



Effects of resistance training on physiological and biomechanical factors in marathon runners: Reactive strength vs. heavy weight training

Student

Rizaan Behardien - BHRMUH003¹

Supervisor

Emeritus A/Prof Andrew Bosch¹

SUBMITTED TO THE UNIVERSITY OF CAPE TOWN

In fulfilment of the requirements for the degree

MSc (Med) in Exercise Science

February 2025

Affiliations:

¹Division of Physiological Sciences, Department of Human Biology, Faculty of Health Sciences, University of Cape Town

Address for correspondence:

Emeritus A/Prof Andrew Bosch

Division of Physiological Sciences, Department of Human Biology, Faculty of Health Sciences, University of Cape Town

Andrew.bosch@uct.ac.za

Referencing style: University of Cape Town – Harvard method

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.

Plagiarism Declaration

I, **Muhammed Rizaan Behardien**, hereby declare that the work on which this dissertation/dissertation is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

I empower the university to reproduce for the purpose of research either the whole or any portion of the contents in any manner whatsoever.

Signature:

Signed by candidate

.....

Date:15/02/2025.....



FACULTY OF HEALTH SCIENCES (FHS)



Plagiarism Declaration and Supervisor Authentication

Section A: Student Declaration

I, the undersigned, declare that:

1. **Turnitin Submission:** This thesis/dissertation has been submitted to the Turnitin module (or an equivalent similarity and originality checking software) as required for the completion of my degree.
2. **Original Work:** The work presented in this thesis/dissertation is my own, and any references to the work of others have been appropriately cited and acknowledged.
3. **Supervisor Review:** My Turnitin report has been reviewed by my supervisor, and any concerns identified regarding similarity or potential plagiarism have been resolved through consultation.

Student Name: Muhammed Rizaan Behardien

Student Number: BHRMUH003

Signature:  _____

Date: 14/02/2025

Please attach your Turnitin report to this declaration

Section B: Supervisor Authentication

I, the undersigned, confirm that:

1. **Review of Turnitin Report:** I have reviewed the Turnitin report for the thesis/dissertation submitted by [Student Name] Rizaan Behardien. The similarity index percentage and details have been thoroughly examined.
2. **Assessment of Concerns:** Any issues or concerns revealed by the Turnitin report have been discussed with the student and resolved to ensure compliance with the university's academic integrity standards.
3. **Originality Confirmation:** Based on my review, I verify that the thesis/dissertation is original, and the content adheres to the required academic standards for citation and referencing.

Supervisor Name:

Signature:  _____

Date: 14 Feb 2025

Scientific presentations from this dissertation

- Poster presentation at 20th South African Sports Medicine Association Congress 2024, titled: ***Effects of resistance training on physiological and biomechanical factors in marathon runners: Reactive strength vs. heavy weight training***

Acknowledgements

I would like to express my sincere gratitude to Emeritus A/Prof Andrew Bosch for his invaluable guidance, expertise, and support throughout this research project. His mentorship has been instrumental in shaping this dissertation, and I am truly grateful for his patience and encouragement along the way.

I am also deeply appreciative of Innocent Karangwa – the statistician – who provided crucial insights and corrections to our analyses, ensuring the accuracy and reliability of our findings. Their expertise was fundamental in refining the data interpretation and strengthening the overall quality of this research.

A heartfelt thank you to all the participants who dedicated themselves to 12 weeks of rigorous training. Their commitment, discipline, and willingness to contribute to this study played a vital role in its success, and this research would not have been possible without their efforts.

I am also immensely grateful to my family and friends for their unwavering support, patience, and encouragement throughout this journey. Their belief in me has been a constant source of motivation, and their understanding and reassurance during the more challenging moments of this process have meant the world to me.

Lastly, this dissertation would not have been possible without the financial support from the NRF scholarship that funded my three years of study as well as the UCT Research Grant that funded the research activities and equipment. Without these funders' investment and trust in me, my work ethic, and my skills, this dream of mine would not have come to fruition.

Table of Contents

List of abbreviations	9
Scientific presentations from this dissertation	4
Acknowledgements	5
Chapter One: The state of concurrent training for long-distance runners	10
1.1 Overview	10
1.2 Concurrent training: The good, the bad, and the ugly	11
1.2.1 Adding endurance to resistance training	11
1.2.2 The interference effect hypothesis	12
1.2.3 Adding resistance to endurance training	14
1.2.4 Effective prescription and periodisation of concurrent training	15
1.3 A roadmap for running performance: Understand the metrics before pushing the limits	18
1.3.1 Oxygen-dependent variables	18
1.3.2 Oxygen-independent variables	19
1.3.3 Time trial performance	21
1.4 How to push the limits: Uncovering best practice	21
1.4.1 Defining resistance training modalities and muscle performance	22
1.4.2 Running performance improvements elicited by concurrent training	23
1.4.3 Summarising concurrent training best practice	51
1.5 Placing the Puzzle Pieces Perfectly: Correlations and Mechanistic Pathways	53
1.6 Conclusion	58
1.7 Aims and Objectives of this Thesis	58
1.7.1 Aims	58
1.7.2 Objectives	59
Chapter Two: Methodology	60
2.1 Study Overview	60
2.2 Participants	60

2.3	Ethical considerations	61
3.3.1	Privacy and Confidentiality	62
3.3.2	Data Safety and Monitoring	62
2.4	Testing Equipment and Procedures	62
3.4.1	Body Composition Measurements	63
3.4.2	Incremental Treadmill Test	64
3.4.3	Running Biomechanics	65
3.4.4	Maximal Anaerobic Running Test (MART)	66
3.4.5	Reactive-strength Testing	67
3.4.6	Maximal Strength Testing	69
3.4.7	Running Time Trial (5kmTT)	70
2.5	Validity and Reliability	70
2.6	Study Procedure	71
3.6.1	Testing	72
3.6.2	Training	72
2.7	Statistical analysis	87
Chapter Three: Results		88
3.1	Participant characteristics	88
3.2	Training Volume	88
3.3	Body Composition	89
1.1	Muscle Performance Tests	89
3.4.1	1RM	89
3.4.2	Reactive-strength measures	91
1.2	Running Biomechanical Analysis	95
1.3	Maximal Anaerobic Running Test	95
1.4	Running economy and related physiological measures	95
3.7.1	Running Economy	95
3.7.2	VO ₂ max, vVO ₂ max, and Peak Treadmill Speed	96

.....	97
1.5 5km time trial (5kmTT)	102
1.6 Correlational analysis	102
3.9.1 Muscle Performance Tests vs. Physiological and Performance Measures	102
3.9.2 Biomechanical Running Analysis vs. Physiological and Performance Measures	103
3.9.3 Running Economy and Related Physiological Measures vs. Performance Measures	104
3.9.4 Maximal Anaerobic Running Test vs. Performance Measures	104
Chapter Four: Discussion.....	105
4.1 Improvements in time trial performance elicited by concurrent training.....	105
4.2 Understanding the mechanisms underpinning the time trial performance improvements.....	107
4.3 Running biomechanical variables not mechanistically linked to changes in RE	109
Chapter Five: Implications for Future Research.....	110
Chapter Six: Limitations	111
Chapter Seven: Conclusion.....	112
Reference List.....	113
Appendices	131
Appendix 1: A guide to exercise selection and prescription for concurrent training for long-distance runners.	131
.....	132
Source: Barrie (2020).....	132
Appendix 2: Recruitment Advertisement.....	133
Appendix 3: Participation Information Sheet	134
Appendix 4: Consent Form.....	139
Appendix 5: Ethics	141

List of abbreviations

TT	Time trial
RE	Running economy
AMPK	AMP-activated protein kinase
mTOR	mechanistic target of rapamycin complex 1
PGC-1 α	peroxisome proliferator-activated receptor- γ coactivator-1 α
MART	Maximal anaerobic running test
vVO ₂ max	Velocity at VO ₂ max
BLa	Blood lactate threshold
%VO ₂ max	Fractional utilisation
HWT	Heavy weight training
RST	Reactive strength training
EXP	Explosive strength training
END	Muscular endurance training
CPX	Complex training / combination training
SSC	Stretch-shortening cycle
1RM	1-rep-maximum
HIIT	High-intensity interval training
PTS	Peak treadmill speed
CMJ	Countermovement jump
SJ	Squat jump
DJ	Drop jump
RCT	Randomised control trial
SRMA	Systematic review and meta-analysis
EUR	Elastic utilisation ratio
COM	Centre of mass
GRF	Ground reaction force
RSI	Reactive strength index
RSImod	Modified reactive strength index
K _{vert}	Lower limb stiffness
RIR	Reps in reserve
RPE	Rating of perceived exertion

Chapter One: The state of concurrent training for long-distance runners

A narrative review exploring how to effectively implement concurrent training for long-distance runners

1.1 Overview

Dankel et al. (2018) aptly describes that the goal of distance running is to complete a given distance in the fastest time, or at least faster than the next best competitor. Therefore, athletes, coaches and sports scientists always search for new, innovative and effective ways to improve long-distance running performance. Since the publication by Paavolainen et al. (1999) – over two decades ago – there has been a growing interest in concurrent training for endurance athletes. Concurrent training is simply when resistance and endurance exercise are combined into the same training program or training cycle (Wilson et al., 2012). Paavolainen et al. (1999) sparked the scientific community's interest by showing that concurrent training was superior to conventional endurance training for improving running performance. These authors proved that substituting 32% of one's usual endurance training for sprint and jump training significantly improved 5km time trial (TT) and running economy (RE) (Paavolainen et al., 1999). Many studies have duplicated this research methodology but have modified the population of runners tested, the type of resistance training used, and the duration of training prescribed. To date, 31 concurrent training studies have been conducted on long-distance runners (Llanos-Lagos et al., 2024). While many significant findings have been made in these studies over the past 20 years, there are also still unanswered questions and gaps in this rapidly expanding area of research. This narrative review aims to unpack these findings and areas for future research. This review will educate its reader on (1) which concurrent training prescription may produce the best running performance improvements and (2) the number of hypotheses explaining the mechanistic pathways underpinning these running performance benefits elicited by concurrent training.

1.2 Concurrent training: The good, the bad, and the ugly

Even though concurrent training has a simple definition, to effectively put it into practice, one must be cognisant of several facts and nuances. Some factors that need to be understood are the optimal rest periods between resistance and endurance training, how much load should be prescribed, and the dangers and risks associated with concurrent training. This section of the review will explore these factors to provide the reader with a comprehensive understanding of the physiology behind concurrent training and the guidelines to effectively implement it.

1.2.1 Adding endurance to resistance training

When the concept of concurrent training was first posed, it was targeted at strength and power athletes, not to those participating in endurance sports. Concurrent training seemed to pose a conundrum to these strength and power athletes who also intended to perform endurance training (Hickson, 1980). The conundrum facing these athletes was the body of research showing that endurance training attenuated resistance training's hypertrophic and strength gains (Hickson, 1980; Balsalobre-Fernández, Santos-Concejero & Grivas, 2016; Alcaraz-Ibañez & Rodríguez-Pérez, 2018; Blagrove, Howatson & Hayes, 2018; Šuc et al., 2022) – the exact physiological adaptations for which these athletes aim. These findings caused a negative stigma towards concurrent training (Coffey & Hawley, 2017). This physiological phenomenon that produces conflicting exercise adaptations when combining two opposing exercise modalities was coined the 'interference effect' (Hickson, 1980). More than 50 years have passed since the 'interference effect' was first described, yet we are no closer to definitively understanding the mechanism underpinning its physiology (Coffey & Hawley, 2017). Several plausible hypotheses have been suggested and for the purpose of this review, only three will be expounded upon. The reader should be aware that all three of these hypotheses have compelling evidence brought against them. Therefore, none of these explanations should be taken as a clear and definitive understanding of the mechanisms underpinning the 'interference effect' (Coffey & Hawley, 2017).

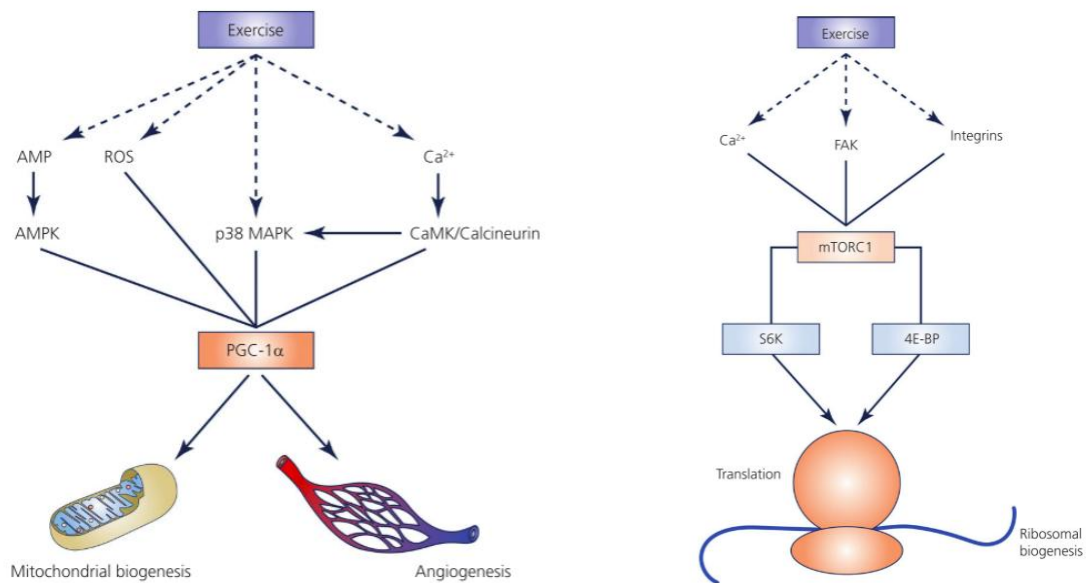


Figure 1.1: Explanatory diagrams from (Coffey & Hawley, 2017) detailing the cascade resulting in PGC-1-alpha eliciting mitochondrial biogenesis and angiogenesis adaptations (*left*), and the mechanisms behind mTORC 1 causing ribosomal biogenesis which results in increased protein synthesis and muscle hypertrophy (*right*).

1.2.2 The interference effect hypothesis

The three hypotheses each address distinct aspects of human physiology in relation to exercise adaptation (Leveritt et al., 1999; Wilson et al., 2012; Coffey & Hawley, 2017). The first addresses responses of the AMP-activated protein kinase (AMPK) and the mechanistic target of rapamycin complex 1 (mTOR) to exercise (Coffey & Hawley, 2017). AMP and AMPK are stimulated by the skeletal muscles' contractile activity and increased energy production during continuous endurance-type exercise. AMPK is one of the activated molecules that form part of a cascade that upregulates peroxisome proliferator-activated receptor- γ coactivator-1 α (PGC-1 α) (Olesen, Kiilerich & Pilegaard, 2010). The upregulation of PGC-1 α is especially important for endurance exercise

adaptation as it stimulates mitochondrial biogenesis and angiogenesis (Hawley, 2009) (see *Figure 1.1*). Mitochondrial biogenesis allows the body to quickly generate oxidative energy to fuel aerobic endurance-type exercise more efficiently. Angiogenesis targets cardiovascular adaptation which results in increased blood vessel production. This allows for a larger blood supply to muscles which need a constant supply of oxygen and energy during this type of exercise (Olesen, Kiilerich & Pilegaard, 2010).

One of the main mechanisms behind resistance training resulting in muscle hypertrophy is via the molecular signalling pathway of mTOR. Once activated, mTOR stimulates a molecular cascade which results in the nucleus manufacturing more ribosomes as well as the upregulation of the translational protein process (Philp, Lee Hamilton & Baar, 2011) (see *Figure 1.1*). Both these effects of mTOR signalling result in increased protein synthesis which are essential building blocks in the anabolic process of muscle hypertrophy. However, when endurance and resistance training are combined, the AMPK pathway suppresses and/or dampens the signalling of the mTOR cascade. Therefore, adaptive responses to the endurance exercise still manifest while the strength and hypertrophic improvements are absent or reduced (Coffey & Hawley, 2017).

The second hypothesis approaches this phenomenon from a cellular level. This hypothesis pins the mechanism of the interference effect on the way satellite cells respond to the opposing exercise modalities. Satellite cells are niche muscular stem cells (Dumont, Wang & Rudnicki, 2015), or undifferentiated myonucleated myogenic cells (Snow, 1978). These cells play a pivotal role in muscle cell repair, regeneration, and growth – key processes also needed in response to exercise (Snow, 1978; Dumont, Wang & Rudnicki, 2015). When stimulated, the satellite cells proliferate until they form new myofibers which help to strengthen and increase the cross-sectional area of the muscle. This process is especially important for muscle strength and hypertrophic adaptation stimulated by resistance training. However, satellite cells inherently have an increased density in slow twitch compared to fast twitch fibre (Mackey et al., 2009). It is thought that this imbalance favours endurance exercise adaptation and dampens the resistance training responses. This may be due to endurance exercises targeting the high-density slow twitch fibres and thus outcompeting the hypertrophic response of less densely populated fast-twitch fibres during concurrent training (Pugh et al., 2018).

The third hypothesis – and also the most rudimentary hypothesis – is that the body's systemic response to external exercise load (Leveritt et al., 1999). A methodological conundrum arises when prescribing exercise load during concurrent training intervention studies (Wilson et al., 2012). This is because compounding training loads within a single training cycle in the concurrent training group can cause athletes to shift into a state of overtraining (Dudley & Djamil, 1985). Overtraining is commonly defined as “prolonged maladaptation to high levels of exercise stress that results in decreased performance and mood state, with symptoms that can continue for weeks or months” (Halsen & Jeukendrup, 2004; Meeusen et al., 2013). Overtraining is characterised by reduced strength and power, as well as overall performance, amongst several other symptoms (Halsen & Jeukendrup, 2004; Meeusen et al., 2013). This third hypothesis suggests that when in a state of overtraining, the symptoms of reduced strength and power may manifest before signs of overall reduced performance are apparent. Therefore, in a concurrent training scenario, these authors suggest that the overtrained athlete will first exhibit deleterious neuromuscular performance and may only experience endurance performance deficits in the long term (Leveritt et al., 1999). However, this is the hypothesis with the least proof, as many studies have found long-term running performance strength improvements elicited by concurrent training (Yamamoto et al., 2008, 2010; Ellery, Keogh & Sheerin, 2012; Rønnestad & Mujika, 2014; Balsalobre-Fernández, Santos-Concejero & Grivas, 2016; Berryman et al., 2017; Denadai et al., 2017; Alcaraz-Ibañez & Rodríguez-Pérez, 2018; Blagrove, Howatson & Hayes, 2018; Barrie, 2020; Ramirez-Campillo et al., 2021; Eihara et al., 2022; Llanos-Lagos et al., 2024).

1.2.3 Adding resistance to endurance training

The above research therefore confirmed that concurrent training does not cause hypertrophic changes. However, when shifting the focus to long-distance runners, there was still hesitancy to add resistance exercise into their programs because it may alter body composition (Yamamoto et al., 2008). This misconception still revolved around the idea that a heavier runner would be a slower runner. This led researchers to investigate the interference effect from the endurance athletes' perspective. As was expected,

research again found no significant increases in body mass or body fat when adding resistance training to an endurance program (Johnston et al., 1997; Støren et al., 2008; Rønnestad, Hansen & Raastad, 2010; Aagaard et al., 2011; Rønnestad et al., 2012; Alcaraz-Ibañez & Rodríguez-Pérez, 2018; Blagrove, Howatson & Hayes, 2018; Ramirez-Campillo et al., 2022; Trowell et al., 2022). In fact, this research suggested that lean-body mass and muscle cross-sectional can increase while maintaining a constant overall body mass in endurance athletes (Rønnestad, Hansen & Raastad, 2010; Ramirez-Campillo et al., 2022). Therefore, especially for endurance athletes, concurrent training should be seen as a beneficial adjunct training modality and the negative stigma should be dismissed.

Instead of being concerned about changes in body composition, runners should pay more attention to how resistance training is periodised into an endurance training program. Incorrect periodisation and exercise prescription could lead to negative running performance outcomes (Plisk & Stone, 2003). The specific prescription factors of concern are the volume and intensity prescribed, as well as the timing, and sequencing of the opposing training modalities. Effectively periodising concurrent training can ensure positive improvements, not only for endurance performance but also for resistance-training-related neuromuscular factors.

1.2.4 Effective prescription and periodisation of concurrent training

A review by Doma et al. (2019) expertly maps out concurrent training guidelines. These guidelines discuss “when”, “how much”, and “what” should be prescribed for effective concurrent training. These recommendations and guidelines are specifically for endurance runners who want to gain maximum benefit from both resistance and endurance training.

The most common way of planning the “when” may be to sequence the endurance training before the resistance exercise (E+S) in a single session. Intuitively, this would save time and ensure the residual fatigue of resistance training does not impact the quality of the endurance training (Doma et al., 2019). Chtara et al. (2005) confirmed this idea in their study which compared E+S, resistance followed by endurance training (S+E),

resistance training only, and endurance training only over 12 weeks. The authors found that E+S produced significantly faster 4kmTT and significantly greater velocities at VO_{2max} (vVO_{2max}) as compared to all other groups (Chtara et al., 2005). However, the same authors also found that E+S produced significantly lower strength and power gains as compared to the resistance-training-only group (Chtara et al., 2008). A similar study comparing E+S and endurance-only training over 24 weeks, also proved that E+S is not beneficial for improving maximal strength in moderately trained endurance runners (Schumann et al., 2016). These findings suggest that E+S may not be the best sequencing of a concurrent training program for long-distance runners aiming to improve running and neuromuscular performance.

S+E is therefore the more appropriate sequencing for endurance runners, but it is not without risks. Running-specific studies have found that – in the short and long term – same-day S+E caused reduced muscle force-generating capacity, increased muscle soreness, and reduced the ability to improve VO_{2max} (Doma & Deakin, 2015; Robineau et al., 2016). This is where the importance of the timing guidelines comes in. Doma et al. (2019) recommended that same-day S+E be avoided altogether. However, in an elite running schedule where the volume of training forces endurance and resistance training to be done on the same day – this cannot be prevented. In these cases, only low- to moderate-intensity endurance training should be performed on the same day as resistance training. An attempt should always be made to avoid same-day resistance and high-intensity endurance as far as possible. Six to nine hours of recovery should also be planned between these opposing training sessions (Doma et al., 2019). However, if same-day training can be avoided, that would be best. The authors recommend that 24-48 hours of recovery be planned between endurance and resistance training sessions with high-intensity endurance training only planned 72 hours after the completion of resistance exercise (Doma et al., 2019). See *Figure 1.2* for an example of what a concurrent training week could look like for a long-distance runner depending on their fitness level and time availability.

There are no specific recommendations concerning “how much” endurance training to include in a concurrent training program. The single recommendation regarding resistance training volume is simple: Do not prescribe excessively high training loads, as

the greater the load the longer the residual fatigue will last post-resistance training (Abboud et al., 2013).

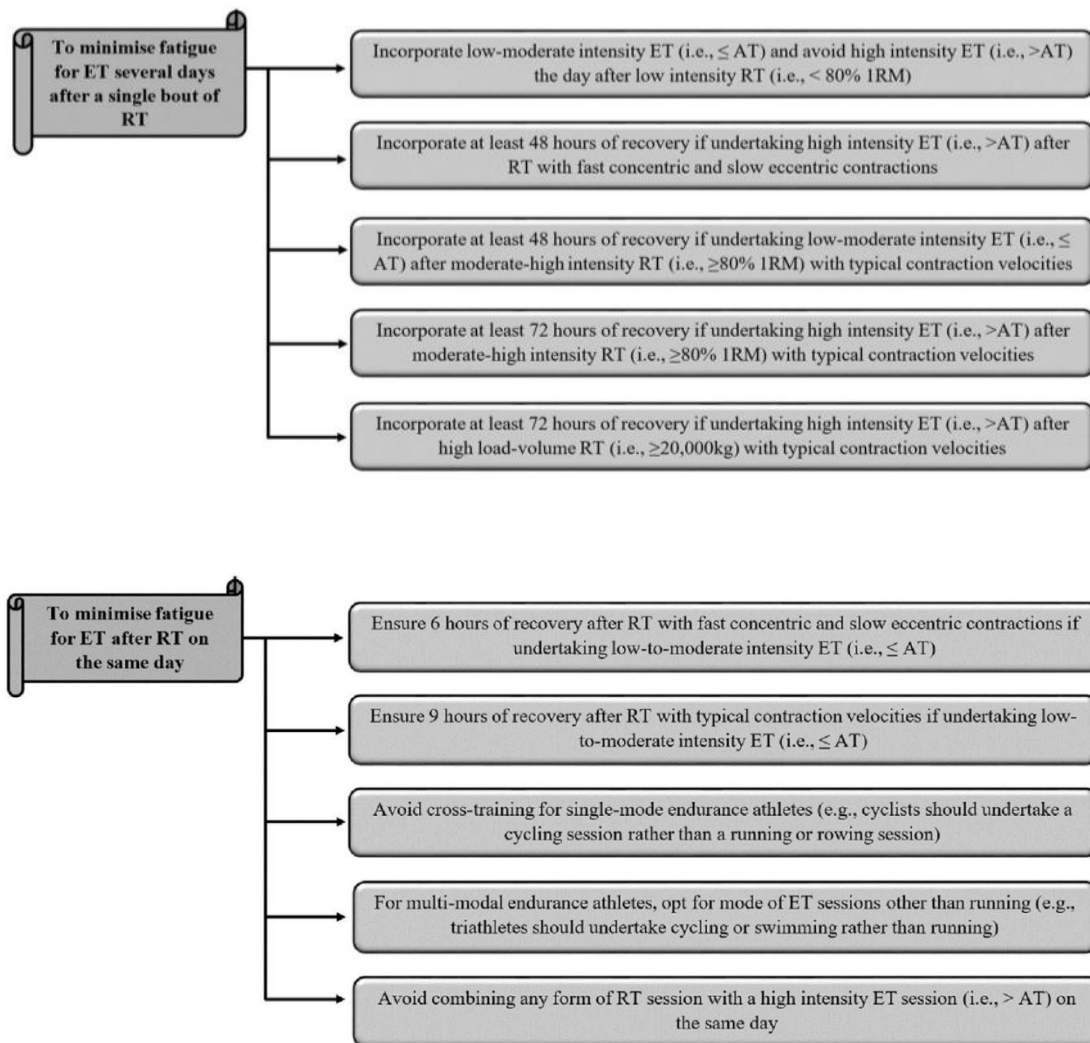


Figure 1.2: Training guidelines outlined by Doma et al. (2019) to guide the planning of a concurrent exercise training week. *ET* = endurance training; *RT* = resistance training; *AT* = anaerobic threshold.

