et al., 2020; Grandou et al., 2020, 2021). Moreover, high-performance strength coaches perceive both the risk and prevalence of OTS within their sport to be low (Bell et al., 2021).

In high-performance strength sport, periodisation is often viewed as the “gold standard” approach to training theory, used to maximize physiological adaptations whilst simultaneously avoiding the OTS (Plisk & Stone, 2003). Although different models exist, a central tenet of periodisation is that training is divided into a number of focused phases of training, structured and designed to achieve peak performance at specific timepoints (Suchomel et al., 2018). Moreover, periodisation is built on the implicit assumption that the magnitude and time course of physiological adaptation can be predicted (Suchomel et al., 2018). Whilst there is evidence to suggest that systematic variation of training can lead to improvements in athletic performance, there is limited evidence to suggest that a superior framework of periodisation exists, or that periodisation is superior to non-periodised training (Afonso et al., 2019; Kataoka et al., 2021; Kiely, 2018). There is little agreement on a universally accepted definition of periodisation, and the term "periodisation" is often used interchangeably with "programming," making it difficult to determine it efficacy against non-periodised approaches (Afonso et al., 2019; Kataoka et al., 2021). Further, when the physiological response to structured training is analyzed at an inter-individual level, athletes typically exhibit variability in training adaptations (Kiely, 2018), making it difficult for the coach to predict how athletes might adapt to structured training. There is a clear scarcity of research investigating periodised training, large heterogeneity between research studies, and a lack of studies investigating the accuracy of predicted adaptations that require further investigation. This presents a problem for strength coaches who intends to use structured periods of high training demand or seek the "best" periodisation framework to achieve FOR and avoid NFOR/OTS, as the specific response to such training cannot easily be predicted and is highly variable (Afonso et al., 2019; Kiely, 2018).

A lack of understanding of the terminology and conceptualization of OTS between expert consensus, sports science researchers and strength coaches have highlighted the need to develop evidence-informed collaboration between strength coaches and sports scientists (Bell et al., 2021). Without guidance from coaches and practitioners, research may not fully elucidate the complexity of the training response to POR, or the multidimensional dilemmas faced by strength coaches when working with high-performance athletes. Previous commentary has highlighted that the best coaches are often years ahead of sports science research when it comes to the prescription and supervision of individualized training (Haugen, 2021). However, research exploring the "secrets" of the athlete training process from the perspective of the coach within sports science literature is limited, and whilst there is an ever-increasing amount of empirical research dedicated to optimizing athlete training practices, there remains a considerable gap between science and good practice (Haugen, 2021; Haugen et al., 2021). As such, involving coaches in the development of knowledge relating to POR is fundamental to improved understanding. Therefore, this study aimed to explore high-performance strength coaches' perceptions of POR and to provide a new way of understanding and conceptualizing the prescription of POR in practice.

5.4 Materials and Methods

5.4.1 Approach to the Problem

A qualitative research design was adopted for this study as it enables the exploration of experiences arising from human behavior (Smith & Sparkes, 2016b). A semistructured interview format was selected to provide a systematic but flexible framework of inquiry to ensure comprehensive information collection (Tenenbaum & Driscoll, 2005). Semistructured interviews are considered an appropriate qualitative research tool where perceptions and opinions of participants can be complex, nuanced, and encompass values, intentions, and ideals (Kallio et al., 2016). Effective semistructured interviews facilitate a dynamic and iterative interaction between interviewer and interviewee (DeJonckheere & Vaughn, 2019) and are designed to promote a deep exploration of participants' experiences and attitudes toward the topic of interest (Jamshed, 2014). Therefore, throughout each interview, participants were encouraged to draw upon their own experiences and to provide experiential responses. Data were analyzed using reflexive thematic analysis using guidelines provided by Braun & Clarke (2006), which facilitated the identification, organization, and subsequent analysis of qualitative data into meaningful patterns (Braun & Clarke, 2006; Nowell et al., 2017).

5.4.2 Participants and Sampling

After ethical approval [ER16222001], volunteers provided informed consent to participate in the study which was conducted according to the 7th revision of the Declaration of Helsinki (World Medical Association, 2013). Fourteen high-performance strength coaches were recruited using an opportunity sampling approach. Participants represented a cross-section of coaches from strength sports: weightlifting; $n = 5$, powerlifting; $n = 4$, sprinting; $n = 2$, throws; $n = 2$, jumps; $n = 1$. Participants were considered high-performance strength coaches if they met the inclusion criteria of ≥ 3 years' experience of coaching to at least national standard in a strength sport (which were defined for the purpose of this research as weightlifting, powerlifting, sprinting, jumps (e.g., long jump, triple jump) or throws sports (e.g., hammer, discus, javelin). A descriptive profile of each participant is located in Table 7. Educational achievement ranged from high school qualifications to doctorate, with 6 participants possessing an undergraduate degree in a relevant subject area as their highest academic qualification, and 5 possessing a postgraduate degree in a related field. Participants held appropriate national governing body certifications, with most also in possession of a strength and conditioning accreditation (e.g., National Strength and Conditioning Association, United Kingdom Strength and Conditioning Association). The sample size deemed appropriate for this study was led by the principle of data saturation (Saunders et al., 2018). An initial non-probabilistic sample size of ≥ 6 participants was projected to achieve information redundancy and therefore fail to provide additional novel information (Guest et al., 2006). However, because data saturation is difficult to determine before analysis (Braun & Clarke, 2021), participants were continuously recruited until no new themes were identified and interviews failed to return new or novel information.

Table 7. Descriptive characteristics of participants

Participant identification number	Sport	Experience (years)	Experience level
1	Powerlifting	15	International
2	Powerlifting	6	National
3	Weightlifting	4	International
4	Weightlifting	12	International
5	Powerlifting	10	International
6	Powerlifting	5	International
7	Weightlifting	20	International
8	Sprints	10	International
9	Jumps	13	International
10	Weightlifting	9	International
11	Throws	21	International
12	Weightlifting	57	International
13	Throws	15	International
14	Sprints	4	International

5.4.4 Procedure

Interviews were collected by the principal investigator (L.B.) either online or face-to-face depending on geographical location and availability. Due to the exploratory nature of the research, a semistructured interview approach was chosen to facilitate flexible and in-depth information collection whilst remaining objective and focused on the research question (Kallio et al., 2016). An interview guide was developed by the principal investigator as part of a broader qualitative exploration into strength training practices in high-performance coaching and refined and adapted during pilot interviews (see Appendix 1 for a copy of the interview guide). During each interview, the lead investigator collected detailed field notes to act as prompts for further questions, and to ensure topics were explored in sufficient depth. Participants were encouraged to answer questions comprehensively, providing detailed experiences and examples. Online interviews were recorded using European Union General

Data Protection Regulation-compliant software (Skype Ltd, version 15, Luxembourg). Face-to-face interviews were conducted in a mutually agreed, unobtrusive environment, and audio was captured using a digital voice recording device (Zoom, Hn1 digital voice recorder 2.0, UK). Interviews were transcribed verbatim and both audio recordings and transcripts from each interview were exported to a password-protected external hard drive (Seagate Technology PLC, Fremont, California, USA) for storage. Participants were randomly assigned an identification number between one and 14 (using a random number programme) so that personal information could be anonymised during publicizing of results.

5.4.5 Reflexivity

The principal investigator of this research is a Senior Lecturer in sport and exercise science with both practical experience and research interest in strength sports, and who has previously published qualitative research using reflexive thematic analysis. The primary research question was developed as part of a wider investigation into the understanding of NFOR/OTS in strength sports from the perspective of the high-performance coach; a topic that lacks qualitative analysis.

In qualitative research, *reflexivity* is an integral aspect of transparency during qualitative research practice (Korstjens & Moser, 2018) and acknowledges how the relationship between researcher and participant might influence the construction of knowledge during the research process (Nyirenda et al., 2020). To enhance trustworthiness and reflexivity, the background of the principal investigator was made transparent to participants prior to each interview. Moreover, the principal investigator sought to remove any pre-conceived assumptions relating to the research topic and distinguish their own ideas and experiences from those held by participants to aid objectivity during information collection and analysis (Price & Martin, 2018). To strengthen the credibility, accuracy and trustworthiness of this research, an audit trail of notes made during each interview were maintained, as well as the development of a code book, and notes made during research team meetings.

5.4.6 Data Analysis

Interview transcripts were exported to NVivo Pro (v11.4.1.1064, Flexera Software LLC; Itasca, IL, USA) and analyzed using reflexive thematic analysis as described by (Braun & Clarke, 2006). The first stage of analysis involved repeated listening to interview recordings, as well as reading of transcripts and field notes. During this stage, sections of text from each transcript were highlighted if they provided preliminary "points of interest" based on overall meaningfulness and relevance. These initial ideas were used to develop codes; labels assigned to aspects of the dataset that summarize important concepts and have relevance to the research question (Braun & Clarke, 2006; Nowell et al., 2017). Next, codes were organized into broad themes that helped to categorize important information related to the research question into meaningful patterns. Subthemes were developed to assist in organizing the large dataset into specific elements and to aid in the reporting of results (Braun & Clarke, 2006).

When research is aimed at informing practice, trustworthiness (a term used synonymously with reliability and validity within qualitative research), is an important step to ensure applicability of findings (Nowell et al., 2017; Roberts et al., 2019). To ensure trustworthiness, themes and subthemes were reviewed and refined throughout the data analysis process, in that they were updated, amended, deleted, or merged regularly as recommended by Braun & Clarke (2006). A codebook was created and updated by the principal investigator to facilitate reflexivity and objectivity, and to maintain an audit trail of data saturation (Braun & Clarke, 2020; Guest et al., 2006). To enhance methodological rigor, members of the research team each individually and blindly coded a sample transcript at the early stages of analysis, discussed their interpretation of data patterns and proposed themes during a research team meeting (Nowell et al., 2017). This process allowed scrutiny of data and an opportunity to consider alternative interpretations (Cutcliffe & McKenna, 2001). Additional research team meetings were organized at regular and important intervals during the analysis process, and written records were maintained to develop an audit trail of methodological decisions (Nowell et al., 2017). In the final stage of analysis, themes were confirmed by all members of the research team once it was determined that they were sufficiently clear, comprehensive, and fully captured the overall content of the data (Braun & Clarke, 2006; Nowell et al., 2017).

5.5 Results

The central concept of *planned overreaching* was organized into three themes to reflect the objectives of the research: *creating enough challenge, training prescription*, and *questioning the risk to reward*. Subthemes were developed to help manage the large amount of data and assist in the publicizing of information (see Figure 11, for a schematic representation of themes). To assist with the broadcasting of results, anonymised quotations have been used within the main report, attributed to the corresponding participant using the unique identification numbers presented in Table 7. Additional punctuation and parenthetical text have been added to direct quotations where required to improve comprehension.

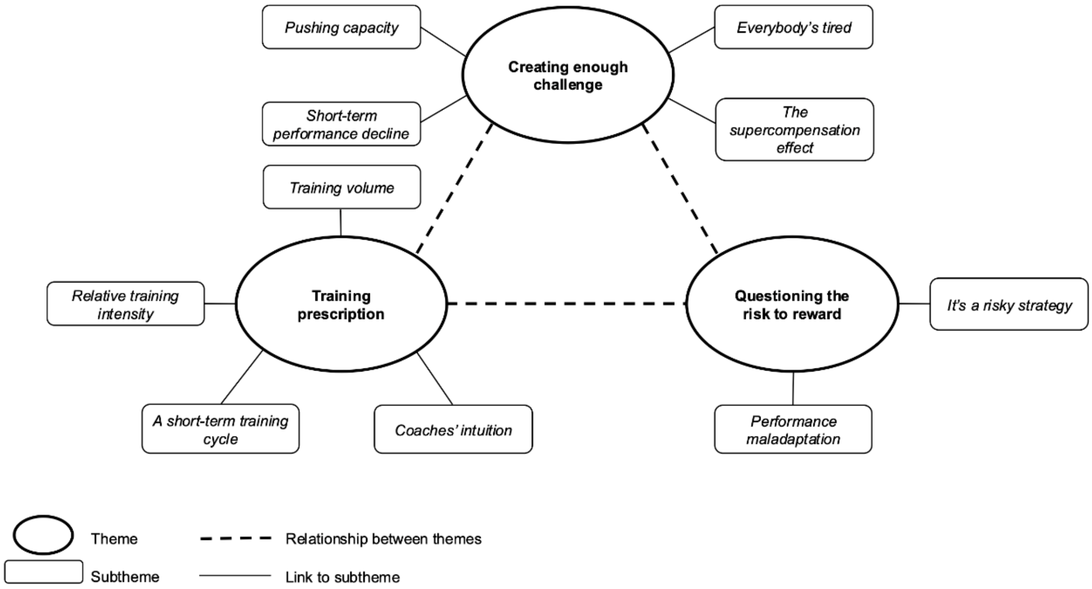

Figure 11. Schematic diagram of themes and subthemes

5.5.1 Creating Enough Challenge

In this theme, participants described POR as an opportunity to intentionally increase training demand to invoke the physiological adaptations that would result in positive performance improvement. Participants described how POR should "*overload*" and "*test*" the athlete, and that feeling "*beat-up*" and "*fatigued*" was an anticipated part of the training process. At times, symptoms of fatigue and muscle soreness were used "*as a marker*" to indicate successful training demand, and participants were "*not afraid*" of "*testing*" and pushing athletes "*hard.*" Participants described that whilst it was normal for athletic performance to decrease during, and in the days or weeks following POR, the end goal was to observe performance improvement above initial baseline, or "*supercompensation.*" The terms "*impact week,*" "*super-impact cycle,*" and "*red week*" were used colloquially to describe POR.

5.5.1.1 Pushing Capacity

Participants described the increase in training demand during POR as the "*driver*" of physiological adaptation and an opportunity to "*create enough challenge*."

> "*When you're on this cycle, you're really testing your body*" (11).
>
> "*The purpose (of planned overreaching) is to push capacity. It's to force adaptation in the body by imposing greater demands than they've had previously, or recently*" (9).

Participants revealed that when undertaking POR, athletes would "*feel shit*" and "*beat up.*" But this was considered both procedural and anticipated. For this reason, it was common for participants to educate or "*warn*" their athletes in advance of the "*serious fatigue*" they would experience during and in the days following POR.

> "*You ramp it up (training demand) to as much as they can deal with... to the point (that) it's about to crush them and kill them, and only then do you let them recover*" (9).

Athletes would be encouraged to "*smash it*" during POR. It was considered the point in the training programme where the athlete should "*push themselves to the limit*" and "*give it everything.*"

> "*Can the lifter hack the training... the hard training? Do they really want it enough to be able to train hard enough to do these impact cycles? Can they handle pushing themselves right to the limit when they feel like they're going to be ill because they've really pushed themselves?*" (11).

5.5.1.2 Everybody's Tired

A consequence of undertaking high training demand during POR was an increase in "*soreness,*" feeling "*beat up*" and looking "*like crap.*" These were considered completely normal outcomes. In most cases, such manifestations were considered "*great markers*" to indicate that training demand was sufficiently challenging.

> "*There are several times with athletes that they feel fucking shit and beat up going into the gym*" (2).
>
> "*I will not wrap my athletes up in cotton wool. Everybody's tired every single day because that's the nature of the beast. But that's almost the aim of training. They're being loaded every other day. Sessions that make them vomit*" (8).
>
> "*Fatigue is a great marker for 'have we done enough to produce the reaction we want… or the adaptations we're hoping for?'*" (13).

5.5.1.3 Short-Term Performance Decline

A decrease in performance both during, and in the days and weeks that followed POR, was often described as just a "*part of training.*" Participants accepted that when undertaking POR, assessments of athletic performance would "*suffer.*" This was viewed as evidence that POR was "*testing enough.*"

> "*In the winter, guys will lift so much that they can't actually jump. Literally*" (10).
>
> "*This is the interesting thing… I want to drive them down physiologically. They've got to feel shit for a long period of time… and I want to create so much stimulus that adaptation goes through the roof. I want that supercompensation*" (14).
>
> "*They'll be grumpy, they'll be sore, and performance is really compromised*" (12).
>
> "*The impact week is where they're working under some serious fatigue*" (1).
>
> "*Along with that overreaching comes fatigue. I don't chase fatigue, but I'm aware it's going to happen… and (I) have no problem with that*" (2).
>
> "*Fatigue is part of training… you can't hide from it*" (8).
>
> "*They're three, four weeks into a fucking heavy block, they've done a lot of volume. I don't want them to be jumping as high. I don't believe that you should be fully or need to be fully recovered from every session. This idea that you need to optimize recovery, that you're fully recovered for every subsequent session? That's just not feasible*" (2).

5.5.1.4 The Supercompensation Effect

Participants revealed that the overall objective was to observe an improvement in performance relative to baseline after the initial period of performance decline. This was referred to as the "*compensation piece," "rebound"* or "*supercompensation effect"* by participants. This effect was expected to occur within "*a couple of days"* to "*4 or 5, weeks"* after completion of the POR training cycle.

> "*If they recuperate properly, they find (that) they've improved… and then they understand that's what it takes to be a top athlete"* (11).

> "*…and then they wouldn't touch the gym at all, and they would get this huge kind of overshoot… the big compensation piece at the other end"* (10).

5.5.2 Training Prescription

In this theme, participants described how they manipulated and organized training variables during POR. Most participants favoured a combination of increased daily/weekly training volume with high relative training intensity to elicit the stimulus necessary to invoke the physiological adaptations necessary to observe a meaningful improvement in performance. POR was typically prescribed for a duration of 7–14 days (maximum 3 weeks) and performed several (5–8) weeks before competition.

5.5.2.1 Training Volume

Most participants revealed that training volume was the main variable by which POR was achieved. Such changes in training volume were facilitated through an increased number of training sessions per week, or through multiple training sessions per day. Increases in volume "*varied by athlete"* but would typically be "*ramped up"* or "*doubled"* to limit recovery between bouts and to "*train under fatigue from the session the previous day."*

> "*Volume is the stimulus and load is the consideration. It's always volume that I'll manage or manipulate during the overreach"* (9).

> "*This is where we look to accumulate more volume*" (2).
>
> "*On impact week we might increase the number of sessions from three or four to five or six. We might have multiple sessions per day… am and pm*" (9).

5.5.2.2 Relative Training Intensity

For some participants, an increase in relative training intensity was considered just as important as training volume to elicit the necessary increase in training demand. For one participant, it was an increase in relative training intensity, increased independent of volume, that provided the stimulus during POR.

> "*I mean, load is probably more important… not so much volume. I'm really looking at quality over quantity… volume is actually driven more toward mediocrity to be honest*" (14).

For many participants though, it was the concomitant increase in training intensity and training volume that provided the "*unique feature*" of POR.

> "*There's always got to be a point in training which is high-volume and high-intensity for you to elicit the right response*" (6).
>
> "*If you're going for maximum volume, you're working up into the 90-95% intensity range… and working up to 100% maximum on your volume*" (11).
>
> "*In the impact weeks, we'll do slightly heavier percentages, maybe for more sets*" (9).

5.5.2.3 A Short-Term Training Cycle

Participants rarely prescribed POR for periods of more than 2 weeks. For most, a 7–14-day training cycle was preferred, however, the specific number of training sessions within that period was dictated by individual athlete "*tolerance*" and response, varying from "*every other day*" to "*multiple sessions per day.*"

> "*The length of the overreach will tend to be eight sessions over fourteen days*" (3).

"*They'd do like a ten-day or two-week block… smashing it for two or three weeks in the gym"* (12).

Importantly, POR was only implemented several weeks before a competition, to leave sufficient time for recovery and adaptation.

"*I would be setting that specific block probably 8 to 4 weeks out (from competition)"* (6).

How frequently POR was applied throughout the overall training programme was dictated by competition schedule. Additionally, the number of POR cycles completed within a training year was also determined by the athlete's previous experience of high training demand and their subsequent response as "*some athletes can tolerate more training and others can't."*

"*I would say two (overreach) cycles in a twelve-week block. No more"* (11).

"*My go-to would be every four to six weeks in a ten to twelve-week phase. On the run-up to the competition, you might have two to three impact weeks"* (9).

For some, POR was a training tool used "*sparingly,"* reserved only for preparation for more important competitions or "*serious blocks"* of training.

"*We don't (overreach) often. It just depends on the importance of the competition"* (3).

5.5.3 Coaches' Intuition

Participants conceptualized POR as a flexible and individualized aspect of training, relying on their "*intuition"* and "*the art of coaching"* to guide the way that POR was organized and prescribed. Whilst there was congruence between participants in the overall objective of POR (to achieve FOR timed relative to competition), the precise strategy, magnitude and duration of a POR cycle was a highly individualized process, conducted using tacit knowledge and previous experience rather than reliance on rigid programming structure or objective assessment and monitoring.

> "*Obviously a part of (planned overreaching) is actually having the intelligence to know when to step back when you need to step back and step forward when you need to step forward"* (14).

> "*These are the types of things you might try: "let's do a block of high-intensity, low volume work (and) see how you respond. Next time. Let's do moderate, moderate" … and you do this for serious blocks to see what system the athlete seems to respond best (to) in terms of increases in overall strength"* (2).

5.5.4 Questioning the Risk to Reward

In this theme, participants described the risks associated with POR: injury, "*burnout"* and/or "*overtraining."* Participants explained that a positive performance adaptation (FOR) was not always guaranteed when undertaking POR: "*some people respond really well… some people break down completely."* Moreover, a lack of knowledge, understanding, time and/or confidence resulted in some participants choosing to avoid using POR altogether in favor of "*less risky"* training methods.

> "*I'm always cautious. The fact is, it's like jumping two-footed into a swimming pool"* (14).

> "*I don't think it's worth pushing an athlete when they are failing to extremes. I've been coached like that. And I got very injured. I'm still dealing with the effects today"* (8).

5.5.4.1 It's a Risky Strategy

Some participants chose to avoid prescribing POR due to a lack of knowledge and/or confidence in their ability to organize training with "*precision"* in a way that elicited a positive performance outcome and avoided maladaptation. Participants described the difficulty in "*hitting the sweet spot."* This was attributed to (1) the highly individualized athlete response to POR and (2) a lack of effective and reliable monitoring tools to proactively assess when training demand was sufficient to elicit the desired effect.

> "*You know, overreaching is a risky strategy"* (6).
>
> "*(Planned overreaching) is not really the kind of strategy that I would do to try and get performance gain. I probably just don't know enough about it… I think you need to be on the ball full time, doing omega waves [heart rate variability] every day, you know, looking at monitoring the sleep, monitoring the nutrition, calorie intake, all that kind of stuff to be able to start understanding that stuff"* (10).
>
> "*I'm always questioning the risk to reward outlook on it… If they were a full-time professional, I think I'd have a lot more time to monitor them and a lot more time to actually go 'let's get a little bit deeper on this"'* (14).
>
> "*Some people respond really well to high-intensity work, high volume work (where) they're doing lots of doubles, triples. Some people break down and don't respond well to that"* (2).

For one participant, limited in-person coaching contact and emphasis on remote/online coaching was provided as a justification for avoiding POR.

> "*You have to overreach with such precision. If I'm working with somebody who I don't see all the time and they're doing it remotely, I don't feel confident enough in my ability to be precise enough with the programming to get that exactly right. I don't think I can. I'm not going to lie to them (the athlete). I say, well, if you do this exactly perfectly, you can be supercompensated in a week? Nah."* (5).

At times, an element of "*hope"* was required when undertaking POR, particularly when performance changes need to be timed accurately relative to competition.

> "*Ultimately, you'd 'hope' that if the overreach is correct then the physical element should (be) supercompensated by the time they get into competition"* (3).

5.5.4.2 Performance Maladaptation

POR was considered by some participants to increase the risk of musculoskeletal injury, attributed to the combined effects of reduced coordination (caused by an increase in fatigue) and insufficient recovery between training bouts.

> "*You're putting the athlete at risk (during overreaching). If you put them to that stage of fatigue through the gym work, then they're just neurally… they're just not coordinated. And when they're doing the running and the jumping work, they're far more at risk of injury at that point"* (10).
>
> "*What's interesting is sometimes they continue to get worse rather than rebound after"* (1).

For one participant, undertaking periods of high-volume training combined with high-intensity training might result in "*burnout"* (a term that they used synonymous to injury).

> "*Powerlifting athletes often do periods of quite high-intensity coupled with quite high-volumes… and these (can) generally lead to drastic improvements in strength in the short-term, but all the time end up in, the term is… "burnout". They just end up with loading issues and injury… and actually, athletes will generally phrase (it) as "got burnt out," but really, it's just, 'got injured'"'* (2).

At times, participants alluded to a "*fine line"* between insufficient, optimal and excessive training demand ("*banging the athlete up a little)*. However, participants were generally dismissive of the risk of long-term performance decline indicative of OTS.

