COMPARING INTERNAL AND EXTERNAL LOAD DEMANDS TO A MODERATE VERSUS HIGH INTENSITY RESISTANCE CIRCUIT SESSION

by

DANIEL GAUCI

A thesis submitted to the University of Birmingham for the degree of
MASTERS OF SCIENCE BY RESEARCH

School of Sport, Exercise and Rehabilitation Sciences

College of Life and Environmental Sciences

University of Birmingham

March 2023

UNIVERSITY OF
BIRMINGHAM

University of Birmingham Research Archive

e-theses repository

This unpublished thesis/dissertation is under a Creative Commons Attribution 4.0 International (CC BY 4.0) licence.

You are free to:

Share — copy and redistribute the material in any medium or format

Adapt — remix, transform, and build upon the material for any purpose, even commercially.

The licensor cannot revoke these freedoms as long as you follow the license terms.

Under the following terms:

Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made. You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.

No additional restrictions — You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits.

Notices:

You do not have to comply with the license for elements of the material in the public domain or where your use is permitted by an applicable exception or limitation.

No warranties are given. The license may not give you all of the permissions necessary for your intended use. For example, other rights such as publicity, privacy, or moral rights may limit how you use the material.

Acknowledgements

I am extremely grateful to Dr Barry Drust for the time and effort invested into both this project and my development as a researcher. This research would not have been possible without your guidance. Furthermore, I am deeply indebted to Dr Leigh Breen, Dr Tom Brownlee, Dr Liam Anderson and Dr Sam Lucas whose help was invaluable.

Great thanks is also required for every participant. I understand the time and effort this study needed and this was massively appreciated. Additionally, I would like to extend thanks to each of my peers within the school as well as to many within the greater university, their support both in and outside of the project was crucial.

Finally, thank you to my family for their support throughout my academic journey.

Abstract

Rationale: The development of strength and conditioning abilities is integral to both health and athletic performance. Combined training has been increasingly utilised to provide a concurrent stimulus with lower time-demands and other unique purported advantages compared to traditional training. However, limited data exists on the training response to different load intensities, hindering the ability to modulate and apply a combined stimulus. Therefore, the current study aimed to compare metrics of internal and external load utilising a Moderate (55% 1RM) versus High intensity (75% 1RM) resistance circuit session. **Methods:** Healthy resistance-trained males (n=10) performed both circuits in a randomised cross-over fashion. Pre and post-exercise, assessments of capillary blood lactate, maximum voluntary contraction, broad and countermovement jumps were undertaken. Furthermore, during exercise: heart rate, muscle activation, differentiated RPE and repetitions completed were recorded. 6 participants also completed measures of recovery at 24/48/72 h post-circuits. **Results:** The Moderate intensity session provided a significantly greater number of repetitions per set (all p = <0.0001), total volume load (14682 ± 3404 kg vs 13370 ± 3140 kg, p = 0.0023) and increase in blood lactate (14.24 ± 4.84 mmol/L vs 10.39 ± 2.12 mmol/L, p = 0.0156), whilst the High session resulted in greater mean muscle activity (71 ± 8% vs 45 ± 3%, p = 0.0065) plus a lower post-exercise mean countermovement jump height (31 ± 6.2 cm vs 32.7 ± 6.6 cm, p = 0.0452). No decrement in recovery measures was found after either circuit. **Conclusion:** This data suggests that moderate intensity RCT provides a greater anaerobic load, but with larger indicated neuromuscular loading in the High session. Also, an equally large cardiovascular load and low recovery burden was identified between the circuits. These findings therefore help inform the application of a combined stimulus.

Table of contents

1. Introduction

2. Literature review

3. Methods

4. **Results**

5. Discussion

Reference list

List of Figures

List of Tables

Abbreviations

HIFT	High intensity functional training
RCT	Resistance circuit training
HIPT	High intensity power training
VO_2/VO_{2max}	Oxygen utilisation/Maximal oxygen utilisation
NFOR	Non-functional overreaching
RT	Traditional resistance training (not in a circuit format)
MM	Multi-modal training
PGC1a	Peroxisome proliferator-activated receptor gamma coactivator 1-alpha
AMPK	AMP-activated protein kinase
MPS	Muscle protein synthesis
MPB	Muscle protein breakdown
mTORC	Mammalian target of rapamycin
1RM	One repetition maximum
ATP	Adenosine triphosphate
MCT1/4	Monocarboxylate transporter 1/4
HIIT	High-intensity interval training
HRCT	High-intensity resistance circuit training
RM	Repetition maximum
MVC	Maximum voluntary contraction
CMJ	Countermovement jump
BIA	Bioelectrical impedance analysis
RPE	Rating of perceived exertion
DV	Dependent variable
SD	Standard deviation
ANOVA	Analysis of variation
EMG	Electromyography

Definitions

Endurance training the targeted development of aerobic fitness

Conditioning training the targeted development of function across the specific energy pathways (anaerobic alactate/anaerobic glycolytic/aerobic) required for a sport or activity

Traditional strength/resistance training low frequency muscular contractions against external resistance, in a non-circuit format

Resistance circuit training the performance of rounds involving single sets of alternating traditional resistance exercises in quick succession

Concurrent training the concomitant development of both strength and conditioning qualities within a training programme

Combined training the utilisation of multi-joint movements in a high-density matter, with the goal of providing both strength and conditioning loading within the same session

External load the physical work demands of an exercise session, relating to both the intensity (e.g., speed, power output, load) and volume (e.g., exercise duration, repetitions completed) of the bout

Internal load the physiological stress induced by an exercise bout (e.g., blood lactate, heart rate, perceived exertion)

Strength/conditioning-specific load the stimulus for adaptation in strength/conditioning related metrics

Neuromuscular adaptation enhancement in neural and/or structural systems that enable an improved force output

1. Introduction

1.1 Overview

Concurrent training is defined as the concomitant development of both strength and conditioning qualities within a training programme (Coffey and Hawley, 2017). Divergent adaptations are often experienced in response to the completion of endurance versus resistance training, justifying the inclusion of both modalities for various populations (Garcia-Hermoso et al., 2018; Wood et al., 2001). On one hand, resistance exercise enables adaptations such as hypertrophy of both type I and type II muscle fibres (Kosek et al., 2006), as well as neural adaptations including increased motor unit activation and firing rates (Sale 1988). On the other hand, endurance exercise stimulates both central adaptations such as cardiac hypertrophy (Child et al., 1984) and peripheral adaptations, including increased skeletal muscle capillary density (Coyle et al., 1988) and mitochondrial content (Holloszy, 1967). Together, concurrent training has the potential to enable increased strength, power and aerobic performance, increasing overall functional capacity (Wood et al., 2001). Furthermore, a meta-analysis by Garcia-Hermoso et al (2018)., illustrated the potential for greater improvements in key indices of health from concurrent training compared to isolated aerobic exercise. This was demonstrated via greater increases in lean mass, reductions in adiposity and improvements in metabolic and cardiac health profiles, in the concurrent training group. This combination of strength and conditioning abilities is particularly advantageous to team sport athletes, with strong positive correlations found between both maximal aerobic capacity and strength with team sport performance (Gabbett and Seibold, 2013; Wisloff et al., 1998). Thus, targeted enhancement of multiple physical attributes via concurrent training appears important for the optimisation of both health and athletic performance.

However, since Dr Robert Hickson’s original observation of a decrease in their strength performance upon the addition of endurance work into his training, and the replication of this effect in his subsequent research (Hickson, 1980), questions have arisen surrounding the efficacy of concurrent training due to the potential interference between resistance and endurance modalities. Albeit, even with further evidence implicating an inhibition of lower body strength and hypertrophy in response to concurrent training versus isolated resistance training (Wilson et al., 2012), overall, the performance of both resistance and conditioning training appears efficacious and is widely undertaken by both elite and (Garcia-Pinillos et al., 2020; Seipp et al., 2022) recreational athletes (Garcia-Pinillos et al., 2020). However, achieving an optimal resistance and conditioning training frequency utilising this approach does require a high weekly session frequency. This demand appears potentially problematic when considering the intensive competitive schedules of many athletes, for example, players in the top tiers of European football only possess an average of 4 days of rest between matches (Fifpro, 2021). Therefore, there is limited time availability for resistance and conditioning prescription and coaches may not always prioritise this. Furthermore, in the general population only 42% of females and 34% of males are meeting physical activity recommendations (Office for Health Improvement and Disparities, 2022), with previous research identifying lack of time as a primary barrier to exercise (Silliman et al., 2004; Stutts, 2002). As a consequence, in place of separate resistance and conditioning sessions, the concept of a single session that is effective in instead simultaneously providing strength and endurance loading could have significant applications for both the recreational exerciser and the athlete.

Along this vein, many intra-session concurrent training solutions have indeed been developed. Here, we employ the umbrella term ‘Combined Training’ to encompass any training protocol that emphasises multi-joint movements in a high-density matter, with the goal of providing both strength and conditioning loading within the same session. Notable examples of combined training include high intensity functional training (HIFT), also commonly referred to as CrossFit, resistance circuit training (RCT) and high intensity power training (HIPT). Although combined training is not a novel concept, with the initial popularisation of resistance circuit training dating back to the 1970s (Gotshalk et al., 2004), the increasing popularity of CrossFit (Rally Fitness, 2017; Henderson, 2018) demonstrates that there is a continued and seemingly growing public interest in combined training methodologies, alongside common utilisation within elite sport (Crowley et al., 2018).

Contemporary strength and conditioning coaches within elite sport report the inclusion of RCT in their athletic programmes for aims ranging from the “development of metabolic systems” to the targeting of “strength and muscular endurance” (Crowley et al., 2018). Additionally, the CrossFit training system was developed by Greg Glassman in 1996, with the broad objective of “preparing trainees for any physical contingency”, thus seeking to produce athletes that exhibited a balance between strength, power, balance, agility, flexibility and endurance (CrossFit, 2020). Therefore, these combined modalities share a common concurrent training goal, however, clear diversity exists in the exact methods employed to achieve this. For example, the fundamental design of an RCT session consists of rounds of single sets of differing traditional resistance exercises completed in succession, with minimal rest between exercises. RCT is somewhat flexible in that sets can involve both the utilisation of low intensities (40-60% of one-repetition maximum (1RM)) with high repetitions (12-15), or higher intensities (>60% 1RM) with lower repetitions (<12) (Munoz-Martinez et al., 2017). CrossFit training also involves a circuit design; however, it employs three distinct modalities: gymnastics, metabolic conditioning and weightlifting, with the session design either comprising of: a) the completion of as many repetitions as possible completed within a time limit, or b) the completion of a designated work volume as quickly as possible (CrossFit, 2020). To summarise, a range of unique combined protocols have been established, with a high uptake of these seen in both athletic and non-athletic populations, and with the common goal of developing multiple physical capacities concurrently.

Promisingly, there is positive acute (Alcaraz et al., 2008; Marin-Pagan et al., 2020) and chronic data (Martinez et al., 2017; Ramos-Campo et al., 2021) regarding the efficacy of combined training to elicit concurrent adaptation, however, the available literature on this area is limited compared with more traditional forms of concurrent training (Feito et al., 2019). Importantly, the effectiveness of combined training will be directly influenced by the prescription of training variables (i.e., intensity and volume) (American College of Sports Medicine, 2009; Laursen et al., 2010). However, there is a scarcity of available data on the relationship between these training variables and the resultant exercise stimulus. This research appears especially crucial for combined training, considering the potentially dynamic and interlinked relationship between strength and conditioning variables within sessions. For example, a change in load intensity will likely influence factors including movement speed, work volume, and muscle recruitment, not only affecting the resistance stimulus but potentially also the nature of the conditioning loading. As such, a lack of clarity here limits the ability of trainees to make educated decisions on combined training design dependent on the session goal(s).

Therefore, the present study intended to inform the application of a combined stimulus. RCT was designated as the combined training modality of choice due to the lower technical demands and more defined session structure compared to other combined modalities, thus enabling a more isolated analysis of the role of intensity.

1.2 Aims

Specifically, our primary aim was to compare the acute internal and external load demands of a moderate versus high intensity resistance circuit session. A secondary aim was the provision of supplementary data on the potential efficacy of a combined stimulus for trained individuals.

2. Literature review

2.1 Overview

Before the research question could be investigated, certain fundamental assumptions needed to be determined. First and foremost, the identification of possible unique applications for combined training is necessary in order to justify its potential implementation over more researched and traditional concurrent methodologies. Crucially, as a concurrent training methodology, it is then important to establish the actual efficacy of combined training for mediating concurrent adaptation before any further investigation into methods of application of the modality is warranted. Once this is established, a complete probe of the existing literature on the relationship between load intensity and subsequent responses to combined training is similarly important to understand the novelty, and therefore, potential application of any eventual data.

With these aims: a) potential benefits to the utilisation of combined training versus traditional concurrent models are explored b) then, fundamental principles of effective athletic training are outlined, with an exploration of how combined training may align with these c) next, the real-world effect of combined training is investigated, involving an examination of the literature to determine the magnitude and array of any resultant concurrent adaptation d) finally, characterisation of the existing evidence-base on the influence of intensity on responses to combined training is undertaken.

2.2 The Potential Utility of Combined Training Methodologies

Assuming the purported potential of combined training to significantly enhance both strength and conditioning performance is valid, multiple distinct benefits appear possible from the adoption of such a methodology. Firstly, before any physiological benefits are considered, an exercise programme is only as effective as how willing a subject is to engage with it, and the rapid decrements in physical performance experienced in response to the cessation of training (Mujika and Padilla, 2000) reinforce how vital the appeal and sustainability of an exercise programme is. As referenced prior, the time-demand of training can be significantly restrictive for both athletic and non-athletic populations (Duehring and Ebben, 2010; Silliman et al., 2004). Promisingly, RCT research demonstrates the capacity to complete the same intensities and volumes of exercise as with traditional resistance training (RT), but often with less than 50% of the time-requirement (Alcaraz et al., 2008; Marin-Pagan et al., 2020). On top of this, research suggests a meaningful conditioning load can be derived from combined training, with work-matched resistance training in a circuit versus non-circuit fashion producing higher VO_2 (+75%) and heart rate (+39%) responses (Marin-Pagan et al., 2020). Therefore, this could reduce the time needed for the completion of additional conditioning training sessions, representing a significant overall reduction in training time.

Although the high ratings of exertion that have been recorded with combined protocols could be an area of concern (Butcher et al., 2015; Marquez et al., 2017), these exertions appear to be accompanied by a range of positive psychological responses. Surveys of CrossFit participants demonstrate a greater motivation to exercise for feelings of affiliation, enjoyment and challenge in comparison to both individual and group-based resistance trainees (Fisher et al., 2017). Furthermore, within military populations, HIFT elicits both greater enjoyment and intentions to continue exercise than traditional Army Physical Training (Heinrich et al., 2012). Finally, many combined protocols also utilise interval designs, with interval training constituting one of the top 10 worldwide fitness trends in 2022 (Thompson, 2022) and having been reported to produce at least equal, and often higher, exercise enjoyment ratings than steady state exercise in recreationally active individuals (Stork et al., 2017). This demonstrates the array of attractors and facilitators to exercise that are satisfied with combined training, suggesting that this methodology should appeal to a wide population, whilst enabling a high subsequent exercise adherence.

Alongside these positive psychological responses, there is also potential for some key physiological advantages to the performance of combined training over more traditional exercise modalities. Considering elevated adiposity increases the risk of cardiovascular disease, diabetes, cancers and all-cause mortality (Centers for Disease Control and Prevention, 2022), with 2/3 of UK adults being overweight or obese (NHS Digital, 2022), the development of effective interventions is crucial. Excess body fat is also an issue for the athlete, with this essentially representing non-functional mass and therefore resulting in decrements to exercise economy, with additional consequences for thermoregulation, summating to a significant detriment to performance (O’Connor et al., 2007). Exercise is a common intervention for the reduction of body fat, as such, exercise modalities that are particularly effective in this aim are greatly attractive (Skov-Ettrup et al., 2014). Notably, a

66% greater energy expenditure has been observed in response to an RCT session versus volume-matched resistance training in a non-circuit fashion (Marin-Pagan et al., 2020). Plus, further and perhaps even more significant benefits are seen post-exercise with a 23% elevation in resting energy expenditure in the 22 hours after a resistance circuit (equalling ↑452 Kcals), as opposed to a mere 5% elevation with traditional RT (↑98 Kcals) (Paoli et al., 2012). This promising acute data appears to translate to meaningful long-term phenotypic effects, with meta-analytical data demonstrating a mean 4.3% decrease in fat mass from RCT (Ramos-Campo et al., 2021), as well reductions of ~8% experienced with HIFT (Feito et al., 2018; Heinrick et al., 2015), consolidating the validity of utilising combined training for this goal.

Further physiological benefits may also be achievable. In response to an exercise stress, there is an initial decrement in performance as fatigue is experienced. If adequate recovery is provided, a super-compensation effect can occur as both fatigue is ameliorated and the physiological capacity is not only restored, but actually elevated above that of baseline to prepare for future demands, enabling an increase in performance (Bompa, 1983). However, if adequate recovery is not achieved on a consistent basis then fatigue will be unable to dissipate, leading to a state of non-functional overreaching (NFOR). This involves a plateau in performance alongside symptoms of chronic fatigue, with the potential to persist for anywhere from 2 weeks to several months (Meeusen et al., 2013). Not only could this impact training quality and competitive performance, but perhaps even more concerningly, significant increases in the incidence of injury and illness are observed during periods of overreaching (Dupont et al., 2010; Gleeson et al., 2012). The presence of NFOR in elite sport is a concern with ~30% of elite Swiss athletes suggested to have experienced the condition within their career, and a prevalence of 10-15% per season observed in elite academy footballers (Matos et al., 2011; Schmikli et al., 2011). Interestingly, combined training may have a potential use in alleviating fatigue accumulation (Haddock et al., 2016). Using resistance circuit training as an example, this design enables the provision of both strength and conditioning loading in a single session, but importantly in contrast to mixed modality sessions which achieve this via the alternation of strength and conditioning exercises, here the conditioning loading is instead achieved solely via the specific implementation of the resistance exercise. Therefore, RCT potentially targets multiple adaptations with a single workload (see *Figure 1*), perhaps allowing a reduced total training load and lower associated fatigue compared to performing resistance and conditioning training separately (Hulin et al., 2014; Meeusen et al., 2013; Putlur et al., 2004; Rowell et al., 2018). However, it is important to note that at present there is not sufficient physiological evidence to confirm this hypothesis.

To summarise, the application of combined training could have multiple significant benefits for athletic populations as well as the recreational exerciser, therefore, several potential key uses for combined training exist, justifying investigation into its implementation.

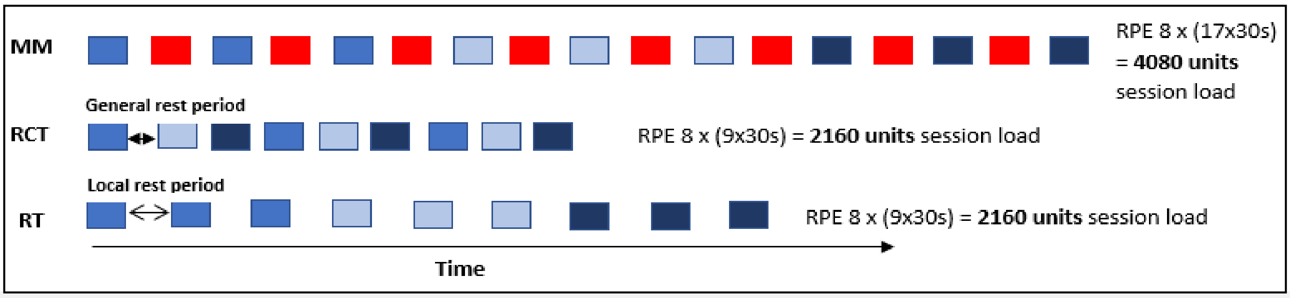


Figure 1. A diagram of the training load (utilising the session RPE method (Foster, 1998)) from comparative resistance circuit (**RCT**), traditional resistance (**RT**), and multi-modal (**MM**) training sessions. *Figures calculated assuming that each set has an RPE of 8 and a duration of 30 s.

Key: Resistance exercise *A*. 🟥 Resistance exercise *B*. ▭ Resistance exercise *C*. ▬ Cardiovascular exercise

2.3 Efficacy of Combined Training

2.3.1 Principles of training

Whether interested in the development of health or skill-related components of fitness (Jarani et al., 2015), there are certain integral training principles which any deviance from may result in a significant detriment to adaptation (Gelman et al., 2022; Morrissey et al., 1995). As a less established training modality, it is first important to ensure that combined training can be aligned with these principles in order to validate its potential use for both general and athletic populations. These core principles include: 1) the principle of overload 2) the principle of progression 3) the principle of specificity (Winters-Stone et al., 2013).

Firstly, the principle of overload dictates that for phenotypic adaptation to occur, a training stimulus greater than that the individual is habitually accustomed to is required, therefore mediating a meaningful perturbance to homeostatic functioning (Rhea and Alderman, 2004). The magnitude of this stress is integral to the adaptation process, as if great enough, the system will be stimulated to develop to best meet the demands of the stressor (Selye, 1976). It is therefore important to confirm that combined training sessions can provide significant loading to a range of physiological systems. Significantly, this threshold for overload is raised in trained individuals (Ahtiainen et al., 2003; Coffey et al.,2006; Gelman et al., 2022) as they are accustomed to greater training stress. Thus, in order to reliably evaluate the magnitude of the concurrent stimulus provided by combined training, data on both the acute session load and the chronic training effect is required across a range of ability levels. Promisingly, initial data appears to support the capacity for combined training to provide a significant strength and conditioning load (Alcaraz et al., 2008; Marin-Pagan et al., 2020; Ramos-Campo et al., 2021). For example, RCT has been found to enable the completion of a uniform resistance volume to traditional RT, but with a significantly greater accompanying cardiorespiratory response, in well-trained football players (Marin-Pagan et al., 2020).

Interrelatedly, continual and systematic application of training stress above habitual levels is necessary to ensure sustained progression over a long-term period (American College of Sports Medicine, 2009; McNicol et al., 2009). This principle of progression can be applied via multiple mechanisms, including via increases in the frequency or volume of training, in the intensity of training, or alternatively by variations in the specific exercises performed. There would appear to be no clear reason as to why this principle could not be applied with combined training; an extra weekly session could easily be implemented (frequency), an increased set duration and/or number could be utilised (volume), changes in load and/or speed of movement have the potential to influence intensity, and different exercises could be included to alter the focus of a training session (type). However, difficulty could arise from the interrelated nature of the strength and conditioning stimulus provided with combined training, as it is unclear whether any adjustments in load intensity or session volume could have disparate impacts on the resistance-specific versus the conditioning-specific load.

Finally, adaptation to exercise training is specific to the particular system stressed and the resultant signalling response (Egan and Zierath, 2013). Therefore, the principle of specificity would imply that in order to maximise the adaptive potential, training should be as specific as possible to the target response (Atherton et al., 2005; Hickson, 1980).

However, the very nature of combined training requisites for a lack in specificity, in that the overarching objective is the concomitant development of multiple physical capacities. Therefore, some potential limitations are raised. Firstly, whilst traditional concurrent training includes separate resistance and conditioning sessions within a training cycle, confirmation is needed that a single session combined stimulus could indeed provide the same range and magnitude of strength and conditioning loading. Furthermore, as is the case with traditional concurrent training programmes, combined training is subject to the aforementioned ‘interference effect’ (*pg. 2)*, wherein the performance of endurance training in a mesocycle can compromise the strength training response (Hickson, 1980; Wilson et al., 2012). On one hand, acute interference (Fyfe et al., 2014), involving an impaired resistance training performance due to residual fatigue and detractions in energy availability induced by endurance exercise, appears unlikely to have a significant effect on combined training considering that both the resistance and endurance workloads are completed simultaneously. On the other hand, chronic interference due to the antagonistic nature of resistance versus endurance-specific signalling and structural responses (Fyfe et al., 2014) may likely influence adaptation.