The final set of guidelines regarding “what” type of resistance training to prescribe in a concurrent training program stems from the findings of two conducted by these same authors (Doma & Deakin, 2013, 2014). These studies assessed running time to

exhaustion, knee extensor torque and running economy (RE) six hours after resistance training sessions (Doma & Deakin, 2013, 2014). One study prescribed fast concentric and eccentric tempos (Doma & Deakin, 2014), whilst the other prescribed fast concentric and slow eccentric tempos (Doma & Deakin, 2013). The study which prescribed faster eccentric exercise tempos elicited higher RE values with a greater reduction in knee extensor torque post-resistance training (Doma & Deakin, 2013). The ability of the slower eccentric tempos to limit the residual fatigue in a subsequent run makes it better suited for a concurrent training program (Doma et al., 2019). This implies that heavy-weight training (HWT) with more controlled tempos may be more beneficial for runners than explosive training (EXP) with quicker eccentric components. Doma et al. (2019) further recommended avoiding the prescription of supersets and giant sets, as well as training to failure. Avoiding these training techniques will assist in further limiting the effects of residual fatigue. One can be confident that a concurrent training program developed using these guidelines will be effective and evidence-based.

1.3 A roadmap for running performance: Understand the metrics before pushing the limits

Before delving into the best concurrent training practices for running performance improvements, one should first comprehensively understand the physiological determinants of running performance. It is difficult to comprehend how and why an intervention works if one does not fully understand the intricacies of the outcome variable(s) being measured. Therefore, this section will first expound on variables like $VO_2\text{max}$, RE fractional utilisation, lactate threshold, $vVO_2\text{max}$, velocity during the maximal anaerobic running test (vMART), and time trial performance. Not only will the physiology behind these variables be explained, but also how they are improved through training.

1.3.1 Oxygen-dependent variables

Up until more recently, oxygen-dependent factors like $VO_2\text{max}$, RE, lactate threshold,

and fractional utilisation of $VO_2\text{max}$, have primarily been used to measure and predict endurance running performance (Midgley, McNaughton & Jones, 2007). $VO_2\text{max}$ “represents the ability of an individual to consume oxygen maximally per unit of body mass and time” (Saltin & Astrand, 1967; Morgan et al., 1989), and RE is defined as “the VO_2 measured during a steady state submaximal running speed” (Conley & Krahenbuhl, 1980; Morgan et al., 1989). Fractional utilisation of $VO_2\text{max}$ ($\%VO_2\text{max}$) is calculated by expressing RE as a fraction of $VO_2\text{max}$ (di Prampero et al., 1986; Coyle, 1999). Using a multiple linear regression model, di Prampero et al. (1986) developed an equation to accurately predict race velocity based on these oxygen-dependent variables (*Running velocity = $\%VO_2 \times VO_2\text{max} / RE$*). This was coined the “energetic model” for predicting running performance (di Prampero et al., 1986). This equation accounted for up to 70% of the variability in race performance and thus became widely used as a key performance-predicting tool for long-distance runners (di Prampero et al., 1986).

The fourth oxygen-dependent variable is the lactate threshold (BLa) or onset of blood lactate accumulation (OBLa). This is a term used to define the highest work rate, speed, or oxygen uptake an athlete can maintain before there is an exponential increase in blood lactate concentration with a further workload increase (Lorenzo et al., 2011). If the athlete were to go any faster than this specified threshold, they would begin to fatigue quickly. This variable has also been shown to be useful in predicting long-distance running performance. Running velocity and power output at the lactate threshold were strongly ($r = 0.89, p < 0.05$) correlated with a 60-minute TT (Lorenzo et al., 2011), and very strongly ($r = 0.98, p < 0.05$) correlated with marathon race performance (Farrell et al., 1979). These four oxygen-dependent variables were all used in the energetic model to account for 95% of the variance in TT performance (McLaughlin et al., 2010). Cleverly, these authors used the VO_2 produced at the lactate threshold as the $\%VO_2\text{max}$ in the energetic model’s equation (McLaughlin et al., 2010). Together, these variables have played a vital role as the primary predictors of running performance for approximately two decades.

1.3.2 Oxygen-independent variables

Oxygen-dependent factors can be very useful predictive tools. However, when looking at

elite and competitive marathon racing, athletes need to maintain fast speeds throughout the marathon distance. These speeds also inevitably culminate in a sprint finish and a “kick” at the end of competitive races (Beattie, 2019a). Due to these increased work rates during competition, at times distance runners require more energy than the oxygen-dependent energy-producing pathways can provide (Paavolainen, Nummela & Rusko, 2000). Therefore, Noakes (1987) hypothesised that it is not oxygen-dependent variables limiting maximal performance but oxygen-independent running muscle power factors. These factors include the maximum speed reached during a maximal aerobic test (peak treadmill running speed (PTS) (Segabinazi Peserico, Zagatto & Machado, 2014), $\dot{V}O_{2\max}$ (McLaughlin et al., 2010), and $\dot{V}MART$ (Nummela et al., 2006)

The MART was designed to test an athlete’s capacity to produce power, as well as their neuromuscular efficiency at maximal running speeds in a semi-fatigued state (Nummela et al., 2006). The suggestion to include $\dot{V}MART$ when attempting to predict performance was based on the fact that $\dot{V}MART$ significantly correlated with the 5km time trial velocity ($r = 0.77$, strong; $p < 0.001$). Furthermore, $MART \dot{V}O_{2\text{gain}}$ – which was calculated as the oxygen demand ($\dot{V}O_2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) of running during the final lap of the MART ($\dot{V}MART$) subtracted by the $\dot{V}O_{2\max}$ – accounted for more variance in race performance than the traditional energetic model ($5\text{km velocity} = 0.066 \times \dot{V}O_{2\max} + 0.048 \times MART \dot{V}O_{2\text{gain}} - 0.549$; $r^2 = 0.73$; $p < 0.001$) (Nummela et al., 2006). In this study, the energetic model only predicted 56% of the variance in 5km performance as compared to the 73% predicted by the Nummela et al. (2006) equation that included muscle power factors.

Peak treadmill speed (PTS) and $\dot{V}O_{2\max}$ are closely related, differing primarily in what inferences can be made from their data. PTS and $\dot{V}O_{2\max}$ use a direct running test and physiological determinants of running to predict overall running performance, respectively (McLaughlin et al., 2010). PTS is defined as the final velocity that is maintained for a full 30- or 60-second running stage during a standard ramped/incremental treadmill test protocol (Noakes, Myburgh & Schall, 1990). By comparison, $\dot{V}O_{2\max}$ is calculated by using both $\dot{V}O_{2\max}$ and RE data. The RE data gets plotted on a set of axes and gets extrapolated to the speed at $\dot{V}O_2 \max$. More specifically, an equation is developed using a simple linear regression model based on all the RE data. The $\dot{V}O_{2\max}$ is inputted as the y-intercept in this equation and the x-intercept is then

calculated. This x -value is taken as the $\dot{V}O_2\text{max}$ (Bernard et al., 2000; McLaughlin et al., 2010). As with the MART, these variables have been closely associated with running performance. In their respective studies, PTS ($r = 0.83-0.97, p < 0.05$) (Noakes, Myburgh & Schall, 1990; Stratton et al., 2009) and $\dot{V}O_2\text{max}$ ($r = 0.97$) (McLaughlin et al., 2010) were found to be the variable most closely correlated to TT performances and thus best-predicted running performance. The data examined in this section justifies the importance of understanding and testing both oxygen-dependent and independent factors. This comprehensive approach is essential for investigating running performance.

1.3.3 Time trial performance

The final piece of the puzzle in holistically understanding running performance is TT performance. Even though various measures that closely correlate to and predict TT performance have been explained above, in certain cases, there is variability that these tests or models cannot account for (Daniels, Yarbrough & Foster, 1978). Since TT most closely mimics the scenario of a competitive race by realistically simulating the physiological responses to a race environment (Russell et al., 2004), Rosenblat et al. (2021) recommends that TT should always be included in an assessment of running performance. Ultimately, there are no lab-based competitions where prizes are awarded for the best RE or the greatest mean power outputs (Dankel et al., 2018). Runners win races by running the fastest over a given distance – and this is exactly what a well-constructed laboratory-based time trial assesses.

1.4 How to push the limits: Uncovering best practice

After understanding the science behind resistance exercise physiology, and the intricacies around the determinants of endurance running performance, one can now explore how this all comes together in practice. In this section, the concurrent training regimen that best improves running performance will be explored. The concepts

discussed below provide the information and skills to plan and prescribe an effective concurrent training program.

1.4.1 Defining resistance training modalities and muscle performance

In this review, resistance exercise modalities will be grouped into five different categories: Heavy-weight training (HWT), explosive-weight training (EXP), reactive-strength training (RST), muscle endurance strength training (END), and complex training (CPX). CPX has been defined as any intervention that combines two or more modalities. For an overview of the remaining four modalities see *Table 1.1*, below (De Villarreal, Izquierdo & Gonzalez-Badillo, 2011; Denadai et al., 2017; Alcaraz-Ibañez & Rodríguez-Pérez, 2018).

Studies have investigated various components of muscle strength and performance. The most common is the 1-repetition-maximum (1RM) test which measures maximal strength. The test is comprised of several sets of a specific exercise (e.g. squat for lower limb strength tests) that increases in weight until the maximum weight is reached where only a full single rep can still be performed with the correct form (Verdijk et al., 2009; Seo et al., 2012). If it is not ideal to push someone to their true 1RM, 1RM it can be predicted using equations or 3-5RMs. When attempting to understand RST performance, various maximal jump performances are tested. Athletes usually have three attempts with their best attempt being recorded. Jumps like the countermovement jump (CMJ) are used to assess maximal power, whereas drop jumps (DJ) are used to assess the stretch-shortening cycle efficiency (SSC). The SSC is the ability to effectively and rapidly transfer eccentric elastic energy into concentric force and power (Kubo, Kawakami & Fukunaga, 1999). An efficient SSC is essential across many sporting codes – including endurance running. These measures and exercise modalities will be discussed as concurrent training best practices are explored.

Table 1.1: An overview of the characteristics of the different resistance training modalities included in this review.

Exercise parameter	HWT	EXP	RST	END
Weight	≥80% 1RM	<80	Mostly done using body weight or <40%1RM	≤50% 1RM
Intensity/ Speed/ Tempo	Traditionally slow concentric and eccentric phases. Maximum movement can be cued during the concentric phase	High speed focused	Rapid movements where elastic energy is quickly transferred from the eccentric back to concentric phase Variable – depending on prescribed intensity	Volitional
Rep range	≤8	3-6	or difficulty (unilateral vs bilateral, increased box height, etc.)	≥15
Exercise examples	Barbell back squat, Leg press, Romanian deadlift	Olympic lifts, weight squat jumps	Jumps, drop jumps, hops, skipping, hurdle jumps	Bodyweight squats, Lunges, calf raises

1.4.2 Running performance improvements elicited by concurrent training

To uncover best practices in concurrent training prescription, the following discussions will describe the changes in muscular and running performance metrics elicited by various concurrent training modalities. Within each subsection, the modalities that produce the best results will be highlighted. This will help unpack the nuances each

modality can provide for a long-distance runner engaging in concurrent training. *Table 1.2* outlines detailed descriptions of the modalities described below in the text.

1.4.2.1 *Maximal Strength*

Maximal strength is the ability of a muscle to produce maximum force and is improved via neurological and/or structural adaptations to training (Folland & Williams, 2007). A systematic review and meta-analysis (SRMA) that investigated the influence of concurrent training on neuromuscular factors found this training modality to have an overall positive and beneficial effect on lower limb strength (Trowell et al., 2020). The authors did not discriminate between the types of concurrent training (HWT, RST, COMB, etc.) but rather pooled all the data together for their analysis. Therefore, Trowell et al. (2020) found concurrent training of any type to have a positive moderate effect on knee extensor (Standardised mean difference (SMD) = 0.69 [95%CI: 0.29, 1.09]; n = 6), plantar flexor (SMD = 0.74 [95%CI: 0.21, 1.26]; n = 4), and maximum squatting strength (SMD = 0.63 [95%CI: 0.13, 1.12]; n = 6).

A more recent meta-analysis unpacked these findings in more detail (Prieto-González et al., 2024). By using Hedges g effect sizes (ES) Prieto-González et al. (2024) showed that HWT (Hedges g = -1.10 [95%CI: -1.86, -0.35], large; p = 0.004) and CPX (-0.653 [-1.04, -0.26], moderate; p = 0.001) in comparison to control groups, produced the greatest improvements in maximal strength. Therefore, HWT and CPX could be used to equally good effect to produce maximal strength gains.

Ramirez-Campillo et al. (2021) further elaborated on maximal strength improvements by solely investigating jump training in their SRMA. There was no overall significant effect of RST on maximal strength gains in this study (Ramirez-Campillo et al., 2021). However, all but one study employing HWT as their intervention (n = 7/8, 88%) did show positive and significant improvements in maximum strength. The only study which lacked significant concurrent-training-elicited strength gains used an isometric strengthening protocol (Fletcher, Esau & MacIntosh, 2010). However, isometric training should not be written off as ineffective. A 2023 randomised controlled trial (RCT) established that using isometric

mid-thigh pulls and isometric seated calf raises produced a significant 11.1% increase in relative MVC (Lum et al., 2023).

Not surprisingly, the two HWT studies that produced the largest improvements in maximal strength across the literature employed similar interventions (Johnston et al., 1997; Vikmoen et al., 2016). Johnston et al. (1997) and Vikmoen et al. (2016) both used compound isokinetic exercises trained to failure with female athletes. These studies produced statistically significant improvements of 38.5% (Johnston et al., 1997) and 40.4% (Vikmoen et al., 2016), with the next best HWT investigating both sexes only eliciting a significant 27.1% increase in lower limb 1RM (Støren et al., 2008). Interestingly, the study that produced the greatest overall 1RM increases investigated the effects of CPX on male marathon runners (Vorup et al., 2016). To accommodate the CPX exercise, participants reduced their baseline endurance training by up to 58%. This CPX protocol significantly increased the 1RM squat and 1RM leg press by 79% and 110%, respectively. These studies provide valuable context to the Prieto-González et al. (2024) findings that suggested that only HWT and CPX were effective at improving lower limb 1RM.

Additionally, meta-analysed results from an SRMA investigating concurrent training effects by sex and training status corroborate these above-mentioned trends (Huiberts, Wüst & van der Zwaard, 2024). These authors found that concurrent training only had deleterious effects on males' maximal strength (Hedges $g = -0.43$ [95%CI: -0.64, -0.22], $p < 0.001$) and not females' (0.08 [95%CI: -0.34, 0.49], $p = 0.72$) and that highly trained strength athletes were only protected from this concurrent training interference effect (Huiberts, Wüst & van der Zwaard, 2024). Therefore, when attempting to improve maximal strength one needs to be cognisant of the fact that female athletes may be more primed for HWT concurrent training. One also needs to understand that maximal strength improvements in runners who are not strength-trained may be negatively impacted by the interference effect. Furthermore, when maximal strength is the primary outcome, one should focus on HWT and CPX concurrent training for the best results.

Table 1.2: Descriptive characteristics using the FITT-VP principles of exercise prescription of strength protocols used in studies outlined within this review.

Study	Subjects	Classification of resistance training	Frequency of training	Intensity	Time	Type	Volume (reps x sets)
Fletcher, Esau & MacIntosh (2010)	Highly trained males	ISO	3/wk	80% maximal voluntary contraction (MVC)	8 wks	ISO plantarflexion	20s x 4
Lum et al. (2023)	Recreationally trained males + females	ISO	2/wk	MVC	6 wks	Mid-thigh pulls, isometric seated calf raises	5 x 2-4
Johnston et al. (1997)	Moderately trained females	HWT	3/wk	6-20RM	10 wks	Parallel squat, lunge, bent knee heel raise	2-3 x 6-20
Vikmoen et al. (2016)	Highly trained female duathletes	HWT	2/wk	4-10RM	11 wks	Half squat, unilat leg press, unilat standing hip flexion, ankle plantarflexion	3 x 4-10
Støren et al., (2008)	Highly trained males + females	HWT	3/wk	4RM	8 wks	Half squat	4 x 4
Vorup et al., (2016)	Highly trained males	HWT	2/wk	4-10RM	8 wks	Back squat, leg press, deadlift	4 x 4-10
		CPX (HWT + Sprt)	2/wk	HWT* + Sprt: 90-95% max speed	8 wks	HWT* + Sprt	HWT* + Sprt: 30s x 4-10

Table 1.2: cont.

Study	Subjects	Classification of resistance training	Frequency of training	Intensity	Time	Type	Volume (reps x sets)
Li et al. (2019)	Highly trained males	HWT	3/wk	80-85% 1RM	8 weeks	Back squat, Bulgarian squat, Romanian deadlift	5 x 5
		CPX (HWT + RST)	3/wk	HWT* + BW	8 weeks	HWT* + RST: 40cmDJ, sgl leg hop, dbl leg hurdle	5-6 x 3
Damasceno et al. (2015)	Moderately trained males	HWT	2/wk	3-10RM	8 weeks	Back squat, leg press, plantarflexion, knee extension	3-10 x 2-3
Andrade et al. (2018)	Recreationally trained males + females	RST	3/wk	BW	4 weeks	30cm & 50cm DJ	10 x 3
Spurrs, Murphy & Watsford, (2003)	Moderately trained males	RST	2-3/wk	BW	6 weeks	SJ, scissor jump, dbl leg bound, alt leg bound, sgl leg hop, DepthJ, dbl & sgl leg hurdle jump	10-12 x 2-3
Pellegrino, Ruby & Dumke (2016)	Recreationally trained males + females	RST	2-3/wk	BW	6 weeks	SJ, scissor jump, dbl leg bound, alt leg bound, sgl leg hop, modified DepthJ, dbl & sgl leg hurdle jump	10-12 x 2-3

Table 1.2: cont.

Study	Subjects	Classification of resistance training	Frequency of training	Intensity	Time	Type	Volume (reps x sets)
Ferrauti, Bergermann & Fernandez-Fernandez, (2010)	Moderately trained males + females	HWT	2/wk	87-93% 1RM	8 weeks	Leg press, knee extension, knee flexion, hip extension, ankle extension	3-5 x 4
Patoz et al. (2023)	Recreationally trained males + females	CPX (END + EXP + Sprt)	1-4/wk	BW	8 weeks	Lunge, step up, uphill run, squat, forward lunge, stair jump	20-40s x 2-4
		CPX (RST + Sprt)	1-4/wk	BW	8 weeks	Plyo lunge, plyo lateral step up, downhill run, bilat hop, alt bound, DJ	20-40s x 2-4
Ache-Dias et al. (2018)	Recreationally trained males + females	RST	2/wk	BW	4 weeks	Cont. CMJ	30s x 4-6
Willy & Davis (2011)	Recreationally trained females	END	2/wk	BW	6 weeks	Hip ext rot, hip abd, clamshells, pelvic hikes, sgl leg squat, side-band-walks	(5s hold x 10) x 2
Snyder et al. (2009)	Physically active females	END	3/wk	60% 1RM	6 weeks	Standing hip ext rot, standing hip int rot, weighted pelvic hikes	AMRAP x 1

Table 1.2: cont.

Study	Subjects	Classification of resistance training	Frequency of training	Intensity	Time	Type	Volume (reps x sets)
kovgaard et al. (2014)	Moderately trained males	CPX (EXP + Sprt)	2/wk	EXP: 4-15RM + Sprt: 100% max speed	8 weeks	EXP: Squat, deadlift, leg press + Sprt	EXP: 4-8 x 3-4 4 + Sprt: 30s x 3-4
Bonacci et al. (2011)	Moderately trained males + females	CPX (RST + END)	2-3/wk	RST: BW + END: 60%1RM	9 weeks	RST: CMJ, ankle jumps, alt bound, skipping, sgl leg ankle jump, cont jump, scissor jump + END: Leg press, knee lifts, squats, hamstring curl	6-20 x 1-5
Barnes et al. (2013)	Highly trained males + females	HWT	2/wk	Not prescribed, only guided	7-10 weeks	Squat, sgl leg calf raise, hamstring curl, box step up, deadlift, split squat, monster walk	3-10 x 2-4
		CPX (HWT + RST)	2/wk	HWT* + BW	7-10 weeks	HWT* + RST: Box jump, sgl leg hop, CMJ, alt leg bound	3-10 x 1-4
Millet et al. (2002)	Highly trained males + females	HWT	2/wk	>90%1RM or 3-5RM	14 weeks	Hamstring curl, leg press, seated press, parallel squat, leg extension, and heel raise	3-5 x 3-5
		CPX (RST + Sprt)	1-4/wk	BW	8 weeks	Plyo lunge, plyo lateral step up, downhill run, bilat hop, alt bound, DJ	20-40s x 2-4

Table 1.2: cont.

Study	Subjects	Classification of resistance training	Frequency of training	Intensity	Time	Type	Volume (reps x sets)
Piacentini et al. (2013)	Moderately trained males + females	HWT	2/wk	85-90% 1RM	6 weeks	Half squat, calf raise, lunges, eccentric quads exercise, leg press	3-4 x 4
Sedano et al. (2013)	Highly trained males	CPX (RST + END)	2-/wk	RST: BW + END: 70% 1RM	12 weeks	RST: Hurdle jumps, horizontal jump + END: Squat, prone leg curl, seated calf raises, seated leg extension	10 x 3
Hamilton, Paton & Hopkins' (2006)	Highly trained males	CPX (RST + Sprt)	1-3/wk	RST: BW + Sprt: 100% max speed	5-7 weeks	RST: Sgl leg 40cm DJ + Sprt	RST: 20 x 3 + Sprt: (30s x 5) x 3
	Moderately trained males	END	2/wk	BW	8 weeks	Squats, lunges; HWT squat, leg press	40-50s x 3
Mikkola et al. (2011)		HWT	2/wk	4-6RM	8 weeks	Squat, leg press	4-6 x 3
		CPX (HWT + RST)	2/wk	HWT* + RST: 0-40% 1RM & BW	8 weeks	HWT* + RST: SJ, cont SJ, scissor jumps	HWT* + 5-10 x 2

Table 1.2: cont.

Study	Subjects	Classification of resistance training	Frequency of training	Intensity	Time	Type	Volume (reps x sets)
Paavolainen et al. (1999)	Highly trained males	CPX (RST + END + Sprt)	<i>Not reported</i>	RST: BW + END: 0-40% 1RM + Sprt: 100% max speed	9 weeks	RST: Alt leg jumps, CMJ, DJ, hurdle jumps, sgl leg hops, 5jump test + END: Leg press, knee extension + Sprt: 20-100m sprints	RST: 30-200 jumps per session + END: 5-20 reps per set + Sprt: 5-10 sprints
Lundstrom, Betker & Ingraham (2017)	Moderately trained males + females	CPX (RST + Sprt)	1/wk	RST: BW + Sprt: 100% max speed	12 weeks	RST: Frog jumps, alt leg bounds, sgl leg hops, lateral jumps, forward/backward hops, SJ, scissor jumps, DepthJ, box jumps + Sprt: 30-60m	RST: 8-20 x 1-2 + Sprt: 2-4
Machado et al. (2019)	Recreationally trained males	RST (DJ-focused)	2/wk	BW	8 weeks	45cm DJ	30s x 6
		RST (SJ-focused)	2/wk	BW	8 weeks	Cont. SJ	30s x 6

Table 1.2: cont.