> "*Yeah, it's hard to pick a point where it's not worked… or I've 'overtrained' them"* (3).
>
> "*I haven't had anyone feeling 'pretty broken' yet"* (14).

In many cases, the risk attributed to miscalculation of training during POR was not in the potential maladaptive response caused by excessive training demand, but by a lack of performance improvement caused by insufficient training demand.

> "*I'm always questioning the risk reward outlook on it. Am I putting enough risk in that programme to get the desired reward?*" (14).
>
> "*Worst case scenario hurt the person or just bang them up for a little while and they don't actually super compensate... or you undershoot it and then you just essentially didn't work hard enough... and those outcomes are much more likely than exactly hitting the sweet spot*" (5).

5.6 Discussion

The aim of this study was to examine high-performance strength coaches' perceptions and experiences of POR and to determine how coaches conceptualize POR as a training tool. We identified three themes that provide important practical information regarding POR from the perspective of the strength coach: *creating enough challenge*, *training prescription*, and *questioning the risk to reward*. Findings demonstrate that POR is typically implemented in the weeks preceding competition, achieved through a deliberate and sometimes considerable increase in training volume and/or training intensity, for a period of 7–14 days. A short-term decrease in performance capacity, both during and in the days to weeks following training is an anticipated consequence of POR. Moreover, when combined with symptoms of fatigue, soreness, and reduced motivation to train, short-term performance decline was used as a benchmark to confirm sufficiently challenging training demand. Some participants chose to avoid prescribing POR due to a lack of knowledge, confidence, and/or increased risk of training maladaptation (i.e., musculoskeletal injury). Participants approached the design of POR in an intuitive and individualized way, relying on both tacit knowledge and previous experience to inform programming decisions to achieve the best outcome. Additional findings note the disconnect between POR conceptualized by the high-performance strength coach and the POR protocols used in previous well-controlled research studies.

5.6.1 What Did Coaches Consider the Objective of Planned Overreaching to Be?

Participants conceptualized POR as a tool to induce the physiological adaptations required to achieve a meaningful standard of performance improvement. POR was described as a point within the overall training programme where the athlete could be challenged with intense and frequent overloading of training. As such, participants anticipated that both during, and in the days that followed completion of POR, athletes would experience a relative decrease in physical performance. Additional symptoms of increased general fatigue, musculoskeletal soreness and negative mood were also to be expected and used procedurally to verify that training was sufficiently challenging. Whilst the primary aim of POR was to observe an increase in athletic performance, participants accepted there was an inherent element of both "*hope*" and "*risk*" when undertaking POR, aware that even through carefully organized POR, either a lack of performance improvement (caused by insufficient training demand challenge) or maladaptation (caused by excessive and/or prolonged training demand) could occur.

POR has led to both improved sport specific and general measures of performance indicative of FOR (Bazyler et al., 2017a; Fry et al., 1993, 2000a; Häkkinen et al., 1989; Pistilli et al., 2008; Suarez et al., 2019; Warren et al., 1992). However, POR has also resulted in training maladaptation indicative of NFOR (Fry et al., 1998, 2006, 1994c, 1994b; Purdom et al., 2021). Within expert consensus, the response to overloading training has been described as a continuum, where FOR precedes NFOR and OTS manifests as an extension of NFOR if training persists/recovery is insufficient (Meeusen et al., 2013). However, the response to recurrent overloading training (as observed during POR) is multifactorial and complex, and therefore is likely to be an oversimplification (Kataoka et al., 2022). This is reflected in the findings from this research, as several participants described successful POR (i.e., results in FOR) as a flexible and intuitive process guided by tacit knowledge and experience, as opposed to a rigid approach to programming or reliance on prognostic assessment to guide decision making.

5.6.2 How Did Coaches Organize and Manipulate Training During Planned Overreaching?

Participants implemented POR through an increase in training volume (achieved through increased daily or weekly training) and/or relative training intensity. In many cases, it was the concomitant increase in volume and relative training intensity that provided the unique stimulus necessary to invoke physiological adaptation and subsequent performance improvement. POR was considered a short-term, "impact" cycle, often prescribed for periods of 7–14 days, used sparingly across the competition schedule. No single best practice method of POR was revealed during this research. Instead, POR was individualized to the athlete in an intuitive way, suggesting that the coach's experience is an important factor in successful POR, and not just the increase in training demand. Consequently, participants rarely alluded to detailed changes to specific intensities, exercise selection or total volume.

In contrast to the intuitive, instinctive approach to POR revealed by participants of this research, previous studies have used well-controlled prescriptive high-volume (Fatouros et al., 2006; Lowery et al., 2016; Wilson et al., 2013) and high-intensity (Fry et al., 1998, 2006, 1994a, 1994c, 1994b, 2000b; Nicoll et al., 2016; Sharp & Pearson, 2010; Sterczala et al., 2017) (resistance exercise POR protocols to investigate potential diagnostic markers of FOR and NFOR/OTS. Such protocols have incorporated either single exercise (typically the barbell back squat) (Fry et al., 1998, 2006, 1994a, 1994c, 1994b, 2000b; Nicoll et al., 2016; Sterczala et al., 2017) and multiple exercises (Drake et al., 2017; Fatouros et al., 2006; Kraemer et al., 2006; Lowery et al., 2016; Ratamess et al., 2003; Sharp & Pearson, 2010; Volek et al., 2004), and both traditional strength-based exercises (squat variations, pulls and presses) and sport-specific exercises (snatch, clean and jerk, throwing drills) (Bazyler et al., 2017a; Fry et al., 1993, 2000a; Hartman et al., 2007) have been selected. Overall, the number of studies reporting either no performance maladaptation (i.e., return to baseline) or performance improvement outweigh those that have observed NFOR/OTS (Bell et al., 2020; Grandou et al., 2020). Taken as a body of literature, these protocols indicate which types of training might increase susceptibility to NFOR/OTS, but due to methodological heterogeneity makes comparisons between research studies difficult. Moreover, an absence of follow-up performance assessments, and failure to reliably induce physiological, biomechanical, or hormonal alterations has led to a lack of reliable assessment for the prognostic identification of NFOR/OTS. To date, no standardized POR protocol exists within the literature, however, the development of a single best practice POR protocol might be misplaced given the complexity of high-performance strength training and variability in response to POR.

Participants of this research developed POR with the objective to enhance the physiological adaptations required to achieve a meaningful standard of performance improvement. Conversely, many of the protocols used in previous research studies have been designed not to *improve* physical performance, but to *induce* a state of training maladaptation for the purpose of elucidating diagnostic information. Consequently, current understanding of NFOR/OTS is limited (and likely insufficient) due to incongruence between the mechanisms being explored during previous research and their intended outcome within a practical context. Whilst the number of POR studies reporting return to baseline or FOR outweigh those that have observed NFOR or OTS (Bell et al., 2020; Grandou et al., 2020), it is unsurprising that some types of POR are likely to increase the susceptibility to maladaptation, such as those including repeated use of daily high volume maximal loads with low exercise variation (Bell et al., 2020; Grandou et al., 2020). For example, the most commonly-prescribed protocol used in the literature (10 x 1 repetition at 100% one-repetition maximum squat machine for 14 successive days) was developed as an "*overtraining protocol"* to identify potential markers of training maladaptation, and has reported consistent performance decrements indicative of NFOR or the OTS (Fry et al., 1998, 2006, 1994c, 1994b). However, based on what participants of our research reveal about POR, this protocol does not reflect the typical approach to POR used within a high-performance strength sport training environment to enhance performance. Whilst research designed to induce training maladaptation does provide important contextual information that a dose-response "threshold" might exist (as well as possible markers to identify maladaptation), caution must be given when transferring those findings into the practical training environment, where the design and prescription of POR is more intuitive and flexible.

Previous research has indicated that there is not only variability in the physiological response to different approaches to POR training (e.g., high-volume vs. high-intensity) (Bell et al., 2020; Fry & Kraemer, 1997; Grandou et al., 2020), but that differences might also occur in a group of individual athletes undertaking the *same* training protocol. These differences are likely to be modulated by multiple factors including genotype (Clarkson et al., 2005), sex differences (Hunter, 2016), muscle fiber typology (Bellinger et al., 2020; Lievens et al., 2020), age, and biological maturation (Moran et al., 2017). Additional factors such as level of competition/status (elite vs. non-elite) (Kreher & Schwartz, 2012b) and the athlete's "stress capacity" (i.e., the ability to tolerate the combined effects of training and non-training stressors) (Kenttä & Hassmén, 1998; Stults-Kolehmainen & Bartholomew, 2012) are also likely to play a role in the response to POR. It is therefore completely plausible that some athletes will be more predisposed to the effects of training maladaptation during periods of POR, and therefore POR would need to be individualized to the athlete to achieve an optimal performance outcome. This might, in part, reflect why participants of this study approached the implementation of POR intuitively, and on an athlete-by-athlete basis. Moreover, the high inter-individual and exercise-specific variability in response to POR may in part explain why there is a lack of reliable markers and measures able to detect NFOR/OTS. The absence of a single, reliable marker to detect training maladaptation is unsurprising when this is considered, and future research should explore the inter-individual response to POR to further understanding in this field.

5.6.3 What Did Coaches Consider the Potential Risks of Planned Overreaching to Be?

Participants of this research were largely unconcerned about the risk of NFOR or OTS caused by POR. However, some did consider POR to be a strategy that *could* result in musculoskeletal issues (i.e., injury) if the demands of training were miscalculated. For others, the risk involved in undertaking POR was more related to providing an insufficient training demand (and therefore a lack of challenge) that would not elicit a positive response; a concern attributed to a lack of knowledge and/or confidence in prescribing effective POR.

Previous research has indicated that injury prevalence in strength sports such as powerlifting and weightlifting is relatively low, especially when compared to contact sports (Keogh & Winwood, 2017). Additionally, the prevalence of musculoskeletal injury reported in the strength sport literature is low (Bell et al., 2020; Grandou et al., 2020), with only a single study reporting musculoskeletal injury as a concomitant symptom of maladaptation following POR (Fry et al., 2001). Conversely, high-performance strength coaches consider musculoskeletal injury to be the most common symptom of NFOR/OTS (Bell et al., 2021), and competitive strength athletes who have experienced an unexplained decrease in performance report musculoskeletal issues (i.e., aches and pains) as the most common symptom of maladaptation (Grandou et al., 2021). It is worth noting that musculoskeletal issues have been most frequently reported where the decrease in performance lasted <1 week to 1 month, but not >1 month, suggesting aches and pains are more indicative of acute maladaptation and not actually NFOR/OTS. Whilst the general consensus in the literature is that repeated high-intensity resistance exercise might increase the risk of musculoskeletal and musculotendinous injury, injury epidemiology is multifactorial in nature and differs by both proportional injury rate and severity across strength sports (Keogh & Winwood, 2017). There is currently a lack of research investigating the onset of injuries, the manner in which injuries affect training, and the necessary recovery required after musculoskeletal injury in competitive strength sports (Keogh & Winwood, 2017).

5.7 Practical Applications

The information provided by participants of this research better contextualizes POR from the perspective of the strength coach and demonstrates both the intuitive and individualized nature of high-performance strength sport training. Additionally, this research highlights the potential dichotomy between POR protocols used in practice, and those used for the sole purpose of diagnostic identification of FOR and NFOR/OTS within the literature. Expert coaches exhibit characteristics of knowledge, talent, pedagogy, and perseverance, as well as the procedural ability to transfer information rationally using experience and intelligence (Dorgo, 2009). There is also a high level of intuition in identifying and solving programming errors in an instinctive way (LaPlaca & Schempp, 2020). However, such tacit knowledge is difficult to articulate, and coaches are not always aware of their decision making; rather, it is guided by intuition, instinct and experience rather than theory or pedagogy (Nash & Collins, 2006). Previous research has suggested an ever-increasing body of empirical research dedicated to optimizing athlete training practices, yet there remains a considerable gap between science and best practice (Haugen, 2021; Haugen et al., 2021). Participants of this research described POR as a multifactorial and individualized process, and therefore a complex aspect of sports performance support (Greenberg & Clubb, 2021). Therefore, it appears more appropriate to consider the development of "good" training practices and guidelines rather than a single best practice approach to POR, as multiple solutions appear to exist in the context of POR within the "real world" of strength sports, illustrated by the different approaches described in this research (e.g., high training volume vs. high intensity). Such guidelines would provide a framework of decision-making for coaches who wish to attempt POR with their athletes, but at the same time allow flexibility based on marked inter-individual variability in the response to periods of high training demand. As such, the preceding recommendations have been developed to assist both coaches and sport scientists in the development of POR protocols for research and/or training purposes.

5.8 Strengths and Limitations

Participants of this study provided important contextual information relating to their perceptions and experiences of POR within the strength sport coaching community. This information can be used by coaches to further their understanding about the conceptualization and implementation of POR in a real-world setting. However, this study also provides important guidance for sport scientists who intend to design POR protocols that reflect the multidimensional and complex nature of training practices for the purpose of scientific investigation.

The qualitative nature of this research facilitated a reflexive but systematic approach. Verification strategies involved during the analysis of interviews such as development of an audit trail through maintenance of a code book, research team standardization checkpoints, and member checking enhanced the credibility and trustworthiness of the results. Findings should serve not only as a catalyst for further investigation into the nuances of optimal POR (i.e., leading to improved performance relative to initial baseline), but also as an opportunity for collaboration between coaches and sport scientists to improve overall understanding in this domain.

Whilst this study offers new insight into POR, it is recognized that methodological limitations do exist. The participant pool for this research derived from strength coaches within a homogeneous community. Future research might benefit from the perspectives of a broader scope of coaches (i.e., those involved in sports where strength training is an important, but not the only component of the overall training programme such as intermittent sports or those involving concurrent training methods). The recruitment strategy used for this research followed an opportunity, snowball approach, focused primarily on social media. Whilst this provided an efficient and fair approach to recruitment, it might also have biased participants who regularly accessed social media, whilst simultaneously excluding those who met the inclusion criteria, but were unaware of the opportunity to participate in the research.

Chapter 6: Study 4 - Recommendations for Advancing the Resistance Exercise Overtraining Research

This chapter is based on the following peer-reviewed publication: Bell, L., Ruddock, A., Maden-Wilkinson ,T., Rogerson, D. Recommendations for Advancing the Resistance Exercise Overtraining Research. Appl. Sci. 2022, 12, 12509. https://doi.org/10.3390/app122412509

6.1 Rationale

An important aim of this doctoral programme was to provide sport scientists and practitioners with an actionable and iterative system of OT/OTS knowledge exchange by supporting decision-making (planning of empirical research, planning of successful athlete training programmes) and bridging the gap between research and applied practice. This study utilised a narrative approach to highlight methodological concerns with the existing body of evidence relating to OT/OTS and to propose potential solutions for future research. Such recommendations were developed based on previous findings from this doctoral thesis and acted as scaffolding for the final study of this doctoral thesis (study five). Moreover, the recommendations proposed in this study were developed as an action plan for other researchers intending to undertake rigorous research exploring OT/OTS in strength sports and resistance exercise training. Consequently, the aim of study four was to 1) highlight the conceptual and methodological limitations within some of the current literature, and 2) to propose directions for future research to advance current understanding of OT from the perspective of the sport scientist.

6.2 Abstract

Short-term periods of increased resistance exercise training are often used by athletes to enhance performance, and can induce functional overreaching (FOR), resulting in improved physical capabilities. Non-functional overreaching (NFOR) or overtraining syndrome (OTS), occur when training demand is applied for prolonged periods without sufficient recovery. Overtraining (OT) describes the imbalance between training demand and recovery, resulting in diminished performance. Whilst research into the effects of resistance exercise OT has gathered attention from sports scientists in recent years, the current research landscape is heterogeneous, disparate, and underrepresented in the literature. To date, no studies have determined a reliable physiological or psychological marker to assist in the early detection of NFOR or OTS

following periods of resistance exercise OT. The purpose of this work is to highlight the conceptual and methodological limitations within some of the current literature, and to propose directions for future research to enhance current understanding.

6.3 Introduction

Overtraining syndrome (OTS) is an accumulation of training and/or non-training stress resulting in a decrement in performance capacity, with or without related physiological and psychological signs and symptoms of maladaptation in which restoration of performance capacity may take several weeks or months (Halson & Jeukendrup, 2004; Meeusen et al., 2013). Other than long-term performance decrement, there is no single validated identifier of OTS. Diagnosis requires the exclusion of organic disease, infections, dietary caloric restriction, and insufficient carbohydrate or protein intake (Meeusen et al., 2013). As such, a diagnosis of OTS can only be made once confounding factors have been ruled out (Meeusen et al., 2013). Due to its complex and multifactorial nature, a multidisciplinary approach to understanding and diagnosing OTS is essential (Stellingwerff et al., 2021).

The term "overtraining" (OT) describes the imbalance between training demand and recovery that could result in either diminished performance or an improvement above baseline (Bell et al., 2021; Meeusen et al., 2013). OT is the process of undertaking training with an increase in training volume or intensity of effort, whilst OTS would be a possible outcome of OT. Our recent scoping review (Bell et al., 2020), as well as the explorative systematic review published by Grandou et al. (Grandou et al., 2020), reported minimal evidence of OTS in either competitive strength sports or those undertaking periods of resistance exercise, even after purposeful attempts to impair performance. Our research has also reported that high-performance strength coaches are not concerned with the risk of OTS, and rarely consider such the disorder a consequence of resistance exercise (Bell et al., 2021).

In cases where OT results in performance decrement lasting fewer than several weeks, with no observable performance improvement even after sufficient recovery, the term non-functional overreaching (NFOR) is used (Halson & Jeukendrup, 2004; Meeusen et al., 2013). There is an implication within expert consensus that while OTS shares similarities to NFOR, these conditions cannot be distinguished by the magnitude or type of symptoms, only by retrospective time course to recovery from impaired athletic performance (Meeusen et al., 2013). Functional overreaching (FOR) is considered to be a desirable training outcome where periods of OT lead to an initial short-term reduction in performance, followed by an improvement or "rebound" above the initial baseline (Bellinger, 2020; Carrard et al., 2022). This improvement in performance is only observed after an initial reduction in performance lasting several days (Roete et al., 2021). Interestingly, whilst symptoms of increased fatigue, hormonal disruption, and psychological disturbance (e.g., impaired mood, reduced vigour) are associated with NFOR/OTS, these symptoms may also be present in athletes classified as FOR (Bellinger, 2020). Consequently, FOR can only be differentiated from NFOR/OTS by resulting change in performance and not the symptoms presented.

Research from the endurance sport domain has indicated that the magnitude of performance improvement following FOR is no greater than the improvements observed following the same training without experiencing an initial performance decline (Aubry et al., 2014; Bellinger, 2020). Therefore, intentional attempts to induce a state of FOR through intentional OT might not be required to optimize performance. Nevertheless, high-performance strength coaches regularly use periods of deliberate OT (typically in the weeks preceding competition, referred to as "planned overreaching") to invoke the physiological adaptations necessary to achieve FOR, and consequently, a meaningful standard of performance improvement (Bell et al., 2022a). However, some coaches choose to avoid intentional resistance exercise OT because of a lack of confidence in their ability to detect NFOR, knowledge relating to how OT should be structured to achieve FOR, and uncertainty that OT yields greater performance improvement compared to traditional continuous training. Whilst research into resistance exercise OT has gathered attention from sports scientists in recent years, the field has traditionally focused on the endurance athlete (Cadegiani & Kater, 2017; Halson & Jeukendrup, 2004; Meeusen et al., 2013). Consequently, scientific literature regarding the detection of NFOR and OTS caused by prolonged or excessive resistance exercise is underrepresented (Bell et al., 2020; Grandou et al., 2020).

6.4 Issues with Identifying Overtraining

Previous research has indicated that in endurance sports, OTS might affect 20–60% of athletes at some point in their careers (Halson & Jeukendrup, 2004; Meeusen et al., 2013). However, Weakley and colleagues (Weakley et al., 2022) have cast doubt over those figures, proposing that there are no studies providing objective evidence of performance suppression lasting ≥4 weeks. The current diagnostic tool presented in expert consensus (Meeusen et al., 2013) suggests that for a diagnosis of OTS to be considered, long-term performance suppression and "persistent fatigue or exhaustion" lasting ≥4 weeks are key factors. Whilst performance suppression for <4 weeks might be indicative of NFOR rather than OTS, it might also be reflective of the transient fatigue experienced by athletes in the weeks following OT that might result in FOR given sufficient recovery (Bell et al., 2022a; Travis et al., 2020a). Symptoms of OTS can mimic other diseases, therefore only when confounding factors have been ruled out can a diagnosis be made (Carfagno & Hendrix, 2014). If a diagnosis of OTS is made without the exclusion of confounding factors, misdiagnosis is more likely, and performance decrement experienced by the athlete could be caused by other factors such as illness, insufficient fuelling, or detraining. OTS affects multiple physiological systems and the symptoms presented by athletes vary, suggesting that OTS is a heterogeneous disorder (Cadegiani et al., 2020; Carrard et al., 2022). Existing research has not (and likely will not) yet identified a single reliable physiological or psychological marker to assist in the early detection of OTS (Weakley et al., 2022). Moreover, because OTS can only be differentiated from NFOR by retrospective time-course to performance restoration, the NFOR to OTS threshold is practically indistinguishable.

In our recent review (Bell et al., 2020) we highlighted two cases where resistance exercise OT resulted in a duration of performance decrement potentially indicative of OTS (Cadegiani et al., 2019b; Fry et al., 2006). However, in both cases, methodological considerations need to be addressed. In the study by Cadegiani and colleagues (Cadegiani et al., 2019b), OTS was diagnosed due to prolonged underperformance (classified as ≥10% decrease from previous sport-specific performance), persistent fatigue lasting >2 weeks, and a self-reported increase in sense of effort when undertaking resistance exercise. Whilst this goes some way to indicate an attenuation in performance, the duration of performance impairment was not reported, making a diagnosis of the OTS difficult. Further, compared to healthy participants, those classified as OTS-affected reported lower carbohydrate intake (3 times lower than in participants not classified as OTS-affected) and overall lower energy intake. The authors suggested that OTS could be triggered by the combined effects of high training demand and excessive calorie restriction, stating that “the most remarkable trigger of OTS among high-intensity functional training was the long-term low carbohydrate and calorie intake”. However, expert consensus states that diagnosis of OTS requires excluding factors such as calorie restriction and insufficient carbohydrate intake (Meeusen et al., 2013). Secondly, due to shared pathways, aetiology and symptoms, OTS shares several similarities with relative energy deficiency in sport (REDs); a maladaptive disorder characterized by negative health and performance outcomes triggered by low energy availability (Stellingwerff et al., 2021). Severe or prolonged low energy availability can perpetuate symptoms of performance decline that are indicative of NFOR and low energy availability might blunt training adaptation (Kuikman et al., 2022), therefore decreasing the potential for FOR. It is plausible that participants of this research were suffering from a disruption of physiological processes and compromised performance caused by insufficient fuelling, and not OTS (Logue et al., 2018). However, because energy availability was not reported, this cannot be confirmed.

Fry and colleagues (Fry et al., 2006), investigated if high-intensity OT would result in OTS. The authors defined OT as an increase in training volume or intensity that results in long-term performance decrement i.e., ≥2 wks. A state of OT was determined based on an observed 5% decrease in training-specific criterion (1-repetition maximum squat machine strength assessment). It is worth noting that the performance assessment took place only one week after the completion of the 2-week OT intervention and therefore alterations in performance might simply have been reflective of short-term transient fatigue indicative of the acute adaptive response. In this sense, a lack of follow-up testing did not permit for analysis of individual participant response to OT. Further, the use of a negative 5% performance marker is somewhat redundant considering that the current consensus recommends diagnosis be made on duration ("several weeks to months") and not just the magnitude of performance decrement. The diagnostic tool presented in expert consensus literature (Meeusen et al., 2013) suggests that a >10% decrement in performance would (in part) be necessary to indicate a state of OTS. It is worth noting that arbitrary cut-offs do not determine if the response to training is clinically or practically relevant (Halson, 2014). Again, it is completely plausible that given sufficient recovery, participants might have improved performance relative to baseline and therefore experienced FOR. Follow-up interviews indicated that participants required 2–8 weeks of recovery before they were able to resume "normal" weight training, which the author used to assume the presence of OT. Of course, diagnosis of a complex disorder as severe as OTS based on subjective self-reported reduction in training ability should be taken with caution due to response and recency bias, as well as the potential for athletes to over- or under-estimate the demands of training (Halson, 2014). Moreover, if training demand is reduced prematurely based on the perception of fatigue alone (without corroboration from physiological/performance data), detraining could occur due to early termination of training/insufficient training stimulus (Mujika & Padilla, 2000). Our previous research has indicated that when high-performance coaches prescribe periods of OT, they are not concerned about NFOR/OTS. Instead, they often question whether a miscalculation of training could result in "undershooting" the training stimulus or that they are "not putting enough risk in the program to get the desired reward" (Bell et al., 2022a).