The adaptive response is also highly specific to the intensity and volume of exercise performed. Lower intensity resistance training enables an increased bar velocity, facilitating subsequent adaptations in the maximal rate of force development (American College of Sports Medicine, 2009), as well as allowing the completion of a greater volume load (Buitrago et al., 2012). Conversely, higher intensities enable greater muscle activation and neural adaptation (Morton et al., 2019), generally resulting in superior strength development (Schoenfeld et al., 2017). This disparity in terms of the nature of adaptation with differing training intensities and volumes is also seen with conditioning exercise. High volume, lower-intensity training appears to stimulate the calcium-calmodulin kinase signalling pathway, resulting in the activation of PGC1a (Laursen, 2010), with its performance linked to central adaptations such as increases in cardiac output and haemoglobin mass (Montero et al., 2015). Contrastingly, high-intensity conditioning training appears to activate PGC1a via the AMPK pathway (Laursen, 2010), with its use resulting in peripheral adaptations such as increases in mitochondrial volume and enzyme activity (MacDougall et al., 1998). Therefore, understanding how to modulate both resistance and conditioning intensity, and therein volume, is integral to the application of combined training.

To conclude, the combined training methodology appears mostly applicable to the fundamental principles of effective training programming. Albeit some theoretical limitations exist. The potential for interference between strength and conditioning responses is present, as well as the possibility of the complexity of the combined stimulus providing difficulty with the application of the modality. In order to identify how these potential effectors or detractors translate into a real-world adaptive effect, as well as to clarify the current understanding of how to modulate the loading of a training session, an examination of the existing literature on combined training will be undertaken.

2.3.2 The adaptive potential of Combined Training

Considering the lack of reviews of the combined training literature at present, a thorough examination of the current literature on the efficacy of combined training to elicit concurrent adaptation has been performed.

The acute stress of a training session can be quantified in two ways: a) the internal load b) the external load (Halson, 2014). External load relates to the physical work demands of an exercise session, relating to both the intensity (e.g., speed, power output, load) and volume (e.g., exercise duration, repetitions completed) of the bout. Usefully, external load benchmarks can be identified from existing data, enabling an estimation of the specific session demands necessary to mediate particular adaptations. Furthermore, the monitoring of internal loads i.e., the physiological stress caused by an exercise bout (e.g., blood lactate, heart rate, perceived exertion), can aid the assessment of session efficacy considering that great inter-individual variation has been found in the internal response to a consistent external stimulus (Bagger et al., 2003). Internal measures enable quantification of the transient homeostatic perturbations in response to combined sessions, which if found to be significant, should result in a measurable phenotypic response when systematically repeated over time (Selye, 1976). Although, acute data can give a prediction of the chronic response, longitudinal data is also required to demonstrate an adaptive effect. This chronic data being especially important considering the potentially confounding influence of the interference effect when investigating concurrent training protocols (Fyfe et al., 2014; Hickson, 1980).

For both resistance and conditioning-specific responses, data on both the acute training load and the resultant chronic adaptation to combined bouts is presented. We have: a) firstly, identified key physiological outcomes relating to strength and conditioning performance b) then, internal and external training load markers for their development have been extrapolated from the wider literature c) acute evidence is presented to evaluate the extent to which combined training sessions can align with these training load markers d) finally, the adaptive evidence on the efficacy of combined training to develop these key physiological outcomes is discussed.

2.3.3 Neuromuscular adaptations to Combined Training

Training for an enhanced resistance-trained phenotype

Resistance training is characterised by high load, low frequency muscular contractions. When implemented chronically and systematically, this enables skeletal muscle hypertrophy and enhanced maximal muscular tension, culminating in a greater capacity for force production (Aagaard et al., 2001). Alongside the benefits to force-production, RT provides significant reductions in the prevalence of both acute (relative risk = 0.62) and chronic injuries (relative risk = 0.52) (Laursen et al., 2014), as well as increases in running economy (Barnes and Kilding, 2015), therefore yielding direct benefits for endurance performance (Yamamoto et al., 2008). Although the development of strength and muscle mass with resistance training is often closely associated, the strength of this relationship can vary (Reggiani and Schiaffino, 2020). Considering each of these adaptations has significant individual benefits for both health and performance, these constitute appropriate resistance training outcomes of focus to assess the neuromuscular stimulus of combined training.

Strength refers to the ability to exert force on an external object (Kulig et al., 1984). The importance of such is demonstrated via its positive association with various measures of health, including functional capacity (Kjolhede et al., 2015), cardiometabolic risk factors (Jurca et al., 2005), and all-cause mortality (Gale et al., 2007; Newman et al., 2006). Furthermore, maximal strength is positively correlated with performance characteristics such as rate of force development (Thomas et al., 2015), sprint performance (Seitz et al., 2014), exercise economy (Sunde et al., 2010), as well as overall power and endurance-based performance (Suchomel et al., 2016). Generally, the physiological adaptations responsible for the increases in strength found with the performance of RT can be assigned to a) neural adaptations: including increased muscle activation (Akima et al., 1999; Balshaw et al., 2018), decreased antagonist co-activation (Balshaw et al., 2018; Folland and Williams, 2007) and an increase in motor unit firing rate (Sale, 1988) b) morphological adaptations: primarily detailing increases in muscle size, but additional responses such as alterations in the angle of pennation also likely contribute (Folland and Williams, 2007).

Skeletal muscle hypertrophy relates to an increase in muscle volume. Importantly, hypertrophy has a potentially preventative effect on obesity due to the highly metabolically active nature of muscle tissue (Wolfe, 2006), whilst also being inversely associated with insulin resistance, prediabetes (Srikanthan and Karlamangla, 2011), and mortality risk (Abramowitz et al., 2018). Due to the relationship between muscle mass and maximal strength (Lamb, 1984), hypertrophy is likely to also benefit athletic performance via the same mechanisms as mentioned prior for strength. The magnitude of hypertrophy is dictated via a dynamic balance between muscle protein synthesis (MPS) and muscle protein breakdown (MPB), with a positive net muscle protein synthesis required over time in order to experience increases in lean mass (Burd et al., 2009). Evidence suggests that the mammalian target of rapamycin (mTORC) complexes are integral to these structural responses (Bodine, 2006). mTORC1 specifically, appears to be the primary mediator of the early RT-mediated MPS response (Drummond et al., 2004; Goodman et al., 2019), with its direct phosphorylation of p70S6K and 4EBP, both proteins with key roles in instigating protein translation and resultant protein synthesis. Whereas mTORC2 looks to have a separate role through its regulation of Akt signalling (Ogasawara et al., 2016; Ogasawara et al., 2019), an integral mediator of muscle hypertrophy (Yoon, 2017).

When training for maximal strength, adaptations appear to be somewhat specific to the repetition range employed in training (Campos et al., 2002). A meta-analysis of 21 RT studies by Schoenfeld et al., (2017) demonstrated a significantly greater increase in 1RM when training with high versus low loads (35% vs 28%, $p = 0.003$), with the magnitude of this effect being even greater in trained individuals. Neural adaptations appear to primarily account for this, with a 6-week resistance training programme at 85% versus 35% 1RM resulting in greater gains in maximal strength (28% vs 13%) and greater voluntary activation, without any differences in hypertrophy (Jenkins et al., 2017). The Henneman size principle (Henneman et al., 1965), characterising how the recruitment of skeletal muscle begins with the smallest muscle fibres and progresses to larger fibres as force requirements increase, is likely responsible in part for this finding. This dictates that higher intensity training will be more facilitative for activating the larger, higher force type II muscle fibres (Scott et al., 2001), and consequently likely more efficacious at eliciting adaptations in these, therefore enabling an increased force production (Mitchell et al., 2012; Ogasawara et al., 2013). However, it appears there is potential interindividual variation in the optimal loading for enhancing maximal strength. A meta-analysis from Rhea et al., (2003) identified 80% 1RM as optimal for trained individuals, whilst Peterson et al., (2004) found 85% 1RM to be most effective for athletic populations, with evidence also suggesting the superiority of slightly lower intensities (~60% 1RM) for lesser trained individuals (Peterson et al., 2004; Rhea et al., 2003). Additionally, increases in firing rate have been repeatedly seen with ballistic protocols utilising intensities between 30-40% 1RM in order to facilitate high movement velocity (Del Vecchio et al., 2019; Van Cutsem et al., 1998). Consequently, resistance training modalities that accommodate the implementation of a range of intensities appear optimal for enabling the greatest strength response within a range of populations.

There is a wide breadth of data regarding the influence of external training variables on the nature of hypertrophy. Firstly, greater axons are found in the larger motor units belonging to type II muscle fibres and therefore in order to maximally recruit these, intensities ≥ 80% 1RM appear ideal (Duchateau et al., 2006). However, alternatively utilising lower loads for higher repetitions will stimulate fatigue and subsequently enable activation of these high threshold fibres as additional contractile units are required to maintain force output (Morton et al., 2019). Therefore, if intensity of effort is adequate, significant hypertrophy can be attained at a range of intensities (Schoenfeld et al., 2017).

On the other hand, there is less clarity in the nature of the relationship between training volume and maximal strength. Firstly, multiple independent trials (Mattocks et al., 2017; Ostrowki et al., 1997; Schoenfeld et al., 2019) have identified a lack of significant differences between low and high-volume protocols on strength outcomes. However, it is worth noting that Mattocks et al., on one hand utilised untrained participants who therefore may have had a lower sensitivity to volume (Kraemer et al., 2002), whilst the latter two studies did involve trained participants but with sample sizes of just 11 and 12 subjects per condition respectively. Whereas, meta-analyses of 140 studies from Rhea et al., (2003) and 14 studies from Krieger et al., (2009) found a greater effect when performing multiple versus single sets in trained and untrained individuals, with a magnitude of +46% and a peak effect size found at 3-4 sets/exercise per session (Krieger et al., 2009). Further supporting this, evidence shows a greater potency for moderate (≥ 6 sets) compared to low weekly set volumes (< 6 sets) (Marshall et al., 2011; Ralston et al., 2017), with these moderate volumes also being similarly effective to protocols utilising higher weekly sets according to meta-analytic data (Ralston et al., 2017). Therefore, although significant strength gains can be elicited with minimal training volumes (Mattocks et al., 2017), the collective weight of evidence suggests utilising a moderate volume may allow maximal strength adaptations to be yielded (Krieger et al., 2009; Marshall et al., 2011; Ralston et al., 2017; Rhea et al., 2002).

This positive effect of training volume on strength enhancement may be partially driven by the strong dose-response relationship demonstrated between volume load and hypertrophy (Krieger, 2009; Schoenfeld et al., 2017; Terzis et al., 2010). This relationship is further evidenced as reductions in inter-set rest periods, and the reduced resultant accumulative volume load performed, have been found to be detractive for muscle hypertrophy (Longo et al., 2022; Schoenfeld et al., 2016b). A meta-analysis from Krieger (2010) found performing 2-3 sets versus single sets resulted in significantly greater hypertrophy (effect size = 0.34 vs 0.24), with ≥ 10 sets/muscle group/week appearing optimal (Schoenfeld et al., 2017). Therefore, to achieve gains in muscle size it is important to implement training methodologies that enable the completion of a significant RT volume at either a high load intensity or a high intensity of effort.

Evidence concerning the efficacy of Combined Training to elicit a resistance-trained phenotype

Starting with intensity characteristics, combined training has been regularly implemented at loads ranging from 40% 1RM (Gettman et al., 1982; Harber et al., 2004) up to high load intensities of ~85% 1RM (Marin-Pagan et al., 2020; Martinez-Guardado et al., 2018). Therefore, combined training enables a flexibility in training intensity that appears optimal for strength outcomes. Considering the positive relationship between hypertrophy and strength (Reggiani and Schiaffino, 2020), it is also important to ensure that combined training can be performed to a high intensity of effort. Indeed, many long-term protocols have prescribed participants to work until volitional fatigue (Alcaraz et al., 2008; Hurley et al., 1984), therefore providing the potential for significant stimulation of hypertrophic responses at a variety of intensities (Schoenfeld et al., 2017).

Although there appears a lesser importance of training volume for strength performance (Mattocks et al., 2017; Schoenfeld et al., 2019), for athletes or general exercisers aiming to maximise hypertrophy, high training volumes must be supported (Schoenfeld et al., 2019). Firstly, there is an array of data supporting the tolerance of both untrained (Camargo et al., 2008; Gettman et al., 1982; Piras et al., 2015) and trained participants (Alcaraz et al., 2011; Romero-Arenas et al., 2018) to combined training frequencies of 3 sessions/week for prolonged periods, plus volumes of ≥ 3 sets/muscle group/session have been repeatedly performed (Alcaraz et al., 2008; Paoli et al., 2010; Roberson et al., 2017). In addition, when resistance training has been performed in a RCT format compared to a traditional RT design, no differences have been demonstrated in the volume load completed (Alcaraz et al., 2008). Therefore, key benchmarks relating to training intensity and volume are capacitated via combined training to a similar extent as with RT, indicating a strong potential for improvements in strength and hypertrophy with combined training.

Although the potential of combined training to elicit significant gains in muscle mass and strength appears promising, adaptive data is required to validate this. Firstly, an 8-week training study from Alcaraz et al., (2011) involved two groups of resistance trained males performing both volume and intensity-matched training programmes either in a RCT or traditional RT format. These researchers identified no significant difference in the magnitude of gains in lean mass (RT: + 1.2 kg / RCT: + 1.5 kg) or squat strength (RT: + 45kg / RCT: + 44.2 kg) between the two modalities (Alcaraz et al., 2011). A meta-analysis of 111 resistance training studies identified an average gain of 1.5 kg in muscle mass from chronic RT interventions (Benito et al., 2020), with several combined training protocols eliciting hypertrophy at and above this range in both untrained (Gettman et al., 1982; Harber et al., 2004) and trained individuals (Alcaraz et al., 2011; Murawska-Cialowicz et al., 2015). Furthermore, strength increases of ~40% and ~16% in untrained and trained individuals can be expected in response to resistance programmes lasting from 4 weeks to 2 years (Kraemer and Ratamess, 2004), with enhancements at and above these values found for both untrained (Buckley et al., 2015; Harber et al., 2004; Hermassi et al., 2019;

Hurley et al., 1984) and trained individuals (Alcaraz et al., 2011; Martinez-Guardado et al., 2019) utilising combined programmes. Therefore, there is significant data to support combined training as a similarly potent stimulator of strength and muscle mass to traditional resistance training programmes.

However, it is not enough to solely consolidate the potential of combined training to produce a resistance-trained phenotype. Unless the capacity of the modality to also mediate meaningful conditioning-specific adaptation is proven, it cannot be recommended as a concurrent training methodology.

2.3.4 Conditioning-specific adaptations to Combined Training

Training for enhanced conditioning

Conditioning training is generally characterised by low-load, high frequency muscular contractions, with metabolic conditioning pertaining to the targeted development of the specific energy pathways required for a sport or activity. Adenosine triphosphate (ATP) is the primary energy substrate used to fuel physical work, with the synthesis of this facilitated via both aerobic and anaerobic systems (Gastin, 2001). Enhancing performance across these energy pathways is of great importance for athletes as well as the wider population, therefore, confirming the potential for combined training to facilitate these improvements is integral to its implementation.

Aerobic respiration is the primary energy source for maximal activities greater than ~75 s (Gastin, 2001), including steady-state endurance activity (Gastin, 2001). However, significant aerobic contribution has been found to the performance of repeated sprint activities (Glaister, 2005), and even isolated sprints of 30 s in duration (Medbo and Tabata, 1989; Medbo and Tabata, 1993), consolidating the importance of including aerobic training for a range of athletes. Furthermore, key health benefits are mediated by the performance of aerobic exercise such as delays in all-cause mortality and maintenance of cognitive function (Kramer and Colcombe, 2018).

The most established parameter of aerobic fitness is VO_{2max}, this representing the highest rate at which oxygen can be utilised by the body, and therefore comprising a strong predictor of endurance performance (Costill et al., 1973; Mclaughlin et al., 2010). An individuals' VO_{2max} is dictated by both central and peripheral mechanisms. The central response refers to the ability of the cardiopulmonary system to deliver oxygen to the skeletal muscles during exercise and is a dictated by the capacity of an individual’s cardiac output, pulmonary system, and blood oxygen carrying potential (Bassett and Howley, 2000). Conversely, the peripheral response constitutes the ability of the skeletal muscle to extract and utilise oxygen from the circulation, this dependent on capillary and mitochondrial density, as well as the concentration of oxidative enzymes and the muscle fibre-type composition (Hawley, 2002).

When focusing on enhancing VO_{2max}, it seems necessary to train at least twice per week (Gettman et al., 1976; Wenger et al., 1986), with the ACSM recommending a frequency of 3-5 days/week at or above an intensity of 40-50% VO_{2max} (Garber et al., 2011). It appears that targeting enhancements in maximal cardiac output will enable the most significant improvement in VO_{2max} (Bassett and Howley, 2000). Although cardiac output is a product of heart rate x stroke volume, maximal heart rate does not increase as a product of training (Londeree and Moeschberger, 1982), this therefore isolating stroke volume as the physiological target of choice. Research suggests that stroke volume is primarily determined by cardiac size and in particular the left ventricular mass (La Gerche et al., 2012) and to achieve improvements in this, training needs to target a high and sustained cardiac output (Cooper, 1997). Stroke volume appears to plateau at ~40-75% of VO_{2max} for non-athletic individuals and therefore undertaking exercise at this intensity would be recommended for adaptation (Higginbotham et al., 1986; Rowland, 2005). However, in athletes, stroke volume has been found to increase all the way up to VO_{2max} (Rowland, 2009) and therefore accumulating volumes of training at or near to VO_{2max} may be optimal for this population (Swain, 2005).

When focusing on peripheral adaptations, there is significant crossover within the adaptations mediated via high intensity/low volume training compared to low intensity/high volume training (Burgomaster et al., 2008). This finding is unsurprising considering that even though intense training biases the AMPK pathway (Gibala et al., 2009), and high volume training the calcium-calmodulin pathway instead (Rose et al., 2007), the same end-result of PGC1a activation is achieved (Laursen, 2010). PGC1a activation has been found to induce mitochondrial biogenesis (Adhihetty et al., 2003), fibre-type conversion (Lin et al., 2002), increased fatty acid utilisation (Calvo et al., 2008) and angiogenesis (Arany et al., 2008; Chinsomboon et al., 2009), therefore enabling significant benefits from the performance of either intensity. Albeit, utilising a blended approach appears optimal for endurance performance (Fiskerstrand and Seiler, 2004; Laursen et al., 2002), supporting the implementation of workloads at both ends of the intensity spectrum.

On the other hand, anaerobic respiration is the primary energy source for maximal activities lasting up to ~2 minutes (Gastin, 2001), anaerobic function therefore being crucial to success in short-to-middle distance activities (Brandon, 1995). Additionally, team-sports involve a high frequency of intense activities such as high-speed running, accelerations and jumps (Bloomfield et al., 2007; Gabbett et al., 2014), resulting in a large accumulation of blood lactate (Coutts et al., 2003; Krustrup et al., 2006). Even long-duration endurance athletes may benefit from high anaerobic fitness for actions such as sprint finishes and overtakes. Finally, its utility for non-athletic populations is also significant, with anaerobic exercise performance providing potential improvements in multiple indices of cardiovascular (Salvadori et al., 2014, Temur et al., 2014) and mental health (Mason and Asmundson, 2018; Taylor et al., 2019).

ATP provision during maximal activities < 15 s in duration is predominantly undertaken by the hydrolysis of phosphocreatine, via the anaerobic alactic system (Gastin, 2001). Whilst more sustained intense activity up to ~45-60 s is primarily fuelled by the anaerobic lactic/glycolytic system, wherein glucose undergoes glycolysis in the absence of oxygen (Gastin, 2001). Improvements in anaerobic performance can be facilitated via enhancements in buffering capacity and lactate clearance, as well as increases in the concentration of energy substrates and glycolytic enzymes (Bishop et al., 2011; Hawley, 2002; MacDougall et al., 1998). The rate of lactate clearance from active muscle cells is dependent on the degree of capillarisation and density of lactate proteins (Billat et al., 2003; Thomas et al., 2004), whilst an improved buffering capacity helps alleviate the impact of H+ accumulation, with each mechanism displaying individual associations with anaerobic performance (Bishop et al., 2004; Da Silva et al., 2010; Nevill et al., 1989).

Accumulating training volumes at or above the lactate threshold appears optimal for mediating increases in intramuscular lactate transporters (MCT1 and MCT4) and the associated improvements in lactate clearance (Evertsen et al., 2001; Pilegaard et al., 1993; Pilegaard et al., 1999), with these high training intensities also required for improvements in buffering capacity (Edge et al., 2006; Weston et al., 1996). Furthermore, both short and long duration training intervals have been found to increase the activity of the glycolytic enzymes lactate dehydrogenase, phosphofructokinase, and glycogen phosphorylase (MacDougall et al., 1998; Rodas et al., 2000). Whilst RT with brief rest periods has the potential to enhance resting creatine phosphate and ATP concentrations (MacDougall et al., 1977). Therefore, highly metabolically demanding activity that involves significant recruitment of type II fibres is effective in eliciting adaptation that is advantageous to both anaerobic power and capacity.

Evidence concerning the efficacy of Combined Training to enhance metabolic conditioning

When examining the compatibility of combined training with existing conditioning training benchmarks, firstly, consistent implementation of various combined training protocols at frequencies of 3-5 times/week has been observed (Cosgrove et al., 2019; Petersen et al., 1988; Romero-Arenas et al., 2018), aligning with the ACSM frequency guidelines for the improvement of VO_{2max} (Garber et al., 2011). Furthermore, a 75% greater VO_2 response has been found from RCT versus work-matched traditional RT (Marin-Pagan et al., 2020), with values of ~65% VO_{2max} provided by both RCT and HIFT protocols (Fernandez-Fernandez et al., 2015; Gotshalk et al., 2004; Petersen et al., 1988). This meets the required threshold intensity (≥ 45% VO_{2max}) for adaptations in oxygen uptake in participants with VO_{2max} values between 40-51 $mL \cdot kg^{-1} \cdot min$ (Garber et al., 2011), and is close to the intensity recommended for significant improvements in moderately trained athletes (~70-80% VO_{2max}) (Midgley et al., 2006). Promisingly, this figure is also within the purported optimal range for stroke volume enhancement in non-athletic populations (Rowland, 2005). Although this intensity may not be optimal for improving stroke volume in highly trained individuals (Rowland, 2009), moderate intensity training does enable the performance of high training volumes and consequent calcium-mediated PGC1a activation (Hood et al., 2000), with 65% VO_{2max} also representing the predominant training intensity of multiple high-level endurance cohorts (Föhrenbach et al., 1987; Seiler and Kjerland, 2006), therefore implicating its utility for athletes.

Interestingly, combined training protocols can also provide a very high metabolic stimulus. Blood lactate levels experienced during combined training sessions (Harber et al., 2004; Marquez et al., 2017; Perciavalle et al., 2016) are often equal to those found after the completion of Wingate tests (Fernandez-del-Olmo et al., 2013; Weinstein et al., 1998), as well as repeated sprint activities (Pearcey et al., 2015b), demonstrating the significant contribution of anaerobic glycolysis. Furthermore, due to the use of resistance in combined sessions, more type II fibre recruitment should be expected than during traditional conditioning training modalities (Henneman et al., 1965), further supporting the provision of a high anaerobic load. Overall, a significant stimulus for adaptation in aerobic and anaerobic function appears possible with combined training, however, chronic data is required to identify the nature of any adaptive effect.

Notably, meta-analytic data from Martinez et al., (2017) (n = 118) found that RCT had a significant effect on VO_{2max} in healthy adults (+ 9.7%). This finding has been corroborated by a recent meta-analysis by Ramos-Campo et al., (2021) (n = 897) within which significant enhancements in VO_{2max} (+ 6.3%) as well as aerobic performance were similarly found in untrained but also trained participants in this case. Promisingly, studies generally appear to have identified equal improvements in endurance metrics when comparing the implementation of combined training versus traditional conditioning training (Camargo et al., 2008; Carnes and Mahoney, 2018; Menz et al., 2018), with meta-analyses supporting this conclusion (Sharp et al., 2022). Some research has to the contrary identified an inferior effect of combined training (Piras et al., 2015), albeit participants were untrained and exercise intensity was only monitored for the HIIT condition and not for the combined, therefore, it is possible that the inferior improvement in VO_{2max} could have been influenced by participants utilising a suboptimal exercise intensity. Additionally, even in this case a significant enhancement of +8% in VO_{2max} was still elicited via the combined training.