Study	Subjects	Classification of resistance training	Frequency of training	Intensity	Time	Type	Volume (reps x sets)
Eihara et al. (2024)	Recreationally-moderately trained males + females	RST	2/wk	BW	10 weeks	CMJ, 3-5 rebound jumps, dbl & sgl leg hurdle jumps, 20 & 30cm DJ	3-10 x 3-8
Wondem & Tegegne (2023)	Highly trained males + females	CPX (HWT + RST + Sprt)	3/wk	HWT: 60-90%1RM + RST: BW + Sprt: 100-120% of PTS	12 weeks	HWT: Squat, leg curl, calf raise + RST: hurdle jumps, alt leg bounds + Sprt: neutral – uphill sprints	HWT: 3-14 x 4-6 + RST: 10 x 6 + Sprt: 2- 2.5min/200m x 2-6

Note: HWT – heavy weight training; RST – reactive strength training; CPX – complex training; Sprt sprint training; END – muscular endurance training; CMJ – countermovement jump; SJ – squat jump; DJ – drop jump; DepthJ – depth jump; cont, SJ – continuous SJ; RM – repetitions maximum. The studies were listed in order of when they appear throughout the text.

1.4.2.2 *Reactive Strength and Explosive Power*

Reactive strength and explosive power are respectively described as one's ability to change from an eccentric to concentric muscular contraction quickly (stretch-shortening cycle (SSC)) (Young, 1995), and one's ability to develop maximal forces in minimal time (Zatsiorsky & Kraemer, 2007). Improvements in these muscle performance measures are usually tracked using the reactive strength index (RSI) or vertical jump heights. The RSI is commonly calculated as a ratio of the jump height and contact time during a DJ (Martinez, 2016). Similar to maximal strength adaptations, reactive strength and explosiveness also adapt through mechanisms of improved neural efficiency. However, in this case, it is unique to the SSC (Ache-Dias et al., 2015).

When COMB, HWT, and RST were pooled into a single meta-analysis, Trowell et al. (2020) found that concurrent training was not able to significantly improve jumping height (SMD = 0.22 [95%CI: -0.09, 0.52], small; $p = 0.17$) or RSI (0.48 [95%CI: 0.00, 0.95], small; $p = 0.05$). Prieto-González et al. (2024) went into further detail by explaining that in fact both HWT (Hedges $g = -0.50$ [95%CI: -0.97, -0.04]; ES = 0.24, small; $p = 0.035$) and RST/EXP (Hedges $g = -0.37$ [95%CI: -0.72, -0.02]; ES = 0.18, trivial; $p = 0.041$) had significantly better vertical jump outcomes than control groups. Furthermore, the findings of Ramirez-Campillo et al. (2021) further justify the use of RST within any training program (Hedges's $g = 0.36$ [95%CI: 0.17, 0.55], small; $p < 0.001$). These findings implied that RST in isolation or in combination with other training modalities had a small but significant effect on jump height (Ramirez-Campillo et al., 2021).

Even though a significant effect of CPX was not found on jump height in the meta-analyses, some interventions elicited significant performance effects. The CPX intervention that produced the greatest jump height (12.9%), and RSI (20.0%) improvements was developed by Li et al. (2019). Notably, this was also one of the few studies that found a significant group-by-time effect concerning jump height and RSI where CPX yielded significantly greater results than HWT (Li et al., 2019). Conversely, the most successful HWT was not able to match the jump height improvements (12.9% vs 10.3%) but did surpass Li et al.'s (2019) RSI scores (20.0% vs 24.0%) (Damasceno et al., 2015). This is not surprising, as strength-untrained participants improved jump height

performance irrespective of the strength-training prescription (De Villarreal, Izquierdo & Gonzalez-Badillo, 2011). It is thought that the principle of specificity – particularly the velocity-specific principle – does not apply to undertrained athletes. This hypothesis suggests that any stimulus (i.e. high-load and slow velocity, or low-load and high velocity) driving neuromuscular adaptation is sufficient to improve explosiveness in this undertrained/untrained population (Hakkinen, Komi & Alen, 1985).

As was outlined in the opening paragraph, athletes, coaches, and sports scientists are always striving for the best outcomes. Therefore, one cannot be content with simply “effective” interventions when exceptional results are the aim and goal. Therefore, despite the fact that any training modality may be beneficial for reactive strength improvements in strength-untrained populations, RST/EXP is still by far the most effective option. The best RST intervention improved RSI by 39.5% (ES = 0.2, small), nearly double that mentioned above (Andrade et al., 2018). Another RST study using a greater variety of exercises produced the greatest CMJ height improvements within the available research (13.2%) – this time within a moderately trained population (Spurrs, Murphy & Watsford, 2003). These discussions, as well as the meta-analytical finding that any type of RST training is significantly beneficial, are emphasised by a study solely investigating jump rope training. García-Pinillos et al. (2020) found that simply adding five minutes of SSC-specific jump rope training four times per week can also significantly improve jump height (10.5%) and RSI (13.0%). Therefore, it may be best to prescribe RST exercises that mimic the above interventions aiming to improve explosiveness and reactive strength in long-distance runners.

Despite the above, it must be noted that not all RST training is effective and thus emphasis must still be placed on evidence-based exercise prescription. In the Prieto-González et al. (2024) study, there were two RST interventions which pulled the overall effect size down into the trivial bracket. One of these studies was conducted by Pellegrino, Ruby & Dumke (2016) who found a 0% change in their intervention group after following a program like the Spurrs, Murphy & Watsford, (2003) intervention. There were two key changes that Pellegrino, Ruby & Dumke (2016) made to the original intervention that may have changed its efficacy. Firstly, the sample population was not similar since Pellegrino, Ruby & Dumke (2016) studied recreationally trained males and females, and

Spurrs, Murphy & Watsford, (2003) investigated moderately trained male runners. Secondly, Pellegrino, Ruby & Dumke (2016) also modified one of the key exercises that have been shown to improve the SSC - the depth jump (Flanagan & Comyns, 2008). The authors changed this exercise to focus on landing with a deep knee bend after jumping off a box, instead of focusing on quickly transferring force from eccentric to concentric contractions.

These findings further confirm the importance of SSC-specific exercises to improve jump performance in runners. Additionally, these findings also postulate that RST may be more effective for moderately compared to recreationally trained, and male compared to female athletes. Yet, according to meta-analysed results, there is no significant difference between explosive power improvements between sexes, strength training status or endurance training status (Huiberts, Wüst & van der Zwaard, 2024). Therefore, irrespective of which population is being dealt with the guidelines outlined above should be well-equipped to produce effective reactive-strength-focused improvements.

1.4.2.3 Running Gait Biomechanics

Now that the research regarding muscular performance factors has been detailed above, this section will discuss the effect that concurrent training has on running technique and biomechanics. Even though there is an understanding that strength training alone cannot significantly influence running technique (Snyder et al., 2009; Willy & Davis, 2011), in this section, the best strategies for improving running biomechanics will be outlined. Unfortunately, due to the limited breadth of research on this topic, accurate comparisons between sexes and training status could not be made. However, to still provide a holistic understanding of how to best improve running biomechanics, this section has been broken up into four: running spatiotemporal parameters, kinematics, kinetics, and neuromuscular factors.

When looking at running spatiotemporal parameters, the easiest variables to understand are stride frequency and stride length. Within distance running research, it is understood that stride length is more likely to increase in relation to increases in speed than stride frequency (García-Pinillos et al., 2019; García-Pinillos, Jerez-Mayorga, et al., 2020).

However, in the RST-focused meta-analysis by Ramirez-Campillo et al. (2021), RST was shown to improve speed but not stride length. So too, Trowell et al.'s (2020) biomechanics-focused review did not find concurrent training to have a significant influence on stride length (SMD = 0.55 [95%CI: -0.36, 1.45], small) or frequency (-0.46 [95%CI: -1.13, 0.22], small) when compared to controls. Yet, there was a significant effect on increasing ground contact time while running (SMD = 1.20 [95%CI: 0.23, 2.17], large). Practically this would not be beneficial for improving running technique or performance, as longer ground contact means shorter stride lengths, slower frequencies and slower speeds (Ferrauti, Bergemann & Fernandez-Fernandez, 2010). However, two other studies found CPX and RST to have moderate to small effects on step frequency and stride length, respectively. Patoz et al. (2023) found both END-CPX (Cohen's $d = 0.8$, large) and RST-CPX (Cohen's $d = 0.5$, moderate) to significantly increase step frequency, but only RST-CPX also significantly reduced ground contact time during running (Cohen's $d = 0.5$, moderate). The RST intervention developed by Ache-Dias et al. (2018) did not only find improvements in step frequency and ground contact time, but also in stride length, K_{vert} , and K_{leg} . Of these five variables, only ground contact time did not have a small possibly beneficial effect. Therefore, when using concurrent training for endurance runners, improvements in spatiotemporal running parameters may only occur when using RST or CPX which includes Sprt.

It is not only the Ache-Dias et al. (2015) continuous jumping protocol that had an impact on running kinetics. Much like how toe flexion exercise elicited greater vertical jump performance in a sample of healthy participants (Unger & Wooden, 2000), an intrinsic foot-strengthening protocol produced greater force during the toe-off phase while running (Matias et al., 2016; Taddei et al., 2020). The authors surmised that this may have been possible due to the foot being stabilised in a more biomechanically optimal position at toe-off post-training (Taddei et al., 2020). Feltner et al. (1994) set the basis for these findings by showing that eight weeks of isokinetic ankle exercises can reduce ankle inversion/eversion range during ground contact/heel strike.

Research that focuses on training other than foot and ankle exercises differs regarding their efficacy at changing running technique. Both Willy & Davis (2011) and Snyder et al. (2009) developed similar END hip strengthening protocols. However, only Snyder et al.

(2009) showed a significant reduction in foot eversion and hip internal rotation range of motion; as well as reduced ankle inversion and knee abduction moments during running. Only Snyder et al. (2009) prescribed weighted and individualised exercise. This highlights the importance of increased weight as a stimulus for adaptation, as well as individually prescribing weight for these exercises. Therefore, these findings explain that concurrent strengthening targeting distal or proximal musculature can be effective at improving running spatiotemporal, kinetic, and kinematic variables. Although distal musculature training may be most beneficial.

Neuromuscular running factors are the last set of running biomechanical variables to discuss and possibly the most confusing. Across this research, studies both support and refute certain inventions and outcomes. HWT has been shown to increase muscle cross-sectional area (Vikmoen et al., 2016) whereas CPX studies explain that concurrent training does not stimulate any muscle morphological changes over time (Skovgaard et al., 2014). Furthermore, according to systematically reviewed data, there was no influence of concurrent training on changes in muscular electromyography (Alcaraz-Ibañez & Rodríguez-Pérez, 2018) with only one study finding a significant effect (SMD = 2.1-2.9, large) (Bonacci et al., 2011). Likewise, there were conflicting findings regarding the efficacy of RST and HWT in improving musculotendinous stiffness. Spurrs, Murphy & Watsford (2003) suggested that RST significantly improves musculotendinous stiffness whereas an ISO program developed by Fletcher, Esau & MacIntosh (2010) did not elicit any positive changes.

Due to the limited breadth of the research on this topic, no direct inferences can be made from these data. However, what is currently known is that HWT may increase muscle CSA for females and improve hopping and running stiffness – especially when hamstring exercises are included (Millet et al., 2002; Barnes et al., 2013). This may be due to the increased strength, motor-unit recruitment and muscular coordination of the hamstrings during ground contact events. During these ground contact events, these neuromuscular adaptations may assist in ramping up the co-contraction between the quadriceps and hamstrings which is known to facilitate increased leg stiffness (Fiori et al., 2024). Lastly, it is also apparent that RST may facilitate improvements in musculotendinous stiffness especially of the triceps surae with lower limb stiffness

being linked to running efficiency and injury prevention. In conclusion, even though the idea exists that concurrent training alone may not change running technique, well-targeted exercise protocols have the potential to positively affect spatiotemporal, kinetic, kinematic, and neuromuscular factors within the running gait. Changes and improvements in these biomechanical factors have been found to benefit long-distance runners' injury prevention efforts and thus should not be dismissed (Šuc et al., 2022).

1.4.2.4 *VO₂max*

With all the relevant neuromuscular components of running performance discussed above, the following sections will explore how running physiological variables respond to concurrent training. VO₂max is one of the variables with a clear and resounding consensus. Across four different SRMAs, no significant changes in VO₂max have resulted from concurrent training (Trowell et al., 2020; Ambrosini et al., 2021; Huiberts, Wüst & van der Zwaard, 2024; Prieto-González et al., 2024). So too, no differences have been found between training regimens, sex, or training status (Trowell et al., 2020; Ambrosini et al., 2021; Huiberts, Wüst & van der Zwaard, 2024; Prieto-González et al., 2024). The key insight from these findings is that there is no deleterious effect on overall endurance fitness when engaging in concurrent training of any kind.

1.4.2.5 *Running Economy (RE)*

Interestingly, concerning RE, there seems to be a discrepancy in the findings from earlier (pre-2020) compared to more recent studies. The first three meta-analyses investigating the effects of concurrent training on RE came to the same conclusions (Balsalobre-Fernández, Santos-Concejero & Grivas, 2016; Berryman et al., 2017; Denadai et al., 2017). These authors agreed that – independent of the exercises included and after correcting for bias and heterogeneity – concurrent training had a significant effect on RE (Balsalobre-Fernández, Santos-Concejero & Grivas (2016): SMD = -1.06 [95%CI: -1.56, -0.56], $p < 0.001$; Berryman et al. (2017): SMD = 0.65 [95%CI: 0.32, 0.98]; Denadai et al. (2017): %Δ = -4.8% [±95% Confidence limits (CL): ±1.3], $p < 0.001$). Denadai et al. (2017) did not find significant differences between training types. However, only the pooled

effects of EXP and HWT interventions significantly improved RE. This directly contradicts the most recent meta-analysis that found no significant effect of any type of concurrent training on RE (Prieto-González et al., 2024).

These discrepancies in findings between the reviews may not stem from changes in the literature over time but from the methodological differences between the reviews. The earlier reviews took the change in RE over time into account by using SMD or % Δ (Balsalobre-Fernández, Santos-Concejero & Grivas, 2016; Berryman et al., 2017; Denadai et al., 2017) whereas Prieto-González et al. (2024) used Hedges's g to compare intervention and control groups at baseline and post-intervention, independently. Therefore, in the more recent review, differences that exist between intervention and control groups at baseline may mask significant improvements in RE achieved within the intervention groups over time (Prieto-González et al., 2024). To account for these methodological differences three other SRMA published between 2022–2024 further detailed the effect of different concurrent training regimens on RE. These authors also used the more robust Hedges's g meta-analytical approach but took the change over time into account (Eihara et al., 2022; Barrio et al., 2023; Llanos-Lagos et al., 2024).

These more recent reviews also challenge the longer-standing findings by disagreeing that all concurrent training can have a significant and beneficial impact on RE. These more recent studies show that there is a hierarchy when picking the best training regimen for improving RE in long-distance runners (Eihara et al., 2022; Barrio et al., 2023; Llanos-Lagos et al., 2024). Eihara et al. (2022) only investigated the differences between HWT and RST/EXP and reported HWT to be the superior training modality (HWT: Hedges's $g = -0.32$ [95%CI: -0.55, -0.10], ES = small; vs. RST: Hedges's $g = -0.13$ [95%CI: -0.47, 0.21], ES = trivial). Llanos-Lagos et al. (2024) then clarified that combining training modalities may in fact be the best training strategy (CPX: Hedges's $g = -0.43$ [95%CI: -0.77, -0.08], $p = 0.018$; vs. HWT: Hedges's $g = -0.27$ [95%CI: -0.52, -0.02], $p = 0.039$). These studies also reported non-significant findings for RST/EXP interventions and their effect on RE (Eihara et al., 2022; Llanos-Lagos et al., 2024). However, understanding that RST most closely mimics the muscle contractions and biomechanics of running, Barrio et al. (2023) explored this training modality further.

The “specificity” exercise training principle states that training should represent competition and that more representative training will translate to greater competitive improvements (Pleša et al., 2022). Since isolated RST showed little impact on RE, Barrio et al. (2023) took a different approach by investigating any intervention using RST-type exercises (RST, RST/EXP, CPX). Indeed, the authors found that overall, improvements recorded in RE significantly favoured intervention groups (using any RST-type exercises) compared to control groups (Hedges's $g = 0.60$ [95%CI: 0.07, 1.14], $p = 0.027$; $n = 10$). Furthermore, this study also confirmed that RST-based CPX protocols, had the largest effect size noted in the literature when compared to controls (Hedges's $g = 1.34$ [95%CI: 0.09, 2.59], $p = 0.036$; $n = 4$). Therefore, it may not be that older and more recent reviews contradicted one another but that more recent reviews explained RE improvements elicited by concurrent training in more detail. One can thus appreciate that – barring the Prieto-González et al.'s (2024) unique analysis of the research – concurrent training can have a positive effect on RE. Additionally, it should now be clear that not only is CPX the superior training strategy for improving RE, but more specifically RST-based CPX.

To practically understand how to implement concurrent training in the ‘real world’ the training protocols that elicited the greatest RE improvements are listed below. The two studies that produced the largest ES in comparison to control groups, and the greatest percentage change from baseline are also RST-based CPX protocols (Sedano et al., 2013; Patoz et al., 2023). Patoz et al. (2023) observed the highest ES and percentage change in the literature, specifically in their high-responders RST-based CPX group (ES = 1.8, very large; $\% \Delta = -7.0$). Aside from producing the greatest RE improvements, this study also provided a new perspective on selecting appropriate concurrent training strategies for athletes. By showing the differences between high- and low-responders, this study highlights the fact that athletes can respond differently to a given training stimulus even when descriptively, they are from a similar population (age, sex, training status, etc.) (Mann, Lamberts & Lambert, 2014; Patoz et al., 2023). The nuance that these discussions add to the exercise prescription decision-making process, is that training programs may first need to be trialled on athletes to understand what they best respond to. It must be noted that this RST-based CPX protocol is not only beneficial for recreationally trained runners. In an elite male-only cohort, Sedano et al. (2013) recorded

the second-highest ES in relation to control groups (ES=1.2, large; $\% \Delta = -3.0\%$). However, Llanos-Lagos et al. (2024) determined that HWT may elicit RE changes at faster speeds compared to RST (Llanos-Lagos et al., 2024). This could be due to RST being more beneficial for recreational athletes who have not developed a maximally effective SSC yet and who thus run at slower speeds. Highly trained athletes who already run at faster speeds with greater SSC return, may not benefit from further SSC-targeted RST training. These athletes already run with and utilise their SCC efficiently and may need a different physiological stimulus from HWT to drive RE changes. One can reconcile these studies by recommending that any RST-based CPX program be used for recreational runners, whereas RST-based CPX must include HWT for more elite runners.

Additionally, sex as another moderating variable was not found to have an impact on concurrent training-elicited RE changes when comparing ES (Llanos-Lagos et al., 2024). For the sake of this review, we pooled percentage change scores from studies that exclusively recruited a single sex as their sample population (see *Table 1.3, 1.4, 1.5*). Across HWT, RST, and CPX we found that males recorded greater percentage changes than females. Therefore, even though runners with different training statuses may respond similarly to CPX training, one needs to be cognisant that female athletes may not improve their RE as efficiently as male athletes during a concurrent training program. Lastly, Eihara et al. (2022), Barrio et al. (2023), and Llanos-Lagos et al. (2024) outline the volume and duration of concurrent training that should be prescribed to effectively improve RE. These authors agree that even though session number per week and total number of weeks were not significant variables, the overall total number of sessions is a key factor (Eihara et al., 2022; Barrio et al., 2023; Llanos-Lagos et al., 2024). More sessions with a greater volume resulted in larger RE improvements (Eihara et al., 2022; Barrio et al., 2023; Llanos-Lagos et al., 2024). In conclusion, when aiming to improve RE – one of distance running’s most important physiological variables – one should focus on RST-based CPX training after assessing your athlete’s training preferences. One also needs to be cognisant of the sex and training status of an athlete(s) being trained and should aim to increase the session number and total volume over time for the best results.

Table 1.3: Descriptive characteristics of HWT studies that investigated RE for male and/or female athletes.

Study (Males)	Sample Size	Study weight	Pre RE (SD)	Post RE (SD)	Percentage change
Barnes et al. (2013)	13	16%			-1,7
Berryman, Maurel & Bosquet (2010a)	12	15%	207ml.kg ⁻¹ .km ⁻¹ (15,0)	199,0ml.kg ⁻¹ .km ⁻¹ (12,0)	-3,9
Damasceno et al. (2015a)	9	11%	42,5ml.kg ⁻¹ .min ⁻¹ (3,1)	41,9ml.kg ⁻¹ .min ⁻¹ (4,0)	-1,4
Li et al. (2019a)	9	11%	59,6ml.kg ⁻¹ .min ⁻¹ (3,0)	57,8ml.kg ⁻¹ .min ⁻¹ (4,11)	-2,9
Mikkola et al. (2011)	11	13%	218ml.kg ⁻¹ .km ⁻¹ (10,0)	219ml.kg ⁻¹ .km ⁻¹ (11,0)	0,5
Millet et al. (2002)	7	9%	193,6ml.kg ⁻¹ .km ⁻¹ (4,3)	180,3ml.kg ⁻¹ .km ⁻¹ (20,0)	-6,9
Skovgaard et al. (2014a)	12	15%	195ml.kg ⁻¹ .km ⁻¹ (4,0)	189ml.kg ⁻¹ .km ⁻¹ (4,0)	-3,1
Vorup et al. (2016)	9	11%	54,7ml.kg ⁻¹ .min ⁻¹ (6,0)	52,5ml.kg ⁻¹ .min ⁻¹ (4,6)	-4,0
Total	82	100%	-	-	2,7
Study (Females)	Sample Size	Study weight	Pre RE (SD)	Post RE (SD)	Percentage change
Barnes et al. (2013)	9	33%	-	-	-1,1
Kelly, Burnett & Newton (2008)	7	26%	27,5ml.kg ⁻¹ .min ⁻¹ (3,6)	29,3ml.kg ⁻¹ .min ⁻¹ (2,6)	1,7
Vikmoen et al. (2016)	11	41%	45,8ml.kg ⁻¹ .min ⁻¹ (1,7)	46,1ml.kg ⁻¹ .min ⁻¹ (1,7)	0,3
Total	27	100%	-	-	0,8

Note: Data are represented as means with standard deviations (SD) where available

Table 1.4: Descriptive characteristics of RST studies that investigated RE for male and/or female athletes.

Study (Males)	Sample Size	Study weight	Pre RE (SD)	Post RE (SD)	Percentage change
Berryman, Maurel & Bosquet (2010a)	11	23%	218,0ml.kg ⁻¹ .km ⁻¹ (16,0)	203,0ml.kg ⁻¹ .km ⁻¹ (13,0)	-6,9
do Carmo et al. (2023)	15	31%	226,1ml.kg ⁻¹ .km ⁻¹ (18,4)	215,9ml.kg ⁻¹ .km ⁻¹ (17,7)	-4,5
Lum et al. (2023a)	7	15%	45,3ml.kg ⁻¹ .min ⁻¹ (1,8)	44,6ml.kg ⁻¹ .min ⁻¹ (2,3)	-1,5
Saunders et al. (2006)	7	15%	3,7L.min ⁻¹ (0,5)	3,6L.min ⁻¹ (0,5)	-3,8
Spurrs, Murphy & Watsford (2003)	8	17%	33,35ml.kg ⁻¹ .min ⁻¹ (5,15)	32,2ml.kg ⁻¹ .min ⁻¹ (4,3)	-3,4
Total	48	100%	-	-	-4,3
Study (Females)	Sample Size	Study weight	Pre RE (SD)	Post RE (SD)	Percentage change
Štohanzl, Baláš & Draper (2017) RST30 [RE @ VT2]	9	15%	28,9ml.kg ⁻¹ .min ⁻¹ (2,7)	28,4ml.kg ⁻¹ .min ⁻¹ (2,6)	-1,7
Štohanzl, Baláš & Draper (2017) RST30 [RE @ 7km/h]	9	15%	28,1ml.kg ⁻¹ .min ⁻¹ (2,5)	26,8ml.kg ⁻¹ .min ⁻¹ (3,1)	-4,6
Štohanzl, Baláš & Draper (2017) RST30 [RE @ 9km/h]	9	15%	33,1ml.kg ⁻¹ .min ⁻¹ (2,7)	32,1ml.kg ⁻¹ .min ⁻¹ (3,1)	-3,0
Štohanzl, Baláš & Draper (2017) RST60 [RE @ VT2]	11	18%	31,2ml.kg ⁻¹ .min ⁻¹ (3,5)	30,8ml.kg ⁻¹ .min ⁻¹ (3,5)	-1,3
Štohanzl, Baláš & Draper (2017) RST60 [RE @ 7km/h]	11	18%	24,6ml.kg ⁻¹ .min ⁻¹ (4,2)	23,6ml.kg ⁻¹ .min ⁻¹ (4,9)	-4,1
Štohanzl, Baláš & Draper (2017) RST60 [RE @ 9km/h]	11	18%	29,0ml.kg ⁻¹ .min ⁻¹ (5)	28,6ml.kg ⁻¹ .min ⁻¹ (5,3)	-1,4
Total	60	100%	-	-	-2,6

Note: Data are represented as means with standard deviations (SD) where available

Table 1.5: Descriptive characteristics of CPX studies that investigated RE for male and/or female athletes.