6.5 Developing Resistance Exercise Overtraining Protocols Is a Challenging Task

Studies designed to investigate potential diagnostic markers of NFOR/OTS have incorporated well-controlled but varied resistance exercise OT protocols. Such studies have included both high-volume (Fatouros et al., 2006; Lowery et al., 2016; Wilson et al., 2013) and high-intensity training (Fry et al., 1998, 2006, 2000b, 1994a, 1994c, 1994b; Nicoll et al., 2016; Sharp & Pearson, 2010; Sterczala et al., 2017) that have utilized either single exercise protocols (typically a variation on a squat) (Fry et al., 1998, 2006, 2000b, 1994a, 1994c, 1994b; Nicoll et al., 2016; Sterczala et al., 2017) or multiple exercise training programs (Drake et al., 2017; Fatouros et al., 2006; Kraemer et al., 2006; Lowery et al., 2016; Ratamess et al., 2003; Sharp & Pearson, 2010; Volek et al., 2004). To explore the mechanisms that underpin the response to OT, several of these training protocols have not been designed to improve physical performance (i.e., achieve FOR), but to induce a state of OT for the purpose of elucidating diagnostic and mechanistic information. Interestingly, whilst some (at times extremely challenging) protocols have been developed to induce OT, the incidence of NFOR/OTS is still low. Studies that have failed to report a state of NFOR/OTS are more likely to reflect normal strength training practices (Grandou et al., 2020).

The diverse range of training protocols used in OT research assists in the overall understanding of the response to demanding resistance exercise in a controlled environment, and aids in identifying potential mechanisms and markers that underpin OT due to the high level of control associated with laboratory research. Very few studies have used the same protocol across multiple research studies, therefore substantial methodological heterogeneity makes it difficult to compare results between studies where there is a lack of standardized training factors (i.e., frequency, duration, volume, exercise selection, and intensity of effort). Highly controlled training protocols provide a model on which to study the physiological mechanisms that may contribute to OTS. However, "real world" observational research conducted in environments where there is a risk of OT (i.e., training camps, planned overreaching) has the potential advantage of assessing training outcomes using resistance exercise training designed to induce FOR. The current landscape of protocols used in resistance training OT studies is representative of the many ways in which coaches and practitioners prescribe periods of resistance exercise, therefore should not be perceived negatively. High-performance strength coaches typically approach the prescription of such training intuitively, using an individualized approach (Bell,et al., 2022a). Therefore, the development of a single best practice protocol used across a diverse range of sports, athlete types and complex-chaotic training settings is challenging and would eliminate the flexibility in which intentional resistance exercise OT is prescribed.

Providing objective evidence of performance decrement following prolonged periods of resistance exercise OT is difficult (Weakley et al., 2022). As such, there is a lack of longitudinal research reporting follow-up performance tests, making it difficult to accurately determine if OTS has occurred. It is critical that future studies determine if performance suppression following periods of resistance exercise OT is due to acute fatigue, FOR/NFOR or OTS (or other disorders such as REDs). With a heterogeneous and diverse range of associated symptoms and only a minimal understanding of the underlying mechanisms that dictate the response to

OT, the time course to performance restoration and performance change is currently the only way to differentiate FOR from NFOR/OTS. Performance testing follow-up should be conducted at ≥4 weeks post-intervention to accurately determine NFOR from OTS. However, it is acknowledged that follow-up testing to verify diagnosis might be difficult considering the associated duration and frequency required for data collection.

6.6 Could an Analysis of Inter-Individual Response Variability Be the Next Step to Understanding Resistance Exercise Overtraining?

The concept of individual response variation to a given dose of exercise training is not a new concept (Erickson et al., 2023). It is well established that when a group of individuals undertake the same resistance exercise program, their response to that program will vary, even in groups comprising small sample sizes (Erskine et al., 2010). Some individuals will present meaningful improvements in performance, whereas others will present an adverse response (Pickering & Kiely, 2019; Timmons, 2011). Such variation is largely controlled by genetic and epigenetic factors (Bagley et al., 2020; Carpinelli, 2017; N. Jones et al., 2016; Peltonen et al., 2018) and modulated by genotype (Hubal, Gordish-Dressman, et al., 2005; Hubal, Hoffman, et al., 2005) muscle fibre typology (Bellinger et al., 2020; Lievens et al., 2020), age, and biological maturation (Moran et al., 2017). Additional factors such as the level of competition/training status (Kreher & Schwartz, 2012b) and the individual's "stress capacity" (Kenttä & Hassmén, 1998; Stults-Kolehmainen & Bartholomew, 2012) will also affect performance outcomes. For example, men and women undertaking 12 weeks of resistance exercise reported one-repetition maximum strength changes ranging from 0 to 250% and skeletal muscle hypertrophy of −2 to 59%, suggesting some participants experienced performance changes indicative of FOR, whilst others did not (Hubal, Gordish-Dressman, et al., 2005).

Whilst it is likely that the physiological response to the same program of training will differ between a group of athletes, current understanding of inter- and intra-individual variation in response to resistance exercise remains limited (Afonso et al., 2019), especially in studies designed to induce FOR. Much of the previous research in this area has focused on group-based analysis, where the mean pre-to-post change in an intervention group (typically referred to as an "overtraining" group) is compared to the mean pre-to-post change in a control group (a "normal" training group) (Kiely, 2018; Pickering & Kiely, 2019). Therefore, there is a strong rationale for exploring the individual response to periods of resistance exercise OT. Similar recommendations have been made by Bellinger (Bellinger, 2020), who suggested that future research exploring FOR should focus on the inter-individual response to exercise training and the variable development of performance outcomes following periods of high training demand.

Previous research has reported that trained individuals undertaking periods of either single or multiple sets of high-intensity resistance exercise (including a challenging protocol of 8 sets of back squats at 80% of repetition maximum to volitional exhaustion twice per week) can be classified as "high responders" (>20%) or "low responders" (<10%) based on changes in strength (Marshall et al., 2011). Interestingly, whilst some participants reported improved performance (which could be considered FOR) and others reported a decline in performance, there was no change in energy intake between responder groups either prior to or during the study, suggesting variation in response could not have been attributed to energy intake. A second point to note was that the "peaking phase" of the training protocol (a 4-week high-intensity, low-volume phase designed to reduce the risk of NFOR) was only effective for high responders. Whilst the authors were unsure as to why this was the case, they proposed that the training that preceded the peaking phase was sufficient to evoke the "realization" of strength development. This poses an additional but interesting question relating to the importance of individualizing the tapering phase as well as the organization of increased resistance exercise training demand. This is an area of research that has received minimal attention (Pritchard et al., 2015; Travis et al., 2020) but should be considered in future experimental studies.

It is anticipated that by adopting an individualized approach to resistance exercise, sports scientists and practitioners might optimize resistance exercise OT to achieve FOR and mitigate the negative effects of NFOR or OTS.

6.7 Recommendations for Future Research

- Clinicians and practitioners should cease to refer to short-term (<4 weeks) attenuation in performance as OTS. Instead, a pragmatic approach to the probable causes of a short-term reduction in performance after periods of resistance exercise OT should be taken. Such an approach must consider the multiple factors that might lead to suppressed performance, including changes in training demand, sleep characteristics, insufficient recovery, and non-training stressors such as work-life balance and motivation.
- To determine OTS, it is critical that performance testing should be conducted at ≥4 weeks post-intervention. It is acknowledged that follow-up testing to verify diagnosis might be difficult considering the associated duration and frequency required for data collection, however, longitudinal research studies monitoring performance during a follow-up period is underrepresented in the literature.
- Future research should explore the similarities between OTS and other disorders that lead to physiological impairment and performance decrement (e.g., REDs) to better understand overlaps in aetiology and pathology. It is our view that enhancing understanding of such conditions will strengthen differential diagnosis and subsequent treatment for recovery.
- Well-controlled training protocols designed to induce a state of OT provide a model for determining contributing mechanisms of NFOR/OTS. Studies designed to provide mechanistic information for the early detection of NFOR or diagnosis of OTS should

include a control training period prior to an increase in training load and should also demonstrate adequate control for confounding variables of energy availability and carbohydrate intake to improve the confidence of a true diagnosis of NFOR/OTS.

- Observational data collected during training periods where athletes might be at risk of NFOR/OTS provides an opportunity for sports scientists to conduct "real world" assessment. In environments such as training camps or during periods of planned overreaching, it is important to collect training data to determine performance changes, but also to collect data from uncontrollable factors that might influence the response to training (recovery status, readiness, sleep characteristics, dietary intake, and life stress). However, it is acknowledged that it might be difficult to conduct follow-up testing to verify diagnosis in an observational setting.
- Future research should explore factors that underpin the possible inter-individual response to resistance exercise OT. It is completely plausible that the same period of OT might result in different training outcomes (i.e., FOR or NFOR). Currently, little is known about the factors that influence response heterogeneity following periods of resistance exercise OT.

Chapter 7: Study 5 - The effects of a squat overreaching protocol on performance, perceived recovery, and wellness outcomes: A pilot trial

Bell, L., Ruddock, A., Boriel, J., Maden-Wilkinson, T., Thompson, S.W., Wright, K.J., Burke, K., Rogerson, D. The effects of a 5-day squat overreaching protocol on performance, perceived recovery, and wellness outcomes: A pilot trial

7.1 Rationale

In congruence with stage three of the ARMSS model, study five of this doctoral programme sought to explore possible performance predictors that might influence training outcomes following a period of planned OR (specifically, factors that influence performance change). The overall objective of the study was to guide sport scientists and practitioners with an indication of where to look for solutions, but also to inform stage four of the ARMSS model, where causal inference between previously identified associations is investigated using more robust methodological design (i.e., randomised control trials) (Bishop, 2008). As recommended by the ARMSS model, any stage three study can only be conducted once sufficient descriptive research has taken place. Study five, therefore, was informed by the findings from studies one to four and formed the culmination of the body of work presented in this doctoral programme. Findings from study highlighted a clear absence of appropriate follow up testing in previous research studies, leading to a misinterpretation of NFOR/OTS prevalence. Study two demonstrated that high-performance strength coaches are not concerned about the risk of inducing long-term performance decline during periods of highly demanding resistance exercise. Study three provided a framework by which periods of planned OR could be designed and study four consolidated this framework by providing a series of recommendations for future experimental work exploring OR/OTS.

Due to the novel nature of the research, study five utilised a pilot trial approach in line with current good practice recommendations (Brown et al., 2018; Horne et al., 2018; Thabane et al., 2010). During pilot research, analysis should be mainly descriptive avoiding statistical inferences due to the increased risk of type I statistical error. Using a descriptive pilot approach complied with stage three of the ARMSS model but also reflected the several remaining unknown aspects of OR/OT which had been highlighted in studies one to four. In this sense, a pilot trial permitted a proof-of-concept assessment (Leon et al., 2011) focusing not only on exploring predictors of performance but also on the feasibility of the training protocol itself. The development of a training protocol that could successfully induce FOR or NFOR would act as a starting point for ARMSS studies at stage four.

Study five utilised a highly standardised training protocol, implementing an autoregulatory approach to determine daily load lifted, and a 40% VLT to dictate set end points. This novel approach to exercise prescription during planned OR was undertaken to accurately and objectively prescribe external loads (Weakley et al., 2021b) as a way of ensuring that all participants trained close to muscular failure for all sets (Jukic, Castilla, et al., 2023; Myrholt et al., 2023; Pareja-Blanco et al., 2017), and to dynamically standardise the degree of effort between participants (as well as for the same participants on different training days).

7.2 Abstract

The aim of this study was to characterise the performance and perceptual response to a barbell back squat training overreaching (OR) protocol. Eight male trained participants (age = 24.6 ± 2.8 years; relative to body mass back squat one repetition maximum (1-RM) = 1.9 ± 0.4; training experience = 7.0 ± 3.2 years) participated in a 5-day squat OR protocol (SqOR) followed by a 2-week taper. SqOR consisted of 5 sets of barbell back squats using 80% of daily adjusted 1-RM. A 40% velocity loss threshold was used to determine the set end point. Performance: isometric mid-thigh pull (IMTP) peak force (PF); countermovement jump (CMJ) PF and jump height, and perceptual: perceived recovery scale (PRS) and Hooper Wellness Index (HWI) were recorded at baseline, each day of SqOR, and at select intervals during the taper (POST 1 d, 2 d, 7 d and 14 d). Follow-up back squat 1-RM testing was conducted at POST7 and POST14 to determine strength performance changes relative to baseline. Back squat 1-RM increased by 4.8% at POST7 and 5.2% at POST14. IMTP PF increased by 10.3% at POST7 and POST14. CMJ PF and jump height decreased during SqOR but returned to

baseline by POST7. PRS and HWI worsened during SqOR with the greatest impairment occurring on day 3 (PRS = -41.5%; HWI = 34.4%) and did not return to baseline until POST14 and POST2, respectively. These findings demonstrate that a short-term period of planned OR improves muscular strength performance, but the taper influences when peak strength improvements are observed.

7.3 Introduction

Athletes routinely undertake periods of demanding resistance exercise training to enhance the physiological adaptations that underpin a meaningful improvement in performance (e.g., muscular strength, rate of force development) (Suchomel et al., 2016). To achieve the desired outcome, training is organised strategically to achieve peak performance qualities at specific time points relative to the competition schedule (Suchomel et al., 2016). The development of athletic performance is typically approached in a periodised manner, with some training phases designed to 'drive' physiological adaptation, and others designed to promote recovery through fatigue management (Bell et al., 2023; Fry, 1999) i.e., achieve the most efficient gains in adaptation with the lowest degree of fatigue (Rodríguez-Rosell et al., 2020). Consequently, highly demanding training is periodically counterbalanced with adequate periods of recovery so that a marked improvement in athletic performance can be achieved (Tian et al., 2015). Strength-trained individuals, however, might experience diminishing improvements in muscular strength as training competency increases (Latella et al., 2024; Steele et al., 2023), therefore, a greater relative magnitude of training might be required to elicit further physiological adaptations and prepare athletes for the physical demands of competition (DeWeese et al., 2015a; Pistilli et al., 2008; Rhea, 2004). Prolonged periods of highly demanding resistance exercise training without enough recovery, though, can also lead to maladaptation (Flockhart et al., 2022) (13). This, of course, presents a logistical a challenge for high-performance coaches who wish to maximise athletic improvements whilst mitigating the risk of negative outcomes.

The term "overtraining" (OT) describes the imbalance between training demand and recovery that could result in either diminished performance or an improvement above baseline (Bell et al., 2022b; Meeusen et al., 2013). OT can be intentional (e.g., training camps, impact cycles) or unintentional (e.g., through poor programming, miscalculation of training and recovery or by training hard during periods of high non-training stress). In strength sports, it is common for OT to be implemented into the training programme through planned periods of overreaching (OR) (Bell et al., 2022a; Pistilli et al., 2008). During this phase of training, there is typically an increase in daily or weekly training volume or relative training intensity, generally for a duration of ~5-7 days (Bell et al., 2022a; Pistilli et al., 2008; Stone et al., 2021). Moreover, consecutive training bouts or multiple daily training sessions are undertaken to induce a maximal training stimulus through concentrated loading (Bazyler et al., 2017a; Bell et al., 2022a; Pistilli et al., 2008). Due to the challenging nature of planned OR, it is common for athletes to experience a period of psychophysiological fatigue both during and in the days/weeks following the bout of OR. This side effect is considered to be an expected part of the training process, and coaches do not perceive the increase in fatigue to be problematic (e.g., high risk of injury or long-term training maladaptation) (Bell et al., 2021). Indeed, coaches consider a short-term suppression in performance during planned OR as both an anticipated part of the training response and a sign that the training demand is sufficient to achieve a meaningful improvement in performance (Bell et al., 2022a). Consequently, planned OR is generally followed by a tapering period where training volume is intentionally reduced to facilitate restoration and to aid performance rebound (Travis et al., 2020).

The term OT has also been used colloquially to describe the "overtraining syndrome"; a multifaceted medical disorder characterised by an accumulation of training and/or non-training stress resulting in long-term decrement in performance capacity (Meeusen et al., 2013). Therefore, not only is the term OT used to describe periods of challenging phases of training where recovery is (often intentionally) blunted, it also can refer to the outcome of prolonged (>4 weeks) performance decrement (Meeusen et al., 2013; Weakley et al., 2022). Such broad vocabulary has led to confusion within the literature surrounding the exact definition and diagnosis of OTS, which is perhaps confounded by the use of "overtraining" as both a verb and noun (Budgett et al., 2000; Cadegiani & Kater, 2019a; Lewis et al., 2015).

Functional overreaching (FOR) refers to an initial decrease in performance followed by an improvement in performance relative to baseline after a short period of recovery (often referred to as supercompensation) (Aubry et al., 2014; Bazyler et al., 2017b; Meeusen et al., 2010). Importantly, FOR occurs when an athlete experiences a decrease in training performance followed by full recovery and enhanced competition performance within 1-2 weeks (Tian et al., 2015). In strength sports, utilising blocks of planned OR to achieve FOR is common to enhance competition performance (Bell et al., 2022a). Moreover, planned OR has been used to stimulate FOR as part of a phase potentiation effect, whereby the specific physiological qualities achieved in one block of training enhance the adaptations that occur in the corresponding phase (Cuthbert et al., 2024). Whilst planned OR is a ubiquitous practice within strength sports (and many coaches perceive it to be an important aspect of the overall training programme) (Bell et al., 2022a) there is minimal evidence that training designed to induce strength or power-related FOR is superior compared to a more progressive manipulation of training load (Bazyler et al., 2017b). Evidence from endurance sports is equivocal, with some studies indicating that planned OR might be a viable method of improving performance

(Hellard et al., 2013), whilst others have reported that gains in performance are observed following planned OR, but not when FOR occurs (Aubry et al., 2014; Bellinger, 2020).

Non-functional overreaching (NFOR) refers to stagnation or plateau in athletic performance lasting several days to weeks (~2 weeks) with no improvement in performance relative to baseline (Birrer et al., 2013; Halson & Jeukendrup, 2004; Meeusen et al., 2013). The risk of NFOR appears to increase when highly demanding training is undertaken for a prolonged period without sufficient recovery and has been previously observed in strength athlete populations undertaking training camps, frequent competitions and/or excessive training (Bell et al., 2020; Grandou et al., 2020). Prolonged exposure to excessive resistance exercise training without sufficient recovery might also lead to the overtraining syndrome (OTS), which is generally considered to be a more severe form of NFOR (Meeusen et al., 2013). The risk of developing NFOR (and hypothetically, OTS) increases when training includes excessive or prolonged high-intensity or high-volume resistance exercise, prolonged training monotony (caused by minimal variation in exercise selection or approach) (Foster, 1998; Kreher & Schwartz, 2012a), and repeated training muscular failure (Bell et al., 2020; Grandou et al., 2020).

Competitive strength athletes frequently report symptoms of general fatigue, musculoskeletal pains, and decreased motivation during periods of unexplained underperformance (Grandou et al., 2021). These symptoms appear to manifest regardless of whether performance impairment is short-term (1 week to 1 month) and long-term (1 to 3 months) (Grandou et al., 2021). This makes it difficult for coaches to rely on symptoms of performance impairment to dictate training decisions (i.e., premature cessation of training resulting in an absence of performance improvement or late cessation of intensified training resulting in NFOR). This is further compounded by the high degree of inter-individual variability in magnitude and duration of symptoms of performance impairment (Grandou et al., 2020; Matos et al., 2011).

Previous research has indicated the overall risk of developing NFOR is relatively low following resistance exercise OR, even when training protocols have been designed to induce OTS for the purpose of scientific inquiry (Bell et al., 2020; Grandou et al., 2020). Studies that have attempted to induce OTS have adopted either a high-intensity (Fry et al., 1998, 2006, 1994c, 1994b, 1994a) or a high-volume (Margonis et al., 2007; Sterczala et al., 2017) approach, typically using a squat exercise variation (squat machine or barbell back squat). Findings from these studies have been equivocal, reporting impaired performance (Fry et al., 1998, 2006, 1994c, 1994b; Margonis et al., 2007), no change in performance (Sterczala et al., 2017), or improved performance relative to baseline (Fry et al., 1994a). Such ambiguous findings are likely due to a lack of standardised methodology and diagnostic criteria, as well as inconsistent follow-up testing. For example, in those studies reporting a decrease in performance (apart from Margonis et al., 2007), follow-up performance assessments were performed immediately after completion of the training intervention and not after a recovery period. Therefore, without follow up testing in the days/weeks following completion of the training protocol, it is not possible to accurately determine that NFOR/OTS occurred. Moreover, given that performance is often suppressed for several days before FOR is achieved, it is plausible that individuals in this study were experiencing a pattern of normal restorative processes. .

Given the ambiguous landscape of research and equivocal findings in this domain, it is crucial to better understand the physiological response to resistance exercise OR. This is of particular importance to high-performance coaches and athletes that regularly integrate phases of OR into their training programmes to achieve performance improvements or want to avoid long-term performance decrement through the early detection of NFOR. Therefore, the purpose of this study was to examine the feasibility and safety of a pilot OR protocol designed to induce either FOR or NFOR in a trained population, using appropriately timed follow-up assessments to accurately determine training outcomes. Given the challenging nature of the training protocol designed for this study, we hypothesised that whilst some participants would improve performance relative to baseline, others would experience performance stagnation indicative of NFOR.

7.4 Methods

7.4.1 Experimental approach to the problem

A prospective cohort design utilising repeated measures investigated the effects of a pilot protocol on select performance and perceptual measures. The study consisted of an initial habituation and baseline testing phase (PRE); a 2-week foundation training phase (BASE); a 5-day 'squat overreaching' (SqOR) protocol, and a 2-week taper comprised of two full body resistance training sessions each week (TAPER). SqOR consisted of 5 sets of barbell back squats performed each consecutive day using 80% of daily adjusted 1RM. Each set was performed until a 40% velocity loss was achieved. The use of a 40% velocity loss threshold (VLT) permitted acute alterations in training intensity relative to athlete readiness whilst facilitating an individualised prescription of training volume in comparison to planned training using a predetermined one-repetition maximum (Lum & Howatson, 2023). Previous research has demonstrated that a 40% VLT results in the participant training at (or very close to) concentric muscle failure (Jukic, Castilla, et al., 2023; Myrholt et al., 2023; Pareja-Blanco et al., 2017). Performance (muscular strength, peak force), and perceptual (recovery status, wellness) measures were recorded at select time points during each phase of the programme (Figure. 12).

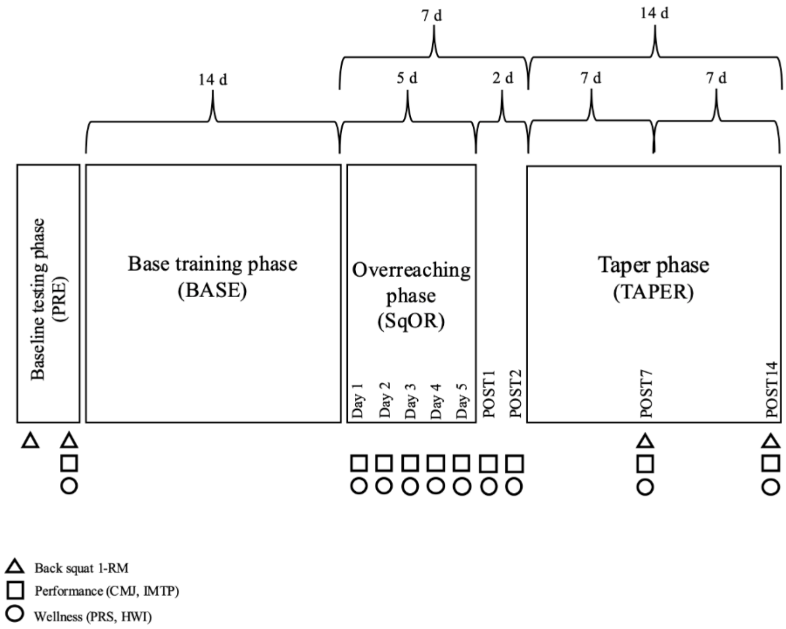

Figure 12. Schematic representation of the study design. CMJ = countermovement jump; IMTP = isometric mid-thigh pull; 1-RM = one repetition maximum; PRS = perceived recovery scale; HWI = Hooper wellness index

To assess the safety, feasibility and appropriateness of the training protocol, a pilot study approach was utilised (In, 2017; Thabane et al., 2010). In physical activity pilot research, small sample sizes may be necessary where there is a limited pool of potential participants, when the research is exploratory in nature, or where data collection might be difficult due to the time required to obtain data (Horne et al., 2018). Where a pilot approach has been utilised in the OT domain (Crawford et al., 2017; Nobari et al., 2021; Wahl et al., 2021), or in exploratory studies investigating the effects of short-term OT on strength performance (Bazyler et al., 2017b; Fry et al., 1994d; Haff et al., 2008; Suarez et al., 2019), sample sizes of 6 to 10 participants are common. Considering the nature of the research question in this study, as well as its experimental design, inclusion criteria, complexity and novelty of the training protocol, and potential for adverse effects, a sample size of 8 participants was deemed sufficient.