Although, the mechanism for these improvements in aerobic function is unclear, significant increases in stroke volume have been identified in untrained (Haennel et al., 1989), as well as active individuals (Petersen et al., 1989). The peripheral response to combined training has not been studied, however, the potential for adaptation has been suggested (Ramos-Campo et al., 2021) and could logically contribute. A caveat exists in the lack of data conducted in athletic populations; however, the available data does indicate a positive effect of combined training in this group (Carnes and Mahoney, 2018; Hermassi et al., 2020; La Torre et al., 2009).

Furthermore, high intensity power training (Romero-Arenas et al., 2018), HIFT (Buckley et al., 2015; Crawford et al., 2018; Murawska-Ciałowicz et al., 2015) and RCT (Myers et al., 2015) have been demonstrated to improve Wingate capacity and power, arguably the most established measure of anaerobic performance (Beneke et al., 2002; Smith and Hill, 1991). Interestingly, these improvements are also at a level similar to that seen from traditional power training (Romero-Arenas et al., 2018) and HIIT (Buckley et al., 2015). This identified enhancement in anaerobic performance is likely as a result of peripheral adaptations, indicated by the associated increase in lactate clearance found (Harber et al., 2004; Petersen et al., 1989), however, the increases in muscular power (Romero-Arenas et al., 2018) and strength (Ramos-Campo et al., 2021) mediated by combined training may also play a role.

2.3.5 Overview of the efficacy of Combined Training for concurrent adaptation

Therefore, it is clear that combined training can elicit concurrent adaptation, with improvements in strength, muscle mass, aerobic and anaerobic performance elicited from a variety of combined protocols in a range of populations. Consequently, research into the application of this modality was justified. However, before any research could be conducted, an examination of the existing literature on the influence of exercise prescription variables on the physiological loading of a combined session was needed to inform the nature of an investigation.

2.4 The influence of load intensity on responses to Combined Training

The volume and intensity of an exercise stimulus directly influences the resultant adaptation; however, it is unclear how adjustments in these variables would affect both the strength and conditioning loading from a combined session. As there is a direct inverse relationship between exercise intensity and volume (Kraemer al., 2004), comparing differing intensities of an exercise modality allows an examination of the role of both variables. Recently, a form of RCT utilising higher intensities (typically 85% 1RM), known as high-intensity resistance circuit training (HRCT), has become increasingly employed in the aim of achieving similar endurance adaptation to traditional RCT (40-60% 1RM), but with a supposedly greater neuromuscular loading (Alcaraz et al., 2011). However, this hypothesis has not yet been validated. Interestingly, a meta-analysis from Martinez et al., (2017) actually identified greater improvements in VO_{2max} with higher intensities, but surprisingly inferior effects on maximal strength compared to lower intensity RCT. Albeit, only a small number of high intensity studies were included, and the latter result may in part be explained by the lower fitness of individuals in the lower intensity studies. A more recent meta-analysis of 45 studies found no significant effect of RCT intensity on either VO_{2max} or strength adaptations (Ramos-Campo et al., 2021). Ultimately, due to the heterogeneity of both the protocols and the participants included in the meta-analyses, the overall conclusion is unclear.

However, there are a few existing studies that have directly compared responses to high and lower intensity combined protocols. Firstly, Paoli et al. (2010) compared the effects of 12 weeks of either a) a lower intensity circuit: involving 3 rounds of 8 minutes of treadmill exercise followed by working at 4 resistance machines at 15 RM, versus b) a higher intensity condition: performing the same circuit, however, with a greater intensity of treadmill exercise and instead performing sets of 6 RM at the 4 resistance stations with a rest pause technique. It was found that this higher intensity protocol provided superior improvements in fat mass and blood lactate clearance, with equal increases in strength to the lower intensity. Although, it is possible that the higher intensity of treadmill exercise may have been responsible for these results instead of the circuit load intensity and the rest pause method could have contributed to the greater neuromuscular adaptation seen. Also, the participants were overweight, untrained adults and therefore it is unclear whether these effects would be replicated with more active individuals. A separate investigation involved active participants performing 12 weeks of either a moderate (70% 1RM) or low intensity (30% 1RM) free weight circuit protocol (Kapsis et al., 2022). The circuit consisted of 4 rounds of 5 resistance exercises, each exercise performed for maximum repetitions within 30 s work periods (1:1 work:rest), with the only differentiator between the two sessions being the load utilised. Interestingly, both sessions resulted in equal increases in lean mass and strength, however, participants were excluded if they had undertaken resistance training in the 6 months prior and this may have contributed to the neuromuscular adaptation experienced even with the use of a supposedly suboptimal intensity (30% 1RM) (American College of Sports Medicine, 2009).

Regarding the available data on the acute response to different combined training intensities, Freitas et al. (2016) prescribed 9 semi-professional basketball players to perform a free-weight circuit involving 2 rounds of 6 exercises, either with a heavy (6 RM) or moderate (45% 1RM) load. The heavy session resulted in greater reductions in repeated sprint performance and post-session countermovement jump (CMJ) height, suggesting a greater neuromuscular load. Albeit, as the same number of repetitions per set were prescribed in both conditions, the total volume load completed would have artificially been much greater in the heavy session, impacting the ability to determine the exact influence of the intensity utilised. Finally, Roberson et al., (2017) had recreationally active subjects perform circuits involving 3 rounds of 7 pneumatic resistance exercises with short inter-set rest periods. These were performed in either a moderate intensity explosive (50% 1RM with maximum velocity concentric + 2 s eccentric), a heavy explosive (80% 1RM with maximum velocity concentric + 2 s eccentric phases), or a heavy controlled (80% 1RM with 2 second eccentric + concentric phases) fashion. Moderate intensities resulted in the highest lactate response in females (no between-group differences for males) and the highest power output for upper body exercise. Whilst the heavy explosive condition resulted in the greatest power output in lower body exercise. Therefore, this paper does demonstrate differences in external and internal load as a result of variations in RCT intensity, however, there are an overall lack of measures thus preventing a comprehensive assessment of the strength and conditioning loading.

2.5 Rationale

To conclude, much of the available research comparing responses to different intensities of combined training is conflicted, with a high proportion of the studies only having a few measures, involving key differences in the circuit design between the conditions, and/or utilising untrained participants. Considering that understanding the physiological effect of adjusting load intensity is crucial to any application of combined training towards specific goals, additional research into this area was justified.

3 Methods

3.1 Ethical approval

Ethical approval was issued by the Science, Technology, Engineering and Mathematics Ethical Review Committee at the University of Birmingham, code: ERN_21-1840.

3.2 Participants

10 physically active males from the University of Birmingham participated in the study. Criteria for inclusion mandated that all participants: were healthy males, aged from 18-40 years old, free from neuromuscular injury, with a minimum engagement in resistance training of ≥ 2 times/week for a period of ≥ 12 months.

Participants were recruited via emails sent to students within the College of Life Sciences at the university, with recruitment posters circulated around buildings on the main campus. In order to ensure that participants were healthy, physically active and met the study inclusion criteria, all participants were required to complete an activity questionnaire as well as a general health questionnaire (General Health and Lifestyle Screening Questionnaire, School of Sport, Exercise and Rehabilitation Sciences, University of Birmingham). Upon completion of these, participants were provided the study information sheet and informed of the participation process. All participants gave written informed consent.

Participants were asked to avoid strenuous exercise for 48 h prior to experimental sessions to minimise residual fatigue. Furthermore, the requirement to arrive in an overnight-fasted state (last meal at 10pm the previous night) limited any unwanted impact of dietary intake on performance. Each participant's initial session start time was noted and all following sessions commenced within ± 2 hours of this to alleviate any circadian effect (Wolff and Esser, 2019).

Table 1.
Participant characteristics

Variable	Mean ± SD
Age (years)	23 ± 3
Body Fat (%)	13.79 ± 8.24
RT experience (months)	33 ± 17
RT frequency (days/week)	4 ± 1
Vigorous activity experience (months)	17 ± 20
Vigorous activity volume (mins/week)	70 ± 63
Deadlift 1RM (kg)	146 ± 33

***Note**. RT/Vigorous activity experience: duration of unbroken participation (<2 weeks absence), Vigorous activity exercise: exercise at the intensity of running, team sports or HIIT (exc. resistance training), RT: resistance training, 1RM: one repetition maximum*

The focus on resistance-trained participants was driven by a) the scarcity of available data on combined training outcomes in trained populations b) the reduced possibility of the cloaking of any potential differences in the physiological response between the circuits, due to the lower threshold for exercise stress in novel exercisers (MacAuley, 2012, pg. 124-127), and c) the increased likelihood of physical tolerance of the circuits. The inclusion requirement for participants to have completed RT ≥ 2 times/week for a period of ≥ 12 months aligns with other resistance-trained benchmarks in the literature (Androulakis-Korakakis et al., 2020; Grgic and Mikulic, 2017), with the resultant frequency of 4 ± 1 days and experience of 33 ± 17 months significantly greater than this (*Table 1.*). Furthermore, the mean maximal deadlift strength of 146 ± 33 kg is equal to or above figures identified in similar resistance-trained cohorts (Banaszek et al., 2019; De Witt et al., 2018; Vigil et al., 2018), whilst at a body composition (13.79 ± 8.24%) mirroring that of young male athletes (Ferri-Morales et al., 2018).

Vigorous intensity conditioning activity was defined as ‘exercise at an intensity that you would not be able to say more than a few words before having to pause to breathe’, with example activities of team sports, circuit/interval training and fast running/cycling. The participants’ experience with this activity was collected to quantify their prior exposure to a metabolically challenging, intense conditioning stimulus, supporting an increased understanding of the ability to translate any study findings to active populations.

3.3 Study design

Participants were required to complete at least 3 visits to the School of Sport, Exercise and Rehabilitation Sciences, undertaking an initial screening and testing session followed by either the moderate or high intensity RCT circuit in a randomised cross-over fashion. 11 participants completed this, with 6 of these participants also attending follow-up sessions 24, 48 and 72 h post-exercise enabling a comparison of the recovery response to each bout and providing an estimation of the neuromuscular stimulus.

Session 1 – Screening and Maximal Strength Testing

At least 48 h prior to the first circuit session, participants visited the laboratory to complete measurements of body composition and maximal strength, as well as familiarisation with the study protocol.

Firstly, body composition was identified via bioelectrical impedance analysis as a supplementary quantification of the fitness status of each participant. Next, a general warm-up was completed prior to jump familiarisation. This involved 5 minutes of light exercise on a cycle ergometer, followed by a series of active mobility exercises involving all major muscle groups. For both jump types, sets of 5 repetitions were completed with 1 minute rest between sets. The familiarisation process was completed either when a standardised consistency of jump height/distance was achieved in a set, or if this was not achieved, when the maximum of 4 sets were completed. Familiarisation was included to aid jump consistency and limit the impact of a learning effect on session outcomes.

Maximal strength testing was preceded by a specific warm-up involving a gradual progression in load of each exercise included in the maximal test, providing both practice with the exercise technique and ensuring physical readiness. One-repetition maximum (1RM) testing followed the NSCA protocol (Baechle and Earle, 2008) and was performed on a series of traditional resistance exercises: the landmine press, conventional deadlift, latissimus pulldown, chest press and 45° incline leg press. As the circuit sessions involved the same exercise series, the maximum values achieved here were subsequently used to assign the individual session loads for each participant. Furthermore, muscle activation was recorded during the leg press 1RM as a reference figure for the lower limb muscle activation later recorded during the circuit.

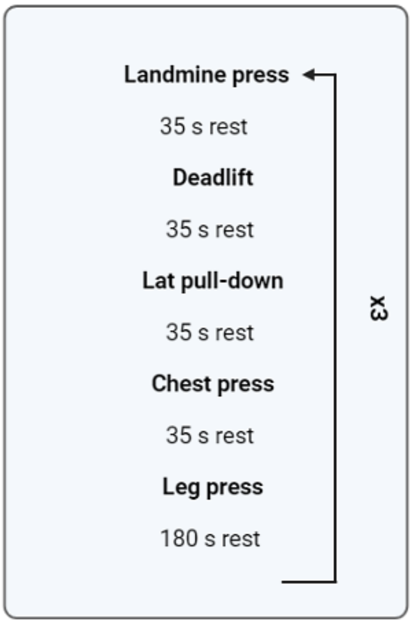
Session 2 – Resistance Circuit Training Bout

Participants came into the laboratory to complete either the High or Moderate protocol first in a randomised fashion. Measures of external and internal load were completed before, during and immediately post-exercise.

Firstly, a Hooper questionnaire was administered to the participant resulting in the provision of an overall wellness score. Upon completion, the general warm-up completed in *Session 1* was replicated prior to the commencement of neuromuscular testing. Maximum voluntary isometric knee extension contractions (MVC) were then performed, with this repeated post-exercise as a relevant measure of fatigue due to the significant involvement of the quadriceps in the leg press (Alkner et al., 2000) exercise. Additionally, the countermovement jump and the standing broad jump were performed pre and post-exercise providing measures of lower limb muscle function in the vertical and horizontal dimensions respectively. Next, a specific warm-up was undertaken. This involved a set of 8-10 repetitions for the High circuit or 10-12 repetitions for the Moderate circuit at each individual station, using 75/85% of the actual session load for lower/upper body exercises respectively. A finger prick blood sample was then taken, with this repeated post-exercise as a measure of the anaerobic load of the bout. Also, a polar heart rate chest strap and watch was fitted to the participant to identify cardiovascular load.

Both the High and Moderate circuits involved a rotation of the same 5 compound exercises, each involving a fundamental movement pattern: the landmine press (vertical press), deadlift (hip dominant), latissimus pulldown (vertical pull), chest press (horizontal press) and 45° leg press (knee dominant). This series enabled the loading of all the major muscle groups in a single session. Evidence supports the efficacy of compound lifts in mediating concurrent adaptations, with greater improvements achieved in maximal strength and VO_{2max} versus performing volume matched single-joint exercise (Paoli et al., 2017). Work periods lasted 35 s followed by a 35 s rest period (1:1 exercise:rest ratio), after which the next exercise in the circuit was performed. Within each set as many repetitions as possible were performed. Each eccentric (down) phase duration was 1 s whilst the concentric (up) phase was executed at a maximal velocity, with verbal direction provided if participants strayed from this tempo.

The structure of the circuit ensured at least 3 min of localised rest between exercises recruiting the same muscle groups. This was informed by a review from de Salles et al., (2009) that found when utilising loads between 50-90% 1RM, 3 min of rest between sets allowed maintenance of repetitions as well as greater increases in strength compared to shorter rest periods. At the end of each round there was also a 3 min general rest period before the next round, with 3 rounds performed in total, resulting in a whole session duration of 22 min. A total session volume of 18 sets was achieved, this demonstrated as an effective volume for improving maximal strength, body composition and shuttle-run performance in prior RCT programmes (Alcaraz et al., 2011). The session design therefore aligns with evidence-based benchmarks, the importance of which being that this investigation therefore provides data on RCT modalities with potential real-world utility. The only separating factor between the two protocols is the weight utilised in the session, the Moderate session utilising loads of 55% 1RM versus the 75% 1RM employed in the high session, this therefore allowing an isolated investigation into the effect of load intensity.



During the circuit, heart rate, repetitions completed and working muscle activation was recorded. Immediately post-exercise, capillary blood lactate was collected, MVC, broad jumps and CMJ were performed and differential RPE were provided.

Figure 2. A diagram of the session design for both circuits. Circuits comprised of 3 rounds of the same 5 exercise stations. 35 s work periods and 35 s inter-set rest periods were utilised, with as many repetitions as possible performed within sets. Also, 180 s inter-round rest periods were implemented. The only difference between the High and Moderate intensity sessions were the loads utilised (75% maximum versus 55% maximum respectively).

Sessions 3-5 – Assessment of fatigue status

Participants returned to the strength lab at 24, 48 and 72 h post-exercise to monitor the fatigue response to each protocol. A standardised warm-up was performed prior to testing of MVC, broad jump and countermovement jump. Furthermore, their wellness state was assessed via the Hooper Index.

This same experimental process was repeated (excluding *Visit 1*) for the randomised second resistance circuit training protocol.

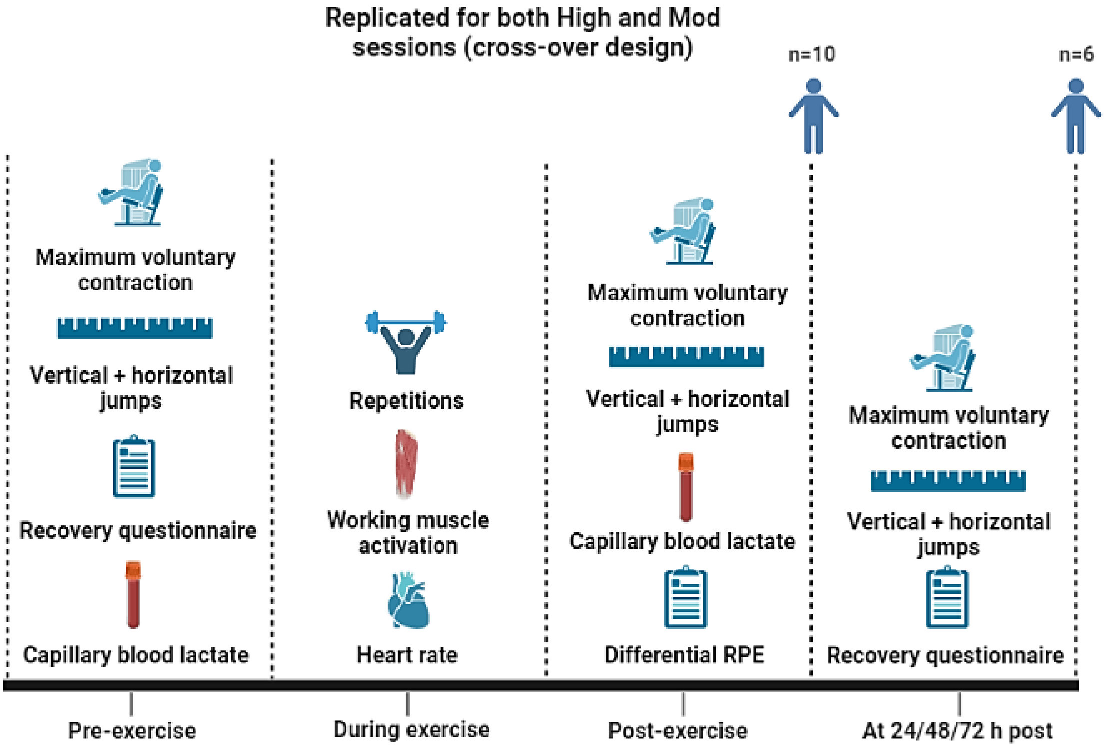


Figure 3. A diagram of the complete measurement protocol. n = 10 refers to the number of participants that completed the circuit sessions only / n = 6 refers to the number of participants who completed both the circuit and recovery sessions.

3.4 Measurements

<u>Body composition</u>

Body fat percentage was identified via bioelectrical impedance analysis (BIA), as participants in a fasted state stood on a Seca mBCA 525 Body Composition Analyzer (Hamburg, Germany). BIA consists of the transmission of a low amplitude current through electrodes in contact with the skin. Since different biological tissues provide differing electrical resistance, this enables the calculation of fat mass and lean body mass. n = 10, equating to a measurement rate of 100%.

Perceived wellness

The Hooper Index (Hooper and Mackinnon, 1995) was administered to the participant, involving the self-rating of fatigue, sleep quality, mental state and muscle soreness on a scale from 1-7. This resulted in the calculation of an overall wellness score (a lower score equating to greater wellness). n = 6, equating to a measurement rate of 100%.

Anaerobic load

A lancet was used to prick the participants' finger and draw a small amount of capillary blood into a 20 µl capillary tube. This capillary tube was placed into a safe-lock cup filled with a haemolysis solution (EKF Diagnostics, Magdeburg, Germany). After insertion of this cup into a Biosen Glucose and Lactate Analyser (EKF Diagnostics, Magdeburg, Germany), a precise reading of the capillary blood lactate was identified (Nowotny et al., 2011). n = 8, equating to a measurement rate of 80%. Blood lactate was unable to be identified in two participants due to the failure to collect a sufficient quantity of blood.

Isolated knee extensor performance

Maximum voluntary contraction (MVC) was measured via a Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA), with participants performing an isometric knee extension effort against a padded lever arm. The lever was fixed in place ensuring a knee angle of 80˚ flexion, as well as a 90˚ thigh-trunk angle. Using their dominant limb, participants completed a 3 s maximal contraction x 3 times, with 60 s rest between each effort. Verbal cues to 'kick against the pad as forcefully as possible' were given, with the lead investigator providing standardised encouragement during each contraction. A peak torque value (N) was identified from each set of 3 attempts. n = 8/n=6, equating to a measurement rate of 80/100% for the circuit/recovery data respectively. MVC was unable to be collected for two participants due to issues with equipment availability.

Vertical jump performance

Vertical countermovement jumps (CMJs) were performed on a dual force plate platform (Hawkin Dynamics, Maine, Portland, USA). Participants began standing in an upright position with their feet placed hip-width apart. They were then instructed to drop to a self-selected depth and jump upwards as high and quick as possible, whilst keeping their hands on their hips throughout the movement. 3 jumps were performed, enabling the collection of peak and mean values for jump height. A rest of 45 s separated each jump attempt. n = 10/n = 9 for the peak and average session data respectively, equating to a 100/90% measurement rate. Due to a measurement error, insufficient data was collected to calculate an average session value in one participant. n = 6 for the recovery data, equating to a measurement rate of 100%.

Horizontal jump performance

Participants stood upright with their toes behind a start line and proceeded to flex their knees and hips, swing their arms, and immediately jump as far forward as possible, aiming for triple extension of the hip, knee and ankle joints before landing with both feet. Distance (in) from the start line to the closest heel of the participant on landing was measured using tape. Three broad jumps were performed, with a 45 s rest period between each, allowing identification of both peak and mean broad jump distances. n = 9/n = 6 amounting to a measurement rate of 90/100% for the circuit data/recovery data respectively. Data was unable to be collected for one participant in the circuit dataset due to joint discomfort.

Session volume

During each working set of the circuits, the lead investigator recorded the number of repetitions completed by the participant using a tally counter. Then, the number of repetitions performed for all sets within a round were added together to identify a mean repetition count for every round of the High and Moderate circuits. The landmine press was excluded from this count as this was the sole unilateral exercise.

Furthermore, the repetition number completed within each set was multiplied by the load utilised for the exercise, enabling the identification of session volume load (kg). n = 9 for both measures, equating to a measurement rate of 90%. Data was unable to be collected in one participant due to human error.

Neuromuscular response

Specialised shorts (Myontec Ltd., Kuopio, Finland) with embedded conductive electrodes were worn by participants during the circuits, enabling the individual monitoring of the electrical activity of the hamstring, quadricep and gluteal muscles. This data therefore allowing an estimation of muscle activation. Data was collected at 1000 Hz and consequently stored and processed using the associated software (Muscle Monitor, Myontec Ltd., Kuopio, Finland) installed onto a laptop. Measurement occurred during each set of the leg press exercise, with the metric of choice being the total muscle load (the combination of each individual muscle signal) peak amplitude (mA) of the hamstring, quadricep and gluteal muscles for each repetition. For each circuit session, the mean repetition total muscle load (for all repetitions over the 3 sets) was calculated and consequently converted relative to the maximal muscle load achieved during the 1RM leg press test. This resulted in the the provision of a mean activation value for each circuit in the form of 'x% 1RM'.

n = 4 participants, equating to a measurement rate of 44%. Measurements were unable to be collected due to excessive signal noise (n = 3) and an incompatible short size (n = 2).