Study (Males)	Sample Size	Study weight	Pre RE (SD)	Post RE (SD)	Percentage change
Barnes et al. (2013)	10	22%	-	-	-0,2
Li et al. (2019a)	10	22%	60,8ml.kg ⁻¹ .min ⁻¹ (4,2)	56,1ml.kg ⁻¹ .min ⁻¹ (2,6)	-7,7
Mikkola et al. (2011)	10	22%	212,0ml.kg ⁻¹ .km ⁻¹ ¹ (17)	210,0ml.kg ⁻¹ .km ⁻¹ ¹ (16)	-0,9
(Paavolainen et al., 1999)	10	22%	51,8ml.kg ⁻¹ .min ⁻¹ (1,2)	47,8ml.kg ⁻¹ .min ⁻¹ (1,3)	-7,7
Sedano et al. (2013)	6	13%	50,9ml.kg ⁻¹ .min ⁻¹ (0,9)	49,5ml.kg ⁻¹ .min ⁻¹ (1,0)	-3,0
Total	46	100%	-	-	-4,0

Study (Females)	Sample Size	Study weight	Pre RE (SD)	Post RE (SD)	Percentage change
Barnes et al. (2013)	10	63%	-	-	-1,0
Johnston et al. (1997)	6	38%	44,5ml.kg ⁻¹ .min ⁻¹ (1,0)	42,8ml.kg ⁻¹ .min ⁻¹ (1,1)	-3,8
Total	16	100%	-	-	-2,1

Note: Data are represented as means with standard deviations (SD) where available

1.4.2.6 Fractional Utilisation

The third oxygen-dependent running physiological factor to be discussed is a combination of both VO₂max and RE. Despite the importance of fractional utilisation – as described above – there is sparse literature concerning this factor. This is likely due to there not being a standardised testing protocol for this metric. When there are no gold standard testing protocols for certain measurements, the test's reproducibility across studies is very difficult. In situations like these, researchers tend to neglect these factors as they may not be comparable to previous or future studies. That being said, there is no systematically reviewed or meta-analysed data concerning the effect of concurrent

training on fractional utilisation. Of the two studies that measured fractional utilisation in the literature, neither found HWT to be beneficial (Ferrauti, Bergermann & Fernandez-Fernandez, 2010; Vikmoen et al., 2016). Concurrent training does not affect $VO_2\text{max}$ and the RE improvements it produces are often subtle. This, therefore, may not be sufficient to trigger significant changes in fractional utilisation. However, these findings are likely not because concurrent training does not affect fractional utilisation, but simply due to the extant literature. Therefore, more research is needed before making any concrete inferences regarding the effect of concurrent training on fractional utilisation in long-distance runners.

1.4.2.7 Onset of Blood Lactate Accumulation (OBLa)

As mentioned above the lactate threshold (LT) or OBLa often plays a key role in accurately prescribing training and racing speeds (Faude, Kindermann & Meyer, 2009). In seminal endurance research investigating cyclists, training at speeds above that which corresponds to the LT increased BLA adaptation (Jacobs et al., 1987; Burgomaster, Heigenhauser & Gibala, 2006). It was thus hypothesised that resistance training that mimics the cardiometabolic stress of this type of high-intensity exercise (HIIT) could improve BLA mechanics. The hypothesis was that exercise should be prescribed with low loads, high reps, and shortened recovery times (Blagrove, Howatson & Hayes, 2018). Indeed, RST-type exercise – that closely resembles this type of exercise prescription – was found to reach the same cardioventilatory thresholds and stimulated the same heart rate and blood pressure responses as HIIT (Arazi et al., 2014; Ducrocq et al., 2019). Performing DJs at a rate of 36 jumps per minute resulted in energy consumption greater than $90\%VO_2\text{max}$ (Ducrocq et al., 2019). This type of training was initially implemented with cyclists in 1991 and was one of the first studies to prove concurrent-training-elicited BLA adaptations in endurance athletes (Marcinik et al., 1991).

In 2024, Prieto-González et al. (2024) found no significant effect of any type of concurrent training on LT or BLA mechanics. Even though there were no significant differences compared to controls, the authors observed that all three HWT intervention groups showed LT improvements (Støren et al., 2008; Ferrauti, Bergermann & Fernandez-Fernandez, 2010; Mikkola et al., 2011). Yet only one out of the three RST/EXP intervention groups was

able to show this type of improvement (Paavolainen et al., 1999; Spurrs, Murphy & Watsford, 2003; Mikkola et al., 2011). When looking at RST-type studies specifically, Ramirez-Campillo et al. (2022) confirmed the above findings. These authors found a small but non-significant effect of RST-type concurrent training on BLA mechanics. Therefore, it must be acknowledged that concurrent training has little to no benefit on BLA mechanics in long-distance runners. Blagrove, Howatson & Hayes (2018) hypothesised that RE can thus improve independently without changes in metabolism since concurrent training tends to improve RE without any changes in BLA.

1.4.2.8 *PTS and vVO_2max*

Now that the discussion concerning the oxygen-dependent running physiological factors is concluded, the discussion can focus on oxygen-independent factors. To maintain conciseness, PTS and vVO_2max have been collapsed into one subsection. The differences and similarities between these metrics have been discussed above and need to be brought to the forefront of one's mind when reading through this section. Much like the BLA results, all studies that measured PTS reported improvements in their intervention groups. However, these changes were not significantly different to controls (Prieto-González et al., 2024). Three HWT (Berryman, Maurel & Bosquet, 2010a; Barnes et al., 2013; Taipale et al., 2013; Damasceno et al., 2015), four CPX (Barnes et al., 2013; Sedano et al., 2013; Taipale et al., 2013, 2014), and two RST/EXP studies (Berryman, Maurel & Bosquet, 2010a; Taipale et al., 2013) showed improvements in PTS from baseline to post-testing. An earlier published review grouped three studies that assessed vVO_2max specifically (Blagrove, Howatson & Hayes, 2018). Only one (Millet et al., 2002) of the three studies (Millet et al., 2002; Mikkola et al., 2007; Vikmoen et al., 2016) recorded improvements in vVO_2max . Similarly, Ramirez-Campillo et al.'s (2021) RST-focused SRMA found no significant effect of any type of RST on vVO_2max or PTS (Hedges's $g = 0.19$ [95%CI: -0.09, 0.47], ES=trivial; $p = 0.186$; $n=9$).

Across the existing research, only three studies logged significant group-by-time effects or between-group differences – all of which only measured PTS (Mikkola et al., 2011; Sedano et al., 2013; Damasceno et al., 2015). Mikkola et al. (2011) registered the greatest percentage change (4.8%) as well as the largest ES (0.94, large) in their END group. This

study's CPX (2.0%; ES = 0.39, small) and HWT (1.3%; ES = 0.56, moderate) also produced significant but smaller changes in PTS (group-by-time (GxT) effect: $p = 0.002$; ES = 0.43, small). Sedano et al. (2013) produced similar results by also showing the efficacy of CPX (4.6%; ES = 0.61, moderate) and END (3.7%; ES = 0.87, large) at eliciting significant PTS adaptations (GxT: $p < 0.05$). Like BLa, PTS is also trained using HIIT-type exercises. Thus, as mentioned above, END-type training (low load, high reps, and shortened rest) that mimics HIIT's cardioventilatory responses may be sufficient to improve PTS (Mikkola et al., 2011). Additionally, PTS also links to neuromuscular and biomechanical efficiency. CPX may, therefore, be able to boost PTS improvements since it can successfully target neuromuscular and biomechanical factors. Even though this is the first outcome variable where END has shown superiority, CPX may still be the more practical option to target the long-distance runner holistically.

Only one intervention study addressed the differences between the sexes (Barnes et al., 2013). For both males and females, there was no difference in the degree to which HWT or CPX increased $\dot{V}O_2\text{max}$. However, there was a small possible chance that HWT was more effective at improving PTS in females (HWT: 4.4% (SD: 3.9) vs. CPX: 2.2% (3.7)) compared to a small likely chance that HWT was more effective for males (HWT: 4.6% (SD: 4.5) vs. CPX: 1.0% (3.7)). The conclusion made here by the authors was that during the competitive phase of the training year, CPX should be avoided for males but may be used for female athletes (Barnes et al., 2013). Yet, another study investigating well-trained male athletes found a larger (2.6%) significant very likely benefit of RST on PTS during the competitive season (Hamilton, Paton & Hopkins, 2006). Hamilton, Paton & Hopkins (2006) prescribed a lower training volume than the Barnes et al. (2013) protocol. Therefore, END or CPX protocols should be prescribed to improve PTS and $\dot{V}O_2\text{max}$ in long-distance runners, with careful consideration of training load during the competitive season, particularly when working with male athletes.

1.4.2.9 *MART and Sprint Speed*

Again, due to the limited extent of the research on this topic, both MART and sprint data were combined into one section. Despite the importance of MART being explained above, research studies are yet to include this test as part of the standardised

assessment of runners. This is likely because the test was only really accepted as a valid and useful assessment tool (Nummela et al., 2006). The hope is that in the coming years, researchers acknowledge the importance of this tool as has happened with VO_2 max and RE treadmill-based tests.

To date, only two studies investigating the effects of concurrent training in healthy adults have used the MART in their testing protocol (Paavolainen et al., 1999; Mikkola et al., 2011). Paavolainen et al. (1999) who investigated elite male runners, tested a CPX program incorporating RST, END, and Sprrt and recorded the largest ES (1.98, very large) between the studies. In the second study, only their HWT group produced a significant change in vMART (2.6% (SD: 2.7); ES=0.52, moderate; $p = 0.012$) but was not statistically different from their CPX and END groups (Mikkola et al., 2011). Even though Mikkola et al.'s (2011) CPX protocol included exercises like the RST and END exercises in Paavolainen et al.'s (1999) protocol, it did not produce significant results. The improvement in MART outcomes is thus likely the result of the sprint training in the Paavolainen et al. (1999) program, and the HWT-elicited neuromuscular changes in the Mikkola et al. (2011). Therefore, sprint-focused CPX and HWT are effective at improving vMART. Future research should investigate whether a combination of these modalities could produce even greater outcomes.

To our knowledge, all the concurrent training studies that tested sprint speed were included in the SRMA evaluating RST-based protocols (Ramirez-Campillo et al., 2021). These authors included six RST-based studies (Paavolainen et al., 1999; Ramírez-Campillo et al., 2014a; Chelly, Hermassi & Shephard, 2015; Lundstrom, Betker & Ingraham, 2017; Blagrove et al., 2018; Li et al., 2019). These six studies assessed sprinting speeds across distances from 20 to 200 metres. Ramirez-Campillo et al. (2021) found a significant small effect of RST on sprinting speeds (Hedges's $g = 0.38$ [95%CI: 0.03, 0.72]; $p = 0.031$). Of these six studies, again, Paavolainen et al. (1999) recorded the largest ES (0.77, moderate) within their CPX intervention group for maximum speed reached in 20 metres. In close second is the Lundstrom, Betker & Ingraham (2017) study (males: SMD = 0.73 vs. females: SMD = 0.14) which also tested a Sprrt-based CPX intervention. Their male participants produced the greatest improvements in the 200-metre dash across all concurrent training research (males: -8.6% vs. females: -4.1%).

Even though there is a large difference between the sexes in this study (Lundstrom, Betker & Ingraham, 2017), another study testing RST found equivocal improvements in 20-metre sprinting speed between male and female athletes (Ramírez-Campillo et al., 2014a). Thus, no moderating effects of sex can be inferred regarding MART and sprinting changes elicited by concurrent training. These results demonstrated that CPX – incorporating RST and Spirt – best improves sprinting speed and vMART in long-distance runners.

1.4.2.10 Time Trial Performance

The most important factor in this review is understanding whether there is a “real-life” practical improvement in running performance elicited by concurrent training. This is where TT takes centre stage. The most recent SRMA only found CPX to have a significantly greater impact on TT than control groups at post-testing (Hedges’s $g = 3.07$ [95%CI: 0.59, 5.56]; ES = 1.27, very large; $p = 0.015$) (Prieto-González et al., 2024). Keep in mind the limitations of the interpretations of this Prieto-González et al. (2024) review discussed above. Eihara et al. (2022) ratified the lack of significant HWT and RST findings by reporting small but nonsignificant and significant but trivial effects of HWT (Hedges’s $g = -0.24$ [95%CI: -1.04, 0.55]) and RST (Hedges’s $g = -0.17$ [95%CI: -0.27 – -0.06]) on TT, respectively. The only study across both modalities that produced a moderate ES (SMD = 0.52) cannot be ignored and will be discussed below (Machado et al., 2019).

Despite limited significant meta-analytical results, Alcaraz-Ibañez & Rodríguez-Pérez (2018) observed TT improvements in nine out of ten intervention groups in their SRMA (HWT: (Damasceno et al., 2015); EXP: (Berryman, Maurel & Bosquet, 2010a); RST: (Spurrs, Murphy & Watsford, 2003; Berryman, Maurel & Bosquet, 2010a; Ramírez-Campillo et al., 2014a); CPX: (Paavolainen et al., 1999; Hamilton, Paton & Hopkins, 2006; Sedano et al., 2013; Skovgaard et al., 2014)). The only study not to register significant changes in TT investigated elite female duathletes (cycling + running) using a 40-minute TT (Vikmoen et al., 2016).

Furthermore, Ramirez-Campillo et al. (2021) showed a significant moderate effect of any RST-based concurrent training on TT (Hedges’s $g = 0.88$ [95%CI: 0.22, 1.54]; $p = 0.009$).

These significant findings from Alcaraz-Ibañez & Rodríguez-Pérez (2018), Ramirez-Campillo et al. (2021), and Prieto-González et al. (2024) suggest that– yet again – RST-based CPX may be the most beneficial modality for improving TT in long-distance runners.

The study that produced the largest change in TT from baseline to post-testing (% Δ in 2kmTT = 22.4%; ES = 0.31, small) employed a simple DJ-based RST with recreationally trained male and female runners (Andrade et al., 2018). Another study that also observed a significant GxT effect for this type of RST intervention recorded an even larger ES (DJ-focused: ES=1.00, large; % Δ in 5kmTT=11.6% & SJ-focused: ES=0.62, moderate; % Δ in 5kmTT=9.3%) (Machado et al., 2019). However, the lower methodological quality of this study and its participants' training status (endurance training: 3-4/week, 5kmTT: < 25min, training history: limited, BMI: >25, overweight) must be noted. (Eihara et al., 2024) attempted similar RST training to the Machado et al. (2019) protocol but changed the volume, exercise intensity, and inter-set rest intervals. Even though more overall volume was prescribed in the Eihara et al. (2024) program, the intensity compared to Machado et al. (2019) was much lower. Eihara et al. (2024) prescribed the DJ from lower heights, with longer recovery periods (2min vs 30sec), and with less time jumping per set (6-18sec vs 30sec) when compared to Machado et al.'s (2019) prescription technique. It is likely the reduction in neuromuscular and cardioventilatory stress that resulted in limited transference over to running performance in Eihara et al.'s (2024) study. This highlights the importance of accurately and meticulously prescribing exercise that correctly targets physiological adaptations in long-distance runners.

Above, we have outlined the most beneficial form of concurrent training for TT improvements. However, these interventions were only trialled on recreational runners. The two CPX studies that reaped the greatest improvements in TT performance conducted their study on well-trained and elite runners (Sedano et al., 2013; Wondem & Tegegne, 2023). Sedano et al. (2013) observed a significant GxT effect with the largest CPX ES (3kmTT: ES = 0.69, moderate). 10 years later, Wondem & Tegegne (2023) modified Sedano et al.'s (2013) approach by adding SpRT to the END- and RST-based CPX protocol, as well as increasing the intensity from END to HWT. This newly developed CPX training program also recorded a significant GxT effect in relation to its control groups. Most

importantly it elicited the largest improvements in TT performance of any CPX (% Δ in 5kmTT = -7.2%; $p < 0.001$; ES = 4.53, very large). Over 12 weeks, Wondem & Tegegne (2023) was able to improve their CPX group's 5kmTT by more than 30 seconds. Therefore, from the above results, it is clear that RST-based training – with the correct intensities – can produce substantial improvements in TT performance for recreational athletes. It also seems that CPX-type training is needed to stimulate significant effects in TT performance in well-trained and elite runners. When prescribing CPX protocols for your more elite runners, RST-based CPX should be used to guarantee one is reaping the greatest TT performance for long-distance runners.

1.4.3 Summarising concurrent training best practice

The purpose of this summary is not to recap the best modality for each neuromuscular and running outcome. Rather it is to understand which modality can holistically effectively train a long-distance runner. It is to understand which modality positively affects as many components of physical fitness and running performance as possible. Furthermore, it aims to collate the more specific prescription strategies for this modality by referring to the FITT-VP principles. Lastly, it also serves to outline whether factors like sex and training status should play a role in one's exercise prescription decision-making matrix or not.

Seven of the ten outcomes mentioned above have all classified CPX as superior in some form or another. More specifically, several metrics also noted RST-based CPX as the most beneficial modality. Only PTS, kinetic and kinematic changes favoured END, with neuromuscular running factors favouring RST, as well as maximal strength development favouring HWT. Therefore, unless the goal of one's training program is something specific, it may be most practical to develop a CPX or RST-based CPX for endurance running athletes. When developing a CPX protocol one should not need to uniquely prescribe exercises depending on the sex of the athlete. However, it may be useful to test which type of exercises in the CPX program your athlete best responds to, before finalising your training program. Furthermore, one needs to be cognisant of the training status of your athlete especially when targeting TT performance. The data showed that

less may be more when dealing with recreational runners, but that high-intensity CPX is needed for more elite athletes.

“Intensity” and “Type” of training from the FITT-VP principles have been addressed above. However, more specific guidelines for “Frequency”, “Time”, “Volume”, and “Periodisation” can be found in an astute summary of concurrent training prescription techniques by Barrie (2020). As explained in the RE section one should not set strict prescription rules concerning frequency and time/duration. One should simply ensure that the concurrent training stimulus has been applied sufficiently. More sessions mean greater impact and benefit for running performance. Denadai et al. (2017), Blagrove, Howatson & Hayes (2018), and Ramirez-Campillo et al. (2021) all explain that using anywhere between 1-3 sessions per week is acceptable. Therefore, in general, two sessions per week for a full 12-week training cycle would be the most practical. Studies to date, have yet to answer whether the number of sessions can inevitably accumulate to produce positive results, or whether a plateauing effect emerges. Therefore, future studies must address the time-course of these adaptations to ensure more rigorous guidelines concerning “Time” can be developed.

As Barrie (2020) has highlighted, following the accepted “Volume” prescriptions for the respective training modalities can simply be followed for concurrent training as well. For example, HWT guidelines are high weight with low reps and RST being BW or low weight with higher reps. However, one can further refine RST by making sure each rep is completed in two seconds and that each set is performed for a minimum of 30 seconds (Machado et al., 2019; Andrade et al., 2021) . These types of nuances in exercise prescription are not described in the literature for other modalities like HWT, END, and EXP.

Most concurrent training studies did not classify what “Period” of the training cycle the intervention was implemented. Many studies simply speak of “regular training” and do not mention real-life performance or competitive racing results. What Barrie (2020) has recommended concerning periodisation is based on a handful of studies and general training guidelines (see *Appendix 1*). For elite athletes – especially male athletes – high volumes of HWT or CPX may be detrimental to race performance (Barnes et al., 2013). However, isolated RST at lower volumes during the competitive phase of a season is still

beneficial (Hamilton, Paton & Hopkins, 2006). During, or leading up to these competitive periods, athletes tend to increase their race-paced training load (Haugen et al., 2022). Therefore, RST's high cardioventilatory stimulus above $VO_2\text{max}$ which mimics this race-pace type training may result in its added benefit during this training phase (Arazi et al., 2014; Ducrocq et al., 2019). Furthermore, the tapering of "Volume" and "Intensity" that Barrie (2020) uses across the training season can be traced back to the fatiguing effects of exercise on competitive performance. In team-sport athletes, it is recommended to taper the volume and load of plyometric training pre-competition to avoid deleterious effects on competitive performance (Lievens, Bourgois & Boone, 2021). Many of the concurrent training HWT protocols prescribed training until failure in each set. According to Morán-Navarro et al. (2017) avoiding training to failure in the competitive training cycle will also avoid residual fatigue from impacting one's competitive advantage. Thus, in a long-distance running concurrent training program, "Volume" and "Intensity" should undulate depending on the proximity of a competitive phase. To date, no analysis has been done to analyse the most effective periodisation strategy. Therefore, more research is needed comparing different periodisation techniques at different points in the macrocycle before concrete recommendations can be made in this regard. In conclusion, one should follow the above guidelines and recommendations when attempting to develop a concurrent training program for long-distance runners. These recommendations and guidelines will ensure the development of an evidence-based program primed to guide athletes to greater running performances.

1.5 Placing the Puzzle Pieces Perfectly: Correlations and Mechanistic Pathways

Above we have outlined guidelines for concurrent training best practice in long-distance runners. Yet there are still pieces of this puzzle missing – the *why* and *how*. *Why* does RST-based CPX seem to be the most effective training modality, and *how* does it impact running performance differently from other less effective modalities? The effectiveness of CPX may practically and clinically make sense. Within conditioning, rehab, and sports medicine, there is seldom one specific unique exercise, technique or treatment modality

that far out-performs other available options. CPX provides the option of creating multiple different training stimuli to target various performance-enhancing effects. Thus, this “shotgun” or “cumulative” approach makes the most practical sense (Llanos-Lagos et al., 2024). However, from a scientific physiological point of view, we are still very much in the dark.

Beattie (2019) identified that resistance training primarily affects two running physiological factors that influence running performance. One is an increase in maximal running speeds, and the other is an improvement in RE. These facilitate the capacity to run faster absolute speeds during competition, as well as being able to sustain faster submaximal speeds for extended periods of time. The mechanisms underpinning these running physiological improvements elicited by concurrent training have been hypothesised several times in the literature (Balsalobre-Fernández, Santos-Concejero & Grivas, 2016; Denadai et al., 2017; Trowell et al., 2020; Ramirez-Campillo et al., 2021; Šuc et al., 2022; Llanos-Lagos et al., 2024).

These mechanistic hypotheses are primarily based on the seminal works of Paavolainen et al. (1999). These authors described the concept that anaerobic power and capacity combined with neuromuscular efficiency played a core role in how resistance training transfers over to running performance. The first hypothesis is based on the capacity of concurrent training to increase motor unit recruitment, improve muscular coordination (Balsalobre-Fernández, Santos-Concejero & Grivas, 2016; Denadai et al., 2017; Trowell et al., 2020; Llanos-Lagos et al., 2024), influence muscle coactivation (Balsalobre-Fernández, Santos-Concejero & Grivas, 2016; Trowell et al., 2020), and preferentially favour more efficient type 1 muscle fibres (Balsalobre-Fernández, Santos-Concejero & Grivas, 2016; Trowell et al., 2020; Llanos-Lagos et al., 2024) which in turn enhances endurance runners’ neuromuscular efficiency. These neuromuscular adaptations could then produce more effective vertical and horizontal GRF while running. More effective running kinetics may facilitate improvements in RE and spare power-producing capacity for later in races where sprint finishes are beneficial (Balsalobre-Fernández, Santos-Concejero & Grivas, 2016; Trowell et al., 2020; Llanos-Lagos et al., 2024).

The second hypothesis focuses more on the effects on the SSC. Šuc et al. (2022) proposed that the improvements in elastic energy utilisation produced by concurrent training are central to mechanisms underpinning its effect on running performance. The authors explained that elastic energy relies upon two neuromuscular metrics: Muscle stiffness and RSI (Šuc et al., 2022). Greater muscle stiffness means less concentric muscle activation to produce energy while running. As a result, the reduced need for concentric muscle activity reduces energy expenditure while running, and thus reduces RE (Balsalobre-Fernández, Santos-Concejero & Grivas, 2016; Denadai et al., 2017; Trowell et al., 2020; Ramirez-Campillo et al., 2021; Šuc et al., 2022; Llanos-Lagos et al., 2024). Komi (2000) found that up to 50% of force production during running could be channelled from efficient elastic energy utilisation. However, Ramirez-Campillo et al. (2021) hypothesised reductions in ground contact times to be the most important factor in transferring concurrent training adaptations over to running performance. Since stiffness and RSI can change independently, these authors proposed RSI and not muscle stiffness as the primary mechanism underpinning running performance improvements induced by concurrent training.