7.4.2 Participants

After institutional ethical approval was granted (ER48910004), eight male participants (mean ± *SD*; age = 24.6 ± 2.8 years, stature = 175 ± 4 cm, body mass = 83.6 ± 9.9 kg) provided informed consent to participate in the study. Participants had 7.0 ± 3.2 years of resistance exercise training experience and a relative (to body mass) parallel barbell back squat of 1.9 ± 0.4 kg/body mass. Participants were not permitted to undertake any other form of resistance exercise training during the duration of the study period, therefore any competitive athlete currently within a competition phase was excluded from recruitment. Those who reported a contraindication to exercise (e.g., heart disease, severe musculoskeletal injury) or indicated previous anabolic steroid use were also excluded from the study. Inclusion criteria followed the recommended prerequisites for studies exploring markers of NFOR/OTS (Meeusen et al., 2013). Similar inclusion criteria have been used elsewhere (Fry et al., 2006; Myrholt et al., 2023; Nicoll et al., 2016; Wilson et al., 2013). None of the participants had previous experience of undertaking intentional periods of OT as part of their habitual training.

Stature (cm) was collected at the initial visit using a commercial height measure system (Seca Leicester, Birmingham, UK). Body mass (kg) was recorded (prior to any physical activity) using a Hawkin Dynamics force plate (Hawkin Dynamics Generation 3; Westbrook, ME, USA). All participants completed a health screening questionnaire and informed consent before data were collected.

7.4.3 Procedures

7.4.3.1 Training programme

The training programme was organised into three distinct phases (Figure 12). In phase one, participants completed a 14-day base foundation phase (BASE) consisting of two full-body resistance exercise training sessions each week, each separated by ≥72 hours (Table 1). BASE was designed by two strength and conditioning coaches (KW, KB) in conjunction with the lead investigator and was designed to ensure participants started SqOR in a similar state of trainability and readiness. The aim of the BASE training phase was not to stimulate further adaptations or to improvement performance per se, but to dissipate fatigue whilst minimising the effects of detraining. This approach has been utilised elsewhere when investigating resistance exercise OT (Kraemer et al., 2006). To accommodate individual differences and to regulating the degree of effort, BASE utilised a repetitions in reserve rather than prescribing a pre-determined number of repetitions (Bastos et al., 2024).

Phase two of the programme was a 5-consecutive-day SqOR protocol consisting of 5 sets of barbell back squats performed using 80% of daily 1-RM (see Figure. 13 for a schematic representation of each training day). Training sessions were at the same time of day (± 1 hour). During the SqOR phase, no other resistance exercise (including upper body training) was permitted. At each visit, participants were instructed to perform as many repetitions as possible during each set, and sets were terminated only when a velocity loss of 40% (VL40) was achieved, or when participants reached momentary muscular failure (i.e., despite attempting to, the individual cannot complete the concentric portion of the repetition without deviating from the correct form) (Steele et al., 2017). A 5-minute rest period was provided between sets to standardise inter-set recovery and to reflect the typical rest time recommended for strength training when higher volume loads are utilised (Schoenfeld et al., 2016). Moreover, longer rest periods were considered more likely to facilitate greater maintenance of barbell velocity (García-López et al., 2007), allowing for completion of more repetitions in the corresponding set.

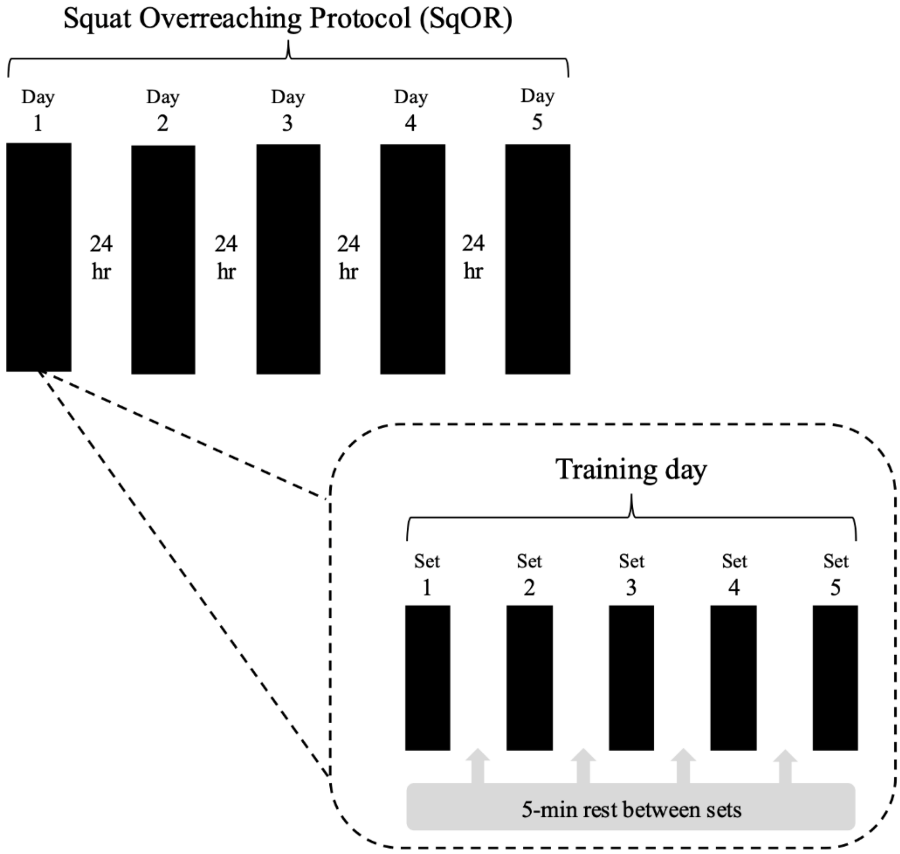

Figure 13. Schematic representation of the SqOR training phase and individual training days

When developing complex interventions, there is often a trade-off between answering novel, broad research questions and those that are more narrow or specific (Skivington et al., 2021). Notably, the design of novel interventions should be adapted to the context; approached in phases, focusing on the feasibility of more critical aspects of intervention in the early stages of trials (Skivington et al., 2021). Once the primary aspects of the intervention have been assessed, supporting aspects can be revised. Given the challenging nature of the SqOR protocol, a lack of standardised or accepted warm-up protocol for OR research, and the importance of both the physical and psychological aspects of the warm-up (e.g., mental preparation strategies) on readiness to train (McGowan et al., 2015), participants were permitted to complete their preferred warm-up activities rather than a standardised series of exercises. A similar approach to the warm-up has been used elsewhere in the strength training research (Thompson et al., 2023).

All sessions were overseen by the principal investigator and a team of experienced strength and conditioning coaches (JB, KW, KB), all of whom have previous experience with high-performance athletes. Following completion of SqOR, participants were instructed to refrain from all exercise for the following 2-d before commencing the third phase of the programme.

Table 8. BASE training programme

Training session 1			Training session 2		
BB back squat	2 x 8	75% 1-RM	BB back squat	2 x 8	75% 1-RM
Romanian deadlift	2 x 5	75% 1-RM	BB bench press	2 x 8	75% 1-RM
DB shoulder press	2 x 8	75% 1-RM	Goblet lateral lunge	2 x 6	75% 1-RM
Pull-ups	2 x 6	2 RIR	Single arm DB row	2 x 8	75% 1-RM
Calf raises	2 x 8	75% 1-RM	Pallof press and rotate	2 x 8	2 RIR
Close grip bench press	3 x 8	75% 1-RM	Banded ankle knee rockers	1 x 10	2 RIR
Straight-arm sit-ups	1 x 10	2 RIR	KB hip openers	1 x 10	2 RIR
Russian twists	1 x 10	2 RIR			

BB = barbell; DB = dumbbell; KB = kettlebell; RIR = repetitions in reserve

In phase three, participants were instructed to complete a 14-day taper (TAPER) consisting of two individual full-body sessions each week, separated by ≥72 hours (Table 2). Like BASE, TAPER was designed by two strength and conditioning coaches (KW, KB) using recommendations provided by Travis and colleagues (Travis et al., 2021). TAPER followed a step taper approach where training volume was decreased each week over the 2-week period.

The aim of the taper was to mitigate fatigue, minimise detraining effects, and enhance recovery before follow-up performance testing. Importantly, the taper should also provide a psychological break from monotonous training (Pistilli et al., 2008; Winwood et al., 2023). Due to the specialised nature of SqOR (i.e., squat only), and the perceived high risk of participant drop-out (due to the combined effects of training monotony and the duration that each participant had refrained from their normal training by the beginning of the tapering period), the research team decided that TAPER should follow a whole body training approach and not just focus on the barbell back squat. That way, participants were permitted to return to a more varied training but with per-determined exercise selection performed at a standardised intensity of effort.

Table 9. TAPER training programme

Training session 1			Training session 2		
BB back squat	3 x 6	75% 1-RM	BB back squat	3 x 6	75% 1-RM
Romanian deadlift	3 x 5	75% 1-RM	Glute ham raise	3 x 8	75% 1-RM
DB shoulder press	3 x 8	75% 1-RM	BB bench press	3 x 6	75% 1-RM
Seated straight-arm pull	3 x 8	75% 1-RM	Single arm DB row	3 x 8	75% 1-RM
Band pull apart	3 x 10	2 RIR	DB lateral raise	3 x 8	75% 1-RM
Close grip bench press	3 x 8	75% 1-RM	BB reverse curls	3 x 8	75% 1-RM

BB = barbell; DB = dumbbell; RIR = repetitions in reserve

7.4.3.2 Barbell back squat

Participants were permitted to wear a weightlifting belt, knee sleeves, preferred footwear and adopt a preferred back squat stance and technique (i.e., high bar or low bar), but required to maintain those preferences for the duration of the study (Fry et al., 2000b). All participants used a standard Olympic weightlifting bar (20kg Eleiko bar, Eleiko, AB, Halmstad, Sweden). Participants performed the eccentric phase of the back squat under control (~2 s) until a parallel position was achieved, and to complete the concentric phase of the exercise "as fast as possible, with maximal intent". Parallel depth was defined as the inguinal fold being level with the musculature of the knee (Fry et al., 2000b). Participants were given strong verbal encouragement, supervision, and feedback throughout each set to ensure safe and appropriate lifting technique (i.e., proper depth and maximal intent for all repetitions were achieved).

7.4.3.3 One repetition maximum testing and load-velocity profile

Two individualised load-velocity profiles (LVP) were conducted before BASE (Figure. 12), separated by ≥72 hours. The first baseline LVP was conducted to ascertain the participant's back squat 1-RM and the second baseline LVP was conducted to ascertain the mean concentric velocity (MCV) at specific percentages of the 1-RM. Procedures followed those outlined by Thompson and colleagues (Thompson et al., 2021). A follow-up LVP was conducted 7-days (POST7) and 14-days (POST14) following completion of SqOR to assess changes in strength performance. Therefore, 1-RM assessment (as part of the LVP) was conducted a total of four times during this study.

Following an individualised, standardised warm-up, participants completed five repetitions at body mass only (using a wooden dowel), three repetitions at 30%, 40% and 50% 1-RM, two repetitions at 60%, 70% and 80% 1-RM, and one attempt at 90% and 100% of the 1-RM. A maximum of five attempts were given to find a true 1-RM. Five minutes of rest were provided between attempts. Participants were instructed to perform the eccentric phase of each attempt with control (~ 2 seconds) and the concentric phase of every repetition with "maximal intent and velocity". MCV from the fastest repetition of each load was recorded. LVP data were collected with a linear position transducer (GymAware RS PowerTool; Kinetic Performance Technologies, Canberra, AUS). The validity, reliability, reproducibility, and sensitivity of this system have been reported elsewhere (Jukic, King, et al., 2023; Weakley et al., 2021a), with barbell velocity considered both reliable and valid using this device (ICC > 95%; CV < 5%).

7.4.3.4 Autoregulation of training

To ensure an appropriate daily training load for each day of SqOR (i.e., to accommodate for acute changes in readiness), the MCV from the 80% 1-RM (ascertained from the baseline LVP) was used to determine the daily load lifted. To determine the daily load lifted, participants completed 5 reps of the baseline 50% 1-RM, 2 repetitions at 70% 1-RM, and 2 repetitions of 80% 1-RM. The daily load lifted was subsequently adapted if the fastest of the two repetitions at 80% 1-RM was +/- 0.03 $m.s^{-1}$ from the velocity obtained during the baseline LVP (Thompson et al., 2021).

7.4.3.5 Velocity loss threshold

One of the common features of planned OR is high-volume, high-intensity resistance training performed close to, or at, muscular failure (Bell et al., 2020; Grandou et al., 2020). A VL40 was selected for this study as previous research has shown that performing repetitions with this degree of velocity loss results in the participant training at, or very close to, concentric muscle failure (Jukic, Castilla, et al., 2023; Myrholt et al., 2023; Pareja-Blanco et al., 2017). Previous literature has elucidated that training with higher velocity loss thresholds leads to larger total training volumes per set and increased mechanical, metabolic and perceptual disturbance (Jukic, Castilla, et al., 2023). Higher velocity loss thresholds (such as VL40) lead to reduced peak and mean power across a set of barbell back squats (compared to lower velocity loss thresholds such as ≤20%), likely because of the effects of neuromuscular fatigue as the set progresses nearer to muscular failure (Weakley et al., 2020). Moreover, VL40 leads to increased muscle damage and impaired mechanical performance compared to lower velocity loss thresholds (Muñoz-López et al., 2022). For example, Cornejo-Daza et al., (2024) reported that VL40 during back squat exercise impaired both jump and squat performance for 24 hrs post-exercise. Consequently, frequent high velocity loss threshold utilisation might impair both maximal strength and impulse adaptations and increase the risk of NFOR, particularly if insufficient rest is provided between training bouts (Cornejo-Daza et al., 2024).

The velocity of all repetitions during SqOR was displayed in real time. VL40 was set relative to the fastest repetition of each set (which acted as the reference repetition) (Jukic et al., 2023). For example, if the fastest repetition for a given set was 0.77 $m.s^{-1}$, the VL40 would be 0.46 $m.s^{-1}$. Participants were instructed to complete as many repetitions as possible for each set until they could no longer complete the concentric portion of the repetition without deviating from the correct form (momentary muscular failure) or until the GymAware device indicated that VL40 had been reached. Current research (albeit scarce) has observed that during a set of barbell back squats using 80% 1-RM, a total of 5.3 ± 1.5 repetitions were performed by well-trained males to VL40 relative to the fastest repetition of the set (Pareja-Blanco et al., 2020). The research team actively provided feedback on velocity and general technique during each repetition and set and encouraged each participant to complete all repetitions with maximal intent.

7.4.5.6 Countermovement jump

The countermovement jump (CMJ) was performed using Hawkin Dynamics force plates to record jump height and peak propulsive force at PRE, before each day of SqOR, at POST1 and POST2, and at select intervals during TAPER (POST7, POST14) (Figure. 12). The reliability of the device has been reported elsewhere (Badby et al., 2023; Merrigan et al., 2022). Participants were instructed to stand with feet shoulder-width apart and remain motionless for 2 seconds so that body weight could be accurately determined. This method has previously been determined as the gold standard for identifying the start of the unweighting phase of a

CMJ by detecting a change in body weight by 5 x *SD* (Owen et al., 2014). Each jump was performed with hands on hips to reduce the effects of arm swing. After a countdown of "3, 2, 1, jump!", participants were encouraged to jump with maximal effort, with a self-selected eccentric phase depth. A duration of 60-120 seconds rest between trials was provided and 3 trials were performed in total, with the best attempt recorded for that day.

7.4.5.7 Isometric mid-thigh pull

The isometric mid-thigh pull (IMTP) was performed using guidelines from Comfort and colleagues (Comfort et al., 2019). Hawkin Dynamics force plates set at a sampling rate of 1000Hz were used to record peak isometric force at PRE, before each day of SqOR, at POST1 and POST2, and select intervals during TAPER (POST7, POST14) (Figure. 12). Following an individualised and standardised warm-up, the bar position was adjusted so that it replicated the start of the second pull phase of the clean, resulting in standardised knee and hip angles of 120–135° and 140–150°, respectively. Participants first performed a 50% maximal effort warm-up IMTP for ~3 seconds. After a brief rest, a second attempt was performed with 75% maximal effort, followed by another attempt with 90% maximal effort, both for ~3 seconds. Participants maintained an upright torso throughout each attempt (maximum 5-10° forward lean). As pretension is undesirable when assessing IMTP performance, participants were asked to adopt a relaxed position before the start of each test (1 second quiet standing; <50 N change in force). Following a countdown of "3, 2, 1, Push!", participants were instructed to "push your feet into the ground as hard and as fast as possible" for < 5 seconds per trial. For all trials (including warm-up attempts), lifting straps were used to ensure that grip strength was not a limiting factor. Each participant completed 3 trials at each testing session, with 60-120 seconds rest between attempts. The best attempt of the three trials was used each day.

7.4.5.8 Perceived Recovery Scale

The perceived recovery scale (PRS) is designed to indicate an individual's day-to-day level of perceived recovery using a 0-10 scale (Laurent et al., 2011). Participants were asked to rate their perceived recovery using the following verbal descriptors: "very poorly recovered/extremely tired" was scored 0, "adequately recovered" scored 5, and "very well recovered/highly energetic" was given a score of 10. A score between 0–2 is associated with a decline in performance, 4–6 typically results in similar performance in the corresponding bout of training, and a score of 8–10 represents an expected increase in performance. PRS was recorded upon arrival at the testing laboratory at PRE, before each day of SqOR, at POST1 and POST2, and select intervals during TAPER (POST7, POST14) (Figure. 12).

7.4.5.9 Hooper Wellbeing Index

A modified version of the Hooper Wellbeing Index (HWI) (Hooper & Mackinnon, 1995) was used and consisted of four dimensions: stress, sleep quality, fatigue, and muscle soreness. Each of the four dimensions was scored by participants, with 1 being "very, very good" and 10 being "very, very bad". The sum of the four scores was used to calculate the global HWI score. Lower scores indicate better wellbeing, and higher scores indicate poor relative wellbeing. HWI was recorded upon arrival at the testing laboratory at PRE, before each day of SqOR, at POST1 and POST2, and select intervals during TAPER (POST7, POST14) (Figure. 12).

For both PRS and HWI, participants were provided with a printed version of each scale and asked to point to and verbally state their scores so that the researchers could record them.

7.4.4 Statistical analysis

As this study was a pilot trial utilising a convenience sampling approach, no sample size calculations were performed (Whitehead et al., 2016). Pilot studies typically have low sample sizes and are often underpowered. Moreover, large variations between participant outcomes can occur, leading to an increased risk of type II statistical errors; therefore, it is not recommended that formal significance testing is undertaken (Lancaster et al., 2004). Current good practice guidelines in pilot research advocate the use of descriptive statistics and estimation (i.e., confidence intervals; CIs) to assist with the assessment of precision (Eldridge et al., 2016; Kannan & Gowri, 2015; Lee et al., 2014). Therefore, all performance and perceptual measures are reported as mean ± *SD* as well as CIs and relative percentage change (where appropriate). To indicate the degree of inter- and intra-individual variability for performance and perceptual parameters, the coefficient of variability (CV%) was calculated (CV% = (*SD*/mean)*100). Smallest worthwhile change (SWC) was used to define the smallest change of practical importance for 1-RM (Marocolo et al., 2019; Swinton et al., 2018) was calculated by multiplying the between-participant *SD* by 0.2, which is appropriate for highly trained sports participants (Marocolo et al., 2019). Analyses were conducted using SPSS software version 26.0 (SPSS Inc. Chicago, Illinois, USA).

7.5 Results

Fifteen participants were screened for eligibility. Of those, three did not meet the eligibility criteria as they were elite-standard athletes currently within a competition phase. Two individuals failed to attend initial screening, and one individual withdrew before completing baseline testing due to an injury unrelated to the study. A total of nine participants were recruited for the study; however, one participant withdrew after completing the first day of SqOR because of an unrelated acute illness. The data from the eight participants who completed the study were included in the final analysis (Figure 14).

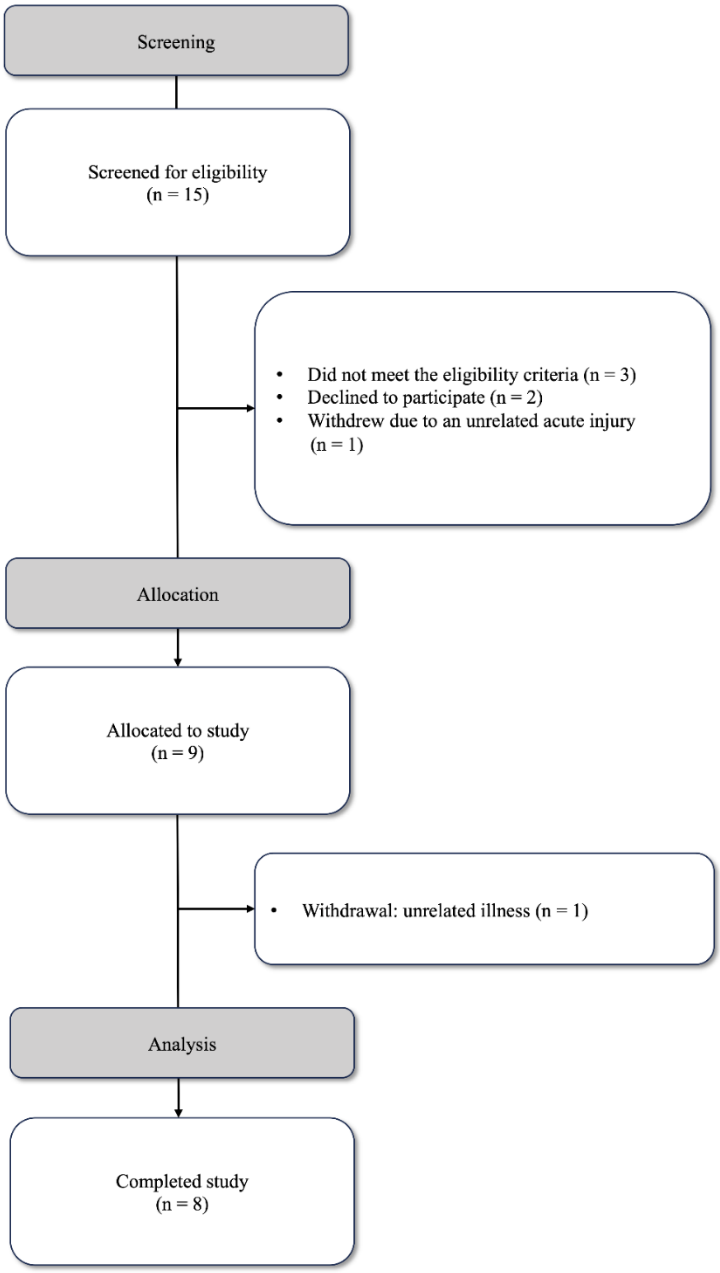

Figure 14. Pilot study flow diagram

Compliance for all aspects of the study (defined as total number of training and testing sessions attended for the 8 participants) was 100% (each participant attended 11 separate visits over a 6-week period). No participant reported any serious adverse events (e.g., musculoskeletal injury, cardiovascular event, rhabdomyolysis) due to participation in the study. Participant characteristics are presented in Table 3.

Table 10. Baseline participant characteristics

Characteristic	Mean ± *SD*
Age (y)	24.6 ± 2.8
Stature (cm)	175 ± 4
Body mass (kg)	83.6 ± 9.9
Resistance training experience (y)	7.0 ± 3.2
One-repetition maximum:	
Absolute (kg)	158 ± 30.1
Relative to body mass	1.9 ± 0.4
Isometric midthigh pull peak force (N)	3568 ± 602
Countermovement jump:	
Peak force (N)	2283 ± 370
Height (cm)	42 ± 8

7.5.1 Training Characteristics

The mean number of repetitions completed over the five days of SqOR was 170.0 ± 38.0 [CI = 143.7 to 196.3]. The largest number of repetitions completed was on day 4 (37.4 ± 10.8 [CI = 29.9 to 44.9]) and the lowest was on day 1 (32.6 ± 6.8 [CI = 27.9 to 37.4]) (Figure 15). The within- and between-participant variability for repetitions completed across the five days was 6.9 to 37.2 and 14.5 to 36 CV% respectively.