Cardiovascular response

Participants wore a Polar T31 chest-strap heart rate monitor (Polar Electro Oy, Kempele, Finland) during the circuits. The chest-strap monitors the electrical activity of the cardiac muscle and is connected to a Polar watch enabling the display and storage of heart rate data, therefore, providing mean heart rate (bpm) for each circuit. n = 9 participants, equating to a measurement rate of 90%. Heart rate was unable to be measured in one participant due to the limited range of strap lengths available. Working heart rate, involving the monitoring of heart rates for each round individually, and excluding the 3 minute inter-round rest periods, was measured only in 3 persons.

Perceived exertion

10 minutes post-exercise, participants were asked to provide an Overall (RPE-O), Chest (RPE-C) and Muscular (RPE-M) RPE value using the 15-category Borg Perceived Exertion Scale (Pandolf, 1982). This is a scale that ranges from 6-20 (6 indicating no strain and 20 indicating maximal strain) and aims to determine perception of the exercise intensity. Overall RPE provides an estimation of the overall system exertion, with RPE C (effort of the heart + lungs) and RPE M (active muscles) providing individual effort inputs for the central and peripheral systems respectively (Ribeiro et al., 2013). n = 10, equating to a measurement rate of 100%.

3.5 Statistical analysis

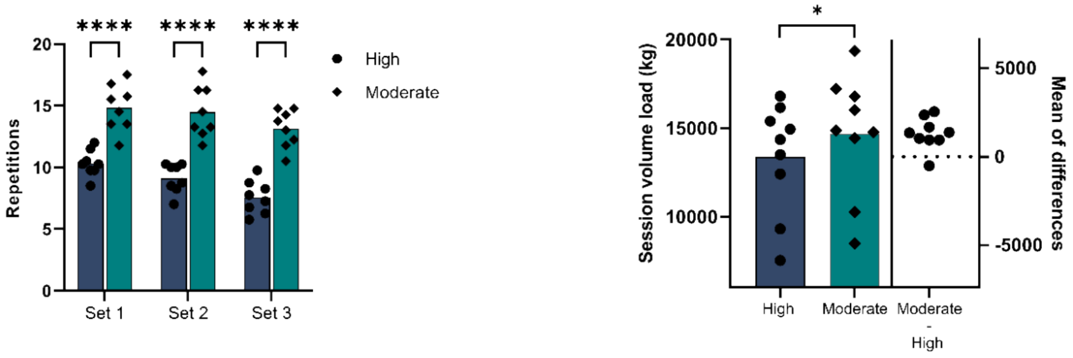
Statistical analyses were performed using GraphPad Prism 9 software (v 9.4.1, Dotmatics, Boston, USA). Tests were run to identify differences between the means of specific dependent variables (DVs) within the same group of participants when undertaking both the High and Moderate intensity sessions. Normally distributed data was analysed using a paired-samples T-test. When assumptions of normality were not met, a Wilcoxon matched-pairs test was run.

Additionally, two-way repeated measure ANOVAs were performed to assess both between-condition and within-condition differences for particular DVs. When statistical significance was achieved, Šidák-corrected post-hoc comparisons were utilised to determine main and interaction effects. Greenhouse-Geisser corrections were undertaken for any data found to violate sphericity. Statistical significance was set at $P<0.05$ for all tests. Data is expressed as mean ± standard deviation (SD).

4 Results

4.1 Session external load

Figure 4. Graphical representation of external load in the High and Moderate circuits



External load. comparison of: the number of repetitions completed per set (**A**) and the total session volume load completed (load x repetitions) (**B**) between both the high (dark blue) and moderate intensity (light blue) sessions. # Indicates significant time effect. * Indicates significant group effect ($P<0.05$). Mean and individual data points are plotted, with differences in the high and moderate intensity session values for each participant displayed in figure **B**.

Table 2.

Comparison of external load between High and Moderate intensity sessions.

	Session intensity	
Variable	High	Moderate
Load intensity (% 1RM)	75	55
Repetitions: set 1	10 ± 1$^{*\#2,3}$	15 ± 2$^{*\#3}$
Repetitions: set 2	9 ± 1$^{*\#1,3}$	14 ± 2$^{*\#3}$
Repetitions: set 3	8 ± 1$^{*\#1,2}$	13 ± 2$^{*\#1,2}$
Session volume load (kg)	13370 ± 3140*	14682 ± 3404*

Note. **denotes between group significance $^{\#}$denotes within group significance, ^{1} for example specifies the within-condition difference is with set 1. Data presented as mean ± standard deviation*

Both total session volume load and repetition number per set were collected, enabling an understanding of whether the prescribed difference in load intensity resulted in dissimilar exercise performance. Furthermore, comparing repetitions performed across sets provides an indicator of the neuromuscular load of a session.

Session volume load

Total session volume load (kg) is displayed in *Figure 4(B)* (n = 9). A paired sample T-test revealed that the Moderate intensity session resulted in a significantly greater volume load than the High intensity session, t (8) = 4.393, p = 0.0023.

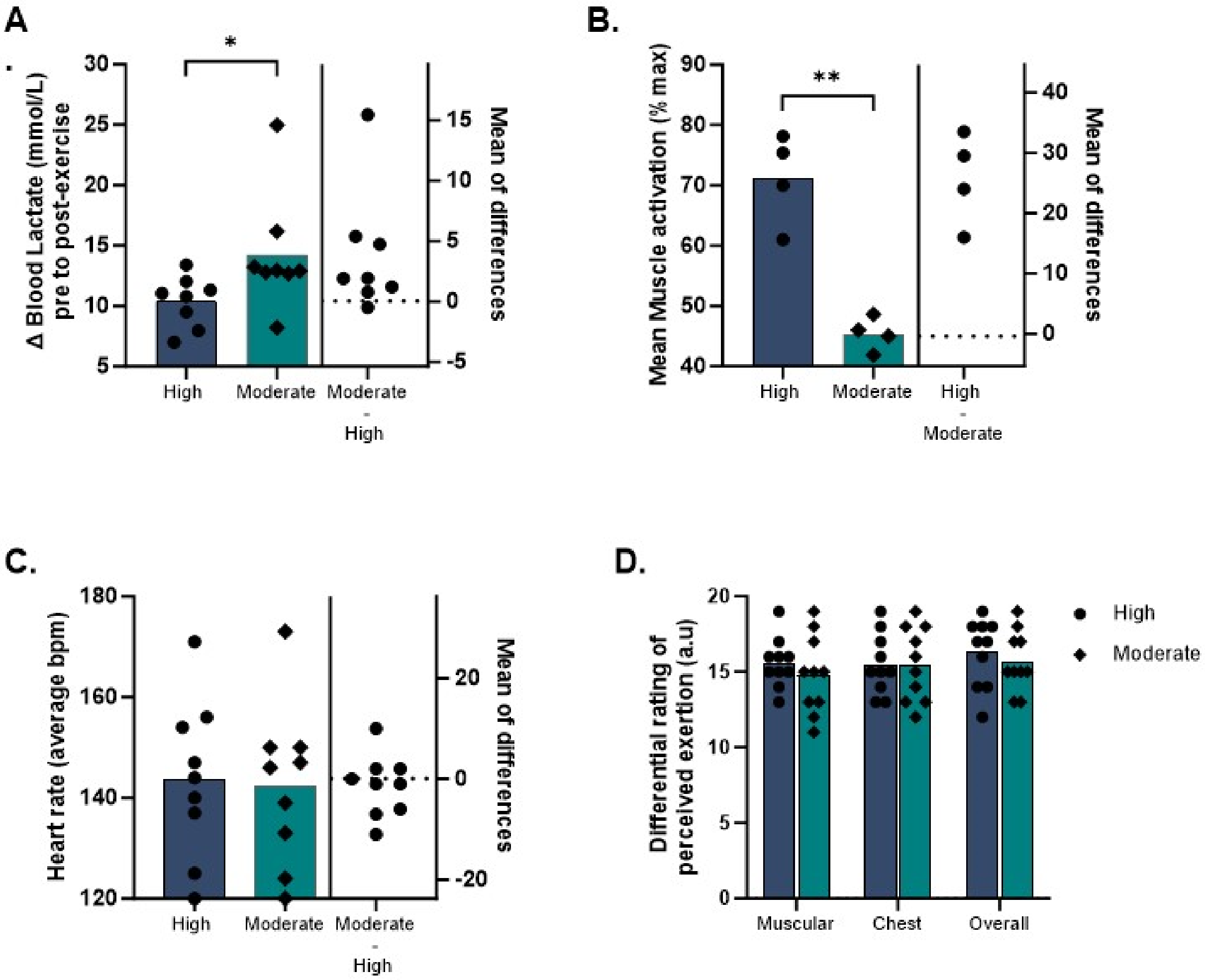
Repetitions performed

Average repetitions completed per set are displayed in *Figure 4(A)* (n = 9). A 2 condition x 3 set repeated measures ANOVA demonstrated a significant main effect of the set number on the number of repetitions performed F (2, 14) = 22.66, p<0.0001. Post-hoc analysis of the High session revealed a significant decrease in repetitions from the first set to both set 2 (p = 0.0142) and 3 (p <0.0001), as well as an additional significant decrease from set 2 to set 3 (p = 0.0018). Contrastingly, there was no significant decrease in repetitions from the first set of the Moderate session to the second (p = 0.6685), however, there was a significant reduction in repetitions from both set 1 (p = 0.0008) and set 2 (p = 0.0059) compared to set 3. There was no significant set number x session type interaction effect F (2, 14) = 2.351, p = 0.1318. Therefore, the identified significant decrease in repetitions performed between the first and last sets of both circuits indicates a similar presence of neuromuscular fatigue.

Furthermore, a significant main effect of the session type on the number of repetitions performed was found F (1, 7) = 211.1, P<0.0001. Post-hoc analysis revealed that when comparing set 1, set 2, and set 3 between the circuits, the Moderate session had a significantly higher number of repetitions performed for each respective set (all p = <0.0001).

4.2 Session internal load

Figure 5. Graphical representation of internal load in the High and Moderate circuits



Internal load. comparison of: the change in blood lactate from pre-to-post exercise (**A**), the lower limb muscle activation during sets of the leg press normalised to the 1RM value (**B**), the average whole session heart rate (**C**), and ratings of perceived exertion of the working muscles, the chest and the overall body (**D**) between both the high (dark blue) and moderate intensity (light blue) sessions. # Indicates significant time effect. * Indicates significant group effect (P<0.05). Mean and individual data points are plotted. Also, for figures **A,B,C** differences in the high and moderate intensity session values are plotted for each participant.

4.2.1 Anaerobic load

Table 3.
Comparison of the anaerobic load between the High and Moderate intensity sessions.

	Session intensity	
Variable	High	Moderate
Blood lactate pre (mmol/L)	3.78 ± 1.77	3.77 ± 1.51
Blood lactate post (mmol/L)	14.17 ± 1.76	18.01 ± 4.93

Note. *Data presented as mean ± standard deviation*

Capillary blood lactate

The change in capillary blood lactate (post-session mmol/L – pre-session mmol/L) for each circuit is displayed in *Figure 5(A)* (n = 8), this measure comprising an indicator of the anaerobic pathway utilisation during an exercise bout. As this data was not found to be normally distributed, a Wilcoxon matched-pairs test was employed here as opposed to the paired-samples T-test utilised for other measures. The Wilcoxon test identified a significantly greater increase in blood lactate for the Moderate intensity circuit (14.24 ± 4.84 mmol/L) compared to that seen in the High intensity session (10.39 ± 2.12 mmol/L) ($p = 0.0156$). The median change in blood lactate for the High session was 10.93 mmol/L compared to 12.93 mmol/L for the Moderate session. Therefore, this data suggests that the Moderate session produced a higher anaerobic load.

4.2.2 Cardiovascular response

Table 4.
Comparison of the cardiovascular response between the High and Moderate intensity sessions.

	Session intensity	
Variable	High	Moderate
Overall heart rate (bpm)	144 ± 16	142 ± 16
Heart rate round 1	146 ± 22	150 ± 27
Heart rate round 2	161 ± 15	159 ± 15
Heart rate round 3	164 ± 16	165 ± 7

Note. *Data presented as mean ± standard deviation*

Heart rate

Mean heart rate (bpm) is displayed in *Figure 5(C)* (n = 9), providing an estimation of the cardiovascular load of the session. A paired-samples T-test found no significant difference between mean heart rate during the High and Moderate intensity sessions, t (8) = 0.6532, p = 0.5319. Therefore, suggesting the intensity did not have a significant impact on the cardiovascular load.

4.2.3 Neuromuscular response

Table 5.
Comparison of the neuromuscular response between the High and Moderate intensity sessions.

Variable	Session intensity	
	High	Moderate
Activation (% 1RM)	71 ± 8*	45 ± 3*

Note. **denotes between group significance denotes between group significance #denotes within group significance. Data presented as mean ± standard deviation*

Lower limb muscle activation

Average repetition muscle activation (% Max) for both circuits is displayed in *Figure 5(B)* (n = 4), this an indicator of the neuromuscular stimulus of the bouts. A paired-samples T-test demonstrated that the High intensity session resulted in a significantly higher average muscle activation compared to the Moderate intensity session, t (3) = 6.797, p = 0.0065.

4.2.4 Perceived exertion

Table 6.
Comparison of perceived exertion between the High and Moderate intensity sessions.

Variable	Session intensity	
	High	Moderate
RPE muscular (6-20)	16 ± 2	15 ± 3
RPE chest (6-20)	16 ± 2	16 ± 2
RPE overall (6-20)	16 ± 2	16 ± 2

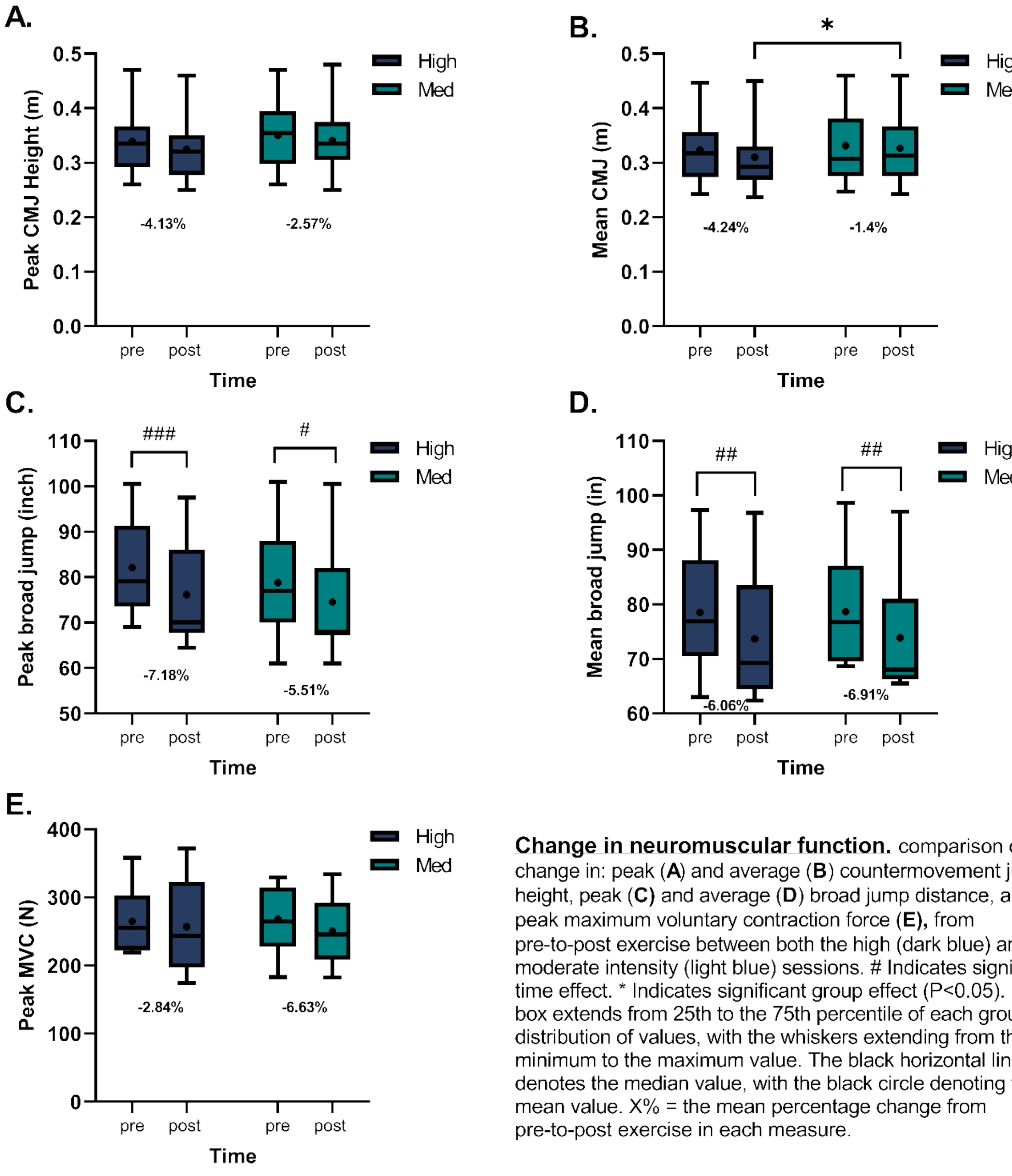
Note. *Data presented as mean ± standard deviation*

Differential ratings of perceived exertion

Ratings of perceived exertion (RPE) for the working muscles, the chest and the overall body are displayed in *Figure 5(E)* (n = 10), providing a subjective indicator of training load. A 2 condition x 3 category repeated measures ANOVA demonstrated there was no significant effect of RPE type on RPE score F (2, 18) = 0.8228, p = 0.4551. Also, no significant effect of session type on RPE score was revealed. F (1, 9) = 0.7101, p = 0.4212. Furthermore, no significant RPE type x session type interaction was found F (2, 18) = 0.7959, p = 0.4664. In summary, the data suggests an even distribution of subjective load across the physiological systems in both circuits, as well as no significant impact of load intensity on perceived exertion.

4.3 Session fatigue response

Figure 6. Graphical representation of physical performance metrics before and after the High and Moderate circuits



Change in neuromuscular function. comparison of the change in: peak (**A**) and average (**B**) countermovement jump height, peak (**C**) and average (**D**) broad jump distance, and peak maximum voluntary contraction force (**E**), from pre-to-post exercise between both the high (dark blue) and moderate intensity (light blue) sessions. # Indicates significant time effect. * Indicates significant group effect (P<0.05). Each box extends from 25th to the 75th percentile of each group's distribution of values, with the whiskers extending from the minimum to the maximum value. The black horizontal line denotes the median value, with the black circle denoting the mean value. X% = the mean percentage change from pre-to-post exercise in each measure.

The collection of multiple subjective and objective measurements enabled an estimation of the fatigue response to the circuit bouts. Physical performance measurements between pre-to-post exercise (*Figure 6*) provide an indication of the magnitude of the performance decrement. Whilst the physical recovery data provided up to 72 hours also allows the determination of the fatigue duration, plus the potential identification of any neuromuscular supercompensation, together providing an indication of the neuromuscular stimulus.

4.3.1 Horizontal jump performance

Table 7.
Quantification of horizontal jump performance in response to the High and Moderate intensity circuits

	Session intensity							
	High				Moderate			
Measure	Pre	24	48	72	Pre	24	48	72
Peak broad jump (in)	76.3	-2.9%	-3.5%	-2%	76.7	-1.4%	-1.4%	-2%
Mean broad Jump (in)	73.9	-2.8%	-2.3%	-2.7%	75.8	-3.1%	-3.1%	-3.3%

Note. *Percentage change figures refer to the difference between the mean value at each respective timepoint and the mean pre-exercise value.*

Broad jump distance

The broad jump is a measure of lower limb muscle function in the horizontal dimension, therefore, providing an indicator of neuromuscular fatigue biased towards the hip extensors (Fukashiro et al., 2005).

Pre-to-post exercise performance

Peak broad jump distance (in) measured between pre-to-post exercise is reported in *Figure 6(C)* (n = 9). A 2 condition x 2 time repeated measures ANOVA demonstrated a significant effect of time on peak broad jump distance F (1, 8) = 29.75, p = 0.0006. Post-hoc analyses showed that peak broad jump distance decreased significantly from pre- to post-exercise in both the High (82 ± 10 in vs 76 ± 11 in) (p = 0.0003) and Moderate intensity conditions (79 ± 12 in vs 75 ± 13 in) (p = 0.016). However, no significant effect of session type was identified F (1, 8) = 2.673, p = 0.1407. Furthermore, no significant time x session type interaction was found F (1, 8) = 2.332, p = 0.1652.

Average broad jump distance (in) measured between pre-to-post exercise is reported in *Figure 6(D)* (n = 9). A 2 condition x 2 time repeated measures ANOVA identified a significant effect of time on average broad jump distance F (1, 8) = 31.42, p = 0.0005. Post-hoc analyses revealed that average broad jump distance decreased significantly from pre- to post-exercise in both the High (78 ± 11 in vs 74 ± 12 in) (p = 0.0016) and Moderate intensity conditions (79 ± 11 in vs 74 ± 11 in) (p = 0.0025). No significant effect of session type was revealed F (1, 8) = 0.01488, p = 0.9059. Additionally, there was no significant time x session type interaction. In summary, both peak and average broad jump distance significantly decreased after both the High and Moderate intensity circuits, with no difference found between the circuits, indicating a notable neuromuscular stimulus from both sessions,

Recovery response

Peak (n = 6) and average (n=6) broad jump values (m) were identified pre-exercise, and 24/48/72 hours post-exercise for both circuits (*Table 7*).

A 2 condition x 4 time repeated measures ANOVA found no significant effect of time F (1.864, 9.318) = 1.108, p = 0.3654 or session type on peak broad jump distance F (1, 5) = 0.2293, p = 0.6522. Furthermore, no significant time x session type interaction was found F (1, 8) = 2.332, p = 0.1652.

Also, no significant effect of time F (1.540, 7.698) = 2.523, p = 0.1484, or session type F (1, 5) = 1.505, p = 0.2746 on average broad jump distance was identified. Additionally, no significant time x session type interaction was found F (2.078, 10.39) = 0.1250, p = 0.8905. Therefore, there were no significant differences in peak or average broad jump between timepoints or between circuits, suggesting the absence of both sustained fatigue and supercompensation regardless of the intensity.

4.3.2 Vertical jump performance

Table 8.
Quantification of vertical jump performance in response to the High and Moderate intensity circuits

	Session intensity							
	High				Moderate			
Measure	Pre	24	48	72	Pre	24	48	72
Peak CMJ (cm)	31.2	+1.4%	+4.6%	+5.9%	32.5	-0.3%	+0.9%	+5.8%

Mean CMJ (cm)	30.1	+1.4%	+1.2%	+3.1%	31	-0.9%	-0.4%	+2.9%

Note. *Percentage change figures refer to the difference between the mean value at each respective timepoint and the mean pre-exercise value.*

Countermovement jump height (CMJ)

The CMJ is a measure of lower limb muscle function in the horizontal dimension, therefore, providing an indicator of neuromuscular fatigue biased towards the knee extensors (Fukashiro et al., 2005).

Pre-to-post exercise performance

Peak countermovement jump height (cm) measured between pre-to-post exercise is displayed in *Figure 6(A)* (n = 10). A 2 condition x 2 time repeated measures ANOVA identified a significant effect of time on peak CMJ height F (1, 9) = 9.898, p = 0.0118. However, post-hoc analyses revealed a non-significant decrease from pre-to-post exercise in both the High (33.9 ± 6.1 cm vs 32.5 ± 6.2 cm) (p = 0.1074) and Moderate (35 ± 6.6 cm vs 34.1 ± 6.5 cm) (p = 0.3832) conditions. No significant effect of session type was found F (1, 9) = 4.098, p = 0.0736. Additionally, no significant time x session type interaction was seen F (1, 9) = 0.2113, p = 0.6567.