With that being said, these hypotheses have mostly been developed based on observational findings and cross-sectional correlational analyses. Most of these findings do not consider the effect of an intervention on the outcomes of interest. These snapshots in time cannot be used to justify the efficacy of interventions improving certain factors over time. Furthermore, SRMA findings have seemed to negate the very foundations of these hypotheses altogether. O'Sullivan et al. (2019) could not corroborate the idea that changes in RE directly impact changes in TT. The authors thus cautioned against inferring TT improvements simply from positive RE findings. Likewise, Trowell et al. (2020) guarded against implying that biomechanical changes caused by concurrent training can influence TT. Changes in biomechanics did not transfer over into running performance (Trowell et al., 2020). Ramirez-Campillo et al. (2021) also found no effect of concurrent-training-generated stiffness on TT. Assessing different training modalities within the same controlled methodological scenarios provides a different perspective concerning these hypotheses. Insights from RCTs thus provide a direct

comparison between different mechanisms possibly at play in relation to different training modalities.

Mikkola et al. (2011) corroborated the idea that different modalities elicit distinct running improvements. The authors found that HWT and CPX (RST + EXP) improvements were linked with changes in neuromuscular (electromyography, maximal strength, CMJ performance), and oxygen-independent factors (vMART). However, END was primarily associated with changes in oxygen-dependent factors (blood lactate and $VO_2\text{max}$). Berryman, Maurel & Bosquet (2010) attempted to investigate which components of the above CPX protocol were producing the main performance-enhancing improvements. However, the authors found that RST and EXP produced similar running performance improvements linked with similar RE and CMJ height changes. These authors noted that including RSI scores in their analyses may have been the best method to uncover differences between these modalities (Berryman, Maurel & Bosquet, 2010a). Most recently, a study compared HWT and RST and was able to confirm distinct outcomes elicited by these two modalities (Eihara et al., 2024). HWT only increased 1RM calf raises and RST only improved jump performance. However, this protocol did not enhance TT and thus little value concerning the mechanisms underpinning running performance can be derived from this study (Eihara et al., 2024).

To truly understand mechanistic causation, carefully constructed RCTs using ANOVA, regression, and mediator analysis are needed. Although correlational analysis alone cannot imply causation (Schober & Schwarte, 2018), the relationship between variables of interest can assist hypothesis development concerning causal and mechanistic pathways. Within concurrent training research, there is a significant lack of correlational analysis findings. This is likely due to small sample sizes and underpowered studies. However, what was found to be associated with TT improvements was CMJ height (Pellegrino, Ruby & Dumke (2016): $r > -0.55$, $p < 0.005$) and relative peak power (Lum et al. (2019): $r = -0.4$, $p = 0.01$), RSI (García-Pinillos, Lago-Fuentes, et al. (2020): $r = -0.48$, $p < 0.001$) and stiffness (García-Pinillos, Lago-Fuentes, et al. (2020): $r = -0.34$, $p < 0.01$). Furthermore, studies found that both oxygen-independent (RE [Paavolainen et al. (1999): $r = -0.54$; Pellegrino, Ruby & Dumke (2016): $r = 0.83$, $p < 0.001$] & velocity @ OBLA [Pellegrino, Ruby & Dumke (2016): $r > -0.8$, $p < 0.001$]) and -dependent running factors

(vMART [Paavolainen et al. (1999): $r = 0.55$]) correlated with changes in TT. Concurrent training studies were also able to establish associations between RE and changes in 1RM calf raise (Eihara et al. (2024): $r = -0.477$, $p = 0.046$), 5CMJ (Paavolainen et al. (1999): $r = -0.63$), and velocity at the onset of blood lactate accumulation (Pellegrino, Ruby & Dumke (2016): $r > -0.6$, $p < 0.001$) and over a 20-metre sprint (Paavolainen et al. (1999): $r = -0.49$), , respectively. No significant correlations were found between RE and Kvert (Ache-Dias et al. (2015): $r = 0.12$; $p > 0.05$), and Kleg (Ache-Dias et al. (2015): $r = 0.12$; $p > 0.05$), respectively. These results point to reactive-strength metrics being particularly important to change in TT and RE. However, this may be a case of RST and not HWT studies conducting correlational statistical analyses. It may not be a case of significant RST findings out-competing negative of insignificant HWT findings. There is also evidence that both supports and negates the “anaerobic and neuromuscular capacity” hypothesis mentioned above. More research is still needed to establish a clear trend in these data to provide better insights to inform theories and hypotheses regarding mechanistic pathways and factors.

To further our understanding of these hypotheses, more SRMA and RCT studies must unpack links between neuromuscular, biomechanical, and running factors via regression and moderator analyses. Individual RCT studies should also focus on comparing isolated modalities and not a single modality to a control. There is now sufficient evidence to show concurrent training is superior to conventional endurance running training (Lum et al., 2023). RCTs must also ensure that their training protocol induces beneficial running performance improvements. Without this, inferences on mechanistic pathways are impossible. Lastly, RCTs should also include as many appropriately selected neuromuscular, biomechanical, and running-related assessment tools in their study designs. This guarantees a holistic understanding of the changes occurring as a result of the concurrent training and ultimately the mechanistic pathways. Only once these steps have been taken within future research may we begin to shed further light on the currently hypothesised mechanisms mentioned above.

1.6 Conclusion

This narrative review has covered all the essential information needed to incorporate resistance exercise into a long-distance runner's training program. This review outlined the concept of concurrent training, along with its advantages and pitfalls. Additionally, this review detailed the foundational knowledge of the two components of concurrent training: resistance and endurance exercise prescription and testing. The guidelines for concurrent training best practices were then discussed so that one may translate this scientific knowledge into the 'real-world'. Lastly, the potential mechanisms underpinning these running adaptations produced by concurrent training were unpacked. It also highlighted how much more research is needed to develop a concrete theory regarding these mechanisms. These gaps for future research also included understanding the time-course of adaptations elicited by concurrent training, which periodisation strategy best enhances concurrent training, and how isolated training modalities compare to one another. Therefore, the study that serves as the basis for this Masters thesis aimed to address these gaps by directly comparing HWT and RST, measuring the training adaptations at several points during the intervention period, using a blocked periodisation approach, and testing several potential running physiological, neuromuscular, and biomechanical mechanistic factors.

1.7 Aims and Objectives of this Thesis

1.7.1 Aims

This thesis aimed to understand whether heavy weight (HWT) or reactive strength (RST) exercise would produce the greatest running performance improvements within an 8-week concurrent training program for long-distance recreational runners. Furthermore, it aimed to gain a better understanding of the time-course of these concurrent-training-induced adaptations as well as their underpinning mechanisms. This three-pronged approach ensured that many of the gaps in the literature were addressed. Addressing these gaps allowed this research to target the production of new and novel research findings that would push this area of research forward.

1.7.2 Objectives

The objectives of this thesis were:

1. To determine the time course of the changes in:
 - a. running performance by using a 5km time trial
 - b. physiological determinants of running performance (oxygen-dependent capacity (running economy and VO_2max) and oxygen-independent capacity (PRS, vVO_2max , and vMART))
 - c. neuromuscular factors (1RM, reactive strength index, CMJ height, eccentric utilisation ratio (EUR), and stiffness)
 - d. and changes in running biomechanics (ground contact time, flight time, vertical oscillation of centre of mass (COM), and ground reaction force (GRF)),by measuring these outcomes every 4 weeks.
2. To determine the mechanisms underpinning these changes by establishing whether any correlations exist between:
 - a. running performance by using a 5km time trial,
 - b. physiological determinants of running performance (oxygen-dependent capacity (running economy and VO_2max) and oxygen-independent capacity (PRS, vVO_2max , and vMART)),
 - c. neuromuscular factors (1RM, reactive strength index, CMJ height, EUR, and stiffness),
 - d. and changes in running biomechanics (ground contact time, flight time, vertical oscillation of COM, and GRF).
3. To measure body fat, body weight, as well as lower limb circumference to confirm that these concurrent training interventions do not result in muscular hypertrophic and body weight changes.

Chapter Two: Methodology

2.1 Study Overview

This study used a quantitative experimental approach using a two-group repeated measures randomised controlled trial (RCT) research design. Both groups followed a concurrent training program. One included a reactive-strength training (RST) program while the other included a heavy-weight training (HWT) program. Only two intervention groups were included in this study because previous research has already proven concurrent training, in general, to be superior to control groups solely following endurance training (Lum et al., 2023). This study lasted 12 weeks. It started with one familiarisation week and one week for baseline testing. After randomly sorting participants into either of the two groups, they participated in two four-week training blocks separated by two follow-up testing weeks. The training interventions were overseen and coached by one of the researchers who is a physiotherapist (BSc Physiotherapy, UCT) and a personal trainer (National Personal Training Certificate, Trifocus Fitness Academy). The in-person training and testing sessions took place within the UCT biomechanics and running lab, as well as the Sports Science Institute of South Africa's (SSISA) gym.

2.2 Participants

Using 0.44 (Li et al., 2019) as the smallest meaningful effect, setting the alpha value to 0.05, and the power to 80% the G*Power software (v3.1.9.7, Universitet Kiel, Germany) was used to calculate the optimal sample size for this study design. A total of 12 participants were needed in each group for a sufficiently powered study. Participants for this current study were recruited from local running clubs. Online ads were sent out to these running clubs requesting the administrators to disseminate them to their respective club's members. Hard copies were also handed out at local races during the recruiting period (Appendix 2). Interested athletes could follow a URL or scan a QR code to be directed to the study's online application form. If the athletes fitted the inclusion

criteria they could sign up and then were sent the participant information sheet via email (Appendix 3). After reading the information sheet, if the athletes were still willing to participate in the study they then signed and sent back their informed consent forms (Appendix 4).

The inclusion criteria for athletes in this study were simply that they needed to have completed a half or full marathon within the last six months, train a minimum of three times per week for the last six months, and have not completed resistance training similar to the training being implemented in this current study. Athletes were excluded if they had, or were, recovering from an injury. They were contacted again once they were back to their baseline training load and were asked if they were still interested in participating in the current study. Runners were also excluded if they suffered from a health condition that may be exacerbated by the testing or training to be completed in the study and would consequently put the participant at an undue health risk. The participants who were included in the study were sorted into two intervention groups using a blocked randomisation approach to ensure homogeneity. Participants were sorted to ensure similar sex distribution, age, VO₂max, and training volume across both groups.

2.3 Ethical considerations

This study received ethical approval from the Human Research and Ethics Council of the University of Cape Town (UCT) (UCT HREC 674/2022) (Appendix 5). As this was an exercise intervention study, there were risks associated with some of the testing and intervention activities/techniques used – albeit a low risk. These risks included: Discomfort, possible muscle cramp, excessive fatigue, and possibly a cardiovascular incident/discomfort due to maximal exercise testing; sustaining a muscle sprain/ligament strain/contusion during the testing due to falling, incorrect biomechanics, or excessive fatigue; and discomfort due to someone touching one's body during tests like the skinfold assessment. To avoid all preventable incidents there was a qualified trainer, physiotherapist and first aider (RB) with participants during all in-person training sessions at the SSISA facility.

3.3.1 Privacy and Confidentiality

This study also adhered to the Protection of Personal Information (POPI) Act, No. 4 of 2013 which promotes the protection of personal information by public and private bodies. This study did not need to personally identify the participants and thus the personal details of the participants remained confidential throughout the study. This was done by de-identifying each participant using a unique identification number which was established from the time of signing the consent form. Only the research team had access to the personal information attached to these unique identification numbers.

3.3.2 Data Safety and Monitoring

This spreadsheet that stored the personal information of participants was password protected and stored on an online database on the UCT OneDrive platform. The secondary Excel database that was used to store all training and testing data was also password-protected and backed up on a hard drive, computer, and OneDrive. This Excel spreadsheet only used the unique identification numbers as references for the participants. Therefore, the anonymity of the participants was preserved throughout the experimental period in this write-up.

2.4 Testing Equipment and Procedures

The participants underwent several tests to understand their overall running performance, physiological factors affecting running performance, neuromuscular and biomechanical efficiency, and body composition. This testing protocol may seem overly extensive but many of these tests are done simultaneously or in conjunction with one another. Most of these tests were completed relatively quickly and in quick succession. Furthermore, each test was chosen to target specific mechanisms that may explain improvements in endurance running performance elicited by concurrent training. The tests were categorised as follows:

- Body composition testing:
 - o Height and weight were measured to assess body mass index (BMI),

- A seven-point skinfold test was used to measure body fat percentage,
 - and the mid-thigh and mid-calf circumferences were taken to assess muscle mass.
- Physiological determinants of running:
 - The submaximal treadmill test measured running economy (RE) at five different running speeds.
 - The ramped incremental treadmill test assessed VO_2max , velocity at VO_2max ($v\text{VO}_2\text{max}$), and peak treadmill running speed (PTS).
 - The maximal anaerobic running test (MART) measured velocity during the fastest anaerobic running speed ($v\text{MART}$), the energy demand of running at the fastest anaerobic running speed (O_2Demand), and whether this demand is greater than VO_2max ($\text{O}_2\text{Deficit}$).
 - Running biomechanics:
 - Ground contact time, flight time, vertical oscillation of COM, GRF, and leg stiffness were tested during the fastest submaximal treadmill running speed using a mobile app (MyJumpLab).
 - Neuromuscular:
 - The back squat assessed 1-rep maximum (1RM) strength.
 - The squat jump (SJ), counter-movement jump (CMJ), and drop jump (DJ) were used to measure lower body power, reactive strength, and lower limb stiffness (K_{vert}).
 - Running performance:
 - 5km treadmill time trial (TT) assessed direct running performance.

3.4.1 Body Composition Measurements

Participants' body weight was measured on a digital scale and was recorded to the nearest 0.1kg. Height was then measured using a stadiometer – rounding off to the nearest 0.1cm (Li et al., 2019). BMI was subsequently calculated as a ratio of body weight over height squared ($\text{kg}\cdot\text{m}^{-2}$). A seven-point skinfold test was also performed using a skinfold calliper (GoFit, Tulsa, Oklahoma). Measurements were taken at the triceps,

subscapular, biceps, supraspinale, abdominal, front thigh, and medial calf (Withers et al., 1987). The median value of three measurements taken at each site (mm). The sum of these seven median values was used to calculate body fat percentage. An eighth skinfold measure was taken at the posterior sub-ischial site one-third down the length of the thigh. This specific skinfold was used with thigh circumference measures to calculate muscle thickness. Using a tape measure, circumference measures were taken at four sites: 1) Immediately distal to the gluteal fold, 2) at the point 33% of the distance between the gluteal fold and the popliteal crease, 3) at the point of the smallest knee circumference above the patellar, and 4) at the bisection of the patella horizontally. These anthropometric variables were used to calculate muscle thickness for the quadriceps and the thickness of the total of quadriceps and hamstrings using the following equations (Davies & Sargeant, 1975; Katch & Katch, 1975):

- Quadriceps thickness (cm) = $0.1390(\text{Girth @ sub-ischial site, } 1/3 \text{ length of thigh}) - 0.0414(\text{Posterior sub-ischial skinfold}) + 0.0469(\text{Girth @ gluteal fold}) - 5.7527$
- Quadriceps + Hamstring thickness (cm) = $0.2105(\text{Girth @ sub-ischial site, } 1/3 \text{ length of thigh}) - 0.07345(\text{Posterior sub-ischial skinfold}) + 0.1087(\text{Girth @ gluteal fold}) - 7.8868$

3.4.2 Incremental Treadmill Test

This test consisted of two components: The submaximal and ramped tests. These tests assessed RE, VO_2max , vVO_2max , and PTS. The incremental treadmill test was completed on a treadmill (HP Cosmo treadmill, Viasys LE 500 CE; HP Cosmos Sports & Medical GMBH, Nussdorf-Traunstein, Germany) during which oxygen consumption was measured using a metabolic gas analyser (Cosmed Quark CPET; Rome, Italy). On completion of the test, the Borg scale was used to measure RPE from 6-20. Before commencing the test, the analysers were calibrated for volume using a 3L calibration syringe, and O_2 and CO_2 concentrations using a certified gas mixture (Beattie et al., 2017). Once the participant reported to the lab, they were allowed to warm up using dynamic mobility exercises, self-myofascial release, and a treadmill running warm-up of their choice. Thereafter, the submaximal test began. This test included running at five different submaximal speeds for three minutes each. The participant's average training

speed was recorded, and the submaximal running speed was set at $2\text{km}\cdot\text{hr}^{-1}$ slower than this. The second running speed was set at $1\text{km}\cdot\text{hr}^{-1}$ slower than the participant's training speed, with the third equivalent to their training speed. The fourth and fifth submaximal speeds were set at $1\text{km}\cdot\text{hr}^{-1}$ and $2\text{km}\cdot\text{hr}^{-1}$ faster than the participant's training speed, respectively. Oxygen consumption was measured during the last 60 seconds of each stage. These data were then used to calculate RE ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$) for that specific running stage.

Once all five submaximal running stages were completed, the second component of the treadmill test commenced – the ramp test to volitional exhaustion. For this component, the treadmill speed was initially increased by $0.5\text{ km}\cdot\text{hr}^{-1}$ faster than the final speed during the final submaximal running stage. The participants ran at this speed for 30 seconds. Thereafter, the speed then increased by a further $0.5\text{ km}\cdot\text{hr}^{-1}$ every 30 seconds. The test continued until the participant could not maintain the treadmill speed any longer and reached exhaustion. The test was counted as a valid assessment if: the RPE was greater than or equal to 18 and the respiratory exchange ratio (RER) was greater than or equal to 1.20.

During this ramped component of the treadmill test, the VO_2 was calculated by averaging the last three measurements taken during the final five seconds of the respective 30-second stages. The $\text{VO}_{2\text{max}}$ was taken as the highest of these recorded readings and not necessarily during the final 30-second stage completed.

The PTS was taken as the maximum speed reached during the final 30-second stage run during the ramped component of the treadmill test, whereas $v\text{VO}_{2\text{max}}$ was calculated by extrapolating the five submaximal VO_2 measurements into a linear graph. This linear graph was extended until it intersected the participant's $\text{VO}_{2\text{max}}$ (represented on the y-axis). This point of intersection represented the $v\text{VO}_{2\text{max}}$.

3.4.3 Running Biomechanics

During the incremental treadmill test, a mobile phone (Samsung Galaxy A32, Samsung Electronics, South Korea) was set up on a tripod behind the treadmill. Using the mobile phone, the running gait was video recorded from a posterior angle during the final

submaximal running speed within the first component of the treadmill test. The recording captured a minimum of 12 consecutive steps, with the middle eight steps analysed. The running gait was analysed during the fifth submaximal running speed as this speed was most closely associated with the participants' racing speed. Improvements in biomechanics while running at one's competitive speed were most important to understand the impact on competitive performance. Changes at these speeds gave insights into changes the participants were likely to experience in "real-life" competitive scenarios. Once the test and video had been captured, it was exported into the MyJumpLab mobile application whose validity and reliability will be discussed later in this chapter (v1.2.1, Android PlayStore, Carlos Balsalobre). The body mass and height of the participants, as well as the speed at which they were running during that video, were inputted into the app. The time at which each contact and take-off point occurred also needed to be manually inputted on the app. Once the steps were determined, the app calculated the ground contact time, flight time, step frequency, vertical oscillation of centre of mass (COM), ground reaction forces (GRF), and leg stiffness. Stiffness is defined as the ability of an object or limb to limit deformation by withstanding the force being applied to it (Brazier et al., 2019). When calculating leg stiffness, the assumption is made that all the lower limb joints, muscles, ligaments and tendons work together allowing the leg to be classified as a single isolated spring system (Pruyn, Watsford & Murphy, 2016). The impact of body weight was taken as the applied force and the limiting of deformation as the change in COM.

3.4.4 Maximal Anaerobic Running Test (MART)

The MART was performed on a 133-metre indoor running track in the SSISA gym. The participants were required to complete 10 x 150m sprints, separated by 100 seconds of recovery. The initial test developed by Rusko, Nummela & Mero (1993) was focused on elite male and female athletes and thus this test had a set starting speed ($4.75\text{m}\cdot\text{s}^{-1}$). During our pilot, starting at this speed meant that recreational athletes could not complete all 10 pre-fatiguing laps. The initially set starting speed of $4.75\text{m}\cdot\text{s}^{-1}$ was linked to an elite runner's average VO_2max (Rusko, Nummela & Mero, 1993a). Therefore, for the sake of this study's sample population, the starting speed of the MART was individualised

to each participant's $VO_2\text{max}$. This new individualised starting speed was calculated based on the equation for calculating the VO_2 during the first version of the MART (Rusko, Nummela & Mero, 1993a):

$$- \quad VO_2 \text{ (ml.kg}^{-1}\text{.min}^{-1}\text{)} = 12.v\text{(m.s}^{-1}\text{)} + 54.g(\%)\text{.}v\text{(m.s}^{-1}\text{)} + 3.5$$

Each participant's $VO_2\text{max}$ was inputted in place of VO_2 , and the constant 0.052 was used for level ground running as stipulated by Rusko, Nummela & Mero (1993). The equation was re-ordered to solve for "v" which was taken as the participant's starting speed. Participants were guided by the track's pacing lights for this starting speed and the subsequent eight laps.

At the start of each lap, a five-metre running start was always allowed so that the participants reached the current lap's speed before it officially began (Nummela et al., 2006). After the completion of each 150m run, the speed was increased by 1.4km.hr^{-1} (0.41m.s^{-1}). The process was repeated for all initial nine laps of the test. The 10th sprint was run at the participant's desired maximal running speed – not guided by the pacing lights. This final lap was timed using a stopwatch.

vMART was calculated using the average speed of this 10th lap (Nummela et al., 2006). The oxygen demand at the vMART was also calculated, using the formulae adapted from Londeree (2012) and used in the second iteration of the MART focused on overground running (Nummela et al., 2006):

- Oxygen demand imposed by the MART:
 - o $\text{MART } VO_{2(\text{demand})} \text{ (ml.kg}^{-1}\text{.min}^{-1}\text{)} = 0.205 \times v\text{MART(m.min}^{-1}\text{)} + 0.109 \times [v\text{MART(m.min}^{-1}\text{)} / 60]^2 - 6.1$
- The ability to run (produce work/power) above $VO_2\text{max}$:
 - o $\text{MART } VO_{2(\text{gain})} \text{ (ml.kg}^{-1}\text{.min}^{-1}\text{)} = \text{MART } VO_{2(\text{demand})} \text{ (ml.kg}^{-1}\text{.min}^{-1}\text{)} - VO_2\text{max (ml.kg}^{-1}\text{.min}^{-1}\text{)}.$

3.4.5 Reactive-strength Testing

The participants began the jumping testing protocol with a light five-minute warm-up involving a light aerobic running warm-up, dynamic mobility exercises, and self-

myofascial release consisting of foam rolling. As with the running gait biomechanical measures, the outcomes for all the jumps included in this component of neuromuscular testing were also calculated using the MyJumpLab app. Each jump was thus also recorded using the same mobile phone set on the same tripod 1.5 meters away and directly in front of the participants. For each jump test, three trials were allowed that were separated by a maximum of one minute's rest. Only the best jump was used for the analysis. To calculate the jump metrics, the MyJumpLab also needed the participants' height and mass which had already been inputted for the running gait assessment. As with the running gait assessment, the take-off and landing time points were manually tagged for each video within the app. The app then used height, weight, and tagged timestamps to calculate jump height, power, force, and velocity.

The first set of tests assessed the slow-SSC by measuring the CMJ. The participants stood with both heels on a demarcated line with their hands on their hips in front of the mobile phone and tripod. The participants were instructed to perform a quick downward squat, to a self-selected depth, and follow it up with a maximally explosive upward jump. The participants were not allowed to use their arms for momentum. The maximum jump height of this jump was not only recorded for the overall analysis but also to calculate the modified reactive strength index (RSI_{mod}). RSI_{mod} is calculated as a ratio of the time (seconds) to take-off, from the initial downward movement of the participant, and the maximum jump height.

The SJ was then performed after one minute of rest. In this test, the participant started their jump from a knee flexion angle of 90 degrees that was held for three seconds. They were then expected to jump maximally upwards. The participants were again instructed to keep their hands on their hips throughout the jump. A SJ was only valid if there was minimal evidence of eccentric movement before take-off (Pruyn, Watsford & Murphy, 2016). The maximum SJ height was used with the CMJ height to calculate the EUR. EUR (CMJ:SJ) signifies how much the participant relies on the elastic energy contribution of the CMJ as compared to the stationary start of the SJ to produce maximal power (Pruyn, Watsford & Murphy, 2016).

Once the participants rested for another minute, the fast-SSC efficiency was tested using DJs. The DJ was performed from a 30-centimetre box positioned in front of the

mobile phone and tripod. The participants were instructed to step off the box with their dominant leg – with their hands on their hips – and aimed to land with both feet equally on the floor. As the participants landed, they were expected to immediately jump maximally and vertically upwards. The cue to the participants was that they should try to be in contact with the ground for as little time as possible. The trials were only counted when the participants did not excessively bend their hips or knees during the eccentric component of the jump and their hands did not leave the hips (Li et al., 2019). The data collected from this test was used to calculate the reactive strength index (RSI). RSI is the ratio of contact and flight time (seconds). The RSI explains how well an athlete exploits the fast-SSC to produce elastic energy (Beattie et al., 2017).