The mean load per repetition (calculated using 80% of predicted daily 1-RM) for day 1 was 125.6 ± 20.4 kg [CI = 111.5 to 139.7]. The lowest mean load per repetition occurred on day 2 (119.6 ± 25.6 kg [CI = 101.9 to 137.4]) and the largest on day 5 (129.3 ± 22.7 [CI = 113.5 to 145.0) (Figure 15). Within-participant variability for mean load per repetition across the 5 days was 2.9 to 7.5 CV% and between-individual variability was 16.2 to 21.4 CV%.

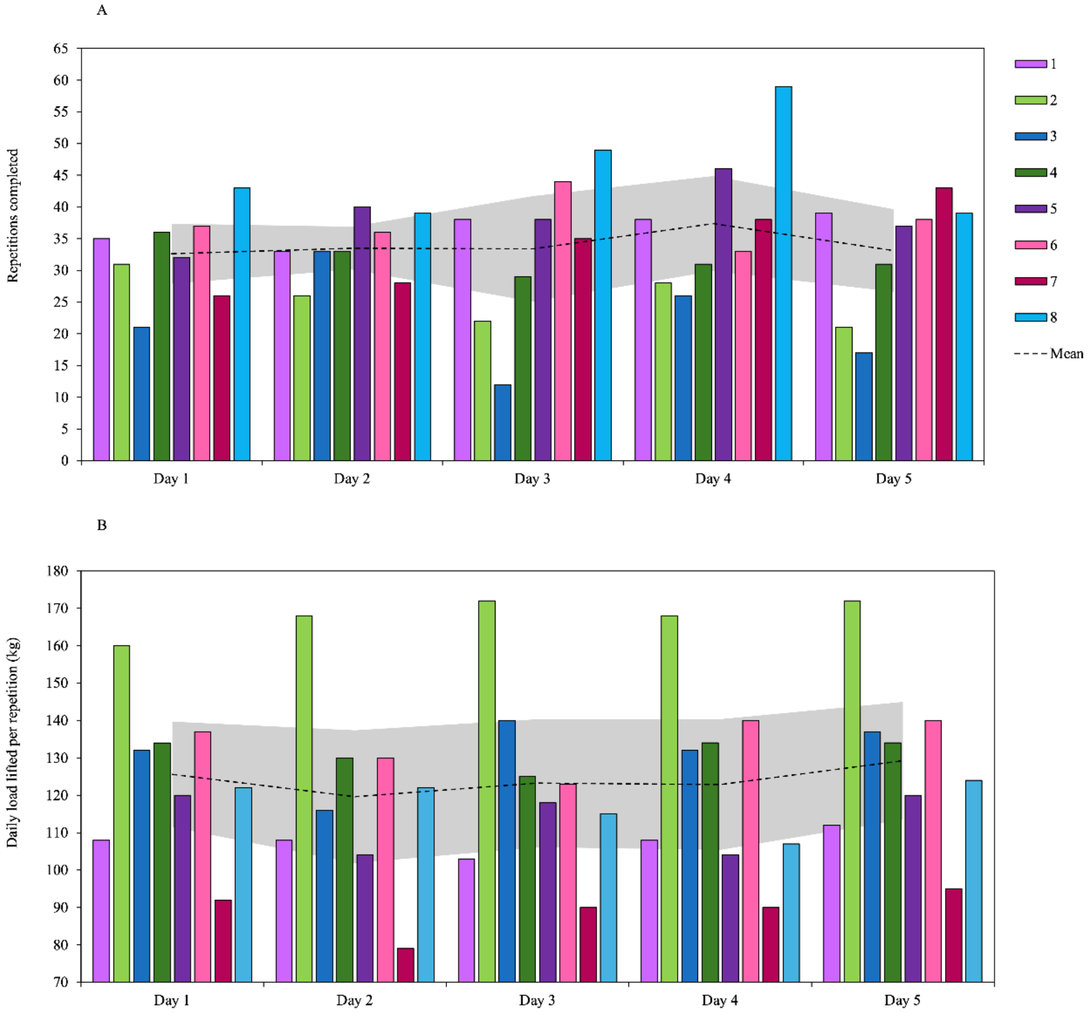

Figure 15. Group mean and individual data for each day of SqOR for A. repetitions completed, and B. daily load lifted per repetition (kg). Shaded area indicates 95% confidence intervals.

Participants completed a total volume load (load x repetitions x sets) of 20640.4 ± 4441.5 [CI = 17563 to 23718] kg over the 5 days (Figure 16). The greatest daily mean volume load was on Day 4 (4459 ± 929 kg [CI = 3815 to 5103]) and the lowest was on Day 3 (3961 ± 1264 [CI = 3084 to 4837] kg). Within-participant CV% ranged from 6.7 to 30.5 and between-participant CV% ranged from 20.6 to 31.

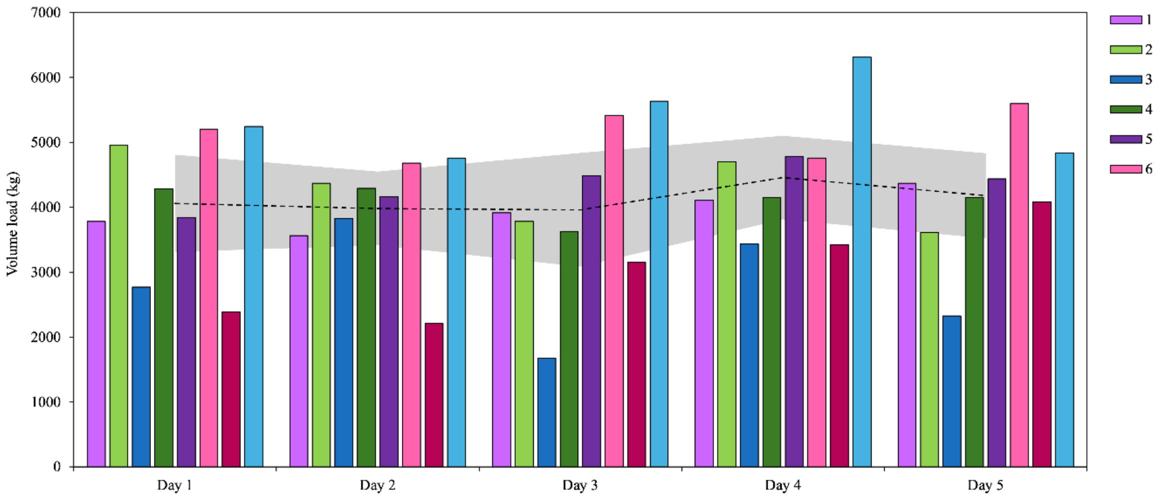

Figure 16. Group mean and individual data for volume load. Shaded area indicates 95% confidence intervals.

7.5.2 Performance changes

7.5.2.1 One-repetition maximum

The group mean 1-RM at PRE was 158.9 ± 30.1 [CI = 138.1 to 168.2] kg. At POST7, 1-RM was 166.6 ± 30.4 [CI = 145.6 to 176.0], which represented a mean percentage increase of 4.8% (7.7 ± 2.9 kg). At POST14, 1-RM was 167.3 ± 31.0 [CI = 145.8 to 176.8], relative to PRE, a mean increase of 5.2% (8.3 ± 5.3 kg). An increase of 0.4% was observed for 1-RM between POST7 and POST14 (0.6 ± 4.8 kg). At POST7, all participants had increased 1-RM relative to PRE (*range* = 2.0 to 12.0 kg; 1.3 to 8.1%). At POST14, six participants increased 1-RM relative to POST7 (*range* = 1 to 5 kg; 0.6 to 2.9%). However, 1-RM for two participants returned to PRE (*range* = -2 to -10 kg; -1.3 to -5.7%). Within-participant CV% ranged from 0.8 to 4.6 and between-participant CV% ranged from 18.2 to 18.9. Figure 17 represents the individual percentage change in 1-RM at POST7 and POST14 relative to PRE. The SWC based on between-participant *SD* was 6.0 kg (3.8%). At POST7, seven participants exceeded the SWC (*range* = 7.0 to 12.0 kg), with six participants exceeding SWC at POST14 (*range* = 9.0 to 13.0

kg). No participants reported improvements in 1-RM that exceeded the SWC between POST7 to POST14 (*range* = -0.2 to 5.0 kg). However, one participant did report a decrease in 1-RM performance (-10.0 kg) between POST7 and POST14. MCV for baseline back squat 1-RM was 0.31 ± 0.06 m.s^{-1}. At POST7, velocity for the new 1-RM was 0.28 ± 0.07 m.s^{-1} and at POST14 it was 0.26 ± 0.06 m.s^{-1}

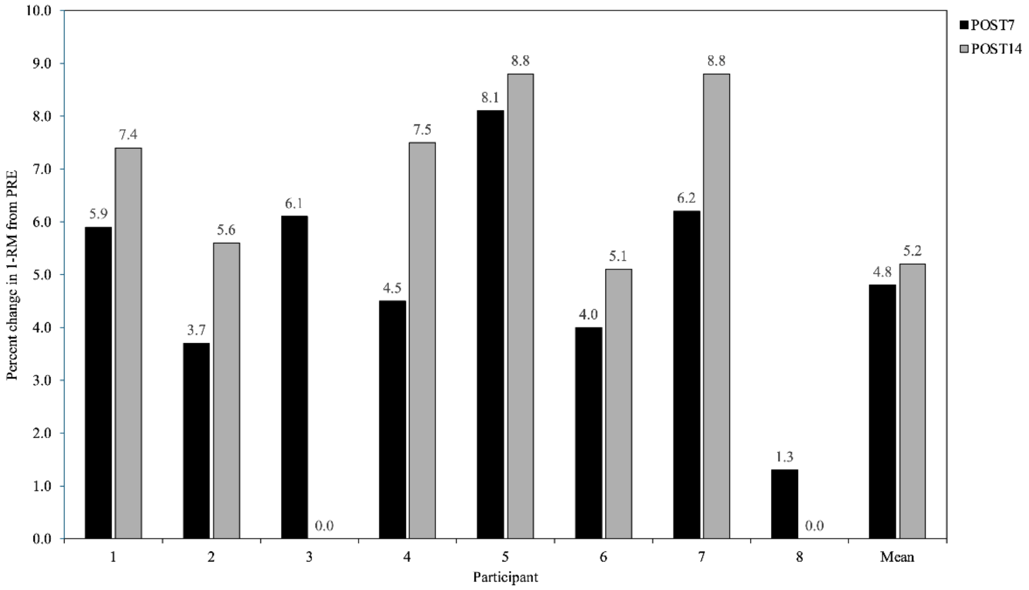

Figure 17. Individual percentage changes in 1-RM relative to PRE at POST7 and POST14. A value of 0.0% represents a return to the baseline 1-RM.

7.5.2.2 Isometric mid-thigh pull

The mean IMTP PF at PRE was 3567 ± 602 [CI = 3151 to 3984] N. At POST7, PF increased by 10.3% relative to PRE (3936 ± 899 [CI = 3314 to 4559] N) and by 11.4% at POST14 (3973 ± 817 [CI = 3407 to 4539] N) (Figure 18). The greatest group mean PF was observed at POST14 and the lowest was at POST 1 (3547 ± 1000 [CI = 2853 to 4240] N; -0.6% relative to PRE). At POST7, seven participants increased PF relative to PRE (*range* = 2.5 to 25.6%) and one participant reported a reduction in PF (-2.9%). At POST14, all participants had achieved an increase in PF (0.1% to 25.7%) relative to PRE. The within-participant CV% was 2.2 to 13.1 and between-participant variability was 13.7 to 28.2 CV%.

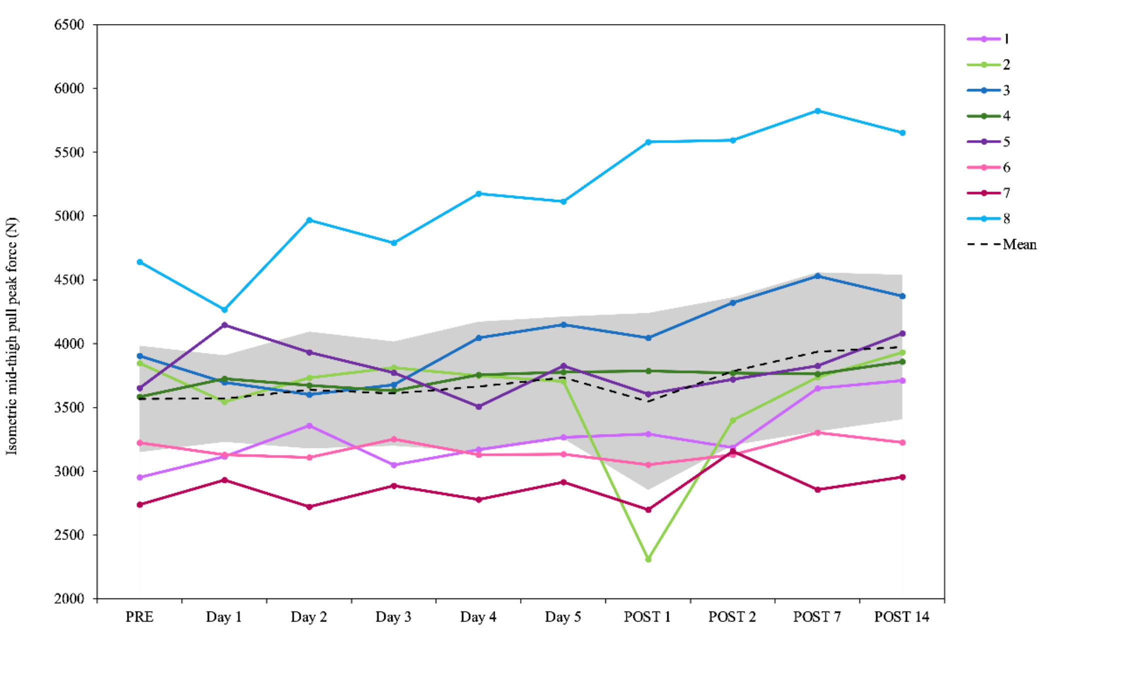

Figure 18. Group mean and individual changes in isometric mid-thigh pull peak force during PRE, SqOR and TAPER. Shaded area indicates 95% confidence intervals.

7.5.2.3 Countermovement jump

Group mean CMJ PF at PRE was 2283 ± 370 [CI = 2026 to 2539] N, which was the greatest recorded across the study duration. At POST7, PF had decreased to 2244 ± 373 [CI = 1986 to 2502] N; -1.7%, and at POST14, PF was still lower than PRE (2247 ± 337 [2014 to 2481] N; -1.6%). The lowest group mean occurred on day 3 (2024 ± 375 [CI = 1764 to 2284] N; -10.9%) (Figure 19). At POST7, three participants had increased PF relative to PRE (0.4 to 18.8%), and five participants reported a decrease (-1.3 to -9.6%). At POST14, three participants increased PF relative to PRE (0.6 to 8.5%), and five participants had decreased (-2.7 to -8.1%). Within-participant variation was 1.9 to 9.5 CV% and between-participant variability was 14.7 to 19.0 CV%.

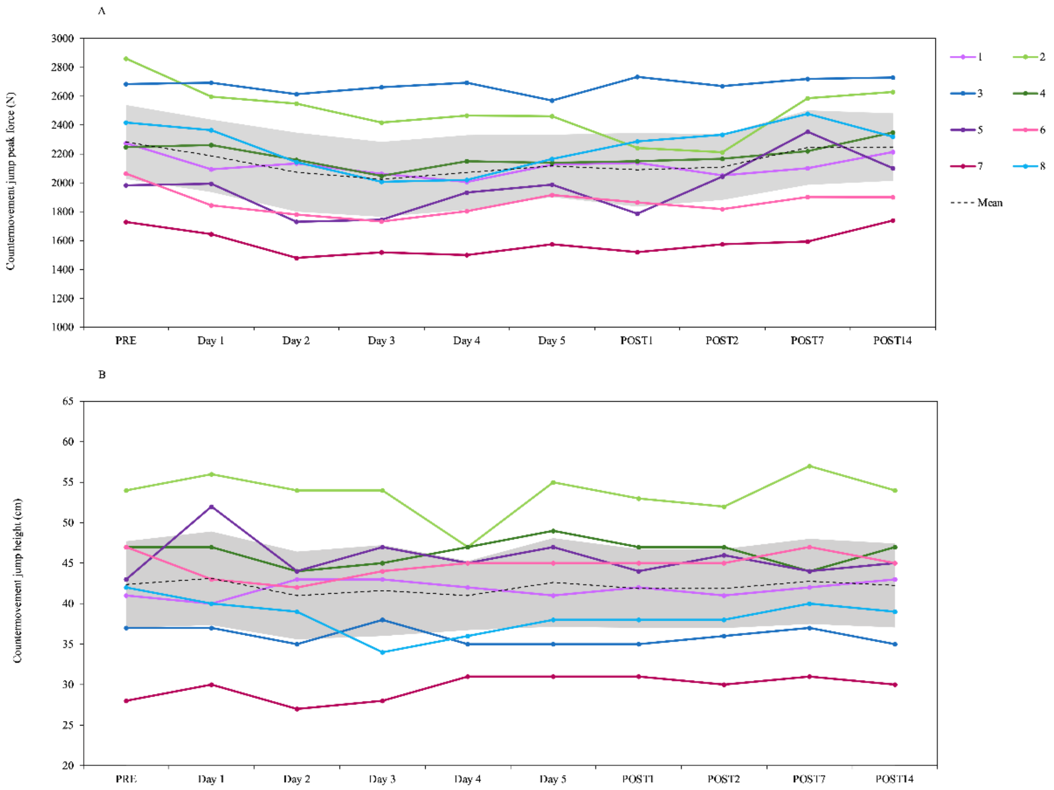

Figure 19. Group mean and individual changes in countermovement jump A. peak force, and B. jump eight during PRE, SqOR and TAPER. Shaded area indicates 95% confidence intervals.

The group mean CMJ height at PRE was 42.4 ± 7.7 [CI = 37 to 48] cm. At POST7, jump height was 42.8 ± 7.6 [CI = 37 to 48] cm; 0.9% relative to PRE, and at POST14 it was 42.3 ± 7.5 [CI = 37 to 47] cm; 0.0%. The lowest recorded CMJ height was on day 2 (41.0 ± 7.8 [CI = 36 to 48] cm; -3.2%) and day 4 (41.0 ± 6.2 [CI = 37 to 45] cm; -3.2%). The greatest jump height occurred on day 1 (43.1 ± 8.4 [CI = 37 to 49] cm; 1.8%) and POST7 (Figure 19). At POST7, four participants increased CMJ height relative to PRE (2.3 to 10.7%), 2 had returned to baseline (0.0%) and two participants experienced a reduction in jump height (-4.8 to -6.4%). At POST14, three participants had achieved an increase in CMJ height (4.7 to 7.1%), two participants had returned to baseline (0.0%) and three reported a reduction in jump height (-

0.3% to -7.1%) relative to PRE. Within-participant variation was 2.5 to 5.8 CV% and between-participant variability was 15.0 to 19.4 CV%.

7.5.3 Wellness changes

7.5.3.1 Perceived Recovery Scale

The mean PRS score at PRE was 8.1 ± 1.0 [CI = 7.4 to 8.8]. At POST7, PRS decreased to 7.3 ± 1.9 [CI = 5.9 to 8.6]; -10.8% and at POST14 had increased to 8.5 ± 1.2 [CI = 7.7 to 9.3]; 4.6% relative to PRE. The lowest recorded PRS was on day 3 (4.8 ± 2.4 [CI = 3.1 to 6.4]; -41.5%) and the highest was on POST14 (Figure 20). Within- and between-participant variability were 8.3 to 54.3 and 10.7 to 51.3 CV% respectively.

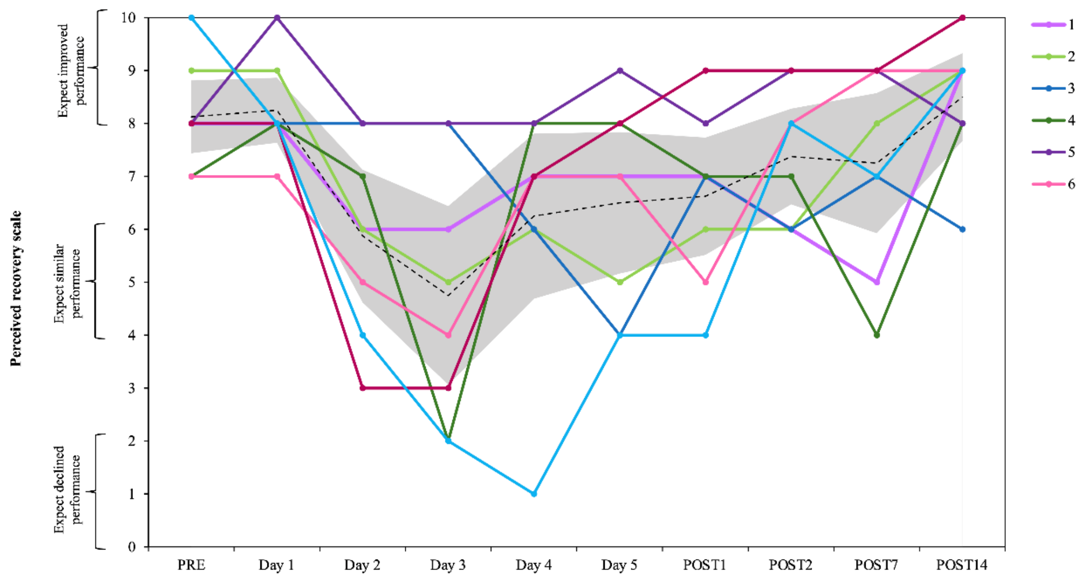

Figure 20. Group mean and individual changes in perceived recovery scale during PRE, SqOR and TAPER. Shaded area indicates 95% confidence intervals.

7.5.3.2 Hooper Wellbeing Index

The group mean score for global HWI (the summation score for all dimensions) at PRE was 11.5 ± 2.8 [CI = 9.5 to 13.5]. Global HWI was lower than PRE at both POST7 (10.4 ± 4.2 [CI = 7.5 to 13.3]; -9.8%) and POST14 (9.9 ± 3.4 [CI = 7.5 to 12.2]; 14.1%). The greatest global

HWI score occurred on day 3 (15.6 ± 4.1 [CI = 12.8 to 18.4]; 34.4%) and the lowest score occurred on POST14. Within-participant variability was 17.1 to 40.1 CV% and between-participant variability was 17.3 to 40.2 CV%.

The group mean score for HWIsleep at PRE was 3.4 ± 1.1 [CI = 2.6 to 4.1]. HWIsleep was lower than PRE at both POST7 (2.9 ± 1.5 [CI = 1.9 to 3.9]; -14.8%) and POST14 (2.9 ± 1.6 [CI = 1.2 to 4.5]; -14.8%). The highest HWIsleep score occurred on POST1 (4.0 ± 1.6 [CI = 2.9 to 5.1]; 18.5%) and the lowest score occurred on POST7 and POST14. Within- and between-participant variability were 27.2 to 59.2 and 31.4 to 63.2 CV% respectively.

The group mean score for HWIstress at PRE was 3.1 ± 1.7 [CI = 1.9 to 4.3]. HWIstress was lower than PRE at POST7 (2.8 ± 1.5 [CI = 1.7 to 3.8]; -12.0%) but had returned to PRE levels at POST14 (3.1 ± 1.6 [CI = 1.5 to 4.8]; 0.0%). The highest HWIstress score occurred on day 1 (3.5 ± 1.9 [CI = 1.6 to 5.4]; 12.0% higher than PRE) and the lowest score occurred on POST2 (2.4 ± 0.9 [CI = 1.5 to 3.3]; -24.0% from PRE). Within-participant variability was 13.1 to 63.3 CV% and between-individual variability was 30.2 to 55.3 CV%.

The group mean score for HWIfatigue at PRE was 2.6 ± 0.7 [CI = 2.1 to 3.1]. HWIfatigue was the same as PRE at POST7 (2.6 ± 1.2 [CI = 1.8 to 3.4]; 0.0%) but had decreased to 2.0 ± 0.8 [CI = 1.2 to 2.8; -23.8%] at POST14. The highest HWIfatigue score occurred on day 3 (4.0 ± 1.6 [CI = 2.4 to 5.6]; 47.6% increase from PRE and the lowest score occurred on POST14. Within-participant variability was 16.6 to 60.4 CV% and between-participant variability was 27.3 to 50.6 CV%. .

The group mean score for HWIsoreness at PRE was 2.4 ± 1.7 [CI = 1.2 to 3.5]. HWIsoreness was lower than PRE at POST7 (2.1 ± 0.8 [CI = 1.5 to 2.7]; -10.5%) and POST14 (1.9 ± 1.2 [CI = 0.6 to 3.1]; -21.1%), suggesting a decrease in perceived muscle soreness relative to baseline (Figure 21). The highest HWIsoreness score occurred on day 3 (6.1 ± 1.5 [CI = 4.7 to 7.6];

257.5% increase from PRE) and the lowest score occurred on POST7. Within- and between-participant variability were 31.9 to 94.6 and 20.3 to 70.9 CV% respectively.