Average countermovement jump height (cm) measured between pre-to-post exercise is displayed in *Figure 6(B)* (n = 9). A 2 condition x 2 time repeated measures ANOVA identified a significant effect of time on average CMJ height F (1, 8) = 9.408, p = 0.0154. However, when examining the post-hoc, a non-significant decrease from pre-to-post exercise was identified in both the High (32.4 ± 6.1 cm vs 31 ± 6.2 cm) (p = 0.0688) and Moderate (33.1 ± 6.9 cm vs 32.7 ± 6.6 cm) (p = 0.2890) conditions. No significant effect of session type was found F (1, 8) = 3.844, p = 0.0856. However, post-hoc analyses identified a significantly higher post-exercise value in the Moderate session, p = 0.0452. Furthermore, no significant time x session type interaction was seen F (1, 8) = 2.044, p = 0.1907. Therefore, there were no differences in average or peak CMJ jump performance from pre-to-post exercise in the circuits, but the lower post-exercise CMJ height in the High session suggests a greater neuromuscular load.

Recovery response

Peak (n = 6) and average (n=6) countermovement jump values (m) were identified pre-exercise, and 24/48/72 hours post-exercise for both circuits (*Table 8*).

A two-way repeated measures ANOVA identified no significant effect of time F (3, 15) = 1.765, p = 0.1968, or session type F (1, 5) = 1.639, p = 0.2566, on peak CMJ height. Additionally, no significant time x session type interaction was found F (3, 15) = 0.5138, p = 0.6789.

A two-way repeated measures ANOVA found no significant effect of time F (3, 15) = 1.205, p = 0.3418, or session type F (1, 5) = 1.281, p = 0.3091, on average CMJ height. Furthermore, no significant time x session type interaction was found F (3, 15) = 0.2585, p = 0.8541. Therefore, there were no significant differences in peak or average CMJ between timepoints or between circuits, suggesting the absence of sustained fatigue and supercompensation regardless of intensity.

4.3.3 Isolated knee extensor capacity

Table 9.
Quantification of knee extensor performance in response to the High and Moderate intensity circuits

	Session intensity							
	High				Moderate			
Measure	Pre	24	48	72	Pre	24	48	72
Peak MVC (N)	256.9	+1.4%	+2%	+1.2%	267.7	+0.5%	+1.7%	+3%

Note. *Percentage change figures refer to the difference between the mean value at each respective timepoint and the mean pre-exercise value.*

Maximum voluntary contraction force (MVC)

Maximum voluntary isometric knee extensions provide an isolated measurement of knee extensor function.

Pre-to-post exercise performance

Peak maximum voluntary contraction force (N) measured between pre-to-post exercise is displayed in *Figure 6(E)* (n = 8). A 2 condition x 2 time repeated measures ANOVA revealed no significant effect of time on peak MVC for the High (265 ± 49.2 N vs 257.3 ± 70 N) or Moderate (267.8 ± 51 N vs 250.1 ± 51.1 N) circuits, F (1, 7) = 1.733, p = 0.2295. Also, no significant effect of session type was found F (1, 7) = 0.05587, p = 0.8199.

Furthermore, there was no significant time x session type interaction F (1, 7) = 0.7517, p = 0.4147. In summary, there was no significant difference in MVC from pre-to-post exercise or between the High and Moderate intensity circuits, suggesting a lack of neuromuscular fatigue regardless of the intensity.

Recovery response

Peak MVC values (N) were identified pre-exercise, and 24/48/72 hours post-exercise for both circuits (*Table 9*) (n = 6).

A two-way repeated measures ANOVA identified no significant effect of time F (3, 15) = 0.1917, p = 0.9004, or session type F (1, 5) = 0.5553, p = 0.4897, on peak maximum voluntary contraction force. Additionally, no significant time x session type interaction was found F (3, 15) = 0.08292, p = 0.9683. Therefore, there were no differences in MVC between timepoints or between circuits, suggesting the absence of sustained fatigue and supercompensation regardless of session intensity.

4.4.4 Perceived wellness

Table 10.
Quantification of subjective wellness in response to the High and Moderate intensity circuits

	Session intensity							
	High				Moderate			
Measure	Pre	24	48	72	Pre	24	48	72
Hooper Index (a.u)	12 ± 5	12 ± 5	12 ± 4	11 ± 4	11 ± 4	12 ± 5	11 ± 4	12 ± 3

Note. *Hooper Index is a multifactorial measure of subjective wellness, a lower score equating to greater wellness. Data presented as mean ± standard deviation*

Hooper index

The Hooper Index is a multifactorial measure of subjective wellness. Hooper index values (*Table 10*) were identified pre-exercise, and 24/48/72 hours post-exercise for both circuits (n=6).

A two-way repeated measures ANOVA identified no significant effect of time F (3, 15) = 0.06545, p = 0.9774, or session type F (1, 5) = 0.1807, p = 0.6884, on Hooper index score. Additionally, no significant time x session type interaction was found F (3, 15) = 0.2658, p = 0.8490. Therefore, there were no differences in Hooper index between timepoints or between circuits, indicating a lack of impact of RCT on subjective wellness regardless of the load intensity utilised.

5 Discussion

The present study aimed to compare the internal and external load demands to a moderate versus high intensity resistance circuit session, ultimately seeking to inform the application of a combined stimulus. The main study findings were: a) the Moderate intensity session resulted in a significantly greater number of repetitions per set, total volume load and increase in blood lactate b) the High session resulted in greater mean muscle activity, plus a more diminished post-exercise countermovement jump height c) finally, heart rate and RPE-chest were equally high between the sessions, and there was a similar lack of impairment for horizontal and vertical jump performance, knee extensor force and subjective wellness for each intensity throughout the recovery period. This data therefore suggests that in trained individuals, both Moderate and High intensity RCT sessions provide a similar cardiovascular and recovery load, with a greater work volume and anaerobic load from the Moderate session, but with a lesser accompanied neuromuscular load compared to the higher intensity. Furthermore, the generally high magnitude of acute loading found in both sessions supports the efficacy of utilising combined training at a range of intensities in trained populations.

5.1 External load

Both volume load (repetitions x load) and the number of repetitions performed for each round of the circuit, were significantly higher in the Moderate versus the High session. This finding is in line with previous studies that have demonstrated a significant inverse relationship between load and volume in traditional RT sessions (Schoenfeld et al., 2016a). However, we could find no previous data on the relationship between load intensity and volume during either RCT or combined sessions, therefore, it is interesting that differences were seen even with the inclusion of timed work periods. Notably, this greater work is likely to result in a higher energy expenditure (Kang et al., 2005), plus a relationship between volume and hypertrophy has been consistently found (Krieger, 2009; Schoenfeld et al., 2017; Terzis et al., 2010). This data demonstrates that the discrepancy in load intensity did result in clear differences in the performance of both circuits, which would indicate that accompanying differences in the internal load are also likely to be seen.

5.2 Conditioning-specific load

However, the cardiovascular response between the two sessions was very similar irrespective of the differences in external load. Not only was no significant difference in mean heart rate identified, but this was corroborated by the equal RPE chest score (exertion of heart and lungs) for both circuits (RPE 16). There appeared to be no previous data on the acute cardiovascular response to differing combined training intensities, although, this finding does align with a meta-analysis from Ramos-Campo et al (2021)., that found no effect of RCT intensity on the VO_{2max} response. Therefore, this suggests that a similar cardiovascular load can be provided by different load intensities of combined training, providing that equal intensities of effort are given, and equivalent work and rest periods are utilised. The High and Moderate sessions achieved mean heart rates at 75% and 74% of the participant's age-predicted maximum (Tanaka et al., 2001), comfortably within the ACSM recommended intensity range (65-90% max) for the enhancement of cardiorespiratory fitness, whilst also at an exercise volume (22 minutes) above the minimum suggested (20 minutes) (Pollock et al., 1998). Furthermore, although working heart rate was only collected in 3 individuals, mean heart rates of > 85% were identified for rounds of both circuits, demonstrating the intensity of the exercise stimulus. This mean heart rate of ~75% max is also consistent with that found from other RCT protocols in the literature (Alcaraz et al., 2008; Marin-Pagan et al., 2020). Overall, it appears that load intensity has little effect on the cardiovascular response to RCT, with both circuits providing a potentially efficacious stimulus for trained individuals.

A significantly greater anaerobic load was experienced from the Moderate versus the High circuit, albeit a sizeable lactate response was still derived from the High session. This influence of intensity is likely driven primarily by the greater number and shorter duration of repetitions in the Moderate session, these factors seen to facilitate greater lactate accumulation in traditional resistance training (Lacerda et al., 2016; Vargas-Molina et al., 2020). To note, even though prescribed repetition velocities were not different between the circuits, participants were instructed to perform maximal speed concentric contractions, with lower loads being more facilitative of greater bar velocities (Loturco et al., 2016). A similar outcome was reported by Roberson et al., (2017) who identified slightly greater lactate from moderate versus high intensity RCT in females, however in contrast to our investigation, no effect of load intensity in the male participants. The contrast between these datasets may be explained by the use of pneumatic resistance by Roberson et al., as the specific equipment utilised provides a lack of eccentric force (Willoughby, 2004) which could therefore reduce total workload and increase skeletal blood flow, consequently alleviating lactate accumulation compared to the free weights and machines used in the current study.

Although, the highly anaerobic nature of RCT is well-supported in the literature, interestingly the lactate values we identified are significantly higher than those in other studies utilising similar intensities. Lactate concentrations between 9-11 mmol/L have been found in protocols with males utilising 70-85% 1RM (Marin-Pagan et al., 2020; Paoli et al., 2012; Roberson et al., 2017), and between 9.5-14 mmol/L in sessions using 40-60% 1RM (Burleson et al., 1998; Harber et al., 2004; Roberson et al., 2017), compared to the 14 and 18 mmol/L from our High and Moderate circuits. An explanation for this could lie in the greater inter-set rest periods provided in certain studies (Burleson et al., 1998; Marin-Pagan et al., 2020; Roberson et al., 2017), and/or the lower volume of work (Paoli et al., 2012), and/or the lesser muscle mass involved in the exercises (Harber et al., 2004; Marin-Pagan et al., 2020). The magnitude of blood lactate accumulation found in the current investigation demonstrates the potentially significant contribution of anaerobic glycolysis to energy provision in trained persons during RCT, further supporting the existing literature evidencing the potential of combined training to aid anaerobic performance (Crawford et al., 2018; Myers et al., 2015).

5.3 Neuromuscular load

As mentioned prior, a significantly greater volume load was performed in the Moderate circuit, however, this was accompanied by a ~25% lower mean repetition EMG amplitude than in the High circuit. Therefore, the volume of work completed by the difficult-to-stimulate, type II muscle fibres may actually have been greater in the High session. The recruitment of these is especially important as these fibres have the greatest capacity to both produce force and to hypertrophy (Scott et al., 2001). This appears to be the first EMG data collected on combined training protocols, but many resistance training studies have similarly demonstrated a greater EMG amplitude from high versus low intensity training (Vigotsky et al., 2016). Although, an equal potential for hypertrophy has been proven with both high and low intensity resistance training protocols (Schoenfeld et al., 2017), therefore EMG data is not a definitive predictor of muscle growth (Vigotsky et al., 2016). It is important to note however that this equivalent hypertrophic response is only experienced when training is taken to failure (Holm et al., 2008; Schoenfeld et al., 2017), as high-repetition, lower-load sets will accumulate fatigue and fast-twitch muscle fibres are then recruited to maintain force output (Morton et al., 2019).

Furthermore, some data has indicated a generally superior effect of training to failure on hypertrophy in trained individuals (Grgic et al., 2022), reinforcing the importance of ensuring that differing RCT intensities can facilitate high intensities of effort. Considering on average only ~9 consecutive reps can be performed at loads of 75% 1RM, compared to ~16 at 55% 1RM (Jovanovic, 2014), it was unclear as to whether the 35 s working sets utilised in our study would enable participants to take sets to failure. However, a muscular RPE equating to ‘hard’ was found in both the High (RPE 16) and Moderate (RPE 15) sessions, representing a high intensity of effort. This together with the decrease in repetitions performed from set 1 to set 3 in both sessions, and the significant decrement in broad jump performance post-exercise, evidences a degree of muscular fatigue that could be facilitative of hypertrophy even with the Moderate session. Albeit, repetitions decreased to a relatively greater degree in the High (-20%) versus Moderate session (-13%) from set 1 to set 3, and post-exercise peak CMJ height was significantly lower in the High session, potentially indicating a greater neuromuscular stimulus from the High load. Interestingly, one study that compared hypertrophic responses between high (70% 1RM) and low load (30% 1RM) resistance circuit training similarly used timed work sets (30 s) and identified equal adaptation between intensities (Kapsis et al., 2022). However, participants were excluded if they had performed RT in the 6 months preceding the study and therefore the stimulus for adaptation would likely have been reduced.

In addition, greater increases in maximal strength have been consistently demonstrated with higher load intensities of traditional resistance training (Schoenfeld et al., 2017) and this effect would likely transfer to combined training. Intriguingly, this has been supported in some studies (Paoli et al., 2010), but not in others (Kapsis et al., 2022; Paoli et al., 2010; Ramos-Campo et al., 2021). Although, there is no clear reason as to why this effect would not translate to combined training, and the aforementioned data may again be influenced by the limited training experience of the participants and the relatively short duration of the training programmes. To summarise, although both circuit sessions seem conducive to hypertrophy in trained individuals, it appears that the High session provided an overall greater neuromuscular load.

5.4 Recovery data

Interestingly, no significant fluctuation was observed in any of the objective and subjective measures of recovery in the present study. The fatigue response can provide an indication of the neuromuscular stimulus of a bout; however, fatigue is not always necessary for adaptation (Folland et al., 2002). Examining the data, the only metric that was downregulated through to 72 hours post-exercise in both sessions, although non-significantly, was broad jump distance, as a -2% decrement in peak broad jump performance was found after both circuits. Here, it is possible that our limited sample size in the study may have produced a type II error preventing statistical significance. The identified decrease in this measure, as opposed to the CMJ for example, may be due to the predominant recruitment of the hip extensors during the horizontal jump pattern (Fukashiro et al., 2005). The hip extensors would have been significantly loaded during both the deadlift and 45° incline leg press exercises in the circuits (Da Silva et al., 2008; Ebben et al., 2009) (6 sets), in contrast to the quadriceps, which are more dominant in the vertical jump pattern of the CMJ (Fukashiro et al., 2005), and would have only significantly contributed during the leg press exercise (Da Silva et al., 2008; Ebben et al., 2009) (3 sets). Therefore, if wanting to limit neuromuscular fatigue from RCT then it appears important to modulate the number of working sets per muscle group. Interestingly, both CMJ and MVC performance were non-significantly greater at 72 hours compared to pre-exercise for both circuits, potentially indicating a neuromuscular supercompensation effect from the bouts. However, it is also possible that a learning effect could have contributed to this improvement, furthermore, the measurements may have been too acute to identify actual supercompensation in a trained cohort therefore further research here is needed.

Furthermore, there were no significant differences between the recovery responses of the two conditions. This is in contrast to previous data demonstrating a greater and more prolonged impairment of recovery from low load versus high load RT to failure (Farrow et al., 2020; Haun et al., 2017). However, in both these studies the low load sets involved much greater time-under load, which would likely also result in greater metabolite accumulation and associated low-frequency fatigue (Ratkevicius et al., 1998), whilst in the present study, sets were restricted to 35 s which would have limited temporal variation between intensities. Additionally, as discussed, it is possible that our use of time limited sets may have prevented subjects reaching failure in the lower load session and therefore inhibiting fatigue. It seems likely that if combined training sets are performed until failure, instead of a set time duration, that lower RCT intensities would result in a greater recovery burden.

Research comparing the magnitude of fatigue from combined training versus traditional concurrent training is scarce. An investigation from Marquez et al., (2017) identified a decrease in knee extensor MVC 10 minutes post RCT, but no decrease after volume-matched traditional resistance training. This contrast is likely due to the greater peripheral fatigue post RCT, as indicated by the decreased resting twitch amplitude, this effect potentially mediated by the accompanied significantly greater elevation in blood lactate and its documented detriment on force production per muscle cross-bridge (Fitts, 2008). Although no decrement in MVC was identified post-exercise in the present study, a non-significant decline was again observed, with our smaller sample size potentially producing a type II error. However, Marquez et al., (2017) only measured fatigue up to 10 mins post-exercise, and there was no conditioning exercise load in the traditional RT condition. Therefore, it is unclear how the extended recovery burden from combined training would compare to traditional concurrent training, although this data suggests that the duration of fatigue after RCT is minimal. This is an important observation for both recreational exercisers and athletes, considering the effect of residual fatigue on exercise performance and injury risk (Dupont et al., 2010; Russell et al., 2015).

5.5 Limitations

5.5.1 Evaluation of measurement reliability

Although steps were taken to consolidate the reliability and applicability of the research, there are still limitations that should be acknowledged. Firstly, an impetus was placed on utilising well researched measures of training load, with efforts made to enforce the reliability of these, however the potential for error is still present.

Measurement standards for our chosen method of bioelectric impedance analysis have been validated against gold-standard techniques such as dual-energy X-ray absorptiometry (Bosy-Westphal et al., 2013). One potential hinderance to measurement reliability derives from variation in acute dietary intake, albeit this was controlled by requesting participants to come to the laboratory in the fasted state (Androutsos et al., 2015).

Next, RPE appears to provide an accurate estimation of internal load in both strength (Lagally et al., 2002), as well as more conditioning focused activities (Impellizzeri et al., 2004), validating the use of differential RPE for combined training (Tibana et al., 2018). Also, the Hooper Index has been validated in its ability to characterise fatigue and appears sensitive to fluctuations in training load (Rabbani et al., 2019). However, even with both presenting strong correlations to objective measures of training load, perceived measures are influenced by personal characteristics such as mood, introversion/extroversion, anxiety and depression (Morgan, 1994). This demonstrates the importance of including objective measures of both strength and conditioning-specific load.

The Polar T31 chest-strap monitor (Polar Electro Oy, Kempele, Finland) utilised in the investigation has been evidenced to provide reliable HR values (Montes and Navalta, 2019), with high agreement to gold-standard methods (Radespiel-Troger et al., 2003). Albeit heart rate is not the most valid assessment of aerobic load during resistance modalities. During RT, skeletal muscle contractions result in vasoconstriction that limits blood flow into and out of the muscle, directly reducing venous return, and requiring an increase in heart rate to maintain cardiac output (Williams et al., 2007). It is difficult however to directly measure oxygen uptake during dynamic exercise, leading to many combined training researchers similarly using heart rate monitoring instead (Alcaraz et al., 2008; Skidmore et al., 2012; Tibana et al., 2018). Promisingly, the inclusion of RPE does help corroborate the findings, as the extremely close identified mean HR values between the circuits are reinforced by the matching RPE-Chest figures.

When rates of anaerobic glycolysis exceed that of aerobic lactate utilisation, there is net lactate accumulation; as such, capillary blood lactate concentration is sensitive to changes in exercise intensity (Beneke et al., 2011). The specific lactate analyser used presently (EKF Diagnostics, Magdeburg, Germany) has been validated in its reliability and accuracy, with evidence of greater accuracy than other comparative analysers at high lactate concentrations (Biosen studies and evaluations, EKF Diagnostics).

Examining the measurement of neuromuscular load, the MBody shorts (Myontec Ltd., Kuopio, Finland) have been evidenced to provide comparable electromyographic values, and measurement reproducibility, to traditional surface EMG (Colyer and McGuigan, 2018). Surface EMG is capable of reflecting muscle excitation; however, signal variation can occur through differences in electrode configuration, subcutaneous thickness, muscle lengths and contraction modes (Vigotsky et al., 2022). Although in this case, the shorts provided controlled electrode positioning between bouts, subcutaneous thickness and muscle lengths will have been consistent due to the cross-over design, and the same exact exercises were compared for the circuits as well as the normalisation bout, therefore, enhancing reliability. As RT stimulates muscle protein synthesis and hypertrophy compared to rest, a case could be made for higher excitation predicting greater adaptation, however, at present the muscle state-hypertrophy dose-response is unclear (Vigotsky et al., 2021).

Additionally, performance of MVCs, broad jumps and CMJs were utilised to provide indications of neuromuscular load and recovery from the circuit sessions. CMJ and broad jumps are sensitive to changes in training load and recovery status (Hiscock et al., 2018; Pearcey et al., 2015a), with the former being a measure of power in the vertical dimension and the latter representing horizontal power. Both jumps do have significant skill components and therefore differences in technique between bouts could have an influence. However, this was counteracted by the utilisation of familiarisation jumps before the experimental sessions. MVC on the other hand has a low technical demand and is highly reliable (Alvares et al., 2015) and therefore it is possible to assume that any variation in scores is directly as a result of the level of neuromuscular fatigue.

5.5.2 Evaluation of study design

Firstly, this is not a training study and thus there is a limited ability to predict the specific adaptive effects of either protocol solely from these acute responses. However, each of the included measures of external and internal load has evidence supporting its association with specific physiological adaptations. The collection of multiple individual internal and external measures for both strength and conditioning-specific load therefore provides a collective weight of evidence regarding the efficacy of either protocol for mediating adaptation (Selye, 1976).

Furthermore, the study sampling may have ramifications for the actual findings, as well as the transferability of these. The sample size (n = 10) is actually similar to that of other investigations in the combined training literature (Alcaraz et al., 2008; Marin-Pagan et al., 2020; Paoli et al., 2010; Romeno-Arenas et al., 2018). However, only 6 participants completed the recovery measures, and various difficulties led to a reduction in the sample for many of the exercise session measures. Although it is normal to experience difficulties in data collection when working with live participants (Benson et al., 2021), lower sample sizes do lead to an increased risk of type II statistical errors, this potentially concealing differences in the response between the two sessions. Also, all participants were healthy, trained individuals, therefore hindering the ability to generalise results to untrained or clinical populations. The utilisation of a counter-balanced cross-over design does however aid reliability. The cross-over component prevents an influence of genetic variation on the identified responses to each session. Furthermore, the counterbalanced session order helps diminish any potential learning effect on results.

Although, participants attended sessions in the fasted state, their peri-exercise nutrition was unmonitored. Therefore, we are not able to rule out an influence of dietary intake on the performance of the circuit and/or recovery sessions. It should be noted however that participants were instructed to maintain their normal diet throughout the study duration, and circuit sessions were performed a maximum of 3 weeks apart, this potentially helping to limit differences in peri-workout nutrition between the two sessions.

Finally, the Moderate (55% 1RM/16 RM) and High (75% 1RM/9 RM) sessions were predicted to be disparate enough to identify any potential influence of intensity on responses to combined training, with this validated by the identified significant differences in external load. However, including a greater range of loads could provide a clearer picture of the influence of intensity.

5.6 Perspectives

As discussed earlier, there are significant gaps in the combined training literature. The present study goes some of the way to addressing these issues, therefore presenting potential applications. The finding that differing intensities of combined training can offer comparative cardiovascular loading, with greater anaerobic loading from moderate intensities, and more significant neuromuscular loading from higher intensities, is novel.

This suggests that combined training can be utilised to provide a greater cardiovascular stimulus than traditional resistance training, with the ability to then tailor the stimulus towards adaptations of interest dependent on the intensity employed. The Moderate intensity and its associated higher lactate response could be utilised if seeking to improve peripheral adaptations and anaerobic performance. This may be advantageous for short-to-middle distance athletes (Brandon, 1995) and for team-sport performance (Gabbett et al., 2014; Krustrup et al., 2006), whilst also possessing as a wider utility due to the positive influence of anaerobic exercise on markers of health (Salvadori et al., 2014; Taylor et al., 2019). It is important to note however that although to a lower degree, significant lactate accumulation was still identified with the High session, suggesting its potential efficacy for anaerobic adaptation.

Conversely, the higher intensity circuit and its seemingly greater neuromuscular stimulus could be preferential for improvements in strength and muscular hypertrophy. This is of significance considering the importance of these capacities on power and endurance-based performance (Suchomel et al., 2016), risk of injury (Lauersen et al., 2014), and overall functional capacity (Kjolhede et al., 2015). However, as discussed, the Moderate intensity is facilitative of a greater volume of work and would likely result in comparative hypertrophy if sets are performed to failure. Overall, this research enhances the ability to tailor a combined stimulus, dependent on the stage of the training cycle, the capabilities of the individual, and the resultant physiological goal(s).