3.4.6 Maximal Strength Testing

The 1RM testing of the back squat was completed using a Smith machine. The depth of the squat was controlled. During the familiarisation sessions a measurement was taken of the participants' deepest squat angle they can achieve while maintaining safe and adequate lumbar lordosis. This height was recorded, and stoppers were placed at a level that most closely accommodated the height. If the height needed to be rounded off, it was also rounded up and not down to be more conservative to protect the form of the participants. The height of the safety stoppers was used for all subsequent testing during the study. A 1RM back squat lift attempt was only counted as valid if the bar reached the safety stoppers, and the participant subsequently reached neutral hip and knee extension (Beattie et al., 2017). At least one spotter was present during this testing procedure.

The 1RM protocol was always performed after the reactive strength testing battery. Therefore, participants were already warmed up and did not need to perform a warm-up again. The starting weight was set at each participant's estimated 50% 1RM. This starting weight was estimated to be equivalent to each participant's body weight. The initial set was completed with 10 repetitions at the estimated 50% 1RM followed by five reps at 70% 1RM, three reps at 80% 1RM, and one rep at 90% 1RM. The participant was then able to self-select the weight the participant felt they could only maximally complete a single full and correct repetition. Each participant had up to six attempts at finding their true

1RM. The maximal weight that the participant could correctly lift within this last set was recorded as the absolute 1RM. Each participant's relative 1RM ratio was calculated by dividing the absolute 1RM by their current body weight. For follow-up mid- and post-testing, the current body weight at that time point was used to calculate the relative 1RM ratio.

3.4.7 Running Time Trial (5kmTT)

This running performance test began with a warm-up at a self-selected pace and time on the treadmill. Thereafter, the treadmill TT began at a gradient of zero degrees, in which the participant needed to complete five kilometres as quickly as possible. The participants had free rein to manipulate the treadmill speed throughout the test. The participants were encouraged to maintain a pace at which they felt they were exerting themselves as much effort as possible. According to O'Sullivan et al. (2019), encouragement given during the TT should be standardised to limit the effect of external factors on the testing performance. Thus, encouragement, motivation and time splits were given to participants after the completion of every kilometre. Receiving this type of information is standard practice in a track or road race. The time taken to complete five kilometres was recorded. O'Sullivan et al. (2019) also recommended that a session rating of perceived excursion (RPE) be taken for the time trial to ensure maximal efforts were expended. This helped to further standardise the TT.

2.5 Validity and Reliability

All the testing protocols used within this study have been validated. However, it is important to note and highlight in this section, two of the newer testing methods that were used to measure running biomechanics and jumping metrics, respectively. These biomechanical and neuromuscular data were measured and calculated using two different functions in the MyJumpLab mobile application. The biomechanical assessment used the Runmatic component of the app, and the jump tests used the MyJump component. Four studies have established the validity and reliability of the

MyJump component by comparing it to the gold standard measurements of the force platforms (Gallardo-Fuentes et al., 2016; Rogers et al., 2019; Bogataj, Pajek, Andrašić, et al., 2020; Bogataj, Pajek, Hadžić, et al., 2020). One study assessed the validity of the Runmatic component against infrared sensors that detected each ground contact during treadmill running (Balsalobre-Fernández, Agopyan & Morin, 2017). These authors found that the outcomes calculated by the app and sensors were equivocal and thus proved the validity of the app's running biomechanical and jump measurements.

2.6 Study Procedure

The first week of the 12-week experimental period was used to visit and familiarise the participants with SSISA, the gym, the exercise laboratories, as well as the testing and intervention protocols. The full experimental protocol was explained again to the participants to confirm that they understood everything in the Information Sheet. Thereafter, their signed Informed Consent Form was confirmed. During this period participants were also asked to send or share their training data for the previous four weeks. This was used as their baseline training load to ensure no drastic increases were noted during the intervention period. Participants were then reminded to keep their endurance training routine as well as their dietary habits as constant as possible during the intervention period.

Thereafter, the participants were shown and given a chance to practice all the testing protocols and try out all the training apparatus and equipment used during the intervention. During this familiarisation session – as mentioned above – the optimal back squat height was established which was consequently used during the 1RM testing. The participants' average training speed was also recorded for use during the treadmill testing. The baseline testing took place a week after the completion of this familiarisation. Thereafter, the first four-week mesocycle training block occurred and the follow-up testing week was scheduled in the fifth week after commencing with the intervention. Another four-week training block was then completed followed up by the final testing week for this study.

3.6.1 Testing

During the testing weeks mentioned above, participants took part in assessments over three days, separated by a minimum of 48 hours (Beattie et al., 2017). To account for diurnal variations in the test outcomes, each participant was assessed at the same time of day across all three testing weeks. Diet and acute fatigue will be controlled by restricting caffeine (<4 hours) and alcohol (<48 hours) intake and encouraging participants to follow their normal day-to-day diet. Participants also needed to arrive for each testing being two hours fasted (Li et al., 2021) and having not engaged in vigorous exercise 24 hours before testing and to follow these same procedures before each testing session.

Each testing week was structured as follows:

Day 1:

1. *Body composition measurements*
2. *Incremental treadmill test and running biomechanics*

Day 2:

1. *Reactive strength and muscle power testing*
2. *Maximum strength testing*
3. *Maximal anaerobic running test (MART)*

Day 3:

1. *Running time trial (5km TT)*

3.6.2 Training

3.6.2.1 Endurance Training

This study did not manipulate the participants' endurance training parameters. As mentioned above, the participants were requested to maintain training loads similar to their baseline as far as possible. All participants' endurance training was captured over the intervention period to ensure that any variations in training load could be accounted for in the final analysis.

3.6.2.2 Resistance Training

The first two and a half weeks of each four-week training block were supervised by the researcher (RB). Thereafter, participants had the choice to complete the remaining three sessions of the training block independently or whether they wanted to continue being supervised at the SSISA facility. The two intervention programs (HWT and RST) were planned to last a maximum of 45 minutes, and take place twice a week for two four-week training blocks. Each training session and block were prescribed with a similar training load (estimated RPE x training volume) across both intervention programs. Each program also followed the principle of progressive overload to avoid monotony and overtraining. To help promote muscular adaptations throughout the intervention a blocked periodisation approach was used. The training load was gradually increased in the first three weeks of the training block. This culminated in a fourth “deload” week which tapered off the training load. Furthermore, the movement patterns and muscle groups targeted in the two intervention groups were similar. By matching load, periodisation structure, and targeted muscles across training regimens, the primary differences between the groups lay in reps, sets, weights, intensity, and rest periods. This approach ensured that the study primarily assessed the impact of exercise type rather than other prescription factors.

The HWT group’s training program was prescribed with weights $\geq 80\%$ 1RM, reps of 3-6, sets of 4-6, and using various lifting tempos. A minimum of two to three minutes of rest was observed between each set. The training program was progressively loaded and periodised by manipulating the weights, tempos, reps and RPE, as well as the types of exercises used within each training week and training block. The RST group’s training program consisted of plyometric-type exercises that only used body weight. These exercises included bilateral and unilateral jumps, hops, bounds and skips. These exercises accumulated to a volume of up to 200 repetitions per session. A minimum of one minute of rest was observed between sets to allow for maximal effort to be maintained. The tempo of these exercises was focused on rapid explosive movements.

Within the RST program, when an exercise was classified as a slow SSC exercise, the participant was expected to exaggerate the pre-loading phase of the jump to allow for maximal power and force generation. This was done using a slow, large range of motion

and eccentric movement, followed by a maximal concentric contraction (i.e., CMJ). On the other hand, fast SSC exercises were performed with more acute joint angles that mimic the running gait. The RST program was progressed and periodised according to principles outlined by Beattie (2019). These exercises were progressed from 'extensive plyometrics' to 'intensive plyometrics'. Extensive plyometrics included exercises performed at submaximal capacities that focused on technique, joint positioning, coordination, and rhythm. Intensive plyometrics included exercises performed to achieve maximal height, minimal ground contact time during jumps, or a combination of the two (Beattie, 2019a).

The training intervention programs are outlined below:

Table 2.1: Maximum Strength Training - Block 1

Exercise	Week 1										Week 2									
	Day 1					Day 2					Day 1					Day 2				
	%1R M	RP E	Re ps	Set s	Temp o	%1R M	RP E	Rep s	Set s	Tempo	%1R M	RP E	Re ps	Set s	Temp o	%1R M	RP E	Re ps	Set s	Temp o
Smith Machine Half Back Squat	85%	2 RIR	3	3	(2/0/2/1)	85%	2 RIR	3	3	(2/0/2/1)	85%	1 RIR	4	3	(2/0/2/1)	87%	1 RIR	3	3	(1/0/1/2)
Smith Machine Romanian Deadlift	85%	2 RIR	3	3	(2/0/2/1)	85%	2 RIR	3	3	(2/0/2/1)	85%	1 RIR	4	3	(2/0/2/1)	87%	1 RIR	3	3	(1/0/1/2)
Bilateral Calf Raises in Smith Machine	85%	2 RIR	3	3	(2/0/2/1)	-	-	-	-	-	85%	1 RIR	4	3	(2/0/2/1)	-	-	-	-	-
Unilat Supine Cable Hip Flexion (attached at ankle)	85%	2 RIR	3	3	(2/0/2/1)	85%	2 RIR	3	3	(2/0/2/1)	85%	1 RIR	4	3	(2/0/2/1)	87%	1 RIR	3	3	(1/0/1/2)
Unilateral Leg Press	-	-	-	-	-	85%	2 RIR	3	3	(2/0/2/1)	-	-	-	-	-	87%	1 RIR	3	3	(2/0/1/1)

Note: RIR – reps in reserve

Table 2.1: cont.

Exercise	Week 3										Week 4 (Deload)									
	Day 1					Day 2					Day 1					Day 2				
	%1RM	RPE	Reps	Sets	Tempo	%1RM	RPE	Reps	Sets	Tempo	%1RM	RPE	Reps	Sets	Tempo	%1RM	RPE	Reps	Sets	Tempo
Smith Machine Half Back Squat	87%	2 RIR	2	3	(3/0/1/1)	91%	0 RIR	2	3	(1/0/V/2)	83%	3 RIR	3	2	(1/0/1/2)	91%	2 RIR	1	3	(1/0/1/2)
Smith Machine Romanian Deadlift	87%	2 RIR	2	3	(3/0/1/1)	91%	0 RIR	2	3	(1/0/V/2)	83%	3 RIR	3	2	(1/0/1/2)	91%	2 RIR	1	3	(1/0/1/2)
Bilateral Calf Raises in Smith Machine	87%	2 RIR	2	3	(3/0/1/1)	-	-	-	-	-	83%	3 RIR	3	2	(2/0/2/0)	-	-	-	-	-
Unilat Supine Cable Hip Flexion (attached at ankle)	87%	2 RIR	2	3	(3/0/1/1)	91%	0 RIR	2	3	(1/0/V/2)	83%	3 RIR	3	2	(2/0/2/0)	91%	2 RIR	1	3	(1/0/1/2)
Unilateral Leg Press	-	-	-	-	-	87%	2 RIR	2	3	(3/0/1/1)	-	-	-	-	-	87%	2 RIR	2	2	(2/0/2/0)

Note: RIR – reps in reserve

Table 2.2: Maximum Strength Training - Block 2

Exercise	Week 1										Week 2									
	Day 1					Day 2					Day 1					Day 2				
	%1R M	RP E	Re ps	Set s	Temp o	%1R M	RP E	Rep s	Set s	Tempo	%1R M	RP E	Re ps	Set s	Temp o	%1R M	RP E	Re ps	Set s	Temp o
Smith Machine Parallel Back Squat	85%	2 RIR	3	4	(3/0/2/1)	-	-	-	-	-	87%	1 RIR	3	4	(1/0/2/0)	-	-	-	-	-
Smith Machine Romanian Deadlift	85%	2 RIR	3	4	(3/0/2/1)	-	-	-	-	-	87%	1 RIR	3	4	(1/0/2/0)	-	-	-	-	-
Bilateral Calf Raises in Smith Machine	85%	2 RIR	3	4	(3/0/2/1)	-	-	-	-	-	87%	1 RIR	3	4	(1/0/2/0)	-	-	-	-	-
Unilat Supine Cable Hip Flexion	85%	2 RIR	3	4	(3/0/2/1)	-	-	-	-	-	87%	1 RIR	3	4	(1/0/2/0)	-	-	-	-	-
Unilateral Leg Press	-	-	-	-	-	85%	2 RIR	3	4	(3/0/2/1)	-	-	-	-	-	-	-	-	-	-

Table 2.2: cont.

Unilateral Calf Raises in Smith Machine	-	-	-	-	-	85%	2 RIR	3	4	(3/0/2/1)	-	-	-	-	-	85%	1 RIR	4	4	(1/0/2/0)
Bulgarian Squat with dumbbells	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	85%	2 RIR	3	4	(2/0/2/1)
Unilat Standing Cable Hip Flexion	-	-	-	-	-	85%	2 RIR	3	4	(2/0/2/1)	-	-	-	-	-	87%	1 RIR	3	4	(1/0/2/0)
Trap Bar Deadlifts	-	-	-	-	-	85%	2 RIR	3	4	(2/0/2/1)	-	-	-	-	-	87%	1 RIR	3	4	(1/0/2/0)

Note: RIR – reps in reserve

Table 2.2: cont.

Exercise	Week 3										Week 4 (Deload)									
	Day 1					Day 2					Day 1					Day 2				
	%1R M	RP E	Re ps	Set s	Temp o	%1R M	RP E	Rep s	Set s	Tempo	%1R M	RP E	Re ps	Set s	Temp o	%1R M	RP E	Re ps	Set s	Temp o
Smith Machine Parallel Back Squat	-	-	-	-	-	91%	0 RIR	3	4	(1/0/V/2)	-	-	-	-	-	91%	2 RIR	1	3	(1/0/1/2)
Smith Machine Romanian Deadlift	-	-	-	-	-	91%	0 RIR	3	4	(1/0/V/2)	83%	2 RIR	2-3	3	(2/0/2/0)					
Bilateral Calf Raises in Smith Machine	-	-	-	-	-	91%	0 RIR	3	4	(1/0/V/2)	-	-	-	-	-	91%	2 RIR	1	3	(1/0/1/2)
Unilat Supine Cable Hip Flexion	-	-	-	-	-	91%	0 RIR	3	4	(1/0/V/2)						91%	2 RIR	1	3	(1/0/1/2)
Unilateral Leg Press	-	-	-	-	-											-	-	-	-	-
Unilateral Calf Raises in Smith Machine	87%	2 RIR	2	4	(3/0/2/1)	-	-	-	-	-	83%	2 RIR	2-3	3	(2/0/2/0)	-	-	-	-	-

Table 2.2: cont.

Bulgarian Squat with dumbbells	87%	2 RIR	2	4	(3/0/2 /1)	-	-	-	-	-	87%	2 RIR	2	2	(1/0/1 /2)					
Unilat Standing Cable Hip Flexion	87%	2 RIR	2	4	(3/0/2 /1)	-	-	-	-	-	83%	2 RIR	2-3	3	(2/0/2 /0)	-	-	-	-	
Trap Bar Deadlifts	91%	2 RIR	2	4	(1/0/1 /2)	-	-	-	-	-						91%	2 RIR	1	3	(1/0/1 /2)

Note: RIR – reps in reserve

Table 2.3: Reactive Strength Training - Block 1

Week 1 + 2									
Exercise	Day 1				Exercise	Day 2			
	%1RM	Reps	Sets	fSSC/ sSSC		%1RM	Reps	Sets	fSSC/ sSSC
Skipping Bilateral	-	30	2	Fast	Skipping Unilateral	-	15	2	Fast
Lateral Pogo Jumps Right	-	10	2	Fast	Pogo jumps forwards	-	10	2	Fast
Pogo Jumps Right	-	10	2	Fast	Pogo jumps backwards	-	10	2	Fast
Bilateral Vertical CMJ with stiff legs	-	5	3	Slow	Stiff Leg Long Jump	-	5	3	Slow

Table 2.3: cont.

Week 3									
Exercise	Day 1				Exercise	Day 2			
	%1RM	Reps	Sets	fSSC/ sSSC		%1RM	Reps	Sets	fSSC/ sSSC
Skipping Unilateral	-	15	2	Fast	Bilateral Skipping	-	30	2	Slow
Lateral Pogo Jumps Right	-	10	2	Fast	Unilateral Pogo jumps forwards	-	10	2	Fast
Pogo Jumps Right	-	10	2	Fast	Unilateral Pogo jumps backwards	-	10	2	Fast
Bilateral Vertical CMJ with stiff legs	-	8	3	Slow	Stiff Leg Long Jump	-	5	3	Slow

Note: fSSC – fast stretch-shortening cycle; sSSC – slow stretch-shortening cycle.

Table 2.3: cont.

Week 4									
Exercise	Day 1				Exercise	Day 2			
	%1RM	Reps	Sets	fSSC/ sSSC		%1RM	Reps	Sets	fSSC/ sSSC
Skipping Unilateral	-	10	2	Fast	Unilateral Pogo jumps forwards	-	10	1	Fast
Lateral Pogo Jumps Right	-	10	1	Fast	Unilateral Pogo jumps backwards	-	10	1	Fast
Pogo Jumps Right	-	10	1	Fast	Stiff Leg Long Jump	-	5	2	Slow
Bilateral Vertical CMJ with stiff legs	-	5	2	Slow	Bilateral Skipping	-	10	2	Slow

Note: fSSC – fast stretch-shortening cycle; sSSC – slow stretch-shortening cycle.

Table 2.4: Reactive Strength Training - Block 2

Week 1 + 2									
Exercise	Day 1				Exercise	Day 2			
	%1RM	Reps	Sets	fSSC/ sSSC		%1RM	Reps	Sets	fSSC/ sSSC
Skipping Unilateral	-	15	2	Fast	Unilateral Pogo jumps forwards	-	10	2	Fast
Unilateral Medial Pogo Jumps		10	2	Fast	Unilateral Pogo jumps Backwards	-	10	2	Fast
Bilateral Hops Medium Hurdles	-	10	2	Fast	Triple Bilateral CMJ Jump (short ground contact)	-	5	2	Fast
CMJ stiff leg landing (height focused)	-	5	4	Slow	CMJ Long Jump Bilateral with stiff landing (distance focused)	-	5	4	Slow

Note: fSSC – fast stretch-shortening cycle; sSSC – slow stretch-shortening cycle.

Table 2.4: *cont.*

Week 3									
Exercise	Day 1				Exercise	Day 2			
	%1RM	Reps	Sets	fSSC/ sSSC		%1RM	Reps	Sets	fSSC/ sSSC
Skipping Unilateral	-	15	2	Fast	Unilateral Pogo jumps forwards	-	10	2	Fast
Unilateral Medial Pogo Jumps	-	10	2	Fast	Unilateral Pogo jumps Backwards	-	10	2	Fast
Bilateral Hops Medium Hurdles	-	10	3	Fast	Triple Bilateral CMJ Jump (short ground contact)	-	5	3	Fast
CMJ stiff leg landing (height focused)	-	8	4	Slow	CMJ Long Jump Bilateral with stiff landing (distance focused)	-	8	4	Slow

Note: fSSC – fast stretch-shortening cycle; sSSC – slow stretch-shortening cycle. Week 3 is prescribed as above but increased the jump distances of the forward-backwards hops; CMJ double jump; and Pogo jumps as compared to Week 1 and 2

Table 2.4: cont.

Week 4									
Exercise	Day 1				Exercise	Day 2			
	%1RM	Reps	Sets	fSSC/ sSSC		%1RM	Reps	Sets	fSSC/ sSSC
Skipping Unilateral	-	15	1	Fast	Unilateral Pogo jumps forwards	-	10	1	Fast
Unilateral Medial Pogo Jumps		20	2	Fast	Unilateral Pogo jumps Backwards	-	10	1	Fast
Bilateral Hops Medium Hurdles	-	10	2	Fast	Triple Bilateral CMJ Jump (short ground contact)	-	5	2	Fast
CMJ stiff leg landing (height focused)	-	8	2	Slow	CMJ Long Jump Bilateral with stiff landing (distance focused)	-	5	4	Slow

Note: fSSC – fast stretch-shortening cycle; sSSC – slow stretch-shortening cycle.

2.7 Statistical analysis

The data analysis was completed using SPSS 27.0 (IBM Corp., Armonk, NY, USA) and R (v4.4.1, R Core Team, Vienna, Austria). All data were represented using means with their 95% confidence intervals (95%CI) after they were checked for normality using the Kolmogorov-Smirnov test and QQ plots of residuals. For the baseline characteristics, one-way ANOVA in SPSS was used to determine any differences between the two intervention groups. To determine the differences between the groups and across the testing time points for running performance, physiological determinants of running performance, neuromuscular and biomechanical factors, as well as body composition, a linear mixed model developed in R was used. These analyses were run by using the *lme4* package (v1.1-35.5, Ben Bolker) and the *lmerTest* package (v3.1-3, Rune Haubo Bojesen Christensen). Furthermore, to obtain the estimated marginal means to compare the groups and specific time points in a post-hoc fashion the *emmeans* package was used (v1.10.6, Russell V. Lenth). Within these models the response variable was identified as the running, neuromuscular, or biomechanical variable being tested; the fixed effects were identified as the testing time point and intervention group; and the random effects were classified as each participant's unique ID. Statistical significance was set at an alpha value of $p = 0.05$. Lastly, to better understand the mechanisms underpinning the training effects, a Pearson's correlation coefficient analysis was used (Skovgaard et al., 2014). The associations between running performance outcomes and the physiological determinants of running, neuromuscular factors, running biomechanical factors, and body composition measurements were calculated, respectfully.

Chapter Three: Results

3.1 Participant characteristics

Of the 24 participants who initially showed interest in the study, only 21 consented to participate and reported for the familiarisation session. Only 16 participants went on to complete at least one follow-up testing session. Three participants completed the baseline testing session but then withdrew due to scheduling constraints. One withdrew after the familiarisation session due to an injury unrelated to the study, and the other had to be excluded as they were also participating in another research study. Of the 16 participants who completed at least one follow-up testing session, only 11 completed the full 8-week training program and the final testing session. Four participants withdrew due to injury: During the period of their follow-up testing (n=1); before beginning their final testing (n=1); and during the period of their final testing (n=2). The fifth participant withdrew before their final testing session due to illness.

The 16 participants included in the study were sorted into either the RST (n = 8) or HWT (n = 8) as described in Chapter Two. This small sample size did cause the current study to be statistically underpowered according to the calculations also outlined in Chapter Two. However, it must be kept in mind that the majority of RCTs in this field of research have published studies with sample sizes ranging from as low as six participants per group (Sedano et al., 2013).

The 16 participants with data from at least one follow-up testing session were included in the mixed-effects model analysis that accounted for missing data. Baseline physical, performance, and strength characteristics are presented in *Table 3.1*. No significant between-group differences were found for any variable and therefore, were suitable for comparison in this randomised-controlled study.

3.2 Training Volume

Weekly training volumes (see *Table 3.2*) remained unchanged throughout the experimental period across both groups.

3.3 Body Composition

Body weight, BMI, and body fat did not show any significant changes across the three testing periods. Only quadriceps muscle thickness ($p=0.04$), and quadriceps + hamstring thickness ($p=0.03$) showed a significant main time effect at post-testing. However, no significant pairwise comparisons were noted for changes across testing points when combining both groups (see *Table 3.3*).

1.1 Muscle Performance Tests

3.4.1 1RM

For both absolute and relative 1RM strength (see *Figure 3.1A*) there were statistically significant time effects across the pre- to mid-testing (*Absolute*: +14.6kg (95%CI: 8.5, 20.7), $p < 0.001$; *Relative*: +0.2 (95%CI: 0.1, 0.3), $p < 0.001$) and pre- to post-testing periods (*Absolute*: +21.8kg (95%CI: 15.1, 28.4), $p < 0.001$; *Relative*: +0.3 (95%CI: 0.2, 0.4), $p < 0.001$). A significant interaction effect was only noted for changes in relative 1RM ratio at mid-testing (*HWT vs. RST*: -0.2 (95%CI: 0.0, 0.3), $p = 0.04$) even though both groups significantly improved their relative 1RM ratio from pre- to mid-testing (*HWT*: +0.3 (95%CI: 0.2, 0.4), +22.3%, $p < 0.001$; *RST*: +0.1 (95%CI: 0.0, 0.2), +7.2%, $p = 0.04$). Furthermore, only the HWT group showed significant improvements in absolute 1RM (+19.9kg (95%CI: 11.4, 28.3), +21.9%, $p < 0.001$) from pre- to mid-testing. However, both groups presented significant improvements in absolute (*HWT*: +25.0kg (95%CI: 34.4, 15.6), +35.0%, $p < 0.001$; *RST*: +18.5kg (95%CI: 9.6, 27.4), +20.8%, $p = 0.001$) and relative 1RM ratio (*HWT*: +0.3 (95%CI: 0.2, 0.5), +35.0%, $p < 0.001$; *RST*: 0.2 (95%CI: 0.1, 0.3), +18.3%, $p < 0.001$) over the pre- to post-testing period.

Table 3.1: Physical, strength and performance characteristics of participants.