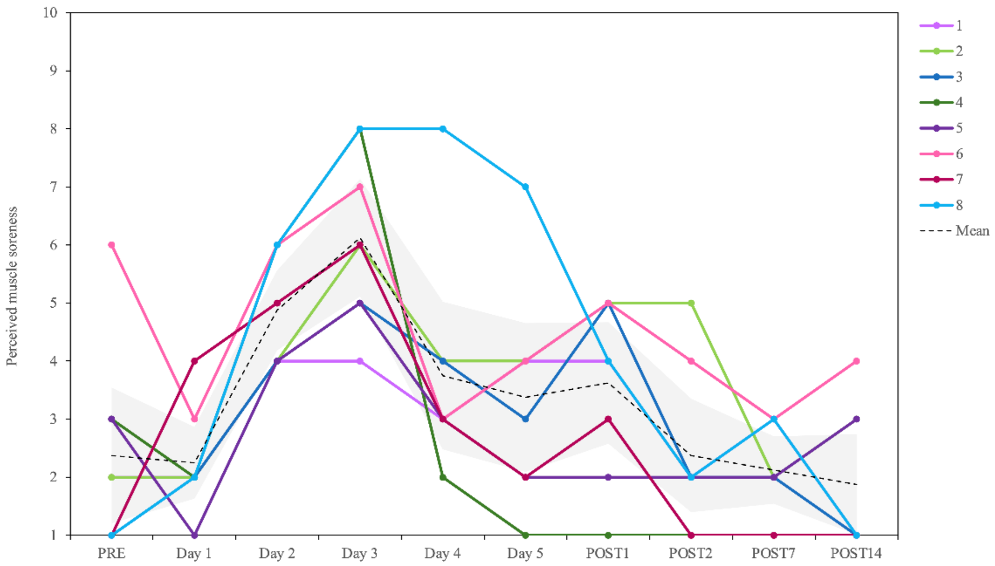

Figure 21. Individual changes in perceived muscle soreness (HWIsoreness) during PRE, SqOR and TAPER.

7.6 Discussion

The purpose of this study was to explore the feasibility and safety of a 5-day back squat OR protocol. This study was the first of its kind because it shows that undertaking consecutive days of high-intensity, high-volume barbell back squat OR using a 40% VLT to dictate set end point results in practically meaningful strength improvements. It also shows that improvements in strength follow an individualised peaking profile which has important contextual implications for how the post-OR taper might be implemented into the training programme. To ensure our methods were robust, we used a highly standardised programme of training consisting of a foundation training phase, a 5-day OR phase, and taper. We incorporated an autoregulated loading approach to accommodate for daily changes in readiness, and integrated performance and perceptual assessments at regular timepoints to monitor acute alterations in training status.

In line with good practice for pilot research (In, 2017; Thabane et al., 2010), this study aimed to evaluate elements of the protocol before future fully powered randomised controlled trials can take place. We hypothesised that the physiological response to SqOR would be variable, with some participants achieving a meaningful improvement in strength performance relative to baseline (i.e., FOR) and others experiencing a decrease in performance lasting several days or weeks with no observed improvements (i.e., NFOR). We did not expect OTS to occur given the overall duration of the protocol. The main findings of this investigation are that 1) completion of SqOR followed by a taper resulted in improved muscular strength that surpassed the SWC, 2) muscular strength gains followed an individualised peaking profile, and 3) undertaking consecutive bouts of resistance exercise whilst under-recovered did not result in long-term performance decrement or any other adverse effect. A plausible explanation for the improvement in muscular strength observed in this study is that the protocol undertaken was sufficient to induce highly specific neuromuscular adaptations in a trained population but not excessive enough to cause maladaptation.

In line with similar research (Fry et al., 1998, 2006, 1994c, 1994b, 1994a; Nicoll et al., 2016; Sterczala et al., 2017), the training-specific criterion measure used to determine performance change in this study was back squat 1-RM. At POST7, strength improvements were observed for all participants relative to baseline. At POST14, six participants observed an additional, albeit smaller 1-RM increase, whilst strength gains had returned to baseline for two participants.

In well-trained athlete populations (such as those recruited for this study), even the smallest of performance improvements are of primary importance (Bernards et al., 2017). Further, it is generally accepted that highly trained individuals improve their strength performance at a lower magnitude compared to untrained individuals (De Camargo et al., 2021; Latella et al., 2024). Therefore, the SWC provides contextual information relating to real world performance changes. This approach has been used in other studies aiming to detect meaningful changes in strength performance following a period of planned OR and is considered an effective way to quantify athlete monitoring practices, particularly during intense periods of training (Coutts et al., 2007; Saw et al., 2018). In this study we estimated the SWC (calculated from baseline 1-RM testing) to be 6kg. At POST7, seven of the eight participants achieved improved 1-RM performance that surpassed the SWC, with six participants maintaining improvements that surpassed the SWC at POST14. Therefore, completion of SqOR followed by a period of tapering augments strength improvements that are practically meaningful. The additional improvement in 1-RM experienced by some participants between POST7 and POST14 did not surpass the SWC, suggesting that whilst a longer taper might have been beneficial for some participants to reach 'peak' improvements in strength (based on absolute change in load lifted), the magnitude of change was not practical meaningful. Importantly, one participant did experience a reduction in 1-RM between POST7 and POST14 that did surpass the SWC (-10.0 kg), suggesting that a meaningful level of detraining had occurred.

FOR occurs when an athlete experiences a temporary (hours to days) decrease in training readiness followed by enhanced performance within 1-2 weeks (Aubry et al., 2014; Bazyler et al., 2017a; Tian et al., 2015). There is currently no accepted threshold by which performance improvements are constituted as FOR (Meeusen et al., 2013). To be more precise, *any* improvement in the criterion measure of performance could be considered FOR based on current consensus, given that it is preceded by a short term period of performance decrement (Claudino et al., 2016; Meeusen et al., 2013). This is likely due to the multifactorial nature of supercompensation and a lack of accepted gold standard test or assessment to differentiate FOR from NFOR (Grandou et al., 2020). Nevertheless, in an applied strength and conditioning environment, coaches seek training-related changes that have practical relevance e.g., whether the change in any given parameter is greater than the smallest practical or meaningful change (Bonafiglia et al., 2021).

In this study, improvements in back squat 1-RM were observed only after an initial decrease in training readiness (as indicated through a reduction in daily load lifted, CMJ height and PF, and perturbations in select measures of perceived recovery and wellness). Moreover, all participants observed a temporary reduction in daily load lifted at varied time points during SqOR. Whilst there is evidence of a supercompensatory effect in maximal strength (as evidenced by 1-RM improvements relative to baseline), there was no indication that FOR had taken place based on current definitions. Indeed, for FOR to have occurred, a reduction in 1-RM would likely need to be observed at POST7. However, all participants had improved muscular strength above baseline at that point. Therefore, it is more likely that the transitory and temporary perturbations in daily readiness (i.e., daily load lifted, CMJ) were independent of 1-RM and reflective of the acute fatigue generally observed during the adaptive response following high-effort resistance exercise training (Raastad & Hallén, 2000; Vieira et al., 2022).

NFOR occurs when athletes undertake a period of intensified training resulting in stagnation or plateau in athletic performance lasting several days to weeks (~2 weeks) with no improvement in performance relative to baseline (Birrer et al., 2013; Halson & Jeukendrup, 2004; Meeusen et al., 2013). As all participants in this study reported an increase in back squat 1-RM relative to baseline, no cases of NFOR occurred.

Undertaking regular high-volume and high intensity of effort training can lead to performance improvements above baseline but also increases susceptibility to NFOR (Grandou et al., 2020). The risk of NFOR developing further increases when repetitive efforts close to muscular failure are performed (Bell et al., 2020; Nóbrega & Libardi, 2016), where exercise-induced muscle damage occurs (Cheng et al., 2020; Kataoka et al., 2022), where there is low variation in exercise selection (Grandou et al., 2020), or where there is insufficient recovery between bouts of training (Sousa et al., 2024). Indeed, several previous studies have reported performance decrements where a high-volume training protocol was performed with repeated high effort using only a single resistance exercise (Fry et al., 1998, 1994c, 1994b; Nicoll et al., 2016; Sterczala et al., 2017). It must be noted though that in those studies reporting a decrease in performance, follow-up testing was performed immediately after completion of the training intervention and not following a recovery period or taper. The absence of NFOR observed in this study is likely, in part, due to follow-up performance testing taking place after a planned taper, which is indicative of real-world training practice (Bell et al., 2023; Pistilli et al., 2008). The taper itself is considered to be an important component of the adaptive process as training during this phase is organised in a way that mitigates fatigue and facilitate physiological adaption (DeWeese et al., 2015b; Hermassi et al., 2019; Travis et al., 2020).

In this study, two athletes achieved peak muscular strength at POST7 before returning to baseline, whereas six participants did not peak until POST14. Importantly, if 1-RM had only been assessed at POST14, (i.e., no 1-RM testing occurred at POST7), NFOR might have been (albeit erroneously) determined based on a lack of performance improvements following SqOR. Therefore, it is important that coaches and sports scientists consider when testing occurs to best determine performance changes. Indeed, the timing of performance change can vary between athletes despite similar training demands (20), with up to <4 weeks of tapering required by some athletes to experience strength improvements following OT (Murach & Bagley, 2015; Travis et al., 2020). Previous research has elucidated variable adaptation kinetics where the *time course* of the adaptive process e.g., the duration required to observe peak performance gains following a period of planned OR varies between athletes, even when undertaking the same training protocol (Marrier et al., 2017; Morin et al., 2020). Therefore, findings from this study might have important implications for how post-OR testing is scheduled and demonstrates that the duration of the taper might influence muscular strength outcomes following a period of OR.

In this study we incorporated several performance and perceptual assessments at select time points throughout the training programme. These assessments were, in part, informed by previous research (Bell et al., 2020; Grandou et al., 2020; Halson & Jeukendrup, 2004; Meeusen et al., 2013) but also by real world high-performance strength coaching practice (Bell et al., 2021; Bell et al., 2022a). When training to muscular failure, suppression of maximal strength and alteration in force-generating characteristics can require <72 hours to resolve (Ishida et al., 2023; Thomas et al., 2018; Vieira et al., 2022). Where exercise-induced muscle damage has occurred (due to extremely high training volumes, eccentric loading or unaccustomed exercise), recovery can require ≤ 96 hours (Monteiro et al., 2019; Morán-Navarro et al., 2017). Therefore (based on the organisation of training during SqOR), we anticipated that participants would be under-recovered during (and after) the training protocol, and that by incorporating daily testing, fatigue, recovery and readiness to train could be appropriately monitored (Grandou et al., 2021).

In strength sports and resistance training programmes, indicators of training readiness often include objective measures of 1-RM, barbell velocity metrics (e.g., MCV), CMJ height and CMJ/IMTP force metrics (Helms et al., 2020; Stone et al., 2003; Tolusso et al., 2022) as well as subjective measures of perceived recovery and wellness (Buoncristiani et al., 2023; Tibana et al., 2016). The combination of both objective and subjective measures permits the coach to make informed decisions regarding how training might be adapted day to day (i.e., autoregulation) (Coutts et al., 2007; Meeusen et al., 2013). Moreover, there are often large correlations between objective and subjective strength performance assessments (Buoncristiani et al., 2023), allowing a degree of flexibility and individualisation when monitoring readiness and recovery. In this study, CMJ PF was lower than baseline each day during SqOR as well as during the taper phase, suggesting that PF derived from CMJ was sensitive enough to detect fatigue. Indeed, previous research has indicated that CMJ PF and jump height provide the most consistent measure of neuromuscular fatigue during periods of OR, providing the coach with an accurate and sensitive assessment to monitor performance and avoid maladaptation (Margonis et al., 2007; Raeder et al., 2016; Ross et al., 2022). Nevertheless, whilst consistent reductions in both CMJ PF were observed in this study, NFOR did not occur. Moreover, reductions in jump performance did not always correspond to the daily load lifted or volume load completed during SqOR. Therefore, caution must be taken when using jump performance in isolation to assess training readiness, as premature termination of training based on reductions in jump performance alone might negatively impact athletes achieving performance gains. Further, based on our findings, a reduction in jump force or height during SqOR is the result of acute fatigue rather than an NFOR as jump performance returned to baseline for most participants within <7 days of completing SqOR.

Interestingly, whilst decrements in CMJ PF were observed during SqOR, IMTP PF increased most days and improved relative to baseline at both POST7 and POST14. IMTP PF is typically used as an indicator of acute neuromuscular fatigue and preparedness for training due to its potential sensitivity to fatigue and strong correlation to 1-RM performance (Beckham et al., 2018; De Witt et al., 2018). Based on findings from this study and previous research, PF might not be sensitive enough to detect meaningful neuromuscular impairment during planned OR and did not appear to relate to daily measures of squat performance (daily load lifted, volume load). Therefore, coaches should be cautious when using IMTP PF to assess daily readiness during periods of intensified training.

In this study, participants reported a large decline in perceived recovery and wellness scores during SqOR, suggesting under-recovery and diminished preparedness between training bouts. Participants reported large increases in perceived muscle soreness and fatigue (both of which peaked on day 3), which appeared to correspond with jump performance (which was also lowest on day 3). Stress and sleep were relatively unchanged relative to baseline throughout SqOR, although stress was higher than baseline on day 1 of SqOR. Participants had a lack of previous experience implementing intentional OT in their training programme and the increased stress reported before SqOR might have reflected a 'pre-microcycle anxiety' or threat state where athletes considered the protocol as challenging or unachievable (Judge et al., 2016). This is, however, speculative and to date there has been no research that has explored perceptions of planned OR from the perspective of the athlete. All subjective measures of recovery and wellness were resolved by completion of the study, suggesting negative alterations in perceived recovery and wellness were indicative of a acute fatigue rather than chronic maladaptation (Ishida et al., 2023; Kreher & Schwartz, 2012a).

Previous literature has indicated that the PRS can detect increased fatigue and muscle damage following periods of high-volume resistance exercise planned OR, and therefore might accurately assess the readiness of an athlete during training sessions across an intensive microcycle. Following high-intensity back squat exercise, PRS appears to be more sensitive to tracking fatigue than objective measures of CMJ jump height and IMTP PF (Brisola et al., 2022). Subsequently, monitoring perceived stress and recovery might help prevent NFOR by warning coaches of reduced recovery during periods of highly demanding, concentrated loading (Nederhof et al., 2008). Nevertheless, during periods of planned OR, training is organised in a manner that recovery between bouts is purposefully impaired. Therefore, temporary decrement in perceived recovery should be expected given the demands of the training microcycle. Therefore, it is unsurprising that participants of this study reported diminished recovery and wellness. Moreover, NFOR did not occur in this study, suggesting that diminished recovery reported by participants was not a warning sign of maladaptation and indicative of the normal adaptive response to highly demanding training. It is also worth noting that perceived recovery is also highly individualised, with research reporting inconsistencies between daily performance measures (back squat MCV, CMJ height) and perceived recovery (Tolusso et al., 2022; Zourdos, Dolan, et al., 2016).

Identifying and discussing the limitations of a pilot study contextualises the importance of its findings (Lancaster & Thabane, 2019). Moreover, acknowledging limitations in pilot trials can improve the quality of future definitive controlled research studies (Eldridge et al., 2016). Therefore, the following information should be considered before during the development phase of future research projects intending to utilise resistance exercise training planned OR protocols.

This study aimed to examine the feasibility and safety of a pilot planned OR protocol in a trained population and was not powered to detect statistical difference. In pilot research, it is not recommended that formal significance testing is undertaken (Lancaster et al., 2004). Consequently, descriptive statistics were used on primary and secondary outcome data and findings in line with recommendations for pilot research (Thabane et al., 2010). Moreover, the emphasis on descriptive statistics should not be viewed as a limitation, rather a way to assess feasibility of the protocol. Whilst SqOR was designed to induce a state of OT for the purpose of scientific inquiry, which was (in some regards) observed through the reduction in daily readiness and diminished perceived recovery), no cases of NFOR occurred. Therefore, it can be argued that the protocol in this pilot was not sufficiently challenging to induce long-term maladaptation. Despite this, the positive performance effects observed suggests consecutive days of high-volume, high-intensity squats might be a promising approach for inducing muscular strength improvements in trained individuals. Consequently, participants from this cohort can inform the feasibility of recruitment from the general well-trained population for a larger implementation of the protocol. It must be noted though that whilst specific inclusion criteria were used to determine the training status of participants, the baseline values across the participant sample were dissimilar. Whilst we consider the inclusion criteria to be robust, future studies might benefit from recruiting a more homogenous participant pool.

SWC was used in this study to contextualise the magnitude of performance change (and to determine performance changes, however, it must be acknowledged that the method by which SWC was calculated in this study might have limitations, since the magnitude of the SWC is affected by the homogeneity of the participant population (i.e., the greater the homogeneity, the lower the SWC) (Buchheit et al., 2014). In this study, the range of PRE 1-RMs was relatively broad (158 ± 30.1; range = 113 to 215 kg), therefore, future research exploring the effects of SqOR on 1-RM would benefit from a larger, more homogeneous pool of athletes to reduce the potential for error.

A 40% VLT was implemented into SqOR to ensure each working set was performed close to muscular failure and to standardise the degree of effort between participants (as well as for the same participants on different training days). We acknowledge though that the number of repetitions completed at a given load within a specific VLT can be variable (Weakley et al., 2021b), likely due to individual athletes' strength-endurance abilities. Moreover, we acknowledge that even the magnitude of velocity loss achieved during a given set cannot necessarily inform proximity-to-failure during resistance exercise training (Refalo et al., 2023). Nevertheless, using a VLT of 40% permitted an increase neuromuscular fatigue but also mitigated the risk of injury that could have been caused by repeatedly 'bailing' the barbell by training to absolute muscular failure. Moreover, the reduction in neuromuscular function (and concomitant increase in fatigue) experienced following a set to failure is not dependent on the number of repetitions completed per se, but the magnitude of velocity loss (and as such, the degree of effort applied) (Rodríguez-Rosell et al., 2020). Consequently, using a high VLT such as the one in this pilot increased the chances of altered perceptual, metabolic and mechanical output which, hypothetically, should have increased the risk of NFOR occurring (Sánchez-Medina & González-Badillo, 2011; Weakley et al., 2021b).

Finally, whilst it is not a limitation of the study per se, the protocol implemented for this pilot focused solely on the barbell back squat exercise and no other resistance exercise was permitted during the SqOR phase. Therefore, the effects of such training within a holistic training programme have not been determined and caution must be taken when applying these results within a practical training environment.

7.7 Practical applications

A growing body of evidence suggests that the prevalence of NFOR is low within strength-trained populations. Moreover, there is little evidence that true OTS has occurred in athletic populations following an intensive period of resistance exercise training (Bell et al., 2020; Bell 2022b; Grandou et al., 2020). Findings from this pilot suggest that a period of planned OR consisting of consecutive days of high-volume, high-intensity back squats induces performance improvements and does not result in NFOR or any other adverse effects. Nevertheless, caution must be taken when attempting to contextualise these findings within a practical training environment and further research is required to understand the utility of such training in a real-world setting.

It is common for strength athletes to intentionally implement OR within specific phases of the competition training programme, therefore future research should continue to examine how such training should be organised to achieve an optimal adaptive response. This study, in part, shows that undertaking consecutive days of resistance exercise might be strategy to induce strength gains within a short period of time. Consequently, future studies must continue to investigate the mechanisms that underpin FOR to better understand the factors that contribute to the adaptive response.

A challenge that future research might have in trying to induce NFOR (for the purpose of scientific inquiry) is the ethical considerations attached to developing more challenging resistance exercise protocols. To examine the maladaptive response to resistance exercise, future research will be required to undertake more challenging protocols, which, of course, might carry inherent and additional risks. Consequently, research ethics committees must be cognisant that that protocols such as SqOR are not as likely to result in maladaptation as originally assumed.

Chapter 8: Main findings, future directions, and conclusion

8.1 Advancing knowledge on overreaching and overtraining in strength sports and resistance exercise training

Prior to embarking on this doctoral programme, the landscape of research exploring OR/OT in strength sports and resistance exercise training was limited. The available body of literature was fragmented and incongruous, lacking critical insight and cohesive communication of the topic. Whilst there had been several laboratory and field-based studies published in the endurance sport domain, strength sports and resistance exercise research had (to a large degree) received much less attention. Consequently, there were several gaps in the literature left to investigate during this doctoral programme. Therefore, this thesis was a purposeful attempt to enhance the quality of OR/OT research in this domain. The primary findings of this doctoral thesis are summarised in Figure 22 and presented as a 'golden thread' where the interlinkage between specific findings from each individual study are interwoven whilst explicitly outlining the most meaningful inferences.

8.2 Achievement of doctoral thesis objectives

Objective 1: To map the current research landscape to enhance understanding of OR/OT within strength sports and resistance exercise training populations.

Objective one was addressed by undertaking a scoping review that followed a novel but robust methodological approach in line with the PRISMA-SCr protocol (Bell et al., 2020). This first study of the doctoral programme (study one) adhered to the recommendations proposed by the ARMSS model and sought to map the current landscape of research to identify possible OR/OT problems faced by sport scientists and practitioners (Bishop, 2008).

Results from the scoping review revealed that the overall number of studies exploring OR/OTS specifically in the context of strength sports or resistance exercise was low. The prevalence of

NFOR in strength sports or following a period of resistance exercise was minimal, with limited evidence that true OTS had occurred in resistance-trained populations (even after intentional attempts to induce training maladaptation). The scoping review also highlighted inconsistencies in terminology, an absence of standardised assessments, and a lack of appropriate follow up testing to accurately determine OR/OTS. This study (along with the explorative review by Grandou et al., (2020) which was published at a similar time as our scoping review) was the first study to objectively outline the prevalence of OR/OTS following periods of resistance exercise training. Therefore, study one provides novel insight for both sport scientists and practitioners. Prior to this review being published, the only other review exploring resistance exercise OTS was published almost thirty year previous and followed a narrative approach rather than a formal methodological approach (Fry & Kraemer, 1997). Findings from the scoping review were contrary to those reported in the endurance domain where the prevalence of OTS is generally considered to be relatively higher (Halson & Jeukendrup, 2004; Meeusen et al., 2013). Finally, the scoping review highlighted several existing gaps in knowledge, as well as areas of research still not undertaken. These gaps formed the basis of the next steps of research in this doctoral programme in line with the ARMSS model. In this sense, study one acted as a catalyst for all future studies in this thesis.

Objective 2: Explore strength sport coaches' experiences and perceptions of overtraining and to provide a novel method of conceptualising overtraining from the perspective of the practitioner.

Objective two was addressed using a qualitative approach (study two), with data collected through semi-structured interviews of experienced high-performance strength coaches. Analysis was undertaken using reflexive thematic analysis, based on guidelines provided by Braun & Clarke (2006). This was the first published study that had explored and communicated perceptions of OR/OTS from the perspective of the practitioner and therefore provided insight into the experiences of those responsible for making key programming decisions; a valuable but often untapped resource in sport science research (Haugen, 2021).

Study two revealed that strength coaches have inconsistent definitions of OTS and favoured more informal, colloquial terminology to describe long-term performance decrement (e.g., “under-recovery”, “fatigue syndrome”, “burnout”). Strength coaches had dichotomous beliefs about OTS and highlighted several diagnostic symptoms that they might look for in a maladapted athlete. The prevalence of OTS within strength sports was considered low, with most coaches revealing that they had never observed long-term reductions in performance with their athletes. Indeed, some coaches believed that their athletes could work at a higher relative load/intensity than is typical of their current training without deleterious effects. Finally, strategies employed by coaches to observe the training response (and identify training maladaptation) favoured simple, subjective assessments rather than objective testing or controlled laboratory protocols.

Coaches strived to adopt an evidence-informed approach when developing resistance exercise training programmes but were largely unaware of expert consensus and guidance on diagnosing OTS if they were to suspect maladaptation. This suggested a lack of effective communication between sport science research and those who will ultimately implement the research in practice; a problem that appears common in the sport research domain (Bishop, 2008; Ruddock et al., 2019).