Furthermore, much of the combined training literature has involved untrained participants. Considering, the higher threshold for adaptation in trained individuals (Ahtiainen et al., 2003; Coffey et al., 2006; Gelman et al., 2022), it is important to ensure that combined training offers a significant concurrent stimulus in higher-ability populations. Promisingly, the circuits enabled a volume of 3-6 sets/muscle group, therefore appearing compatible with the indicated benchmark of ≥ 6 sets/week (Ralston et al., 2017; Schoenfeld et al., 2019) and ≥ 10 sets/week (Schoenfeld et al., 2017) for optimal adaptations in strength and hypertrophy respectively. Furthermore, RPE-muscular scores equated to the ‘high’ level, indicating the intensity of both sessions. ‘High’ RPE-chest scores were also reported, and the mean heart rate (75% max) for the 22 min duration of both circuits aligns with both intensity and volume recommendations for improving cardiorespiratory fitness (Pollock et al., 1998). Finally, capillary blood lactate levels were at or above that previously identified from Wingate tests (Fernandez-del-Olmo et al., 2013; Weinstein et al., 1998), demonstrating the magnitude of the anaerobic stimulus. On top of this, no significant recovery burden was identified from 24 h post-exercise onwards, suggesting that combined training can be performed without significantly compromising performance in the immediate days following, this characteristic being of particular utility for athletic populations. Therefore, our data supports the use of combined training as a concurrent training methodology for athletic/trained individuals, whilst offering significantly lower time-demands to traditional concurrent methodologies, along with other aforementioned potential benefits (*pg.* 5-6) such as an increased energy expenditure and positive psychological responses.

However, as discussed, there are limitations to our research and as such, further investigation is warranted in order to fully elucidate the application of combined training. Consequent research that demonstrates actual adaptive effects to the utilisation of a range of combined intensities, within a range of populations, and potentially utilising more than one combined modality, would be greatly advantageous.

6 Conclusion

In conclusion, when comparing the internal and external load demands of Moderate versus High intensity RCT sessions in trained individuals we identified high markers of both strength and conditioning-specific load regardless of intensity, suggesting their mutual efficacy. However, our data suggests that moderate intensities of RCT provide a greater work volume and anaerobic load, whilst a greater neuromuscular load is offered from higher intensity RCT, with both sessions providing a comparative cardiovascular stimulus and recovery burden. These findings should help provide trained individuals with a clearer idea of how to modulate a combined training session dependent on the session goal. However, further research is needed to confirm whether this relationship between intensity and acute load is consistent when performing other modalities of combined training, within other populations, and whether these differences in the acute response would amount to a variance in adaptation.

List of References

Aagaard, P., Andersen, J. L., Dyhre-Poulsen, P., Leffers, A. M., Wagner, A., Magnusson, S. P., Halkjaer-Kristensen, J. & Simonsen, E. B. 2001. A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. *The Journal of physiology,* 534**,** 613-623.

Abramowitz, M. K., Hall, C. B., Amodu, A., Sharma, D., Androga, L. & Hawkins, M. 2018. Muscle mass, BMI, and mortality among adults in the United States: A population-based cohort study. *PLoS One,* 13**,** e0194697.

Adhihetty, P. J., Irrcher, I., Joseph, A.-M., Ljubicic, V. & Hood, D. A. 2003. Plasticity of skeletal muscle mitochondria in response to contractile activity. *Experimental Physiology,* 88**,** 99-107.

Ahtiainen, J. P., Pakarinen, A., Alen, M., Kraemer, W. J. & Häkkinen, K. 2003. Muscle hypertrophy, hormonal adaptations and strength development during strength training in strength-trained and untrained men. *European Journal of Applied Physiology,* 89**,** 555-563.

Akima, H., Takahashi, H., Kuno, S. Y., Masuda, K., Masuda, T., Shimojo, H., Anno, I., Itai, Y. & Katsuta, S. 1999. Early phase adaptations of muscle use and strength to isokinetic training. *Med Sci Sports Exerc,* 31**,** 588-94.

Alcaraz, P. E., Sánchez-Lorente, J. & Blazevich, A. J. 2008. Physical performance and cardiovascular responses to an acute bout of heavy resistance circuit training versus traditional strength training. *The Journal of Strength & Conditioning Research,* 22**,** 667-671.

Alcaraz, P. E., Perez-Gomez, J., Chavarrias, M. & Blazevich, A. J. 2011. Similarity in Adaptations to High-Resistance Circuit vs. Traditional Strength Training in Resistance-Trained Men. *The Journal of Strength & Conditioning Research,* 25**,** 2519-2527.

Alkner, B. A., Tesch, P. A. & Berg, H. E. 2000. Quadriceps EMG/force relationship in knee extension and leg press. *Med Sci Sports Exerc,* 32**,** 459-63.

American College of Sports Medicine 2009. Progression Models in Resistance Training for Healthy Adults. *Medicine & Science in Sports & Exercise,* 41**,** 687-708.

Androulakis-Korakakis, P., Fisher, J. P. & Steele, J. 2020. The Minimum Effective Training Dose Required to Increase 1RM Strength in Resistance-Trained Men: A Systematic Review and Meta-Analysis. *Sports Medicine,* 50**,** 751-765.

Androutsos, O., Gerasimidis, K., Karanikolou, A., Reilly, J. J. & Edwards, C. A. 2015. Impact of eating and drinking on body composition measurements by bioelectrical impedance. *J Hum Nutr Diet,* 28**,** 165-71.

Arany, Z., Foo, S.-Y., Ma, Y., Ruas, J. L., Bommi-Reddy, A., Girnun, G., Cooper, M., Laznik, D., Chinsomboon, J. & Rangwala, S. M. 2008. HIF-independent regulation of VEGF and angiogenesis by the transcriptional coactivator PGC-1α. *Nature,* 451**,** 1008-1012.

Atherton, P. J., Babraj, J. A., Smith, K., Singh, J., Rennie, M. J. & Wackerhage, H. 2005. Selective activation of AMPK-PGC-1α or PKB-TSC2-mTOR signalling can explain specific adaptive responses to endurance or resistance training-like electrical muscle stimulation. *The FASEB Journal,* 19**,** 1-23.

Baar, K. 2014. Using molecular biology to maximize concurrent training. *Sports Medicine,* 44**,** 117-125.

Baechle, T. R. & Earle, R. W. 2008. *Essentials of strength training and conditioning*, Human kinetics.

Bagger, M., Petersen, P. H. & Pedersen, P. K. 2003. Biological variation in variables associated with exercise training. *Int J Sports Med,* 24**,** 433-40.

Balabinis, C. P., Psarakis, C. H., Moukas, M., Vassiliou, M. P. & Behrakis, P. K. 2003. Early phase changes by concurrent endurance and strength training. *J Strength Cond Res,* 17**,** 393-401.

Balshaw, T. G., Massey, G. J., Maden-Wilkinson, T. M., Lanza, M. B. & Folland, J. P. 2019. Neural adaptations after 4 years vs 12 weeks of resistance training vs untrained. *Scandinavian Journal of Medicine & Science in Sports,* 29**,** 348-359.

Banaszek, A., Townsend, J. R., Bender, D., Vantrease, W. C., Marshall, A. C. & Johnson, K. D. 2019. The Effects of Whey vs. Pea Protein on Physical Adaptations Following 8-Weeks of High-Intensity Functional Training (HIFT): A Pilot Study. *Sports,* 7**,** 12.

Barnes, K. R. & Kilding, A. E. 2015. Running economy: measurement, norms, and determining factors. *Sports Medicine - Open,* 1**,** 8.

Bassett, D. R., Jr. & Howley, E. T. 2000. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med Sci Sports Exerc,* 32**,** 70-84.

Beattie, K., Kenny, I. C., Lyons, M. & Carson, B. P. 2014. The Effect of Strength Training on Performance in Endurance Athletes. *Sports Medicine,* 44**,** 845-865.

Beneke, R., Pollmann, C., Bleif, I., Leithäuser, R. & Hütler, M. 2002. How anaerobic is the Wingate Anaerobic Test for humans? *European Journal of Applied Physiology,* 87**,** 388-392.

Beneke, R., Leithäuser, R. M. & Ochentel, O. 2011. Blood Lactate Diagnostics in Exercise Testing and Training. *International Journal of Sports Physiology and Performance,* 6**,** 8-24.

Benito, P. J., Cupeiro, R., Ramos-Campo, D. J., Alcaraz, P. E. & Rubio-Arias, J. 2020. A Systematic Review with Meta-Analysis of the Effect of Resistance Training on Whole-Body Muscle Growth in Healthy Adult Males. *International journal of environmental research and public health,* 17.

Benson, L. C., Stilling, C., Owoeye, O. B. A. & Emery, C. A. 2021. Evaluating Methods for Imputing Missing Data from Longitudinal Monitoring of Athlete Workload. *Journal of sports science & medicine,* 20**,** 188-196.

Billat, V. L., Sirvent, P., Py, G., Koralsztein, J. P. & Mercier, J. 2003. The concept of maximal lactate steady state: a bridge between biochemistry, physiology and sport science. *Sports Med,* 33**,** 407-26.

Bishop, D., Edge, J. & Goodman, C. 2004. Muscle buffer capacity and aerobic fitness are associated with repeated-sprint ability in women. *Eur J Appl Physiol,* 92**,** 540-7.

Bishop, D., Girard, O. & Mendez-Villanueva, A. 2011. Repeated-Sprint Ability — Part II. *Sports Medicine,* 41**,** 741-756.

Blair, S. N., Kohl, H. W., 3rd, Paffenbarger, R. S., Jr., Clark, D. G., Cooper, K. H. & Gibbons, L. W. 1989. Physical fitness and all-cause mortality. A prospective study of healthy men and women. *Jama,* 262**,** 2395-401.

Bloomfield, J., Polman, R. & O'donoghue, P. 2007. Physical Demands of Different Positions in FA Premier League Soccer. *Journal of sports science & medicine,* 6**,** 63-70.

Bodine, S. C. 2006. mTOR signalling and the molecular adaptation to resistance exercise. *Medicine and science in sports and exercise,* 38**,** 1950.

Bompa, T. O. 1983. Theory and methodology of training. *Dubuque, IA: Kendall/Hunt***,** 91-97.

Bosy-Westphal, A., Schautz, B., Later, W., Kehayias, J. J., Gallagher, D. & Müller, M. J. 2013. What makes a BIA equation unique? Validity of eight-electrode multifrequency BIA to estimate body composition in a healthy adult population. *European Journal of Clinical Nutrition,* 67**,** S14-S21.

Brandon, L. J. 1995. Physiological Factors Associated with Middle Distance Running Performance. *Sports Medicine,* 19**,** 268-277.

Buckley, S., Knapp, K., Lackie, A., Lewry, C., Horvey, K., Benko, C., Trinh, J. & Butcher, S. 2015. Multimodal high-intensity interval training increases muscle function and metabolic performance in females. *Applied Physiology, Nutrition, and Metabolism,* 40**,** 1157-1162.

Buitrago, S., Wirtz, N., Yue, Z., Kleinöder, H. & Mester, J. 2012. Effects of load and training modes on physiological and metabolic responses in resistance exercise. *European Journal of Applied Physiology,* 112**,** 2739-2748.

Burd, N. A., Tang, J. E., Moore, D. R. & Phillips, S. M. 2009. Exercise training and protein metabolism: influences of contraction, protein intake, and sex-based differences. *Journal of Applied Physiology,* 106**,** 1692-1701.

Burgomaster, K. A., Howarth, K. R., Phillips, S. M., Rakobowchuk, M., Macdonald, M. J., Mcgee, S. L. & Gibala, M. J. 2008. Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans. *The Journal of physiology,* 586**,** 151-160.

Burleson, M. a. J., O'bryant, H. S., Stone, M. H., Collins, M. A. & Triplett-Mcbride, T. 1998. Effect of weight training exercise and treadmill exercise on post-exercise oxygen consumption. *Medicine & Science in Sports & Exercise,* 30**,** 518-522.

Butcher, S., Judd, T., Benko, C., Horvey, K. & Pshyk, A. 2015. Relative Intensity of Two Types of CrossFit Exercise: Acute Circuit and High-Intensity Interval Exercise. *Journal of Fitness Research,* 4.

Bycura, D., Feito, Y. & Prather, C. 2017. Motivational Factors in CrossFit® Training Participation. 4**,** 539-550.

Calvo, J. A., Daniels, T. G., Wang, X., Paul, A., Lin, J., Spiegelman, B. M., Stevenson, S. C. & Rangwala, S. M. 2008. Muscle-specific expression of PPARγ coactivator-1α improves exercise performance and increases peak oxygen uptake. *Journal of Applied Physiology,* 104**,** 1304-1312.

Camargo, M. D., Stein, R., Ribeiro, J. P., Schvartzman, P. R., Rizzatti, M. O. & Schaan, B. D. 2008. Circuit weight training and cardiac morphology: a trial with magnetic resonance imaging. *British Journal of Sports Medicine,* 42**,** 141-145.

Campos, G. E., Luecke, T. J., Wendeln, H. K., Toma, K., Hagerman, F. C., Murray, T. F., Ragg, K. E., Ratamess, N. A., Kraemer, W. J. & Staron, R. S. 2002. Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones. *European Journal of Applied Physiology,* 88**,** 50-60.

Centers for Disease Control and Prevention (2022). Health Effects of Overweight and Obesity. Available at: https://www.cdc.gov/healthyweight/effects/index.html

Child, J. S., Barnard, R. J. & Taw, R. L. 1984. Cardiac hypertrophy and function in master endurance runners and sprinters. *Journal of Applied Physiology,* 57**,** 176-181.

Chinsomboon, J., Ruas, J., Gupta, R. K., Thom, R., Shoag, J., Rowe, G. C., Sawada, N., Raghuram, S. & Arany, Z. 2009. The transcriptional coactivator PGC-1α mediates exercise-induced angiogenesis in skeletal muscle. *Proceedings of the national academy of sciences,* 106**,** 21401-21406.

Coffey, V. G., Zhong, Z., Shield, A., Canny, B. J., Chibalin, A. V., Zierath, J. R. & Hawley, J. A. 2006. Early signalling responses to divergent exercise stimuli in skeletal muscle from well-trained humans. *The FASEB Journal,* 20**,** 190-192.

Coffey, V. G. & Hawley, J. A. 2017. Concurrent exercise training: do opposites distract? *The Journal of physiology,* 595**,** 2883-2896.

Colyer, S. L. & Mcguigan, P. M. 2018. Textile Electrodes Embedded in Clothing: A Practical Alternative to Traditional Surface Electromyography when Assessing Muscle Excitation during Functional Movements. *Journal of sports science & medicine,* 17**,** 101-109.

Cooper, G. T. 1997. Basic determinants of myocardial hypertrophy: a review of molecular mechanisms. *Annu Rev Med,* 48**,** 13-23.

Cosgrove, S. J., Crawford, D. A. & Heinrich, K. M. 2019. Multiple Fitness Improvements Found after 6-Months of High Intensity Functional Training. *Sports,* 7**,** 203.

Coutts, A., Reaburn, P. & Abt, G. 2003. Heart rate, blood lactate concentration and estimated energy expenditure in a semi-professional rugby league team during a match: case study. *Journal of Sports Sciences,* 21**,** 97-103.

Coyle, E. F., Coggan, A. R., Hopper, M. K. & Walters, T. J. 1988. Determinants of endurance in well-trained cyclists. *J Appl Physiol (1985),* 64**,** 2622-30.

Crawford, D. A., Drake, N. B., Carper, M. J., Deblauw, J. & Heinrich, K. M. 2018. Are Changes in Physical Work Capacity Induced by High-Intensity Functional Training Related to Changes in Associated Physiologic Measures? *Sports,* 6**,** 26.

CrossFit (2020). Level 1 Training Guide (3rd edition). Available at: http://library.crossfit.com/free/pdf/CFJ_English_Level1_TrainingGuide.pdf

Crowley, E., Harrison, A. J. & Lyons, M. 2018. Dry-Land Resistance Training Practices of Elite Swimming Strength and Conditioning Coaches. *The Journal of Strength & Conditioning Research,* 32**,** 2592-2600.

Da Silva, J. F., Guglielmo, L. G. & Bishop, D. 2010. Relationship between different measures of aerobic fitness and repeated-sprint ability in elite soccer players. *J Strength Cond Res,* 24**,** 2115-21.

De Araujo Ribeiro Alvares, J. B., Rodrigues, R., De Azevedo Franke, R., Da Silva, B. G., Pinto, R. S., Vaz, M. A. & Baroni, B. M. 2015. Inter-machine reliability of the Biodex and Cybex isokinetic dynamometers for knee flexor/extensor isometric, concentric and eccentric tests. *Phys Ther Sport,* 16**,** 59-65.

De Salles, B. F., Simao, R., Miranda, F., Da Silva Novaes, J., Lemos, A. & Willardson, J. M. 2009. Rest interval between sets in strength training. *Sports Medicine,* 39**,** 765.

De Witt, J. K., English, K. L., Crowell, J. B., Kalogera, K. L., Guilliams, M. E., Nieschwitz, B. E., Hanson, A. M. & Ploutz-Snyder, L. L. 2018. Isometric Midthigh Pull Reliability and Relationship to Deadlift One Repetition Maximum. *J Strength Cond Res,* 32**,** 528-533.

Drummond, M. J., Dreyer, H. C., Fry, C. S., Glynn, E. L. & Rasmussen, B. B. 2009. Nutritional and contractile regulation of human skeletal muscle protein synthesis and mTORC1 signalling. *Journal of applied physiology (Bethesda, Md. : 1985),* 106**,** 1374-1384.

Duchateau, J., Semmler, J. G. & Enoka, R. M. 2006. Training adaptations in the behaviour of human motor units. *Journal of Applied Physiology,* 101**,** 1766-1775.

Duehring, M. D. & Ebben, W. P. 2010. Profile of High School Strength and Conditioning Coaches. *The Journal of Strength & Conditioning Research,* 24**,** 538-547.

Dupont, G., Nedelec, M., Mccall, A., Mccormack, D., Berthoin, S. & Wisloff, U. 2010. Effect of 2 Soccer Matches in a Week on Physical Performance and Injury Rate. *The American journal of sports medicine,* 38**,** 1752-8.

Ebben, W. P., Feldmann, C. R., Dayne, A., Mitsche, D., Alexander, P. & Knetzger, K. J. 2009. Muscle Activation during Lower Body Resistance Training. *Int J Sports Med,* 30**,** 1-8.

Edge, J., Bishop, D. & Goodman, C. 2006. The effects of training intensity on muscle buffer capacity in females. *European Journal of Applied Physiology,* 96**,** 97-105.

Egan, B. & Zierath, Juleen r. 2013. Exercise Metabolism and the Molecular Regulation of Skeletal Muscle Adaptation. *Cell Metabolism,* 17**,** 162-184.

Evertsen, F., Medbø, J. I. & Bonen, A. 2001. Effect of training intensity on muscle lactate transporters and lactate threshold of cross-country skiers. *Acta Physiologica Scandinavica,* 173**,** 195-205.

Farrow, J., Steele, J., Behm, D. G., Skivington, M. & Fisher, J. P. 2021. Lighter-Load Exercise Produces Greater Acute- and Prolonged-Fatigue in Exercised and Non-Exercised Limbs. *Res Q Exerc Sport,* 92**,** 369-379.

Feito, Y., Hoffstetter, W., Serafini, P. & Mangine, G. 2018. Changes in body composition, bone metabolism, strength, and skill-specific performance resulting from 16-weeks of HIFT. *PLoS One,* 13**,** e0198324.

Feito, Y., Brown, C. W. & Olmos, A. A. 2019. A content analysis of the High-Intensity Functional Training Literature: a look at the past and directions for the future. *Human Movement*.

Fernandez-Del-Olmo, M., Rodriguez, F. A., Marquez, G., Iglesias, X., Marina, M., Benitez, A., Vallejo, L. & Acero, R. M. 2013. Isometric knee extensor fatigue following a Wingate test: peripheral and central mechanisms. *Scandinavian Journal of Medicine & Science in Sports,* 23**,** 57-65.

Fernandez-Fernandez, J., Sabido, R., Moya, D., Sarabia Marín, J. M. & Moya, M. 2015. Acute physiological responses during crossfit® workouts. *European Journal of Human Movement,* 35**,** 114-124.

Ferri-Morales, A., Nascimento-Ferreira, M. V., Vlachopoulos, D., Ubago-Guisado, E., Torres-Costoso, A., De Moraes, A. C. F., Barker, A. R., Moreno, L. A., Martínez-Vizcaino, V. & Gracia-Marco, L. 2018. Agreement Between Standard Body Composition Methods to Estimate Percentage of Body Fat in Young Male Athletes. *Pediatr Exerc Sci,* 30**,** 402-410.

Fifpro (2021) Fifpro Player Workload Monitoring. Available at: https://fifpro.org/media/ltcnnyzc/player-workload-monitoring-report-2021-men-s-football.pdf

Fisher, J., Steele, J. & Smith, D. 2017. High- and Low-Load Resistance Training: Interpretation and Practical Application of Current Research Findings. *Sports Medicine,* 47**,** 393-400.

Fiskerstrand, Å. & Seiler, K. S. 2004. Training and performance characteristics among Norwegian International Rowers 1970–2001. *Scandinavian Journal of Medicine & Science in Sports,* 14**,** 303-310.

Fitts, R. H. 2008. The cross-bridge cycle and skeletal muscle fatigue. *Journal of Applied Physiology,* 104**,** 551-558.

Föhrenbach, R., Mader, A. & Hollmann, W. 1987. Determination of endurance capacity and prediction of exercise intensities for training and competition in marathon runners. *Int J Sports Med,* 8**,** 11-8.

Folland, J. P, Irish, C & Roberts, JC et al. 2002 Fatigue is not a necessary stimulus for strength gains during resistance training. *British Journal of Sports Medicine*, 36, 370-373.

Folland, J. P. & Williams, A. G. 2007. The adaptations to strength training: morphological and neurological contributions to increased strength. *Sports Med,* 37**,** 145-68.

Foster, C. 1998. Monitoring training in athletes with reference to overtraining syndrome. *Medicine and science in sports and exercise,* 30**,** 1164-1168.

Freitas, T. T., Calleja-González, J., Alarcón, F. & Alcaraz, P. E. 2016. Acute Effects of Two Different Resistance Circuit Training Protocols on Performance and Perceived Exertion in Semiprofessional Basketball Players. *The Journal of Strength & Conditioning Research,* 30**,** 407-414.

Fukashiro, S., Besier, T. F., Barrett, R., Cochrane, J., Nagano, A. & Lloyd, D. G. 2005. Direction control in standing horizontal and vertical jumps. *International Journal of Sport and Health Science,* 3**,** 272-279.

Fyfe, J. J., Bishop, D. J. & Stepto, N. K. 2014. Interference between Concurrent Resistance and Endurance Exercise: Molecular Bases and the Role of Individual Training Variables. *Sports Medicine,* 44**,** 743-762.

Gabbett, T. J. & Seibold, A. J. 2013. Relationship Between Tests of Physical Qualities, Team Selection, and Physical Match Performance in Semiprofessional Rugby League Players. *The Journal of Strength & Conditioning Research,* 27**,** 3259-3265.

Gabbett, T. J., Polley, C., Dwyer, D. B., Kearney, S. & Corvo, A. 2014. Influence of field position and phase of play on the physical demands of match-play in professional rugby league forwards. *Journal of Science and Medicine in Sport,* 17**,** 556-561.

Gale, C. R., Martyn, C. N., Cooper, C. & Sayer, A. A. 2007. Grip strength, body composition, and mortality. *Int J Epidemiol,* 36**,** 228-35.

Garber, C. E., Blissmer, B., Deschenes, M. R., Franklin, B. A., Lamonte, M. J., Lee, I.-M., Nieman, D. C. & Swain, D. P. 2011. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise.