Variables	Heavy-weight Training Group [n = 8] [3F; 5M]	Reactive-strength Training Group [n = 8] [3F; 5M]
Age (yr)	38.9 (24.1, 37.7)	38.9 (24.8, 37.0)
Weight (kg)	73.6 (64.6, 82.6)	71.1 (60.5, 81.7)
BMI (kg.m ⁻²)	24.5 (22.6, 26.4)	24.0 (21.7, 26.3)
5km Time Trial (mm:ss)	26:05 (23:08, 29:02)	26:12 (24:28, 27:56)
VO ₂ max (ml.kg ⁻¹ .min ⁻¹)	51.7 (47.8, 55.6)	51.5 (48.0, 55.0)
Speed-1	7.4 (6.9, 7.9)	7.3 (6.8, 7.8)
Speed-2	8.4 (7.9, 8.9)	8.3 (7.8, 8.8)
Speed-3	9.4 (8.9, 9.9)	9.3 (8.8, 9.8)
Speed-4	10.4 (9.9, 10.9)	10.3 (9.8, 10.8)
Speed-5	11.4 (10.9, 11.9)	11.3 (10.8, 11.8)
RE1 (ml.kg ⁻¹ .km ⁻¹)	235.7 (225.8, 245.6)	243.0 (218.3, 267.7)
RE2 (ml.kg ⁻¹ .km ⁻¹)	232.0 (216.6, 247.4)	233.9 (210.6, 257.2)
RE3 (ml.kg ⁻¹ .km ⁻¹)	227.8 (215.6, 240.0)	229.3 (213.1, 245.4)
RE4 (ml.kg ⁻¹ .km ⁻¹)	221.5 (207.7, 235.3)	222.2 (209.1, 235.3)
RE5 (ml.kg ⁻¹ .km ⁻¹)	221.8 (212.7, 230.9)	222.5 (208.2, 236.8)
vMART (m.s ⁻¹)	5.8 (5.5, 6.1)	5.6 (5.0, 6.2)
1RM (kg)	90.8 (72.0, 109.6)	113.6 (95.0, 132.2)
CMJ height (cm)	25.5 (23.3, 27.7)	23.1 (18.1, 28.1)
SJ height (cm)	23.2 (20.6, 25.8)	20.9 (16.5, 25.3)
RSI (cm.sec ⁻¹)	1.6 (1.3 – 1.9)	1.6 (1.3 – 1.9)
Average weekly training volume (km)	69.7 (40.5 – 98.9)	67.3 (44.7 – 89.9)

Note: Values are reported as Means with 95% confidence intervals. F – female; M – male; BMI – Body mass index; VO₂max – maximum volume of O₂ per kilogram per min; Speed – the five submaximal RE speeds were unique to each participant; RE – running economy at speed 1-5; vMART – final velocity during the maximal anaerobic running test; 1RM – one repetition maximum; CMJ – countermovement jump; SJ – squat jump; RSI – reactive strength index. *significant group difference = p>0.05

Table 3.2: Average weekly training volumes reported across three testing periods.

Training Group	Pre-test [HWT = 7; RST = 7]	Mid-test [HWT = 7; RST = 7]	Post-test [HWT = 5; RST = 6]
HWT	67.3km (44.7, 89.9)	72.3km (37.6, 107.0)	65.4km (30.6, 100.2)
RST	69.7km (40.5, 98.9)	56.5km (35.8, 77.2)	72.7km (47.5, 97.9)

Note: Values are reported as Means with 95% confidence intervals. HWT – heavy weight training group; RST – reactive strength training group.

3.4.2 Reactive-strength measures

Out of the 11 reactive-strength metrics measured (see *Figure 3.1B-D*), only RSI (*PRE-POST*: +0.2ms (95%CI: 0.1, 0.4), $p = 0.009$) and RSI_{mod} (*PRE-POST*: +0.1AU (95%CI: 0.0, 0.1), $p < 0.001$) showed significant main time effects, with CMJ_{power} being only metric to produce a significant interaction effect at post-testing (*HWT vs. RST*: -248.5W (95%CI: -53.7, -443.2), $p = 0.02$). Only the RST group showed statistically significant pairwise comparisons from pre- to post-testing for RSI (+0.4ms (95%CI: 0.1, 0.6), 22.4%, $p = 0.01$) and RSI_{mod} (+0.1AU (95%CI: 0.0, 0.1), 39.0%, $p < 0.001$), as well as mid- to post-testing for RSI_{mod} (+0.1AU (95%CI: 0.0, 0.1), 21.6%, $p = 0.04$). Even though there were no main interaction or time effects for changes in CMJ_{height}, the RST group did present statistically significant pre- to post-testing (+3.1cm (95%CI: 1, 5.3), 13.4%, $p = 0.02$) as well as mid- to post-testing results (+3.2cm (95%CI: 1.1, 5.3), 13.9%, $p = 0.02$). Likewise, the RST group also significantly improved their DJ_{height} from mid- to post-testing (+3.8cm (95%CI: 0.9, 6.7), 21.0%, $p = 0.04$). No other statistically significant changes were found for CMJ_{force}, SJ_{height}, SJ_{force}, EUR, or vertical stiffness.

Table 3.3: Body composition measurements across three testing periods.

Body Composition Measure	HWT					RST					Interaction (HWT - RST)	
	Pre-test [n = 8]	Mid-test [n=8]	Post-test [n=6]	%Δ Pre-Mid	%Δ Pre-Post	Pre-test [n = 8]	Mid-test [n=8]	Post-test [n=7]	%Δ Pre-Mid	%Δ Pre-Post	Mid-test	Post-test
Weight (kg)	73.6 (62.8, 84.3)	73.0 (62.2, 83.7)	73.5 (62.8, 84.3)	-0.8%	-0.1%	71.1 (60.4, 81.8)	70.9 (60.2, 81.7)	71.3 (60.6, 82.1)	-0.3%	0.3%	-0.5%	-0.4%
BMI (kg.m ⁻²)	24.5 (22.3, 26.7)	24.3 (22.1, 26.5)	24.6 (22.3, 26.8)	-0.8%	0.4%	24.0 (21.8, 26.3)	24.0 (21.7, 26.2)	24.1 (21.9, 26.3)	0.0%	0.4%	-0.8%	0.0%
Body Fat (%)	19.4 (16.2, 22.5)	18.9 (15.7, 22.2)	19.1 (15.9, 22.3)	-2.6%	-1.5%	18.6 (15.5, 21.7)	18.3 (15.1, 21.5)	18.2 (15.0, 21.4)	-1.6%	-2.2%	-1.0%	0.6%
Quadriceps Thickness (cm)	3.8 (3.2, 4.4)	3.77 (3.2, 4.4)	3.9 (3.3, 4.5)	0.5%	4.3%	3.7 (3.1, 4.3)	3.76 (3.2, 4.4)	3.9 (3.2, 4.5)	2.2%	6.0%	-1.6%	-1.7% ^ε
Quadriceps + Hamstrings Thickness (cm)	8.6 (7.5, 9.6)	8.6 (7.5, 9.7)	8.9 (7.8, 9.9)	0.1%	3.4%	8.4 (7.3, 9.4)	8.5 (7.5, 9.5)	8.8 (7.7, 9.9)	1.6%	4.9%	-1.4%	-1.5% ^ε

Note: Data are presented as means with 95% confidence intervals. *significant difference from pre- to mid-testing; ^significant difference from mid- to post-testing; #significant difference from pre- to post-testing; @significantly different from HWT; \$significant interaction effect; ^εsignificant main time effect. For all superscripted comparisons =[?] $p < 0.05$, =^{??} $p < 0.01$, =^{???} $p < 0.001$.

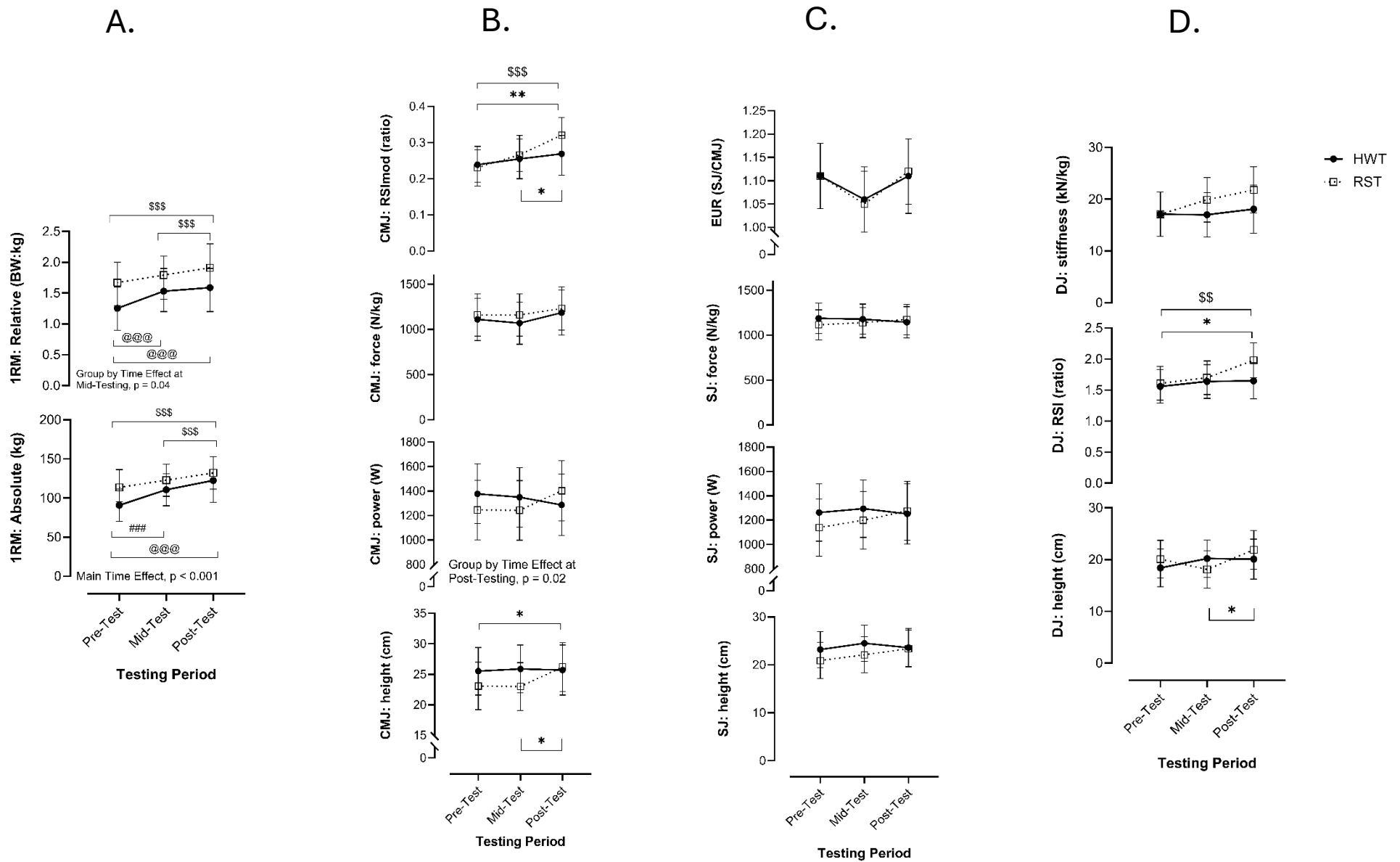


Figure 3.1: A - 1RM results across three testing periods; B – CMJ results across three testing periods; C – SJ results across three testing periods; D – DJ results across three testing periods. Graphs indicate group means with 95%CI. Main effect of time @ $p < 0.5$, @@ $p < 0.01$,

Table 3.4: Gait biomechanical measurements taken while running at speed-5, across three testing periods.

Gait Biomechanics	HWT					RST					Interaction (HWT - RST)	
	Pre-test [n = 8]	Mid-test [n=8]	Post-test [n=6]	%Δ Pre- Mid	%Δ Pre- Post	Pre-test [n = 8]	Mid-test [n=8]	Post-test [n=7]	%Δ Pre- Mid	%Δ Pre- Post	Mid- test	Post- test
Contact Time (ms)	304.1 (277.4, 330.7)	297.7 (271.1, 324.4)	294.0 (267.2, 320.8)	-2.1%	-3.3%	278.4 (253.5, 303.4)	280.6 (255.6, 305.5)	282.1 (257.0, 307.1)	0.8%	1.3%	-2.9%	-4.6%
Flight Time (ms)	49.0 (31.0, 67.0)	54.4 (36.4, 72.3)	55.0 (36.9, 73.2)	10.9%	12.3%	68.1 (51.3, 84.9)	67.8 (50.9, 84.6)	69.1 (52.1, 86.0)	-0.6%	1.4%	11.5%	10.9%
Frequency (Hz)	2.9 (2.7, 3.0)	2.9 (2.7, 3.0)	3.0 (2.8, 3.0)	0.4%	1.4%	2.9 (2.8, 3.0)	3.0 (2.8, 3.0)	2.9 (2.7, 3.0)	-0.3%	-1.4%	0.7%	2.8%
Vertical Oscillation (cm)	5.4 (4.9, 5.9)	5.5 (5.0, 6.0)	5.4 (4.9, 5.9)	1.9%	0.4%	5.5 (5.1, 5.9)	5.6 (5.1, 6.0)	5.6 (5.2, 6.0)	1.3%	1.6%	0.6%	-1.3%
Relative Maximum Force (force/BW)	1.8 (1.7, 2.0)	1.9 (1.7, 2.0)	1.9 (1.7, 2.0)	1.6%	1.6%	21.0 (1.9, 2.1)	2.0 (1.8, 2.1)	2.0 (1.9, 2.1)	-0.5%	0.5%	2.1%	1.1%
Leg Stiffness (kN/m)	8.5 (7.2, 10.0)	8.6 (7.3, 10.0)	9.2 (7.8, 10.6)	0.9%	7.7%	9.3 (8.1, 10.6)	9.2 (7.9, 10.5)	9.3 (8.0, 10.6)	-1.4%	-0.8%	2.3%	8.5%

Note: Data are presented as means with 95% confidence intervals.

1.2 Running Biomechanical Analysis

No significant changes were found for contact time, flight time, step frequency, vertical oscillation, relative maximum force, and leg stiffness measured at speed-5 (see *Table 3.4*).

1.3 Maximal Anaerobic Running Test

From the data recorded during the MART, only vMART ($+0.2\text{m}\cdot\text{s}^{-1}$ (95%CI: 0.1, 0.3), $p = 0.006$) and maximum O_2 demand ($+2.2\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (95%CI: 0.8, 3.6) $p = 0.031$) showed significant time effects across pre- to post-testing (see *Figure 3.2*). However, there were no statistically significant changes noted in the pairwise comparisons. The RST group's results over the pre- to post-testing period only tended to significance for vMART ($+0.2\text{m}\cdot\text{s}^{-1}$ (95%CI: 0.1, 0.3), 3.4%, $p = 0.06$) and O_2 Demand ($+2.6\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (95%CI: 0.5, 4.7), 3.9%, $p = 0.06$). No significant results were found for O_2 deficit.

1.4 Running economy and related physiological measures

3.7.1 Running Economy

The linear mixed-effects model showed no statistically significant effects for the RE data at any of the five speeds tested across both training groups (see *Table 3.5*). Even though statistical significance was not reached, it is important to highlight practically significant changes in these data. Previous research has set the practically significant degree of change or smallest worthwhile change in RE to be between 2.2% and 2.6% (Saunders et al., 2004a,b). The RST group improved at pre- to mid- and pre- to post-testing for speed-1 (*PRE-MID*: -4.1%, $p = 0.49$; *PRE-POST*: -3.7%, $p = 0.59$), -2 (*PRE-MID*: -3.0%, $p = 0.64$; *PRE-POST*: -2.3%, $p = 0.79$), and -3 (*PRE-MID*: -2.20%, $p = 0.69$; *PRE-POST*: -3.38%, $p = 0.45$). The HWT group only improved at speed-5 at pre- to post-testing (-2.4%, $p = 0.82$).

It is also meaningful to highlight the RST group's practically significant improvement compared to the HWT group during pre- to mid- and pre- to post-testing at speed-1 (*PRE-MID*: 2.2%; *PRE-POST*: 7.7%) and speed-3 (*PRE-MID*: 3.5%; *PRE-POST*: 3.3%). There were also practically significant differences between groups for speed-2 (5.3%) and speed-4 (2.3%) at the pre- to mid-testing period.

There were no statistically significant findings in the RE vs. Speed analysis (i.e. faster speeds later on during the treadmill test time) across groups or testing periods by comparing the slopes of these data (see *Figure 3.3*). However, the comparisons between the elevation of the regression lines were – on the other hand – statistically distinct in both the RST ($p < 0.001$) and HWT group ($p < 0.001$). This proves that for every inputted x -value, each regression line will predict a statistically distinct y -value. In essence, RE at a given speed will be statistically distinct across the different testing points in the experimental period.

3.7.2 $VO_2\text{max}$, $vVO_2\text{max}$, and Peak Treadmill Speed

There were no statistically significant effects in $VO_2\text{max}$ and $vVO_2\text{max}$ findings throughout the experimental period. However, there were significant main time effects for PTS across the pre- to mid-testing (+0.85km.hr⁻¹ (95%CI: 0.36, 1.34), $p = 0.002$) and pre- to post-testing period (+1.04km.hr⁻¹ (95%CI: 0.47, 1.61), $p = 0.001$) (see *Table 3.6*). The interaction effect at post-testing for PTS only tended to significance (*HWT vs. RST*: +1.03km.hr⁻¹ (95%CI: -0.1, 2.1), $p = .0.07$). Furthermore, only the RST group showed a significant change from pre- to mid-testing (+1.26km.hr⁻¹ (95%CI: 0.60, 1.92), 8.8%, $p = 0.003$) and from pre- to post-testing (+1.54km.hr⁻¹ (95%CI: 0.80, 2.27), 10.7%, $p = 0.001$).

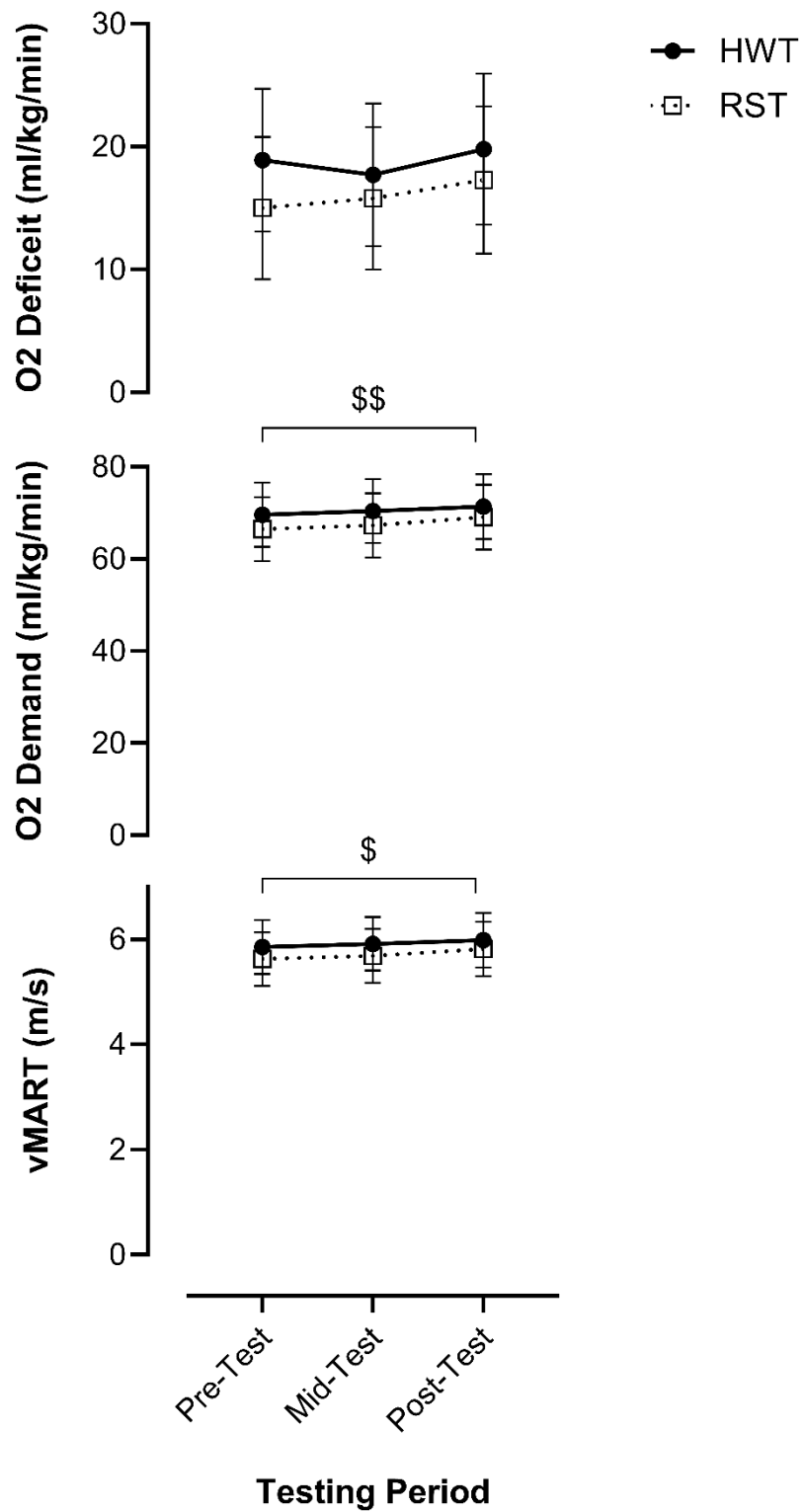


Figure 3.2: Maximal “anaerobic” running test results across three testing periods for velocity at MART, maximum O₂Demand, and final O₂Deficit. Graphs indicate group means with 95% confidence intervals. RST within-group difference * $p < 0.05$.

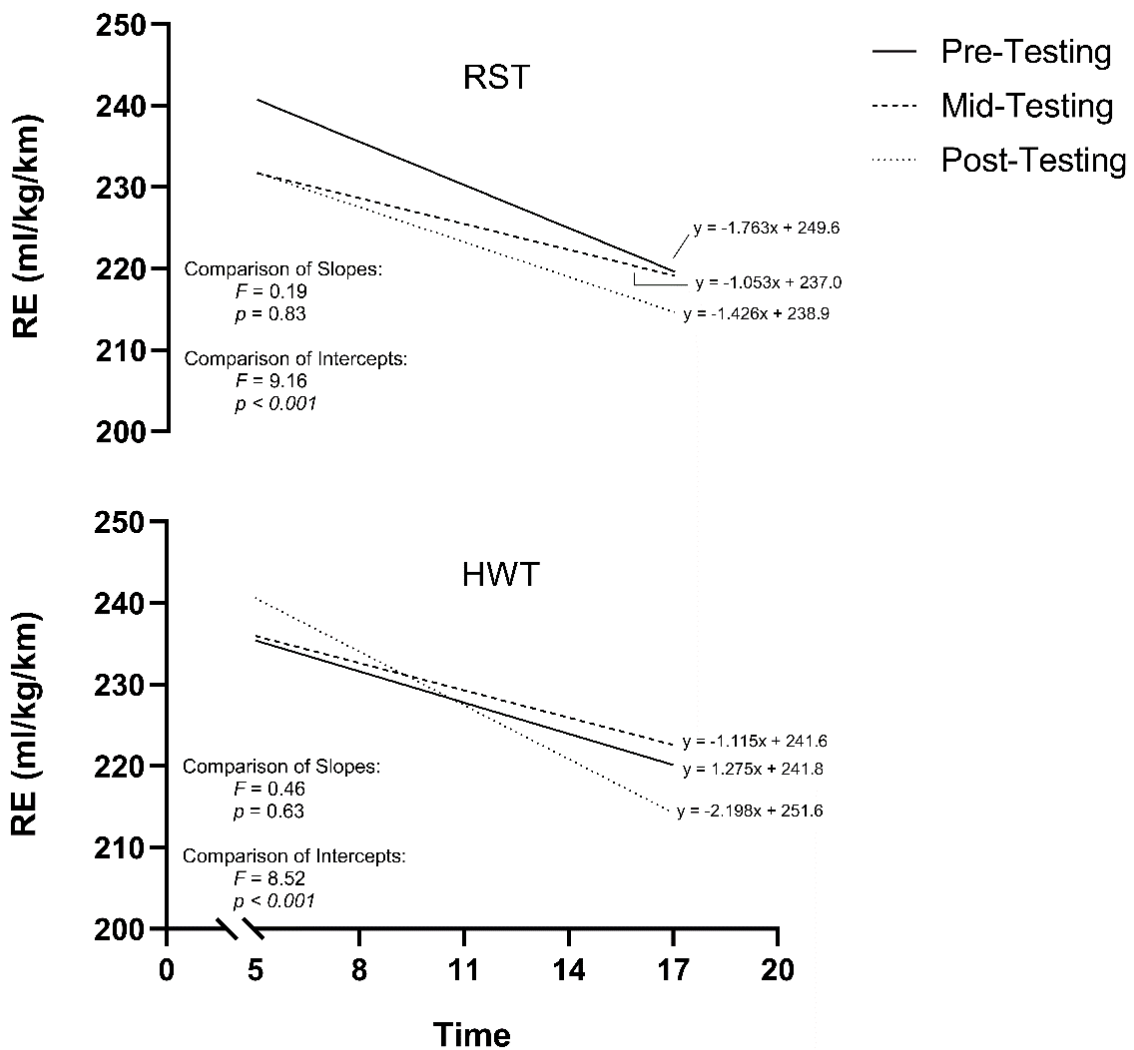


Figure 3.3: Comparison of RE across three testing periods for RST and HWT. Slope equations are provided, as well as the F and p values for each comparison.