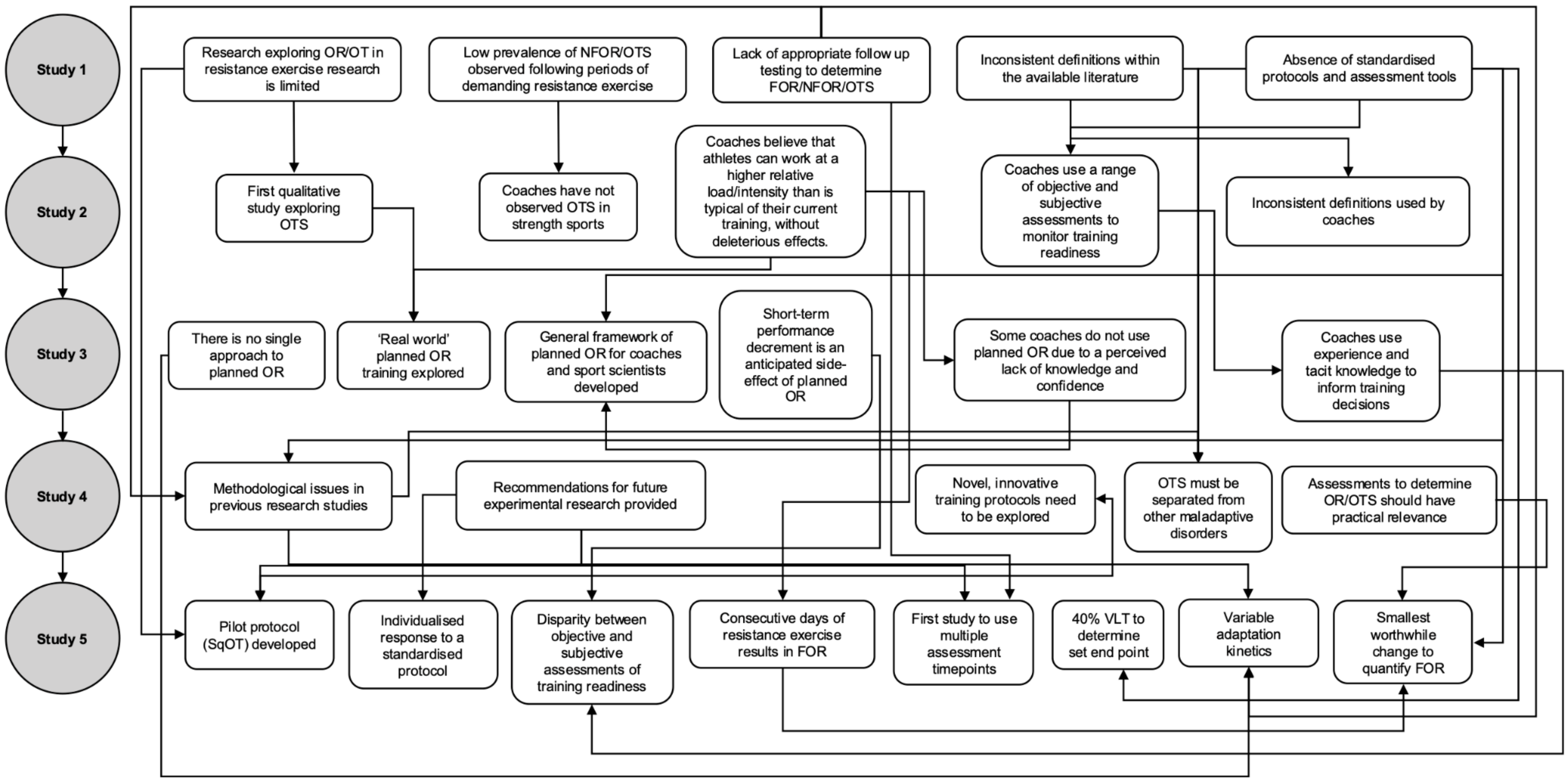

Figure 22. A schematic detailing the golden thread of this doctoral thesis and links between each study.

A lack of effective knowledge translation between the scientific community and strength coaches was perhaps one reason why definitions and general understanding of OTS were inconsistent. Indeed, whilst coaches consider scientific information to be valuable, a perceived inability to access research by practitioners is a barrier to effective knowledge exchange in sport science (Reade & Rodgers, 2009). Therefore, it is perhaps not surprising that coaches interviewed in study two were unaware of consensus documentation relating to OTS. These findings further highlighted the importance of collaboration between the strength coach and sport scientist.

Objective 3: Investigate how strength sport coaches develop, prescribe, and monitor periods of planned OR to facilitate performance improvements whilst mitigating the risk of training maladaptation.

Objective three was addressed using a qualitative approach (study three) where high-performance strength coaches were consulted on their experiences and perceptions of planned OR as part of their programming strategies (Bell et al., 2022a). This study was undertaken as part of the second phase of the ARMSS model and sought to better understand how experienced high-performance strength coaches apply planned OR within a real-world training context, therefore assisting sport scientists in developing more ecologically valid training interventions. This study was the very first to explore and communicate ways in which strength coaches design and prescribe periods of planned OR using a robust qualitative approach. Data were collected in the same way as study two; using semi-structured interviews and analysed using reflexive thematic analysis (Braun & Clarke, 2006).

Study three proposed a general practice-informed framework for sport scientists wanting to develop real world interventions for the purpose of scientific inquiry. Importantly, the recommendations constructed as part of the framework were broad and flexible, representing the many ways by which experienced strength coaches design planned OR. The development of the framework was considered an important step towards effective knowledge exchange and “collective ownership of goals” (Reade & Rodgers, 2009) by acknowledging the importance that experienced practitioners can have in the development of real world solutions to problems such as training maladaptation. Findings from study three also noted that some high-performance coaches do not implement planned OR due to a perceived lack of knowledge or skills. Therefore, the framework was also developed to assist others within the strength coach community in designing their own concentrated loading phases, further assisting knowledge exchange.

Study three reported that coaches perceive short-term performance decrement, both during and in the days to weeks following training, as an anticipated by-product of planned OR. Moreover, an increase in fatigue was generally used as a benchmark to confirm that training demand was sufficiently challenging. Lastly (and perhaps most interestingly) the methods by which coaches intentionally implement planned OR to achieve performance improvements (i.e., through increased relative training volume or intensity, training to muscular failure, increased weekly/daily training frequency) were also identified in studies one and two as risk factors for the development of NFOR.

Objective 4: Provide evidence-based recommendations for sports scientists undertaking resistance exercise OT research, and to propose directions for future research.

Objective four was addressed through publication of a peer-reviewed narrative opinion piece (study four). The opinion triangulated findings from studies one to three and acted as a precursor to the experimental work that formed study five. In this sense, study four was part of the second stage of the ARMSS model advocating that predictors of performance are justified prior to experimental testing (Bishop, 2008). In the opinion piece, concerns were raised regarding with the methodological approach to current OTS research, as well as some of the ethical and methodological barriers that sport scientists might face when developing resistance exercise protocols to investigate OR/OTS. Finally, a series of recommendations were proposed to assist sport scientists in developing robust research studies that reflected aspects of real-world training. These recommendations were then implemented in study five.

Objective 5: To develop and assess the feasibility and safety of a resistance exercise protocol designed to induce OT for the purpose of scientific inquiry.

Objective five was addressed through an experimental study using a pilot approach (study five). This study was the culmination of the previous four studies of this thesis, and used findings generated from those research outputs to explore predictors of performance. Consequently, the final study of this doctoral programme was congruent with the third stage of the ARMSS model.

The main findings from study five were that undertaking a period of high-volume and high-intensity resistance exercise training close to muscular failure resulted in strength gains with individualised adaptation kinetics. Improvements in maximal strength surpassed the smallest worthwhile change (SWC) and, therefore, was indicative of a meaningful change in performance. Importantly, the duration of the post-OR taper period influenced strength gains, with all participants reporting an increase in back squat 1-RM after a 7-day taper period and some reporting an additional (albeit smaller) increase after a second 7-day taper. It is generally accepted that undertaking phases of concentrated loading whilst under-recovered will result in NFOR/OTS (Fry et al., 1992; Haff et al., 2004; Kreher & Schwartz, 2012a), however, no cases of training maladaptation were recorded in this pilot study. This reflected what coaches from study two said; that they were not concerned about OTS following periods of concentrated loading.

8.3 Consolidating findings from this doctoral programme and developing key areas for future research

8.3.1 Based on findings from this thesis, it is unlikely that OTS has occurred in strength sports or following a period of resistance exercise

The sequence of research published during this doctoral programme complied with the ARMSS (Bishop, 2008). The individual published studies were organised in a way that triangulated the prevalence of OR/OTS in the existing literature, but also explored the 'real world' of strength sports (e.g., attitudes towards OTS) through knowledge exchange with practitioners (Figure 23). Study one investigated the prevalence of OTS in the available body of literature using a novel but rigorous scoping review approach (Arksey & O'Malley, 2005). The main findings revealed minimal evidence of OTS occurring in either strength sport populations or in individuals undertaking periods of highly demanding resistance exercise. In the very few studies that did indicate OTS might have occurred, methodological flaws and a lack of follow-up assessment suggested that this was not the case. In studies where follow up testing was implemented and performance decrement exceeded the minimal duration required to consider OTS (> 4 weeks), the magnitude of performance decrement did not exceed the required >10% (Margonis et al., 2007). These concerns were described in more detail in study four as part of a peer-reviewed narrative opinion piece. Importantly, around the time that the scoping review was published, an explorative review of OTS in resistance exercise was published by Grandou et al., (2020). Whilst this review adopted a different methodological approach to the scoping review (favouring an explorative systematic review), findings between each study were congruent, agreeing that there was limited evidence of OTS occurring in resistance exercise trained populations.

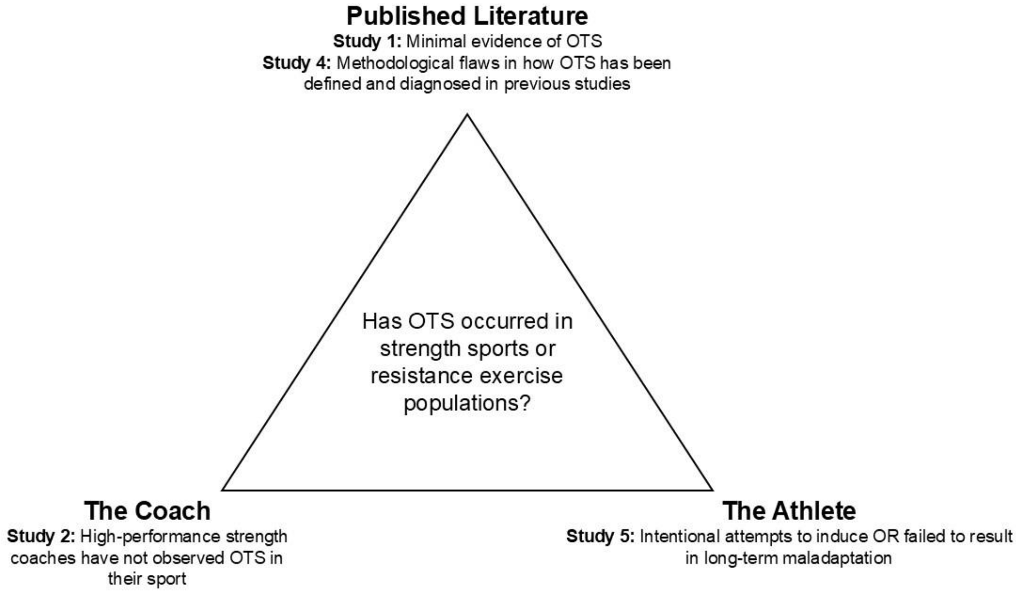

Figure 23. Triangulation of research exploring the prevalence of OTS; from the perspective of 1) the previous literature, 2) the high-performance strength coach, and 3) the athlete undertaking resistance exercise

In study two, experiences and attitudes towards OTS from the perspective of the high-performance strength coach were explored. This was both a novel and important aspect of the doctoral programme that investigated perceptions of OTS from those "on the ground" (Jones et al., 2019). Investigating aspects of sport science from the perspective of the practitioner is an important aspect of stage one of the ARMSS model and was also considered a key step to better understanding the complex problem of OTS in a more integrated manner (Bishop, 2008) and enhancing understanding of the subject through effective collaboration (Otte et al., 2019; Reade & Rodgers, 2009; Rothwell et al., 2020).

In study five of this doctoral thesis, an experimental OR protocol was developed for the purpose of scientific inquiry was developed. The protocol implemented several risk factors for long-term training maladaptation (many of which were described in previous studies from this thesis), such as undertaking excessive or prolonged high-intensity or high-volume resistance exercise (Bell et al., 2020, 2021; Bell et al., 2022a; Fry & Kraemer, 1997; Grandou et al., 2020), prolonged training monotony (caused by minimal variation in exercise selection or approach) (Foster, 1998; Kreher & Schwartz, 2012a), and repeated training to muscular failure (Bell et al., 2020; Grandou et al., 2020). It was hypothesised that undertaking the protocol might lead to an adverse event such as NFOR/OTS, however no adverse effects were observed. Whilst it is acknowledged that this is a single study and caution must be taken when interpreting these results in isolation, these findings do demonstrate that it is perhaps not an easy task to intentionally 'overtrain' athletes.

It is worth noting that during this doctoral programme, the author of this thesis collaborated with Grandou et al., (2021) to explore the prevalence and possible symptomatic profile of training maladaptation in competitive resistance-based athletes. Using a cross-sectional survey with a large convenience sample, main findings revealed that in those athletes reporting an unexplained decrease in performance, most experienced symptoms of performance decrement lasting < 1 month (43.8%). There were relatively few athletes that reported symptoms lasting > 1 month and a very low number experiencing symptoms lasting > 4 months. These findings suggested that whilst it is common for strength athletes to experience feelings of fatigue and musculoskeletal aches and pains, symptoms were typically transient and not indicative of OTS. Importantly, a large proportion of athletes reporting symptoms of maladaptation (92.5%) also indicated the presence of additional non-training related stressors (e.g., work, personal life), suggesting that management of non-training events is an important aspect of maladaptation risk mitigation.

8.3.2 Current criteria for the identification of OR/OTS needs to be revisited

This doctoral thesis has presented evidence to suggest that terminology used to define OR/OTS is inconsistent and often misinterpreted in the published literature. Indeed, the term “overtraining” has seemingly evolved into an overarching term to represent both verb and noun: the process of undertaking highly demanding training, but also an abated, colloquial characterisation of OTS (**Table 2**). Adopting a single definition of OTS within the research has proven difficult and a wide range of terminology has been applied, with several synonyms and alternative terminology existing in the literature (Pope et al., 2018). Such divergent use of terminology has led to confusion about the ‘true’ meaning of the OTS, and it is not surprising that attempts have been made to completely redefine the term (e.g., unexplained underperformance syndrome, paradoxical deconditioning syndrome) (Budgett et al., 2000; Cadegiani & Kater, 2019a). Study two of this doctoral thesis revealed that in a practical environment, strength coaches favour more informal, colloquial terminology to describe OTS and typically develop their own definitions; ones that share with few similarities with expert consensus (Pope et al., 2018). Indeed, practitioners often simplify formal (“dense academic”) language to more user-friendly, action-based terms (Woods et al., 2020), therefore it is unsurprising that coaches use alternative terms to describe the phenomenon of OTS.

The purpose of an expert consensus is to provide robust and objective information that is evidence-informed and transparent (Blazey et al., 2022). Consensus statements should unambiguously guide practitioners so that accurate decisions regarding athlete readiness (i.e., risk of OTS) can be made; this means diagnostic and classification criteria should be based on findings from rigorous research studies to develop best (or good) practice guidelines (Nair et al., 2011). Based on findings from this doctoral thesis, revised taxonomy should be developed that objectively and appropriately defines and distinguishes OR from OTS (and OT from OTS). Current expert consensus statement suggests that OTS is poorly defined and lacks standardised vocabulary (Meeusen et al., 2013). Therefore, an important first step to improving the landscape of OTS research would be to revisit the current definition of OTS, creating a more objective, formalised definition. Within context of the ARMSS, effectively defining the problem is an essential first step to enhancing knowledge; one that cannot be completed without clear taxonomy (Bishop, 2008). Not only will a revised definition enhance conceptual understanding of OTS but provide more measurable criteria for clinicians and sports scientists (who intend to pursue stage four of the ARMSS model and onwards) to assess prevalence and the possible mechanisms that underpin long-term maladaptation (Figure 24).

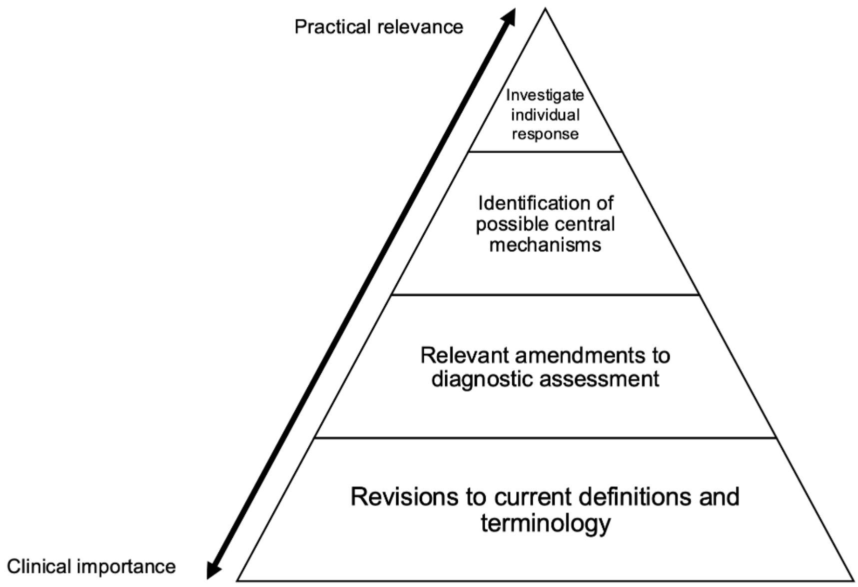

Figure 24. Proposed broad directions for future research to investigate OTS in strength sports and resistance exercise training. direction. The base of the pyramid represents more clinically relevant research domains, with each stage of research becoming increasingly practically meaningful.

Importantly, the research arising from this doctoral thesis revealed that high-performance strength coaches do not fully understand the terminology of OTS and are not fully familiar with expert consensus definitions (Bell et al., 2021). The research published in study two demonstrated that high-performance strength coaches view long-term training maladaptation as a subjective aspect of resistance exercise training that largely relies on identification through experience and tacit knowledge rather than objective scientific assessment. This is juxtaposed with the more analytical, mechanistic lens through which expert consensus and the scientific community view OTS. Of course, the implementation of dynamic, layperson language in a coaching environment facilitates grounding and understanding, however, original meanings behind important terminology can be lost or misinterpreted over time due to misunderstanding and cognitive bias (Chow et al., 2023). Clearly, there still remains a gap between how consensus information is communicated to coaches and athletes (Haugen et al., 2021). This has important implications for how any future definitions or changes to diagnostic or treatments pathways are made known to practitioners.

8.3.3 Future research should seek to separate OTS from related maladaptive disorders or consider amalgamating them into a more global performance decrement syndrome

Strength sports are generally organised into weight classes, with athletes frequently competing in categories below their habitual body weight (Kwan & Helms, 2022). During the competitive phase, it is common for strength athletes to implement specialised dietary approaches where energy intake is restricted to achieve the desired body mass (King et al., 2023). Strategies to make weight often include aggressive dietary practices that increase the risk of REDs, especially when restricted energy intake is coupled with intensified training blocks in the pursuit of competition success (Nelson & Jette, 2023). Surprisingly, there is very little research investigating the prevalence of REDs in strength sports, with much of the current body of literature focusing on endurance sports (Mountjoy et al., 2018), combat sports (Langan-Evans et al., 2020), and sports associated with leanness (rhythmic gymnastics, artistic swimming, figure skating, ballet) (Goldstein & Fukuda, 2020; Oleksy et al., 2019) or aesthetics (Mathisen et al., 2019). Consequently, future research should explore the prevalence of REDs in the strength sport domain, focusing on sports that are characterised by demanding training and an emphasis on aesthetics or extreme dietary practices (e.g., CrossFit) (De Souza et al., 2021).

According to the OTS consensus statement, confounding organic diseases and caloric restriction (i.e., negative energy balance, eating disorders) must be ruled out before diagnosis of OTS can be made. However, it is rare that dietary intake is reported in studies claiming that OTS (or even NFOR) has occurred. Previous commentary has highlighted the close parallels between OTS and REDs, with several overlapping symptoms shared between disorders (Stellingwerff et al., 2021). One of the biggest issues with the current body of research exploring OTS is a lack of reporting on energy and macronutrient intake (Bell et al., 2022b; Stellingwerff et al., 2021). To date, only one study has controlled for dietary intake during a period of intentional OT (Margonis et al., 2007). However, the details of the diet (including energy intake) were not revealed. In athletes presenting symptoms of OTS, as many as 84% indicated low energy availability or low CHO (Stellingwerff et al., 2021). Moreover, in competitive strength athletes reporting symptoms of performance decline lasting 1 to 3 months, 43.4% had implemented dieting (to achieve negative energy balance) in the days/weeks before underperformance occurred (Grandou et al., 2021). For athletes reporting symptoms of underperformance lasting >4 months, dieting prevalence increased to 45%. It is, therefore, plausible that without appropriate dietary analysis, a false positive misdiagnosis of NFOR/OTS can occur due to the confounding impact of under-fuelling on recovery and performance. These concerns were raised in study four of this doctoral thesis, providing examples of methodological issues that resulted in inaccurate identification of OTS (Bell et al., 2022b).

Based on findings from this doctoral thesis and related literature (Stellingwerff et al., 2021), it is recommended that all future research exploring OR/OTS includes transparent and accurate reporting of dietary intake (energy intake and detailed macro and micronutrient profiles). Such reporting should be completed using validated instruments that allow accurate tracking and analysis (Zhang et al., 2021) and mitigate reporting errors. Inevitably, this adds an additional layer of complexity for sport scientists conducting multifaceted research with multiple aspects of data collection, however, recording of dietary intake would allow researchers to differentially diagnose REDs or OTS and, therefore, improve the accuracy of identification/diagnosis.

8.3.4 The potential performance benefits of planned overreaching/concentrated loading

Undertaking concentrated loading phases as part of a strength training periodisation programme isn't a new concept (Abbott, 2016; Issurin, 2008; Stone et al., 1999; Verkhoshansky, 1981). It is common practice for congested training cycles (planned OR) to be embedded within many long-term training models, especially in strength sports (Smith, 2003). For example, conjugate and block periodisation utilise short microcycles of intensified training (i.e., shock microcycles) to stimulate training adaptations at specific time points within the competition training calendar (Issurin, 2016; Plisk & Stone, 2003; Verkhoshansky, 1981). Indeed, this thesis revealed that in strength sports, planned OR is a ubiquitous training practice (Bell et al., 2022a).

Planned OR should be short in duration (~7-14 days), but highly demanding; generally consisting of multiple high-volume or high-intensity training bouts per week (Bell et al., 2022a; Pistilli et al., 2008; D. J. Smith, 2003). In more advanced planned OR, up to 12 sessions per week can be completed (Abadjiev, 1982; Martinez & Kennedy, 2016; Roman, 1984). For example, the Smolov squat programme (a squat specialisation programme created by Sergey Smolov in the 1970s), is a thirteen-week programme consisting of three to four training sessions per week using intensities that reach 100% 1-RM (Finn et al., 2014). Whilst there are several different phases to the Smolov programme, perhaps the most physically demanding is the 'base phase' (weeks three to six). This 4-week cycle comprises four squat sessions per week ranging between 70-85% 1-RM for relatively high volume (e.g., 10 sets of 3 repetitions with 85% 1-RM in week three and 7 sets of 5 repetitions with 90% 1-RM in week five). Anecdotally, coaches and athletes have claimed that completion of this 'Russian squat cycle' can lead to significant improvements in squat strength. However, there is very little empirical evidence to suggest that this approach is superior to any other type of programme. Smolov isn't the only squat specialisation programme used by strength athletes. The Hatch squat programme, for example, consists of twice-weekly training sessions for twelve weeks incorporating back and front squats using intensities of <100% 1-RM.. Similarly, the Tim Swords squat programme involves twice-weekly back squat sessions with an additional front squat training session seven weeks. In this programme, intensities range from 60%- 90% 1-RM. Collectively, these varied approaches to planned OR demonstrate that there is no single way to implement concentrated loading into the strength training programme; which is congruent with findings from study three of this thesis (Bell et al., 2022a).

Whilst undertaking highly demanding resistance exercise might (at least hypothetically) increase the risk of training maladaptation (Fry & Kraemer, 1997; Meeusen et al., 2013), this thesis has demonstrated that the risk of developing NFOR or OTS, in the context of strength sports and resistance training is low (Bell et al., 2020). Contrarily, undertaking periods of concentrated strength training followed by a taper can lead to improvements in strength-specific performance. For example, daily 1-RM squat training performed for a period of one-month (using MCV to autoregulate the daily load) (Martinez & Kennedy, 2016) improved squat strength by 2.3% compared to all time squat performance in a trained weightlifting/track athlete. Similarly, competitive strength athletes completing a 37-consecutive-day resistance exercise programme consisting of a 1-RM back squat followed by 5 sets of 2-3 repetitions using 85-90% 1-RM experienced a significant increase in maximal strength (*range* = 5.8% to 10.8%), suggesting that meaningful changes in maximal strength even in well-trained competitive strength athletes could be achieved in in a relatively short training period (Zourdos, et al., 2016).