García-Hermoso, A., Ramírez-Vélez, R., Ramírez-Campillo, R., Peterson, M. D. & Martínez-Vizcaíno, V. 2018. Concurrent aerobic plus resistance exercise versus aerobic exercise alone to improve health outcomes in paediatric obesity: a systematic review and meta-analysis. *British Journal of Sports Medicine,* 52**,** 161-166.

García-Pinillos, F., Lago-Fuentes, C., Jaén-Carrillo, D., Bujalance-Moreno, P., Latorre-Román, P. Á., Roche-Seruendo, L. E. & Ramirez-Campillo, R. 2020. Strength Training Habits in Amateur Endurance Runners in Spain: Influence of Athletic Level. *International journal of environmental research and public health,* 17**,** 8184.

Gelman, R., Berg, M. & Ilan, Y. 2022. A Subject-Tailored Variability-Based Platform for Overcoming the Plateau Effect in Sports Training: A Narrative Review. *International journal of environmental research and public health,* 19**,** 1722.

Gettman, L. R., Pollock, M. L., Durstine, J. L., Ward, A., Ayres, J. & Linnerud, A. C. 1976. Physiological Responses of Men to 1, 3, and 5 Day per Week Training Programs. *Research Quarterly. American Alliance for Health, Physical Education and Recreation,* 47**,** 638-646.

Gettman, L. R., Ward, P. & Hagan, R. D. 1982. A comparison of combined running and weight training with circuit weight training. *Medicine & Science in Sports & Exercise,* 14**,** 229-234.

Gibala, M. J., Mcgee, S. L., Garnham, A. P., Howlett, K. F., Snow, R. J. & Hargreaves, M. 2009. Brief intense interval exercise activates AMPK and p38 MAPK signalling and increases the expression of PGC-1α in human skeletal muscle. *Journal of Applied Physiology,* 106**,** 929-934.

Glaister, M. 2005. Multiple sprint work: physiological responses, mechanisms of fatigue and the influence of aerobic fitness. *Sports Med,* 35**,** 757-77.

Gleeson, M., Bishop, N., Oliveira, M., Mccauley, T., Tauler, P. & Muhamad, A. S. 2012. Respiratory infection risk in athletes: association with antigen-stimulated IL-10 production and salivary IgA secretion. *Scand J Med Sci Sports,* 22**,** 410-7.

Goodman, C. A. 2019. Role of mTORC1 in mechanically induced increases in translation and skeletal muscle mass. *Journal of Applied Physiology,* 127**,** 581-590.

Gotshalk, L. A., Berger, R. A. & Kraemer, W. J. 2004. Cardiovascular responses to a high-volume continuous circuit resistance training protocol. *Journal of Strength and Conditioning Research,* 18**,** 760-764.

Grgic, J. & Mikulic, P. 2017. Caffeine ingestion acutely enhances muscular strength and power but not muscular endurance in resistance-trained men. *European Journal of Sport Science,* 17**,** 1029-1036.

Grgic, J., Schoenfeld, B. J., Orazem, J. & Sabol, F. 2022. Effects of resistance training performed to repetition failure or non-failure on muscular strength and hypertrophy: A systematic review and meta-analysis. *Journal of Sport and Health Science,* 11**,** 202-211.

Haddock, C. K., Poston, W. S. C., Heinrich, K. M., Jahnke, S. A. & Jitnarin, N. 2016. The Benefits of High-Intensity Functional Training Fitness Programs for Military Personnel. *Military Medicine,* 181**,** e1508-e1514.

Haennel, R., Teo, K. K., Quinney, A. & Kappagoda, T. 1989. Effects of hydraulic circuit training on cardiovascular function. *Med Sci Sports Exerc,* 21**,** 605-12.

Häkkinen, K. & Komi, P. V. 1983. Electromyographic changes during strength training and detraining. *Med Sci Sports Exerc,* 15**,** 455-60.

Häkkinen, K., Alen, M., Kraemer, W. J., Gorostiaga, E., Izquierdo, M., Rusko, H., Mikkola, J., Häkkinen, A., Valkeinen, H., Kaarakainen, E., Romu, S., Erola, V., Ahtiainen, J. & Paavolainen, L. 2003. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol,* 89**,** 42-52.

Halson, S. L. 2014. Monitoring training load to understand fatigue in athletes. *Sports medicine (Auckland, N.Z.),* 44 Suppl 2**,** S139-S147.

Harber, M. P., Fry, A. C., Rubin, M. R., Smith, J. C. & Weiss, L. W. 2004. Skeletal muscle and hormonal adaptations to circuit weight training in untrained men. *Scandinavian Journal of Medicine & Science in Sports,* 14**,** 176-185.

Haun, C. T., Mumford, P. W., Roberson, P. A., Romero, M. A., Mobley, C. B., Kephart, W. C., Anderson, R. G., Colquhoun, R. J., Muddle, T. W. D., Luera, M. J., Mackey, C. S., Pascoe, D. D., Young, K. C., Martin, J. S., Defreitas, J. M., Jenkins, N. D. M. & Roberts, M. D. 2017. Molecular, neuromuscular, and recovery responses to light versus heavy resistance exercise in young men. *Physiological Reports,* 5**,** e13457.

Hawley, J. A. 2002. Adaptations Of Skeletal Muscle To Prolonged, Intense Endurance Training. *Clinical and Experimental Pharmacology and Physiology,* 29**,** 218-222.

Heinrich, K. M., Spencer, V., Fehl, N. & Carlos Poston, W. S. 2012. Mission Essential Fitness: Comparison of Functional Circuit Training to Traditional Army Physical Training for Active Duty Military. *Military Medicine,* 177**,** 1125-1130.

Heinrich, K. M., Becker, C., Carlisle, T., Gilmore, K., Hauser, J., Frye, J. & Harms, C. A. 2015. High-intensity functional training improves functional movement and body composition among cancer survivors: a pilot study. *Eur J Cancer Care (Engl),* 24**,** 812-7.

Henneman, E., Somjen, G. & Carpenter, D. O. 1965. Functional Significance Of Cell Size In Spinal Motoneurons. *J Neurophysiol,* 28**,** 560-80.

Hermassi, S., Wollny, R., Schwesig, R., Shephard, R. J. & Chelly, M. S. 2019. Effects of In-Season Circuit Training on Physical Abilities in Male Handball Players. *The Journal of Strength & Conditioning Research,* 33**,** 944-957.

Hermassi, S., Laudner, K. & Schwesig, R. 2020. The Effects of Circuit Strength Training on the Development of Physical Fitness and Performance-Related Variables in Handball Players. *J Hum Kinet,* 71**,** 191-203.

Hickson, R. C. 1980. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol Occup Physiol,* 45**,** 255-63.

Higginbotham, M. B., Morris, K. G., Williams, R. S., Mchale, P. A., Coleman, R. E. & Cobb, F. R. 1986. Regulation of stroke volume during submaximal and maximal upright exercise in normal man. *Circulation Research,* 58**,** 281-291.

Hiscock, D. J., Dawson, B., Clarke, M. & Peeling, P. 2018. Can changes in resistance exercise workload influence internal load, countermovement jump performance and the endocrine response? *Journal of Sports Sciences,* 36**,** 191-197.

Holloszy, J. O. 1967. Biochemical adaptations in muscle. Effects of exercise on mitochondrial oxygen uptake and respiratory enzyme activity in skeletal muscle. *J Biol Chem,* 242**,** 2278-82.

Holm, L., Reitelseder, S., Pedersen, T. G., Doessing, S., Petersen, S. G., Flyvbjerg, A., Andersen, J. L., Aagaard, P. & Kjaer, M. 2008. Changes in muscle size and MHC composition in response to resistance exercise with heavy and light loading intensity. *Journal of Applied Physiology,* 105**,** 1454-1461.

Hood, D. A., Takahashi, M., Connor, M. K. & Freyssenet, D. 2000. Assembly of the cellular powerhouse: current issues in muscle mitochondrial biogenesis. *Exercise and sport sciences reviews,* 28**,** 68-73.

Hooper, S. L., Mackinnon, L. T., Howard, A., Gordon, R. D. & Bachmann, A. W. 1995. Markers for monitoring overtraining and recovery. *Medicine & Science in Sports & Exercise,* 27**,** 106-112.

Hulin, B. T., Gabbett, T. J., Blanch, P., Chapman, P., Bailey, D. & Orchard, J. W. 2014. Spikes in acute workload are associated with increased injury risk in elite cricket fast bowlers. *British Journal of Sports Medicine,* 48**,** 708-712.

Hurley, B. F., Seals, D. R., Ehsani, A. A., Cartier, L.-J., Dalsky, G. P., Hagberg, J. M. & Holloszy, J. O. 1984. Effects of high-intensity strength training on cardiovascular function. *Medicine & Science in Sports & Exercise,* 16**,** 483-488.

Impellizzeri, F. M., Rampinini, E., Coutts, A. J., Sassi, A. & Marcora, S. M. 2004. Use of RPE-based training load in soccer. *Medicine & Science in Sports & Exercise,* 36**,** 1042-1047.

Jarani, J., Grøntved, A., Muca, F., Spahi, A., Qefalia, D., Ushtelenca, K., Kasa, A., Caporossi, D. & Gallotta, M. C. 2016. Effects of two physical education programmes on health- and skill-related physical fitness of Albanian children. *J Sports Sci,* 34**,** 35-46.

Jenkins, N. D. M., Miramonti, A. A., Hill, E. C., Smith, C. M., Cochrane-Snyman, K. C., Housh, T. J. & Cramer, J. T. 2017. Greater Neural Adaptations following High- vs. Low-Load Resistance Training. *Frontiers in Physiology,* 8.

Jovanovic, M (2014). *How to Create Individualized Exercise Profile in Strength Training?* Available at: https://complementarytraining.net/how-to-create-individualized-exercise-profile-in-strength-training-part-4-velocityexertion-profile/

Jurca, R., Lamonte, M. J., Barlow, C. E., Kampert, J. B., Church, T. S. & Blair, S. N. 2005. Association of muscular strength with incidence of metabolic syndrome in men. *Medicine and science in sports and exercise,* 37**,** 1849.

Kang, J., Hoffman, J. R., Im, J., Spiering, B. A., Ratamess, N. A., Rundell, K. W., Nioka, S., Cooper, J. & Chance, B. 2005. Evaluation Of Physiological Responses During

Recovery Following Three Resistance Exercise Programs. *The Journal of Strength & Conditioning Research,* 19**,** 305-309.

Kapsis, D. P., Tsoukos, A., Psarraki, M. P., Douda, H. T., Smilios, I. & Bogdanis, G. C. 2022. Changes in Body Composition and Strength after 12 Weeks of High-Intensity Functional Training with Two Different Loads in Physically Active Men and Women: A Randomized Controlled Study. *Sports (Basel, Switzerland),* 10.

Kjølhede, T., Vissing, K., De Place, L., Pedersen, B. G., Ringgaard, S., Stenager, E., Petersen, T. & Dalgas, U. 2015. Neuromuscular adaptations to long-term progressive resistance training translates to improved functional capacity for people with multiple sclerosis and is maintained at follow-up. *Mult Scler,* 21**,** 599-611.

Kosek, D. J., Kim, J. S., Petrella, J. K., Cross, J. M. & Bamman, M. M. 2006. Efficacy of 3 days/wk resistance training on myofiber hypertrophy and myogenic mechanisms in young vs. older adults. *J Appl Physiol (1985),* 101**,** 531-44.

Kraemer, W. J. & Ratamess, N. A. 2004. Fundamentals of Resistance Training: Progression and Exercise Prescription. *Medicine & Science in Sports & Exercise,* 36**,** 674-688.

Kramer, A. F. & Colcombe, S. 2018. Fitness Effects on the Cognitive Function of Older Adults: A Meta-Analytic Study-Revisited. *Perspect Psychol Sci,* 13**,** 213-217.

Krieger, J. W. 2009. Single Versus Multiple Sets of Resistance Exercise: A Meta-Regression. *The Journal of Strength & Conditioning Research,* 23**,** 1890-1901.

Krustrup, P., Mohr, M., Steensberg, A., Bencke, J., Kjaer, M. & Bangsbo, J. 2006. Muscle and blood metabolites during a soccer game: implications for sprint performance. *Med Sci Sports Exerc,* 38**,** 1165-74.

Kulig, K., Andrews, J. G. & Hay, J. G. 1984. Human Strength Curves. *Exercise and sport sciences reviews,* 12**,** 417-466.

La Gerche, A., Burns, A. T., Taylor, A. J., Macisaac, A. I., Heidbüchel, H. & Prior, D. L. 2012. Maximal oxygen consumption is best predicted by measures of cardiac size rather than function in healthy adults. *European Journal of Applied Physiology,* 112**,** 2139-2147.

La Torre, A., Vernillo, G., Fiorella, P., Mauri, C. & Agnello, L. 2009. Combined endurance and resistance circuit training in highly trained/ top-level female race walkers: A case report. *Sport Sciences for Health,* 4**,** 51-58.

Lacerda, L. T., Martins-Costa, H. C., Diniz, R. C., Lima, F. V., Andrade, A. G., Tourino, F. D., Bemben, M. G. & Chagas, M. H. 2016. Variations in Repetition Duration and Repetition Numbers Influence Muscular Activation and Blood Lactate Response in Protocols Equalized by Time Under Tension. *J Strength Cond Res,* 30**,** 251-8.

Lagally, K. M., Robertson, R. J., Gallagher, K. I., Goss, F. L., Jakicic, J. M., Lephart, S. M., Mccaw, S. T. & Goodpaster, B. 2002. Perceived exertion, electromyography, and blood lactate during acute bouts of resistance exercise. *Med Sci Sports Exerc,* 34**,** 552-9; discussion 560.

Lamb, D. R. 1984. *Physiology of Exercise: Responses & Adaptations*, Macmillan.

Lauersen, J. B., Bertelsen, D. M. & Andersen, L. B. 2014. The effectiveness of exercise interventions to prevent sports injuries: a systematic review and meta-analysis of randomised controlled trials. *Br J Sports Med,* 48**,** 871-7.

Laursen, P. B., Shing, C. M., Peake, J. M., Coombes, J. S. & Jenkins, D. G. 2002. Interval training program optimization in highly trained endurance cyclists. *Medicine and science in sports and exercise,* 34**,** 1801-1807.

Laursen, P. B. 2010. Training for intense exercise performance: high-intensity or high-volume training? *Scandinavian Journal of Medicine & Science in Sports,* 20**,** 1-10.

Lin, J., Wu, H., Tarr, P. T., Zhang, C.-Y., Wu, Z., Boss, O., Michael, L. F., Puigserver, P., Isotani, E., Olson, E. N., Lowell, B. B., Bassel-Duby, R. & Spiegelman, B. M. 2002. Transcriptional co-activator PGC-1α drives the formation of slow-twitch muscle fibres. *Nature,* 418**,** 797-801.

Londeree, B. R. & Moeschberger, M. L. 1982. Effect of Age and Other Factors on Maximal Heart Rate. *Research Quarterly for Exercise and Sport,* 53**,** 297-304.

Longo, A. R., Silva-Batista, C., Pedroso, K., De Salles Painelli, V., Lasevicius, T., Schoenfeld, B. J., Aihara, A. Y., De Almeida Peres, B., Tricoli, V. & Teixeira, E. L. 2022. Volume Load Rather Than Resting Interval Influences Muscle Hypertrophy During High-Intensity Resistance Training. *The Journal of Strength & Conditioning Research,* 36**,** 1554-1559.

Loturco, I., Pereira, L. A., Cal Abad, C. C., Gil, S., Kitamura, K., Kobal, R. & Nakamura, F. Y. 2016. Using Bar Velocity to Predict the Maximum Dynamic Strength in the Half-Squat Exercise. *Int J Sports Physiol Perform,* 11**,** 697-700.

Lundberg, T. R., Fernandez-Gonzalo, R., Gustafsson, T. & Tesch, P. A. 2012. Aerobic exercise alters skeletal muscle molecular responses to resistance exercise. *Med Sci Sports Exerc,* 44**,** 1680-8.

MacAuley, D (2012). *Oxford Handbook of Sport and Exercise Medicine*, Oxford University Press.

Macdougall, J. D., Ward, G. R., Sale, D. G. & Sutton, J. R. 1977. Biochemical adaptation of human skeletal muscle to heavy resistance training and immobilization. *J Appl Physiol Respir Environ Exerc Physiol,* 43**,** 700-3.

Macdougall, J. D., Hicks, A. L., Macdonald, J. R., Mckelvie, R. S., Green, H. J. & Smith, K. M. 1998. Muscle performance and enzymatic adaptations to sprint interval training. *Journal of Applied Physiology,* 84**,** 2138-2142.

Marín-Pagán, C., Blazevich, A. J., Chung, L. H., Romero-Arenas, S., Freitas, T. T. & Alcaraz, P. E. 2020. Acute Physiological Responses to High-Intensity Resistance Circuit Training vs. Traditional Strength Training in Soccer Players. *Biology,* 9**,** 383.

Márquez, G., Romero-Arenas, S., Marín-Pagán, C., Vera-Ibañez, A., Fernández Del Olmo, M. & Taube, W. 2017. Peripheral and central fatigue after high intensity resistance circuit training. *Muscle & Nerve,* 56**,** 152-159.

Marshall, P. W. M., Mcewen, M. & Robbins, D. W. 2011. Strength and neuromuscular adaptation following one, four, and eight sets of high intensity resistance exercise in trained males. *European Journal of Applied Physiology,* 111**,** 3007-3016.

Martínez-Guardado, I., Ramos-Campo, D. J., Olcina, G. J., Rubio-Arias, J. A., Chung, L. H., Marín-Cascales, E., Alcaraz, P. E. & Timón, R. 2019. Effects of high-intensity resistance circuit-based training in hypoxia on body composition and strength performance. *European Journal of Sport Science,* 19**,** 941-951.

Mason, J. E. & Asmundson, G. J. 2018. A single bout of either sprint interval training or moderate intensity continuous training reduces anxiety sensitivity: A randomized controlled trial. *Mental Health and Physical Activity,* 14**,** 103-112.

Matos, N. F., Winsley, R. J. & Williams, C. A. 2011. Prevalence of nonfunctional overreaching/overtraining in young English athletes. *Med Sci Sports Exerc,* 43**,** 1287-1294.

Mattocks, K. T., Buckner, S. L., Jessee, M. B., Dankel, S. J., Mouser, J. G. & Loenneke, J. P. 2017. Practicing the Test Produces Strength Equivalent to Higher Volume Training. *Medicine and science in sports and exercise,* 49**,** 1945-1954.

Mccarthy, J. P., Pozniak, M. A. & Agre, J. C. 2002. Neuromuscular adaptations to concurrent strength and endurance training. *Med Sci Sports Exerc,* 34**,** 511-9.

Mccormack, S., Jones, B. & Till, K. 2020. Training Practices of Academy Rugby League and their Alignment to Physical Qualities Deemed Important for Current and Future Performance. *International Journal of Sports Science & Coaching,* 15**,** 512-525.

Mclaren, S., Smith, A., Spears, I. & Weston, M. 2016. A detailed quantification of differential ratings of perceived exertion during team-sport training. *Journal of Science and Medicine in Sport,* 20.

Mclaughlin, J. E., Howley, E. T., Bassett, D. R. J., Thompson, D. L. & Fitzhugh, E. C. 2010. Test of the Classic Model for Predicting Endurance Running Performance. *Medicine & Science in Sports & Exercise,* 42**,** 991-997.

Mcnicol, A. J., O'brien, B. J., Paton, C. D. & Knez, W. L. 2009. The effects of increased absolute training intensity on adaptations to endurance exercise training. *Journal of Science and Medicine in Sport,* 12**,** 485-489.

Medbø, J. & Tabata, I. 1989. Relative importance of aerobic and anaerobic energy release during short-lasting bicycle exercise. *Journal of applied physiology (Bethesda, Md. : 1985),* 67**,** 1881-6.

Medbø, J. I. & Tabata, I. 1993. Anaerobic energy release in working muscle during 30 s to 3 min of exhausting bicycling. *J Appl Physiol (1985),* 75**,** 1654-60.

Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D., Raglin, J., Rietjens, G., Steinacker, J. & Urhausen, A. 2013. Prevention, diagnosis, and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. *Med Sci Sports Exerc,* 45**,** 186-205.

Menz, V., Marterer, N., Amin, S., Faulhaber, M., Hansen, A. & Lawley, J. 2019. Functional Vs. Running Low-Volume High-Intensity Interval Training: Effects on VO2max and Muscular Endurance. *Journal of sports science & medicine***,** 497-504.

Midgley, A. W., Mcnaughton, L. R. & Wilkinson, M. 2006. Is there an optimal training intensity for enhancing the maximal oxygen uptake of distance runners?: empirical research findings, current opinions, physiological rationale and practical recommendations. *Sports Med,* 36**,** 117-32.

Millet, G. P., Jaouen, B., Borrani, F. & Candau, R. 2002. Effects of concurrent endurance and strength training on running economy and VO(2) kinetics. *Med Sci Sports Exerc,* 34**,** 1351-9.

Mitchell, C. J., Churchward-Venne, T. A., West, D. W., Burd, N. A., Breen, L., Baker, S. K. & Phillips, S. M. 2012. Resistance exercise load does not determine training-mediated hypertrophic gains in young men. *Journal of Applied Physiology,* 113**,** 71-77.

Montero, D., Cathomen, A., Jacobs, R. A., Flück, D., De Leur, J., Keiser, S., Bonne, T., Kirk, N., Lundby, A. K. & Lundby, C. 2015. Haematological rather than skeletal muscle adaptations contribute to the increase in peak oxygen uptake induced by moderate endurance training. *The Journal of physiology,* 593**,** 4677-88.

Montes, J. & Navalta, J. W. 2019. Reliability of the Polar T31 Uncoded Heart Rate Monitor in Free Motion and Treadmill Activities. *Int J Exerc Sci,* 12**,** 69-76.

Morgan, W. P. 1994. Psychological components of effort sense. *Medicine & Science in Sports & Exercise,* 26**,** 1071-1077.

Morrissey, M. C., Harman, E. A. & Johnson, M. J. 1995. Resistance training modes: specificity and effectiveness. *Medicine and science in sports and exercise,* 27**,** 648-660.

Morton, R. W., Sonne, M. W., Farias Zuniga, A., Mohammad, I. Y. Z., Jones, A., Mcglory, C., Keir, P. J., Potvin, J. R. & Phillips, S. M. 2019. Muscle fibre activation is unaffected by load and repetition duration when resistance exercise is performed to task failure. *The Journal of physiology,* 597**,** 4601-4613.

Mujika, I. & Padilla, S. 2000. Detraining: Loss of Training-Induced Physiological and Performance Adaptations. Part I. *Sports Medicine,* 30**,** 79-87.

Muñoz-Martínez, F. A., Rubio-Arias, J. Á., Ramos-Campo, D. J. & Alcaraz, P. E. 2017. Effectiveness of Resistance Circuit-Based Training for Maximum Oxygen Uptake and Upper-Body One-Repetition Maximum Improvements: A Systematic Review and Meta-Analysis. *Sports Medicine,* 47**,** 2553-2568.

Murawska-Cialowicz, E., Wojna, J. & Zuwala-Jagiello, J. 2015. Crossfit training changes brain-derived neurotrophic factor and irisin levels at rest, after wingate and progressive tests, and improves aerobic capacity and body composition of young physically active men and women. *J Physiol Pharmacol,* 66**,** 811-821.

Myers, T. R., Schneider, M. G., Schmale, M. S. & Hazell, T. J. 2015. Whole-body aerobic resistance training circuit improves aerobic fitness and muscle strength in sedentary young females. *J Strength Cond Res,* 29**,** 1592-600.

Nevill, M. E., Boobis, L. H., Brooks, S. & Williams, C. 1989. Effect of training on muscle metabolism during treadmill sprinting. *Journal of Applied Physiology,* 67**,** 2376-2382.