Whilst the OR cycles undertaken in the previously mentioned studies were several weeks in duration, study five of this thesis revealed that improvements in maximal squat strength could be achieved in a shorter duration. In this sense, performance improvements stimulated by undertaking planned OR might not be dictated by the duration of the training block per se, but by the specific intensity or volume completed within that period. Clearly, there will be a minimal effective dose by which strength gains are stimulated, however, this is yet to be determined experimentally. Consequently, future studies should investigate varied durations (as well as configurations) of planned OR to achieve optimal strength gains whilst being cognisant of the 'efficiency' of each approach.

8.3.5 Experimental testing of performance predictors

Most of the existing literature investigating the effects of planned OR has been conducted using an observational cohort or case study approach (Bell et al., 2020; Grandou et al., 2020). These types of studies provide important contextual information about OR/OT (especially when data are collected during training phases associated with a heightened risk of maladaptation e.g., training camps, planned OR cycles) and an opportunity to collect real world training data (especially if coaches are involved in the planning process). Moreover, prospective cohort studies provide an opportunity to explore several outcome variables and performance predictors that can be decided upon in advance (Mann, 2003). In line with stage three of the ARMSS model, the ability to investigate predictors of performance and identify consistent relationships (Bishop, 2008) between early detectors of training maladaptation and performance outcome is key to advancing knowledge related to OR/OT. However, it can be difficult to conduct follow-up testing in an observational setting and scheduling of testing sessions might not always be possible (Andrade, 2022) due to conflicting availability between coaches, athletes, and sport science researchers. Moreover, whilst observational studies assist in the detection of associations between variables, they do not necessarily infer causality (Ejima et al., 2016). Therefore, sport scientists must be cautious when interpreting results, even when rigorous observational study designs have been adopted.

To advance the field of OR/OTS in strength sports and resistance exercise training, it is important that further research is undertaken. In line with stage four of the ARMSS model, experimental studies designed to infer causality should consider adopting a randomised control trial approach (Bishop, 2008) and be designed in a way that minimises the effects of confounding variables (an example of this could be the effects of low energy availability which, as already mentioned, is not normally reported). There have, of course, already been experimental studies undertaken in the field (usually designed to induce OT for the purpose of scientific inquiry) (Bell et al., 2020; Grandou et al., 2020). However, these studies have often lacked the addition of a 'normal' training group for comparison and there are few studies that have reported individual responses, only group mean changes (Bell et al., 2022b). Given that the response to training and recovery is non-ergodic and statistical analysis at an inter-individual level can yield different results compared to only the group level in sports performance research, future studies seeking to optimise the configuration of planned OR should explore individual response profiles.

8.4 Reflective summary and positionality

Reflexive practice allows the researcher to bridge the gap between theory and knowledge by recognising how the nature and culture of applied practice can enhance scientific knowledge (Huntley et al., 2019). Moreover, by acknowledging their positionality, the researcher can explore how their own background and experiences shape how data is interpreted (Attia & Edge, 2017; Mortari, 2015). This is of particular importance when a mixed method approach has been undertaken and the emphasis of the research is on fostering effective communication between the laboratory and the weights room. Transparently articulating the position of the researcher is arguably one of the creative strengths of a research programme (Jafar, 2018; Nolan et al., 2024). Therefore, the aims of this penultimate section of the thesis aims to 1) articulate my own thoughts about my doctoral journey by reflecting upon my own academic and professional development, and 2) offer my personal perspectives and insights about OR/OTS from the perspective of (perhaps one of few) researchers to embrace qualitative and quantitative methods to study the topic.

I have always had an interest in strength training. I started lifting when I was young and still train regularly today. In some ways, receiving some York spinlock weights (the gold coloured, sand filled ones) and a copy of Bill Richardson's "The Ultimate Physique: Bodybuilding with Mr World" for my fourteenth birthday is the reason I am submitting this thesis. In my professional life I have held several roles where strength training knowledge was important (fitness qualification tutor, strength and conditioning coach, writer for bodybuilding websites, sports science lecturer). So, a doctoral programme exploring aspects of strength training was an inevitability. However, the genesis of this thesis was almost accidental. During my post-graduate study programme, I was invited to support a PhD student who was collecting laboratory data on endurance athlete. The data we were collecting related to training maladaptation, with a specific focus on understanding the mechanisms that underpinned OTS in triathletes. I was encouraged to use the data set from this experiment for my MSc dissertation. Upon completing my post-graduate thesis I was invited to co-publish a literature review with the course lead on OTS in endurance sports (Bell & Ingle, 2013). On reflection, I had no interest in endurance sports whatsoever but found the idea of exploring OTS interesting.

Even though I had a publication to my name prior to embarking on this PhD journey, I knew that I had limited knowledge on how to conduct independent research. I found the idea of undertaking a doctoral programme daunting and probably one of the main reasons why I delayed starting a PhD for so long (a gap of around ten years between postgraduate study and starting the PhD). I have always considered myself to have adequate writing skills and a reasonable level of knowledge when it comes to strength training history. But I was anxious about the laboratory skills (planning, using equipment, data collection) and autonomy I would need to successfully navigate the programme. That said, I also knew that by choosing a topic area like OR/OTS where experimental research was an inevitable (and important) aspect of research, I could face the challenge face on and really develop my skill set.

During this doctoral programme I have published several peer-reviewed research outputs that have generated multiple citations (over 150 at the time of writing). These publications have led to coverage from a range of media outlets (e.g., The Conversation, Yahoo! News), and several podcast appearances. During the last six years (my thesis was completed part time whilst working as a full-time Senior Lecturer), I have collaborated with local and international researchers on topics of mutual interest outside of the central PhD topic area. Some of these 'extracurricular' projects were published without support and guidance from my supervisory team with me as the lead author (Bell et al., 2023; Bell, Nolan, et al., 2022), collaborator (Costa et al., 2024; Grandou et al., 2021; Thompson, 2020), and principal investigator/project lead (Rogerson et al., 2024). Whilst these collaborations were not directly related to this doctoral programme, the opportunity (and privilege) to work with experienced researchers acted as a fantastic learning opportunity that I am sincerely thankful for. These collaborations have also helped me gain knowledge and confidence as an independent researcher, whilst still giving me regular reminders that there is always more to learn.

One of the most challenging obstacles I faced during my doctoral programme was undertaking research during COVID-19. The week that I was due to begin data collection for my first experimental study was the week that national lockdown occurred. This, of course, meant that I had to pivot my programme of research and could not conduct face-to-face research for over 12 months. Indeed, many of the extra research papers I have published were during a time when

I was unable to get into the laboratory to collect primary data. On reflection though, I think that the overall body of work created for this thesis is stronger for experiencing the lockdown restrictions. The pause from experimental work allowed me to revisit my golden thread of research and spend more time 'setting the scene' with research in line with stage two of the ARMSS. It also allowed me time to explore more qualitative work to focus on bidirectional knowledge transfer. At this stage I do feel that approaching OR/OTS purely from a mechanistic, quantitative direction is disregarding the important role that the practitioner can play in understanding the athlete's response to strength training. As such, I strongly advocate collaboration between sports scientists and practitioners in future research in this domain.

As I approach the end of this programme, I feel that I have accomplished a level of independence as a researcher that I did not expect. I have contributed new knowledge within the field of OR/OTS in strength sports and resistance exercise and set a path for future research that I will complete when this programme finishes. My findings have had (and will hopefully continue to have) practically meaningful importance for coaches and sport scientists. When I started this doctoral programme, I was told that "Completing a PhD is essentially you earning your right to conduct independent research". If this is the case, I hope that this thesis appropriately demonstrates this sentiment.

My final thought as I prepare to submit this thesis relates to the existence of OTS. This question was originally asked in 2005 (Halson & Jeukendrup, 2004). However, I feel that a definitive answer to this question was not provided. For me, existence is one of the most important deductive ontological arguments. In his philosophical treatise, *Ethics* (proposition 8; note 2), Baruch Spinoza argued that "(this) cause of existence must either be contained in the nature and definition of the thing defined, or must be postulated apart from such definition" (Spinoza, 1949). Existence, therefore, is harmonious with definition. Based on how OTS is defined, I am not convinced that it exists, and I feel that there is a clear lack of evidence to say otherwise. Of course, it is plausible that OTS *might* exists in the real world outside of the academic sphere. But even then, it is unlikely. There is a clear misinterpretation about what OTS is and (importantly) *is not*. Vague definitions that have been poorly communicated (noun versus verb), a lack of appropriate performance assessment (including the specific timepoints that testing occurs), and complicated/similar symptomatic profiles between OTS and other training-related disorders likely make diagnosis extremely difficult. Therefore, existence is difficult to determine. Interestingly, the very same questions about the existence of OTS are being asked about REDs, a similar maladaptive condition. A recent review by (Jeukendrup et al., (2024) questioned the causal link between low energy availability and REDs symptoms. Moreover, that several aspects of the model are biased and yet to be thoroughly tested. Clearly, there is still much to learn about the existence, prevalence, and aetiology of training maladaptation.

8.5 Thesis summary

This doctoral thesis has progressed the understanding of OR/OTS in strength sports and resistance exercise training through several peer-reviewed publications. Utilisation of a mixed methods approach has enabled not only advancement in knowledge relating to the central topic but ensured a deeper and holistic understanding of training maladaptation by embracing the philosophical position of both the sports scientist and strength coach. A key theme throughout this doctoral programme been to discover new evidence through collaboration and knowledge transfer to understand OR/OTS from multiple perspectives. It is evident from the knowledge created in this thesis that there is still much to explore in the OR/OTS domain, especially in strength sports and resistance exercise training populations. Whilst this thesis has provided novel findings and conceptual insight and progressed understanding using a pragmatic approach, a robust series of future studies are required to better elucidate OR/OTS. The new knowledge outlined in this thesis acts as a basis to undertake appropriate future studies that will aid in this process.

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Appendices

Appendix 1: Interview guide

Introductory questions/background information	*Tell me a bit about yourself and what sport(s) you are involved in?* To cover: - Country of residence - Experience (level of athlete, duration in years) - Highest academic qualification - Professional qualifications
Central interview questions	**General approaches to strength sport** *Would you consider yourself to be involved within elite-level strength sport? If so, how would you define 'elite' athletes in your sport?* *Do you have a specific coaching philosophy? What governs this?* *Do you have a favoured or 'go to' periodized approach to training?* **Monitoring** *Do you monitor athlete progress? If so, how?* *What tests/measures do you use to monitor progress and/or identify fatigue? (do these differ based on purpose?)* *Do you find that athletes experience training-related fatigue often? When?* *What do you think contributes to general fatigue in your athletes?* *From your experience, what types of non-training stressors do you think contribute to athlete fatigue (if any)?* *Would you adapt training if you identified fatigue? If so, how?* **Programming** *Do you use periods of concentrated loading (high training demand) weeks to create performance changes? If so, when, how might that look, and what variables do you alter to elicit those changes?*

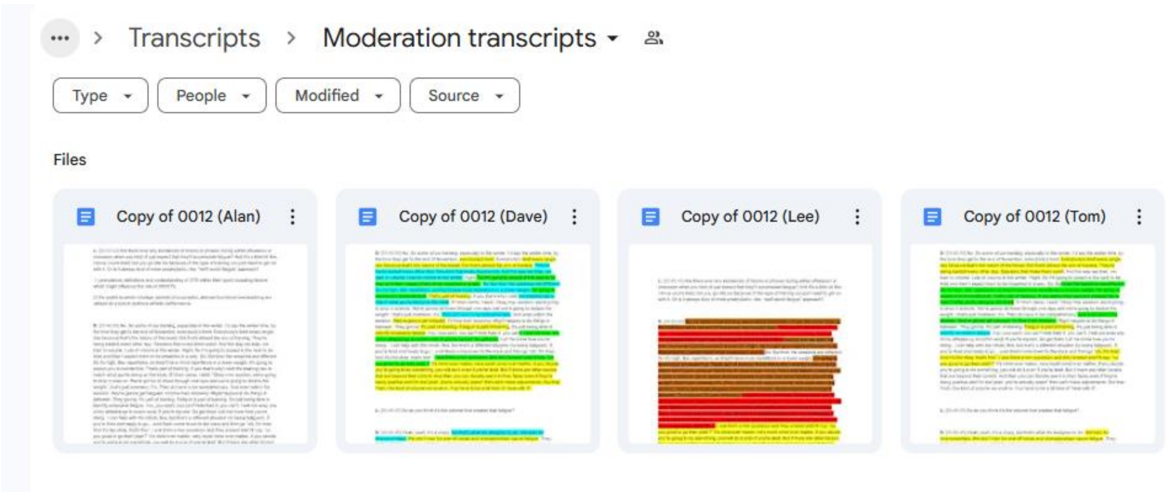
	What are your thoughts relating to high training demand weeks as a training tool (risk/reward)? *(Return back to fatigue questions) Does your approach to monitoring/testing alter based on if an athlete if undertaking intentional periods of high training demand?* *How would you define overtraining?* *Have you observed or experienced overtraining in your sport (or heard of other coaches/athletes that have)?* *Do you think overtraining exists within strength sports?* *What symptoms would you expect to see in an overtrained athlete?* *How long do you think it would take an overtrained athlete to fully recover?* *Do you have any other additional information you would like to add relating to perceptions of overtraining?*
Closing questions	*Before we finish, is there anything you would like to elaborate on or add to the discussion?*

Appendix 2: Excerpts from a coded interview and the thematic analysis process

S: [00:50:17] That's down to knowing the athlete. It's very clear. We have athletes who try every run, every rep, they focus and they they give it their all. There are athletes who are lazy and save it at the beginning and run it at the end. So. And that happens in the gym as well. The ones that come in and stick some weights on and they don't have a plan and they just lift and try and look good. I don't have much time for them. So in terms of knowing the difference between fatigue and "oh, that's too much", it comes down to knowing the athlete. And they show signs, their technique fails, especially in the gym. If your technique is failing, I will stop the session. It doesn't make any sense. You will get hurt and fast. If your back is out or your your hitchign, or your knee's going in when you're addressing the bar and it will hurt quickly. And I think my background, because the mountain of injuries I've had, I'm very respectful of that. I'm very respectful of joints. If your muscle is sore, get over it. But if your joint is hurting, there's a difference between soreness and (it) hurts. If it's hurting, I will stop the session or I will change to do something else because there's always something else you can do. I. I don't think it's worth pushing an athlete when they are failing to extremes. I've been coached like that. And I got very injured. I'm still dealing with the effects today. And at the end of the day, it's a sport and nobody. Nobody should suffer the long term effects. Unless they decide to choose to do it. And they like 80 and then they still got back issues from. I used to have my old coach used to, I think apparently he still does it. Push cars uphill for training, handbreak off, Fiat Uno, run up a hill.

L: [00:52:46] Really?

S: [00:52:47] Pushing it. Yes. Running up stadium stairs with an athlete on your back. A physical person. He came running up stadium stairs, health and safety. But anyway. So it's those kinds of things. That's why I said foundation is the most important thing. I was never strong enough to do that kind of work. They were athletes who were strong enough and they were fine. Never got injured. Said that's why you have to look at the coach and say "okay". You need to know your athlete. Are they able to do that effectively and efficiently. Without hurting themselves. If not, why not? Address the why not. And then come back to the. Come back to the session. Which is why we spend so much time in foundation and technique it



Theme: Overtraining

Overall, this theme looks at how practitioners define and think about overtraining, as well as their experiences, perceptions and beliefs about overtraining in strength sports.

Coach	***Defining overtraining*** This theme includes references to an explanation or definition of overtraining	***Differences between OR/OT*** This theme includes direct reference to overtraining and how it might differ to overreaching	***Perceptions and experiences of OT in strength sports*** This theme includes any thoughts or beliefs around the existence of overtraining, as well as experiences, anecdotes and observations	***Recovering from overtraining*** This theme highlights any reference to recovery time-course and strategies that can be employed to help athletes recover from overtraining	***Symptoms of OTS*** This theme looks at any reference to symptoms that may indicate overtraining
001	*If it becomes... to the point where it means you have to deviate from the plan.If you overreach it's part of the plan, you overtrain you've gone too far. Overtraining, underrecovery, you know, what's the difference? So if as part of the rebound, as part of the recuperation week they don't rebound back to where you expect, you can term that overtraining I guess.*	*I guess there's a fine line between overreaching and overtraining and the difference will be the ability to rebound and bounce back in a short period of time. So you push it hard, back to your previous condition better within a relatively short space of time.. 5 to 10 days.* *If it becomes... to the point where it means you have to deviate from the plan.If you overreach it's part of the plan, you overtrain you've gone too far. Overtraining, underrecovery, you know, what's the difference? So if as part of the rebound, as part of the recuperation week they don't rebound back to where you expect, you can term that overtraining I guess.*	*Overtraining, underrecovery, you know, what's the difference? So if as part of the rebound, as part of the recuperation week they don't rebound back to where you expect, you can term that overtraining I guess.*	*So if as part of the rebound, as part of the recuperation week they don't rebound back to where you expect, you can term that overtraining I guess.*	*In terms of weightlifters (suffering overtraining) it tends to manifest with a lot of my guys more with sort of physical knocks and niggles rather than other ways, some get a bad back, hip pain, shoulder aches, elbows... so joints really.*
002	*In terms of strength sports. I think overtraining is when*	*Overreaching for me is when you allow, when you, well I suppose if*	*From a performance perspective no (I've never had an athlete take*	*In terms of strength sports. I think overtraining is when then, that, just*	

FRAMEWORK ANALYSIS

Coach	**THEME 1: OVERTRAINING**	**THEME 2: OVERREACHING**	**THEME 3: FATIGUE**	**THEME 4: THE IMPACT OF NON-TRAINING STRESS ON PERFORMANCE**
001	Overtraining is seen as 'going too far'. There's no difference between overtraining and under-recovery. There's a fine line between overtraining and overreaching. Overtraining symptoms include knocks and niggles and aches and pains in hips, shoulders, back etc.	Refers to FOR as an impact week where the purpose is to push capacity and improve performance. Overreaching is purposeful and pre-planned. Overall training load is 'ramped up' to the point where the athlete is struggling to cope with the demands. Impact weeks involve increased training frequency for a 7 or 10 day period and focuses on am and pm sessions where strength lifts are in the am and competition lifts are pm. Impact weeks are individualised and tolerance to volume is monitored. Impact weeks purposely focus on training frequency being high so there's limited recovery between sessions. Volume is the main stimulus used. During an impact week athletes know they'll feel fatigued, sleep might be reduced, joints might be sore. Life stress needs to be managed during an impact week or it can result in too much stress.	Flexible programming is important and helps to navigate daily personal distractions and stressors. Is proactive in trying to work around other life stressors when planning a programme. Has used various metrics to monitor fatigue but suggests these can be time-consuming and are often no better than simple intuition. Recovery from fatigue is multifactorial and involves elements of genetics but also lifestyle and attitude.	*Life can get in the way of training and it's important to appreciate the importance of non-training and lifestyle effects.* *Some athletes will tidy up their sleep and diet during an overreach and others won't.* *Weight management is the responsibility of the athlete.* *The coach needs to adjust their approach when an athlete is stressed with exams and moving house.* *Considers unplanned stressors to be important. They need to be managed.*
002	Overtraining takes much longer to return to baseline compared to acute recovery. Overtraining is a progression from overreaching and involves accumulated, chronic fatigue. Has never seen overtraining in their sport and it usually takes a week to 'bounce back' Burnout would result in niggles, injuries etc. that prevent them from training.	Some athletes respond well to high volume/intensity work and others don't so there's an individualistic response. Understanding the athlete's 'capacity' for fatigue is important and some can push hard through it whilst others can't. During heavy blocks of training, some performance metrics will inevitably decrease (i.e. jumps) - doesn't believe that full recovery between sessions is necessary - especially with the tolerance to training some PL athletes have.	Uses an autoregulated approach to programming in order to navigate lifestyle factors and optimise the training effect. Powerlifting can be a monotonous sport. Uses performance at submaximal loads to monitor fatigue. Fatigue can last less than a week. Offers the athlete opportunity to track progress using spreadsheets and questionnaires but	It's rare that a powerlifter will be a full time athlete so managing training around work is important. Athletes end up sacrificing health if they take on too much. It is important to audit an athlete's lifestyle as well as their training. Calorie deficits will have a negative impact on fatigue accumulation.

Appendix 3: Example data management plans and risk assessment

Plan Overview

A Data Management Plan created using DMPonline

Title: Overreaching and Overtraining in Strength-Predominant Sports and Resistance-Based Exercise: A Scoping Review

Creator:lee bell

Principal Investigator: lee bell

Data Manager: lee bell

Affiliation: Sheffield Hallam University

Template: SHU Template for doctoral students

Project abstract:

The aim of this scoping review is to investigate overreaching and overtraining in strength-predominant sports and resistance training populations, as well as sports containing indicative elements of resistance training load. SPORTDiscus, Scopus and Web of Science will be used to extract relevant studies, reviews for treatment. For the purpose of the review, the term strength-predominant sports refers to those where resistance training provides the large majority of training load and includes weightlifting, powerlifting and strongman. The term resistance training refers to any study where the intervention used required participants to complete a short- or long-term intensified/extensified resistance training protocol.

ID: 41981

Last modified: 17-06-2019

Research projectThe adaptive response to resistance exercise overtraining: an exploration of inter-individual factors

Data collection

What data will be produced?

Qualitative and quantitative physical performance data will be recorded. Demographic (age, sex), performance measurements (maximal and explosive strength), blood (creatine kinase, interleukins), and perceptual measures (muscle soreness, fatigue) will be collected. Semi-structured interviews will also be conducted.

Ethical and copyright issues

How will you deal with any ethical and copyright issues?

Data will include both descriptive and inferential-level analysis using standard operating procedures and software. All data is electronic and will be stored in a central access database, linking together Excel spreadsheets, managed by the principal investigator. Raw data files required for data analysis will be stored in appropriately-named folders with all participant details anonymised. The project will be reviewed by the relevant ethics committee. Information sheets and consent forms will be used to ensure that informed consent is gained which allows for the preservation and sharing of the anonymised data. Once consent is provided, each participant will be assigned an ID and all future data anonymised.

Data documentation

How will your data be documented and described?

Data will include both descriptive and inferential-level analysis using standard operating procedures and software. All data is electronic and will be stored in a central access database, linking together Excel spreadsheets, managed by the principal investigator. Raw data files required for data analysis will be stored in appropriately-named folders with all participant details anonymised.

Data storage

How will your data be structured, stored and backed up?

We will use the University's networked Research Store for all master copies of our data. Data will be backed up automatically on a daily basis and can be fully recovered in the case of accidents. All backups are securely kept in two remote locations for a period of 90 days. Access to all folders is restricted to researchers, students and external partners working on the project. At project close down relevant data relating to this project will be securely archived, and all data will be deleted from the Research Store. Google Drive will be used as a collaborative working platform but only where non-personal-sensitive information is involved. Where Google Drive is used, call definitive documents will be transferred to the main project repository on the University research storage infrastructure.

Data preservation

What are the plans for the long-term preservation of data supporting your research?

Sheffield Hallam University

GENERIC RISK ASSESSMENT

The adaptive response to resistance exercise overtraining: an exploration of inter-individual factors (ER48910004)	Location(s): Pearson S&C, Collegiate Hall, Collegiate Campus, Sheffield Hallam University
	RA Ref:

Hazard	Who could be harmed?	Existing safety precautions	Risk level	Additional safety precautions needed to reduce the risk level?	Revised risk level	Action by whom?	By when?	Date completed
High-volume overtraining squat training protocol	Participant	Instructions on how to complete action correctly Musculoskeletal Injury Lower Extremity bone fracture Lower extremity sprain/strain	3x3=9	Participant provided time to complete adequate warm up and acclimatisation period to jumps Participant would be pre-screened for existing/recent injuries. A pre- test medical questionnaire is used to identify risk factors anyone with two or more risk factors will not be permitted to undertake this protocol. Familiarisation training / continuous feedback and coaching from specialist S&C coach Technique would be assessed relative to recognised standards for safe squat technique (NSCA)	2x3=6	Researchers	Before and throughout data collection	
Taking bloods via venepuncture	Participant and researcher	Risk of infection from contact with someone else's contaminated blood. Also risk of puncture site on participant becoming infected by general contamination from surroundings. Risk of infection from sharps (potentially contaminated with	Risk 6 = 2 x 3 High Risk 6 = 2 x 3 High	Only those who have received appropriate training are allowed to collect and analyse blood. A pre- test medical questionnaire is used to screen anyone who is not allowed to have blood taken this is to be completed by the blood taker and anyone identified as "at higher risk" will not be permitted	Risk 2 = L1 x C3 Medium	Researchers	Before and throughout data collection	