Newman, A. B., Kupelian, V., Visser, M., Simonsick, E. M., Goodpaster, B. H., Kritchevsky, S. B., Tylavsky, F. A., Rubin, S. M. & Harris, T. B. 2006. Strength, but not muscle mass, is associated with mortality in the health, aging and body composition study cohort. *J Gerontol A Biol Sci Med Sci,* 61**,** 72-7.

NHS Digital (2022). Health Survey for England, 2021 part 1. Available at: https://digital.nhs.uk/data-and-information/publications/statistical/health-survey-for-england/2021#chapter-index

Nowotny, B., Nowotny, P. J., Strassburger, K. & Roden, M. 2012. Precision and accuracy of blood glucose measurements using three different instruments. *Diabetic Medicine,* 29**,** 260-265.

O'Connor, H., Olds, T. & Maughan, R. J. 2007. Physique and performance for track and field events. *Journal of Sports Sciences,* 25**,** S49-S60.

Office for Health Improvement and Disparities (2022) Physical activity: Applying all our health. Available at: https://www.gov.uk/government/publications/physical-activity-applying-all-our-health/physical-activity-applying-all-our-health

Ogasawara, R., Loenneke, J. P., Thiebaud, R. S. & Abe, T. 2013. Low-load bench press training to fatigue results in muscle hypertrophy similar to high-load bench press training. *International Journal of Clinical Medicine,* 4**,** 114.

Ogasawara, R., Fujita, S., Hornberger, T. A., Kitaoka, Y., Makanae, Y., Nakazato, K. & Naokata, I. 2016. The role of mTOR signalling in the regulation of skeletal muscle mass in a rodent model of resistance exercise. *Scientific reports,* 6**,** 31142-31142.

Ogasawara, R., Jensen, T. E., Goodman, C. A. & Hornberger, T. A. 2019. Resistance Exercise-Induced Hypertrophy: A Potential Role for Rapamycin-Insensitive mTOR. *Exercise and sport sciences reviews,* 47**,** 188-194.

Ostrowski, K. J., Wilson, G. J., Weatherby, R., Murphy, P. W. & Lyttle, A. D. 1997. The effect of weight training volume on hormonal output and muscular size and function. *Journal of Strength and Conditioning Research,* 11**,** 148-154.

Pandolf, K. B. 1982. Differentiated ratings of perceived exertion during physical exercise. *Medicine & Science in Sports & Exercise,* 14**,** 397-405.

Paoli, A., Pacelli, F., Bargossi, A. M., Marcolin, G., Guzzinati, S., Neri, M., Bianco, A. & Palma, A. 2010. Effects of three distinct protocols of fitness training on body composition, strength and blood lactate. *J Sports Med Phys Fitness,* 50**,** 43-51.

Paoli, A., Moro, T., Marcolin, G., Neri, M., Bianco, A., Palma, A. & Grimaldi, K. 2012. High-Intensity Interval Resistance Training (HIRT) influences resting energy expenditure and respiratory ratio in non-dieting individuals. *Journal of Translational Medicine,* 10**,** 237.

Paoli, A., Gentil, P., Moro, T., Marcolin, G. & Bianco, A. 2017. Resistance Training with Single vs. Multi-joint Exercises at Equal Total Load Volume: Effects on Body Composition, Cardiorespiratory Fitness, and Muscle Strength. *Frontiers in Physiology,* 8.

Pareja-Blanco, F., Rodríguez-Rosell, D., Aagaard, P., Sánchez-Medina, L., Ribas-Serna, J., Mora-Custodio, R., Otero-Esquina, C., Yáñez-García, J. M. & González-Badillo, J. J. 2020. Time Course of Recovery From Resistance Exercise With Different Set Configurations. *The Journal of Strength & Conditioning Research,* 34**,** 2867-2876.

Pearcey, G. E. P., Bradbury-Squires, D. J., Kawamoto, J.-E., Drinkwater, E. J., Behm, D. G. & Button, D. C. 2015a. Foam Rolling for Delayed-Onset Muscle Soreness and Recovery of Dynamic Performance Measures. *Journal of Athletic Training,* 50**,** 5-13.

Pearcey, G. E. P., Murphy, J. R., Behm, D. G., Hay, D. C., Power, K. E. & Button, D. C. 2015b. Neuromuscular fatigue of the knee extensors during repeated maximal intensity intermittent-sprints on a cycle ergometer. *Muscle & Nerve,* 51**,** 569-579.

Perciavalle, V., Marchetta, N. S., Giustiniani, S., Borbone, C., Perciavalle, V., Petralia, M. C., Buscemi, A. & Coco, M. 2016. Attentive processes, blood lactate and CrossFit(®). *Phys Sportsmed,* 44**,** 403-406.

Petersen, S. R., Miller, G. D., Quinney, H. A. & Wenger, H. A. 1988. The Influence of High-Velocity Resistance Circuit Training on Aerobic Power. *Journal of Orthopaedic & Sports Physical Therapy,* 9**,** 339-344.

Petersen, S. R., Haennel, R. G., Kappagoda, C. T., Belcastro, A. N., Reid, D. C., Wenger, H. A. & Quinney, H. A. 1989. The influence of high-velocity circuit resistance training on VO2max and cardiac output. *Can J Sport Sci,* 14**,** 158-63.

Peterson, M. D., Rhea, M. R. & Alvar, B. A. 2004. Maximizing strength development in athletes: a meta-analysis to determine the dose-response relationship. *J Strength Cond Res,* 18**,** 377-82.

Pilegaard, H., Juel, C. & Wibrand, F. 1993. Lactate transport studied in sarcolemmal giant vesicles from rats: effect of training. *American Journal of Physiology-Endocrinology and Metabolism,* 264**,** E156-E160.

Pilegaard, H., Domino, K., Noland, T., Juel, C., Hellsten, Y., Halestrap, A. P. & Bangsbo, J. 1999. Effect of high-intensity exercise training on lactate/H+ transport capacity in human skeletal muscle. *American Journal of Physiology-Endocrinology and Metabolism,* 276**,** E255-E261.

Piras, A., Persiani, M., Damiani, N., Perazzolo, M. & Raffi, M. 2015. Peripheral heart action (PHA) training as a valid substitute to high intensity interval training to improve resting cardiovascular changes and autonomic adaptation. *European Journal of Applied Physiology,* 115**,** 763-773.

Pollock, M., Gaesser, G., Butcher, J., Després, J.-P., Dishman, R., Franklin, B. & Garber, C. 1998. ACSM Position Stand: The Recommended Quantity and Quality of Exercise for Developing and Maintaining Cardiorespiratory and Muscular Fitness, and Flexibility in Healthy Adults. *Medicine & Science in Sports & Exercise,* 30**,** 975-991.

Pollock, S., Gaoua, N., Johnston, M. J., Cooke, K., Girard, O. & Mileva, K. N. 2019. Training Regimes and Recovery Monitoring Practices of Elite British Swimmers. *Journal of sports science & medicine,* 18**,** 577-585.

Putlur, P., Foster, C., Miskowski, J. A., Kane, M. K., Burton, S. E., Scheett, T. P. & Mcguigan, M. R. 2004. Alteration of immune function in women collegiate soccer players and college students. *Journal of sports science & medicine,* 3**,** 234-43.

Rabbani, A., Clemente, F. M., Kargarfard, M. & Chamari, K. 2019. Match Fatigue Time-Course Assessment Over Four Days: Usefulness of the Hooper Index and Heart Rate Variability in Professional Soccer Players. *Frontiers in Physiology,* 10.

Radespiel-Tröger, M., Rauh, R., Mahlke, C., Gottschalk, T. & Mück-Weymann, M. 2003. Agreement of two different methods for measurement of heart rate variability. *Clin Auton Res,* 13**,** 99-102.

Rally Fitness (2017) The business of CrossFit: An update on new market research. Available at: https://rallyfitness.com/blogs/news/the-business-of-crossfit-an-update-on-new-market-research-2017

Ralston, G. W., Kilgore, L., Wyatt, F. B. & Baker, J. S. 2017. The Effect of Weekly Set Volume on Strength Gain: A Meta-Analysis. *Sports Med,* 47**,** 2585-2601.

Ramos-Campo, D. J., Andreu Caravaca, L., Martínez-Rodríguez, A. & Rubio-Arias, J. Á. 2021. Effects of Resistance Circuit-Based Training on Body Composition, Strength and Cardiorespiratory Fitness: A Systematic Review and Meta-Analysis. *Biology,* 10**,** 377.

Ratkevičius, A., Skurvydas, A., Povilonis, E., Quistorff, B. & Lexell, J. 1998. Effects of contraction duration on low-frequency fatigue in voluntary and electrically induced exercise of quadriceps muscle in humans. *European Journal of Applied Physiology and Occupational Physiology,* 77**,** 462-468.

Reggiani, C. & Schiaffino, S. 2020. Muscle hypertrophy and muscle strength: dependent or independent variables? A provocative review. *Eur J Transl Myol,* 30**,** 9311.

Rhea, M. R. & Alderman, B. L. 2004. A Meta-Analysis of Periodized versus Nonperiodized Strength and Power Training Programs. *Research Quarterly for Exercise and Sport,* 75**,** 413-422.

Roberson, K. B., Chowdhari, S. S., White, M. J. & Signorile, J. F. 2017. Loads and Movement Speeds Dictate Differences in Power Output During Circuit Training. *The Journal of Strength & Conditioning Research,* 31**,** 2765-2776.

Rodas, G., Ventura, J. L., Cadefau, J. A., Cussó, R. & Parra, J. 2000. A short training programme for the rapid improvement of both aerobic and anaerobic metabolism. *European Journal of Applied Physiology,* 82**,** 480-486.

Romero-Arenas, S., Ruiz, R., Vera-Ibáñez, A., Colomer-Poveda, D., Guadalupe-Grau, A. & Márquez, G. 2018. Neuromuscular and Cardiovascular Adaptations in Response to High-Intensity Interval Power Training. *The Journal of Strength & Conditioning Research,* 32**,** 130-138.

Rose, A. J., Frøsig, C., Kiens, B., Wojtaszewski, J. F. & Richter, E. A. 2007. Effect of endurance exercise training on Ca2+–calmodulin-dependent protein kinase II expression and signalling in skeletal muscle of humans. *The Journal of physiology,* 583**,** 785-795.

Rowell, A. E., Aughey, R. J., Clubb, J. & Cormack, S. J. 2018. A Standardized Small Sided Game Can Be Used to Monitor Neuromuscular Fatigue in Professional A-League Football Players. *Front Physiol,* 9**,** 1011.

Rowland, T. W. 2005. Circulatory Responses to Exercise: Are We Misreading Fick? *Chest,* 127**,** 1023-1030.

Rowland, T. 2009. Endurance Athletes' Stroke Volume Response to Progressive Exercise. *Sports Medicine,* 39**,** 687-695.

Russell, M., Sparkes, W., Northeast, J., Cook, C. J., Bracken, R. M. & Kilduff, L. P. 2016. Relationships between match activities and peak power output and Creatine Kinase responses to professional reserve team soccer match-play. *Human Movement Science,* 45**,** 96-101.

Sale, D. G. 1988. Neural adaptation to resistance training. *Medicine & Science in Sports & Exercise,* 20**,** S135-S145.

Salvadori, A., Fanari, P., Marzullo, P., Codecasa, F., Tovaglieri, I., Cornacchia, M., Brunani, A., Luzi, L. & Longhini, E. 2014. Short bouts of anaerobic exercise increase non-esterified fatty acids release in obesity. *Eur J Nutr,* 53**,** 243-9.

Schmikli, S. L., Brink, M., De Vries, W. & Backx, F. 2011. Can we detect non-functional overreaching in young elite soccer players and middle-long distance runners using field performance tests? *British Journal of Sports Medicine,* 45**,** 631-636.

Schoenfeld, B. J., Ogborn, D., Contreras, B., Cappaert, T., Silva Ribeiro, A., Alvar, B. A. & Vigotsky, A. D. 2016a. A Comparison of Increases in Volume Load Over 8 Weeks of Low-Versus High-Load Resistance Training. *Asian journal of sports medicine,* 7**,** e29247-e29247.

Schoenfeld, B. J., Pope, Z. K., Benik, F. M., Hester, G. M., Sellers, J., Nooner, J. L., Schnaiter, J. A., Bond-Williams, K. E., Carter, A. S., Ross, C. L., Just, B. L., Henselmans, M. & Krieger, J. W. 2016b. Longer Interset Rest Periods Enhance Muscle Strength and Hypertrophy in Resistance-Trained Men. *J Strength Cond Res,* 30**,** 1805-12.

Schoenfeld, B. J., Ogborn, D. & Krieger, J. W. 2017. Dose-response relationship between weekly resistance training volume and increases in muscle mass: A systematic review and meta-analysis. *Journal of Sports Sciences,* 35**,** 1073-1082.

Schoenfeld, B. J., Grgic, J., Ogborn, D. & Krieger, J. W. 2017. Strength and Hypertrophy Adaptations Between Low- vs. High-Load Resistance Training: A Systematic Review and Meta-analysis. *J Strength Cond Res,* 31**,** 3508-3523.

Scott, W., Stevens, J. & Binder–Macleod, S. A. 2001. Human Skeletal Muscle Fiber Type Classifications. *Physical Therapy,* 81**,** 1810-1816.

Seiler, K. S. & Kjerland, G. Ø. 2006. Quantifying training intensity distribution in elite endurance athletes: is there evidence for an “optimal” distribution? *Scandinavian Journal of Medicine & Science in Sports,* 16**,** 49-56.

Seipp, D., Quittmann, O. J., Fasold, F. & Klatt, S. 2022. Concurrent training in team sports: A systematic review. *International Journal of Sports Science & Coaching,* 0**,** 17479541221099846.

Seitz, L. B., Reyes, A., Tran, T. T., De Villarreal, E. S. & Haff, G. G. 2014. Increases in lower-body strength transfer positively to sprint performance: a systematic review with meta-analysis. *Sports Medicine,* 44**,** 1693-1702.

Selye, H. 1976. Forty years of stress research: principal remaining problems and misconceptions. *Canadian Medical Association journal,* 115**,** 53-56.

Sharp, T., Grandou, C., Coutts, A. J. & Wallace, L. 2022. The Effects of High-Intensity Multimodal Training in Apparently Healthy Populations: A Systematic Review. *Sports Med Open,* 8**,** 43.

Silliman, K., Rodas-Fortier, K. & Neyman, M. 2004. A Survey of Dietary and Exercise Habits and Perceived Barriers to Following a Healthy Lifestyle in a College Population. *Californian Journal of Health Promotion,* 2**,** 10-19.

Skidmore, B. L., Jones, M. T., Blegen, M. & Matthews, T. D. 2012. Acute effects of three different circuit weight training protocols on blood lactate, heart rate, and rating of perceived exertion in recreationally active women. *Journal of sports science & medicine,* 11**,** 660-8.

Skov-Ettrup, L., Petersen, C., Curtis, T., Lykke, M., Christensen, A. & Tolstrup, J. 2014. Why do people exercise? A cross-sectional study of motives to exercise among Danish adults. *Public health,* 128**,** 482-4.

Smith, J. C. & Hill, D. W. 1991. Contribution of energy systems during a Wingate power test. *British Journal of Sports Medicine,* 25**,** 196-199.

Srikanthan, P. & Karlamangla, A. S. 2011. Relative Muscle Mass Is Inversely Associated with Insulin Resistance and Prediabetes. Findings from The Third National Health and Nutrition Examination Survey. *The Journal of Clinical Endocrinology & Metabolism,* 96**,** 2898-2903.

Støren, O., Helgerud, J., Støa, E. M. & Hoff, J. 2008. Maximal strength training improves running economy in distance runners. *Med Sci Sports Exerc,* 40**,** 1087-92.

Stork, M. J., Banfield, L. E., Gibala, M. J. & Martin Ginis, K. A. 2017. A scoping review of the psychological responses to interval exercise: is interval exercise a viable alternative to traditional exercise? *Health Psychology Review,* 11**,** 324-344.

Stutts, W. C. 2002. Physical Activity Determinants in Adults:Perceived Benefits, Barriers, and Self Efficacy. *AAOHN Journal,* 50**,** 499-507.

Suchomel, T. J., Nimphius, S. & Stone, M. H. 2016. The Importance of Muscular Strength in Athletic Performance. *Sports Medicine,* 46**,** 1419-1449.

Sunde, A., Støren, Ø., Bjerkaas, M., Larsen, M. H., Hoff, J. & Helgerud, J. 2010. Maximal strength training improves cycling economy in competitive cyclists. *The Journal of Strength & Conditioning Research,* 24**,** 2157-2165.

Swain, D. P. 2005. Moderate or vigorous intensity exercise: which is better for improving aerobic fitness? *Prev Cardiol,* 8**,** 55-8.

Tanaka, H., Monahan, K. D. & Seals, D. R. 2001. Age-predicted maximal heart rate revisited. *J Am Coll Cardiol,* 37**,** 153-6.

Taylor, C., Sanders, R., Hoon, M., Starling, J. & Cobley, S. 2019. Can Sprint Interval Training (SIT) Improve the Psychological and Physiological Health of Adolescents with SMI? *Evidence-Based Practice in Child and Adolescent Mental Health,* 4**,** 219-234.

Temür, H., Vardar, S., Demir, A. M., Palabıyık, O., Karaca, A., Guksu, Z., Ortanca, A. & Süt, N. 2014. The alteration of NTproCNP plasma levels following anaerobic exercise in physically active young men. *Anadolu Kardiyoloji Dergisi/The Anatolian Journal of Cardiology,* 15.

Terzis, G., Spengos, K., Mascher, H., Georgiadis, G., Manta, P. & Blomstrand, E. 2010. The degree of p70S6k and S6 phosphorylation in human skeletal muscle in response to resistance exercise depends on the training volume. *European Journal of Applied Physiology,* 110**,** 835-843.

Thomas, C., Sirvent, P., Perrey, S., Raynaud, E. & Mercier, J. 2004. Relationships between maximal muscle oxidative capacity and blood lactate removal after supramaximal exercise and fatigue indexes in humans. *J Appl Physiol (1985),* 97**,** 2132-8.

Thomas, C., Jones, P. A., Rothwell, J., Chiang, C. Y. & Comfort, P. 2015. An investigation into the relationship between maximum isometric strength and vertical jump performance. *The Journal of Strength & Conditioning Research,* 29**,** 2176-2185.

Thompson, W. R. 2022. Worldwide Survey of Fitness Trends for 2022. *ACSM's Health & Fitness Journal,* 26**,** 11-20.

Tibana, R. A., De Sousa, N. M. F., Cunha, G. V., Prestes, J., Fett, C., Gabbett, T. J. & Voltarelli, F. A. 2018. Validity of Session Rating Perceived Exertion Method for Quantifying Internal Training Load during High-Intensity Functional Training. *Sports,* 6**,** 68.

Tibana, R. A., De Sousa, N. M. F., Prestes, J. & Voltarelli, F. A. 2018. Lactate, Heart Rate and Rating of Perceived Exertion Responses to Shorter and Longer Duration CrossFit® Training Sessions. *Journal of Functional Morphology and Kinesiology,* 3**,** 60.

Tran, J., Rice, A. J., Main, L. C. & Gastin, P. B. 2015. Profiling the Training Practices and Performance of Elite Rowers. *International Journal of Sports Physiology and Performance,* 10**,** 572-580.

Van Cutsem, M., Duchateau, J. & Hainaut, K. 1998. Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *The Journal of physiology,* 513**,** 295-305.

Vargas-Molina, S., Martín-Rivera, F., Bonilla, D. A., Petro, J. L., Carbone, L., Romance, R., Dediego, M., Schoenfeld, B. J. & Benítez-Porres, J. 2020. Comparison of blood lactate and perceived exertion responses in two matched time-under-tension protocols. *PLoS One,* 15**,** e0227640.

Vigil, J. N., Sabatini, P. L., Hill, L. C., Swain, D. P. & Branch, J. D. 2018. Ammonia Inhalation Does Not Increase Deadlift 1-Repetition Maximum in College-Aged Male and Female Weight Lifters. *The Journal of Strength & Conditioning Research,* 32**,** 3383-3388.

Vigotsky, A. D., Ogborn, D. & Phillips, S. M. 2016. Motor unit recruitment cannot be inferred from surface EMG amplitude and basic reporting standards must be adhered to. *European Journal of Applied Physiology,* 116**,** 657-658.

Vigotsky, A. D., Halperin, I., Trajano, G. S. & Vieira, T. M. 2022. Longing for a Longitudinal Proxy: Acutely Measured Surface EMG Amplitude is not a Validated Predictor of Muscle Hypertrophy. *Sports Med,* 52**,** 193-199.

Walhin, J. P., Richardson, J. D., Betts, J. A. & Thompson, D. 2013. Exercise counteracts the effects of short-term overfeeding and reduced physical activity independent of energy imbalance in healthy young men. *The Journal of physiology,* 591**,** 6231-43.

Weinstein, Y., Bediz, C., Dotan, R. & Falk, B. 1998. Reliability of peak-lactate, heart rate, and plasma volume following the Wingate test. *Medicine & Science in Sports & Exercise,* 30**,** 1456-1460.

Wenger, H. A. & Bell, G. J. 1986. The interactions of intensity, frequency and duration of exercise training in altering cardiorespiratory fitness. *Sports Med,* 3**,** 346-56.

Weston, A. R., Myburgh, K. H., Lindsay, F. H., Dennis, S. C., Noakes, T. D. & Hawley, J. A. 1996. Skeletal muscle buffering capacity and endurance performance after high-intensity interval training by well-trained cyclists. *European Journal of Applied Physiology and Occupational Physiology,* 75**,** 7-13.

Williams, M. A., Haskell, W. L., Ades, P. A., Amsterdam, E. A., Bittner, V., Franklin, B. A., Gulanick, M., Laing, S. T. & Stewart, K. J. 2007. Resistance Exercise in Individuals With and Without Cardiovascular Disease: 2007 Update. *Circulation,* 116**,** 572-584.

Willoughby, D. 2004. Pneumatic Resistance Machines Can Provide Eccentric Loading: Response. *Medicine & Science in Sports & Exercise,* 36**,** 1656.

Wilson, J. M., Marin, P. J., Rhea, M. R., Wilson, S. M. C., Loenneke, J. P. & Anderson, J. C. 2012. Concurrent Training: A Meta-Analysis Examining Interference of Aerobic and Resistance Exercises. *The Journal of Strength & Conditioning Research,* 26**,** 2293-2307.

Winters-Stone, K. M., Neil, S. E. & Campbell, K. L. 2014. Attention to principles of exercise training: a review of exercise studies for survivors of cancers other than breast. *Br J Sports Med,* 48**,** 987-95.

Wisløff, U., Helgerud, J. & Hoff, J. 1998. Strength and endurance of elite soccer players. *Med Sci Sports Exerc,* 30**,** 462-7.

Wolfe, R. R. 2006. The underappreciated role of muscle in health and disease. *The American Journal of Clinical Nutrition,* 84**,** 475-482.

Wolff, C. A. & Esser, K. A. 2019. Exercise timing and circadian rhythms. *Current Opinion in Physiology,* 10**,** 64-69.

Wong, P.-L., Chaouachi, A., Chamari, K., Dellal, A. & Wisloff, U. 2010. Effect of Preseason Concurrent Muscular Strength and High-Intensity Interval Training in Professional Soccer Players. *The Journal of Strength & Conditioning Research,* 24**,** 653-660.

Wood, R. H., Reyes, R., Welsch, M. A., Favaloro-Sabatier, J., Sabatier, M., Lee, C. M., Johnson, L. G. & Hooper, P. F. 2001. Concurrent cardiovascular and resistance training in healthy older adults. *Medicine and science in sports and exercise,* 33**,** 1751-1758.

Yamamoto, L. M., Lopez, R. M., Klau, J. F., Casa, D. J., Kraemer, W. J. & Maresh, C. M. 2008. The Effects of Resistance Training on Endurance Distance Running Performance Among Highly Trained Runners: A Systematic Review. *The Journal of Strength & Conditioning Research,* 22**,** 2036-2044.

Yoon, M.-S. 2017. mTOR as a Key Regulator in Maintaining Skeletal Muscle Mass. *Frontiers in Physiology,* 8.