Table 3.5: Running economy (ml.kg⁻¹.km⁻¹) results across three testing periods.

Running Economy	HWT					RST					Interaction (HWT - RST)	
	Pre-test	Mid-test	Post-test	%Δ	%Δ	Pre-test	Mid-test	Post-test	%Δ	%Δ	Mid-test	Post-test
	[n = 8]	[n=8]	[n=6]	Pre-Mid	Pre-Post	[n = 8]	[n=8]	[n=7]	Pre-Mid	Pre-Post		
RE1 (ml.kg ⁻¹ .km ⁻¹)	235.7 (217.1, 254.3)	231.1 (212.5, 249.6)	245.0 (224.7, 265.3)	-2.0%	4.0%	243.0 (224.4, 261.6)	233.0 (214.4, 251.6)	234.0 (214.6, 253.3)	-4.1%	-3.7%	2.2%	7.7%
RE2 (ml.kg ⁻¹ .km ⁻¹)	232.0 (212.4, 251.6)	237.3 (217.7, 256.9)	231.2 (210.4, 252.0)	2.3%	-0.3%	234.0 (214.4, 253.5)	227.0 (207.5, 246.6)	228.7 (208.5, 248.8)	-3.0%	-2.3%	5.3%	1.9%
RE3 (ml.kg ⁻¹ .km ⁻¹)	227.8 (212.4, 243.2)	230.8 (215.4, 246.2)	227.7 (211.3, 244.1)	1.3%	-0.1%	229.3 (213.9 - 244.7)	224.3 (208.9, 239.7)	221.6 (205.8, 237.4)	-2.2%	-3.4%	3.5%	3.3%
RE4 (ml.kg ⁻¹ .km ⁻¹)	221.5 (207.4, 235.7)	228.7 (214.5, 242.9)	219.1 (203.7, 234.5)	3.2%	-1.2%	222.2 (208.0- 236.3)	224.1 (209.9, 238.3)	219.7 (205.0, 234.4)	0.9%	-1.1%	2.3%	-0.0%
RE5 (ml.kg ⁻¹ .km ⁻¹)	221.8 (209.9, 233.8)	218.6 (206.7, 230.6)	216.5 (203.4, 229.6)	-1.4%	-2.4%	222.5 (210.5, 234.4)	218.7 (206.7, 230.6)	218.9 (206.5, 231.4)	-1.7%	-1.6%	0.3%	-0.8%

Note: Data are presented as means with 95% confidence intervals.

Table 3.6: Oxygen-dependent running metric results across three testing periods.

Maximal Oxygen- dependent Metrics	HWT					RST					Interaction (HWT - RST)	
	Pre-test	Mid-test	Post-test	%Δ	%Δ	Pre-test	Mid-test	Post-test	%Δ	%Δ	Mid-test	Post-test
	[n = 8]	[n=8]	[n=6]	Pre- Mid	Pre- Post	(n = 8)	(n=8)	(n=7)	Pre-Mid	Pre- Post		
VO ₂ max (ml.kg ⁻¹ .min ⁻¹)	51.7 (47.3, 56.2)	52.8 (48.3, 57.2)	53.01 (48.3, 57.9)	2.0%	2.6%	51.5 (47.0, 55.9)	51.5 (47.1, 56.0)	51.8 (47.2, 56.3)	0.0%	0.5%	2.0%	2.1%
vVO ₂ max (km.hr ⁻¹)	14.6 (13.0, 16.2)	14.9 (13.3, 16.5)	15.4 (13.7, 17.2)	1.8%	5.4%	14.5 (12.9, 16.1)	14.7 (13.1, 16.3)	14.7 (13.1, 16.4)	1.5%	1.7%	0.4%	3.7%
PTS (km.hr ⁻¹)	15.3 (14.0, 16.6)	15.7 (14.4, 17.0)	15.8 (14.4, 17.2)	2.9%	3.3%	14.4 (13.1, 15.7)	15.7 (14.4, 17.0)	16.0 (14.6, 17.3)	8.7%* [*]	10.7% ^{##}	-5.9% ^{€€€}	-7.3% ^{€€€}

Note: Data are presented as means with 95% confidence intervals. *significant difference from pre- to mid-testing; ^significant difference from mid-to post-testing; #significant difference from pre- to post-testing; @significantly different from HWT; \$significant interaction effect; €significant main time effect. For all superscripted comparisons =[?] $p < 0.05$, ?? $p < 0.01$, ??? $p < 0.001$.

Table 3.7: 5km TT (sec) results across three testing periods.

5km Metrics	TT	HWT					RST					Interaction (HWT - RST)	
		Pre-test	Mid-test	Post-test	%Δ	%Δ	Pre-test	Mid-test	Post-test	%Δ	%Δ	Mid-test	Post-test
		[n = 8]	[n=8]	[n=6]	Pre-Mid	Pre-Post	[n = 8]	[n=8]	[n=7]	Pre-Mid	Pre-Post		
Duration (sec)		1565.6 (1407.7, 1723.6)	1533.0 (1374.6, 1691.3)	1544.6 (1385.8, 1703.3)	-2.1%	-1.3%	1572.4 (1414.4, 1730.3)	1532.4 (1374.1, 1690.7)	1477.4 (1318.1, 1636.7)	-2.5%	-6.0%***	0.5%	4.7% ^{\$}
Km completion time (sec)	1	333.3 (300.6, 365.9)	321.9 (289.1, 354.7)	319.3 (286.3, 352.3)	-3.4%	-4.2%	329.5 (296.9, 362.1)	322.8 (290.0, 355.6)	301.1 (267.8, 334.4)	-2.0%	-8.6%###	-1.4% ^{€€}	4.5% ^{€€€}
Km completion time (sec)	2	320.1 (288.3, 351.92)	312.1 (280.1, 344.1)	312.4 (280.2, 344.6)	-2.5%	-2.4%	321.6 (289.8, 353.4)	313.3 (281.3, 345.3)	296.8 (264.3, 329.3)	-2.6%	-7.7%	0.1%	5.3% ^{€€}
Km completion time (sec)	3	313.4 (279.9, 346.9)	305.7 (272.0, 339.4)	311.2 (277.4, 345.0)	-2.5%	-0.7%	313.0 (279.5, 346.5)	305.7 (272.1, 339.4)	301.2 (267.3, 335.2)	-2.3%	-3.8%	-0.1% [€]	3.1%
Km completion time (sec)	4	304.8 (271.4, 338.1)	300.7 (267.1, 334.3)	307.5 (273.6, 341.4)	-1.3%	0.9%	311.4 (278.1, 344.7)	300.0 (266.4, 333.6)	294.4 (260.1, 328.7)	-3.7%	-5.5%	2.3%	6.4%
Km completion time (sec)	5	294.1 (263.1, 325.1)	293.4 (262.2, 324.6)	295.0 (263.6, 326.4)	-0.3%	0.3%	296.9 (265.9, 327.9)	289.9 (258.7, 321.1)	292.4 (260.7, 324.1)	-2.4%	-1.5%	2.1%	1.8%

Note: Data are presented as means with 95% confidence intervals. *significant difference from pre- to mid-testing; ^significant difference from mid-to post-testing; #significant difference from pre- to post-testing; @significantly different from HWT; \$significant interaction effect; €significant main time effect. For all superscripted comparisons =[?] $p < 0.05$, ^{??} $p < 0.01$, ^{???} $p < 0.001$.

1.5 5km time trial (5kmTT)

The linear mixed-effects model showed there was a statistically significant group by time interaction at post-testing for the 5kmTT (*HWT vs RST*: +73.9sec (95%CI: -17.2, 130.6), $p = 0.02$) (see *Table 3.7*). The pairwise comparisons of the 5kmTT revealed that the RST group improved their performance by 95.0 seconds ((95%CI: 53.5, 136.6), -6.0%, $p < 0.001$) from pre- to post-testing and by 55.0 seconds ((95%CI: 13.5, 96.6), -3.5%, $p = 0.04$) from mid- to post-testing. The time taken to complete each of the five kilometres was tested using the same statistical model. The results for the first (*PRE-MID*: -9.1sec (95%CI: -17.6, -0.6), $p = 0.047$; *PRE-POST*: -20.1sec (95%CI: -29.4, -10.8), $p < 0.001$), second (*PRE-POST*: -15.3sec (95%CI: -24.6, -6.0), $p = 0.003$), and third kilometres (*PRE-MID*: -7.6sec (95%CI: -14.3, -1.0), $p = 0.03$) showed significant main effects of time. These pairwise comparisons only showed that the RST group improved their performance over the first kilometre across the mid- to post-testing (-21.7sec (95%CI: -34.7, -8.8), -6.6%, $p = 0.009$) and pre- to post-testing periods (-28.4sec (95%CI: -41.4, -15.5), -8.6%, $p < 0.001$).

1.6 Correlational analysis

3.9.1 Muscle Performance Tests vs. Physiological and Performance Measures

3.9.1.1 Biomechanical running analysis

No statistically significant correlations were found between any biomechanical variables and the muscle performance test results, across any testing period.

3.9.1.2 Running economy and related physiological measures

At pre- to mid-testing, a significant correlation was found between the $\Delta\text{CMJ}_{\text{force}}$ and ΔRE3 ($r = -0.54$, moderate; $p = 0.03$), as well as ΔRE5 ($r = -0.52$, moderate; $p = 0.04$). Meanwhile, $\Delta\text{SJ}_{\text{force}}$ was only significantly correlated with ΔRE3 ($r = -0.53$, moderate; $p = 0.04$) over the same pre- to mid-testing period. The changes evident from pre- to post-testing for

RSI_{mod}, RSI, and vertical stiffness were significantly correlated to changes in RE3 (RSI_{mod}: $r = 0.50$, moderate, $p = 0.049$; RSI: $r = 0.61$, strong, $p = 0.02$; vertical stiffness: $r = 0.56$, moderate, $p = 0.049$), RE4 (RSI_{mod}: $r = 0.54$, moderate, $p = 0.03$; RSI: $r = 0.71$, strong, $p = 0.007$; vertical stiffness: $r = 0.61$, strong, $p = 0.03$), and RE5 (RSI_{mod}: $r = 0.52$, moderate, $p = 0.04$; RSI: $r = 0.74$, $p = 0.004$; vertical stiffness: $r = 0.73$, strong, $p = 0.005$), respectively. No other significant correlations were noted for RE1, RE2, and PTS across the experimental period.

3.9.1.3 Maximal Anaerobic Running Test

Even though data from vMART and O₂Demand were significant in the linear mixed-effects model, no correlations were found between changes in these data and any muscle performance metrics. However, ΔO_2 Deficit was significantly correlated with both ΔRSI ($r = -0.71$, strong; $p = 0.01$) and Δ vertical stiffness ($r = -0.74$, strong; $p = 0.01$) measured over the same pre- to post-testing period.

3.9.1.4 5km time trial

None of the changes in muscle performance tests statistically significantly correlated with the $\Delta 5$ kmTT. However, the $\Delta 5$ kmTT over the pre- to mid-testing and pre- to post-testing periods moderately correlated with the Δ relative 1RM ratio ($r = -0.53$, moderate; $p = 0.052$) and ΔCMJ_{force} ($r = -0.57$, moderate; $p = 0.065$), respectively, but only tended to statistical significance.

3.9.2 Biomechanical Running Analysis vs. Physiological and Performance Measures

4.9.2.1 Running economy and related physiological measures

The biomechanical running analysis was performed at speed-5. Therefore, changes in metrics only measured at this speed were tested against one another. No statistically significant correlations were found across the experimental period. Only a moderate

correlation between the Δ leg stiffness and Δ RE5 tended to statistical significance over the pre- to mid-testing period ($r = -0.46$, moderate; $p = 0.083$).

3.9.2.2 Maximal anaerobic running test

No changes in any biomechanical analysis variables correlated with the Δ MART across any testing period.

3.9.2.3 5km time trial

There were also no changes in any biomechanical analysis variables that correlated with the Δ 5kmTT across any testing period.

3.9.3 Running Economy and Related Physiological Measures vs. Performance Measures

3.9.3.1 5km time trial

Of all the metrics measured during the treadmill test, only the Δ RE3 statistically significantly correlated with the Δ 5kmTT during the pre- to mid-testing testing period ($r = 0.54$, moderate; $p = 0.048$). A strong correlation between the Δ PTS and the Δ 5kmTT that tended to significance at post-testing is also worth highlighting ($r = -0.61$, strong; $p = 0.084$).

3.9.4 Maximal Anaerobic Running Test vs. Performance Measures

3.9.4.1 5km time trial

Lastly, even though O_2 Demand was not significant in the linear mixed-effects analysis, the ΔO_2 Demand was the only MART variable that statistically significantly correlated with the Δ 5kmTT. This correlation was established over the pre- to mid-testing period ($r = -0.621$, strong; $p = 0.02$).

Chapter Four: Discussion

The most important aim of this study was to determine which – if either – of the training modalities – HWT or RST – resulted in the most significant increase in performance in recreational long-distance runners. Additionally, we aimed to understand the mechanisms underpinning any improvements produced by these training modalities. Finally, we sought to determine the time course of statistically significant physiological and performance adaptations for each training modality.

4.1 Improvements in time trial performance elicited by concurrent training

The improvement in time trial performance after concurrent training was the most valuable finding in this study. Specifically, RST was shown to be a superior concurrent training modality compared to HWT when tested under identical conditions. This is the first time this question has been answered, and this answer does indeed have far-reaching implications in coaching and scientific communities. Each RST training session was completed within half the time of the HWT sessions. Furthermore, the RST used low-cost equipment compared to the barbells, weights, and machines used in the HWT. Therefore, in this study, the most cost- and time-effective training modality was also the most effective at improving running performance.

The fact that the RST group outperformed the HWT group in the 5kmTT results seems to conflict with the most recent meta-analysis by Eihara et al. (2022). This study's meta-analytical results showed that HWT training (Standardised Mean Difference (SMD) = -0.24 (95%CI: -1.04, -0.55), *small*) was more beneficial in improving time trial performance when compared to RST (SMD = -0.17 (95%CI: -0.27, -0.06), *trivial*). However, if one filters these meta-analytical data to include conventional HWT only (Karsten et al., 2016) as well as RST that incorporated drop jump training (Berryman, Maurel & Bosquet, 2010b; Ramírez-Campillo et al., 2014b; Machado et al., 2019), the interpretation of these findings shifts. The SMD of these filtered RST studies (SMD= -0.52

to -0.17, *moderate* to *trivial*) now either equals or exceeds the single filtered HWT study (-0.17, *trivial*). Thus, the filtered data from the Eihara et al. (2022) study favours DJ-focused RST and not HWT. These comparisons prove that the results found in the current study substantiate previous research and do not contradict it as it first appears. Furthermore, these comparisons show that future research should focus on RST – and more specifically – DJ-focused programs which have been proven to have the greatest benefit for long-distance running compared to other modalities.

Another novel finding from the 5kmTT results was the nature in which the pacing strategies changed over time. On average, all the participants ran faster during the first kilometre of the TT when compared to the baseline. However, pairwise analysis showed that only the RST group ran significantly faster during their first kilometre at post-testing compared to their baseline time. The times that the final stages of the 5kmTT were completed showed no significant changes. This means that participants were not necessarily able to finish their 5kmTT running at faster speeds; rather, they were able to run faster early in the 5kmTT and sustain these speeds for longer. These findings contrast, however, those of Damasceno et al. (2015) who found that after eight weeks of strength training their participants ran faster in the last 2800 metres of a 10kmTT. This distinct difference in pacing strategies in response to resistance training may be due to the different distances tested or due to the resistance training modalities used. What both these results prove is that resistance training in general has a fatigue-resistant effect during TT performance. After engaging in concurrent training, runners can sustain faster speeds for longer periods of time – be it at the beginning or end of their run.

Finally, this study's 5kmTT also novelly adds to research that describes the time course of running performance changes in response to concurrent training. This is the first study to show a linear improvement in time trial performance from baseline, through mid-testing at 5 weeks, up until post-testing at 10 weeks. Since no plateauing effect was seen after the two four-week training blocks, RST-based concurrent training may reap even greater TT benefits from training programs lasting longer than eight weeks. Even though there have been RST-based concurrent training studies that prescribed up to 10 weeks of training (García-Pinillos, Lago-Fuentes, et al., 2020b; do Carmo et al., 2021), future studies need to investigate training periods longer than 10 weeks as well as test

participants multiple times during the experimental period. Only once this has been done will we be able to definitively describe the most effective concurrent training periodisation strategies for recreational long-distance runners.

4.2 Understanding the mechanisms underpinning the time trial performance improvements

Our results also showed that only the change in O_2 Deficit during the MART and VO_2 at RE3 was associated with the change in the 5kmTT. However, neither intervention group showed significant changes in O_2 Deficit or RE throughout the study. One must be careful in extracting inappropriate findings from mechanistic analyses that either do not make practical sense or are derived from small sample sizes and underpowered studies. Therefore, the results from this study's correlational analyses must be viewed with the understanding that these results may have little practical significance. For these 5kmTT findings to be impactful, we needed to understand how strength training mechanistically influences changes in running performance. If the mechanistic pathways are well understood, exercise prescriptions for endurance can become more accurate and effective. This would waste less time and effort on exercises that may – in reality – not achieve the desired outcome of improving running performance. This study has not assisted in refining these prescription guidelines. Future research should explore various variables that could clarify the mechanistic influence of resistance training on running performance, specifically in highly powered studies.

A meta-analysis by (O'Sullivan et al., 2019) showed that only HWT interventions produced significant improvements in RE and significant improvements in running performance (Berryman, Maurel & Bosquet, 2010a; Skovgaard et al., 2014). In this current study, there was a significant association between the changes in RE3 and 5kmTT. Therefore, even though the current study's correlational analysis findings may be statistically significant, it is still worth highlighting that these findings align with previous research. Only RE3 – equal to the participants' training speed – was significant in this study's correlational analyses. Albeit with no statistical significance in the linear mixed-effects model, both groups did show practically significant improvements in RE.

Practically significant changes for RE are set to range between 2.2%-2.6% (Saunders et al., 2004a,b). These seemingly small changes translate to minutes and/or seconds that runners can cut off their training and race times. The improved running times make a significant real-life impact on where athletes place at the finish line. The RST group “practically” significantly improved their RE across the first three submaximal speeds tested, whereas the HWT group only reduced their RE5 at post-testing. One theory explaining the significance of these athletes' training speed correlating with 5kmTT performance is that the ability to train faster may lead to improved race times. Therefore, the results from our study do align with current research, stating that concurrent training may help improve RE which may be responsible for the improvements in running performance (O’Sullivan et al., 2019).

The relationship between the changes in the 5kmTT and O₂Deficit during the MART is similar to the model proposed by (Paavolainen et al., 1999). These authors stated that endurance running performance is not solely based on oxygen-dependent exercise capacity but also on running muscle power factors – oxygen-independent factors. These running muscle power factors include vVO₂max, PTS, and the MART variables (vMART, O₂Demand, and O₂Deficit) (Noakes, 1988; Rusko, Nummela & Mero, 1993b; Paavolainen et al., 1999). Running muscle power factors provide insight into the motor unit recruitment efficiency and force production capacity of the lower limbs during high-intensity running (Nummela et al., 2006). Similar to the Paavolainen et al. (1999) model, a recent study also showed a link between O₂Deficit and 5kmTT (Nummela et al., 2006). This study found that Δ O₂Deficit, in a linear regression model with VO₂max, was able to explain 73% of the variance in their 5kmTT performance (Nummela et al., 2006). In essence, the fact that distance running performance also depends on oxygen-independent muscle power factors is corroborated by this current study’s findings.

The relative change in 1RM and CMJ_{force} also showed correlations with the changes in 5kmTT that tended to significance. These findings – again – do align with previous research. Several studies have shown a consistent link between the CMJ and 5kmTT. These studies have found significant correlations between CMJ_{relative power} and a 10kmTT (Lum et al., 2019), as well as between CMJ_{height} and a 3kmTT (Pellegrino, Ruby & Dumke, 2016) and a 2.4kmTT (Ramírez-Campillo et al., 2014a; Lum et al., 2023). Likewise,

research also has proved that increases in 1RM induced by concurrent HWT are also linked to improvements in time trial performance (Balsalobre-Fernández, Santos-Concejero & Grivas, 2016; Denadai et al., 2017; Alcaraz-Ibañez & Rodríguez-Pérez, 2018; Blagrove, Howatson & Hayes, 2018; Eihara et al., 2022). This current study also showed HWT's positive effect on TT – albeit non-significantly. However, more importantly, it was the first study to assess maximum strength in an RST cohort. Therefore, for the first time, this study showed that RST can also significantly improve 5kmTT performance after improving runners' relative 1RM ratio.

It may seem paradoxical that RST can increase maximal strength; however, there is data to explain this phenomenon. Meta-analysed data showed that plyometric training could effectively improve 1RM measures by as much as 20kg (Sáez-Sáez De Villarreal, Requena & Newton, 2010). Another study compared three groups that participated in load-matched plyometric, maximal strength, and combination training. This study found no statistically significant differences between the groups' 1RM improvements (MacDonald, Lamont & Garner, 2012). The data from these studies help explain how the RST group was able to successfully increase their 1RM back-squat. The findings from our study therefore align with previous research indicating that changes in the CMJ and maximal strength may be linked to improvements in running performance. Furthermore, these findings also shed new light on how RST may influence running performance via mechanistic pathways related to relative 1RM ratio changes. Future studies must explore neuromuscular variables in more detail to establish the links between different resistance training modalities and their mechanistic influence on running performance outcomes.

4.3 Running biomechanical variables not mechanistically linked to changes in RE

It has been hypothesised that the RE-enhancing effects of concurrent training may be attributed to its ability to improve running gait biomechanics (Balsalobre-Fernández, Santos-Concejero & Grivas, 2016; Blagrove, Howatson & Hayes, 2018). However,

research has not been able to back this hypothesis up with empirical evidence. (Ferrauti, Bergemann & Fernandez-Fernandez, (2010) found significant improvements in their concurrent training group's contact time and stride length, but these improvements were not linked to meaningful RE changes. In contrast, the (Patoz et al., 2023) concurrent training intervention produced significant RE improvements without any changes in running gait biomechanics. The results from this current study are similar to that of the Patoz et al. (2023) study. This study found minimal improvements in RE, no improvements in running biomechanics, and no association between these two sets of variables. Thus, running biomechanical factors may not be mechanistically significant when investigating concurrent training effects in long-distance runners. Running biomechanics may simply be a set of innate characteristics that we naturally self-optimize (Moore et al., 2019). Therefore, concurrent training interventions may not produce beneficial running biomechanical adaptations because the ability of these changes to transfer over and stimulate changes in RE is limited. Future studies may need to shift the narrative that implies concurrent training elicited RE improvements is underpinned by changes in running biomechanics.

Chapter Five: Implications for Future Research

This current study has not only added to the body of concurrent training knowledge but also opened up new avenues for future research. As explained in Chapter One, there is data to show that complex or combination training (CPX) may be better than using one modality in isolation (Llanos-Lagos et al., 2024). If we understand how the two modalities function independently, we can improve how they are prescribed in combination. This study demonstrated RST's superiority over HWT in improving 5kmTT performance. However, uncertainties remain regarding the differences between these two training modalities across many other tested variables. Future research needs to investigate the differences between RST and HWT in RE, the 1RM back squat, CMJ and other reactive strength variables, as well as the MART variables. Furthermore, unpacking the mechanisms underpinning these changes is of vital importance. Future studies also

need to explore which type of periodisation model may be best suited to these concurrent training regimens. Understanding when it may be best to periodise these programs into a recreational runner's training plan will further enhance the accuracy of the prescription of this training technique. Lastly, future research must investigate how long it takes for adaptation to occur and when a plateauing effect becomes evident. A meta-analysis showed that longer studies produce better results. However, more intervention studies must measure improvements at multiple points during their respective experimental periods. This will provide a more detailed understanding of how long training cycles need to last for maximal concurrent training-elicited running performance improvements to occur. Focusing on these areas in future research will improve how concurrent training is prescribed for distance runners to elicit performance-enhancing effects.

Chapter Six: Limitations

This study produced novel and significant results; however, it also exhibited several methodological weaknesses and limitations. The RST and HWT programs' limitations which have been detailed above, could have been avoided had a full pilot study been conducted. However, due to time constraints, this was not possible. As with many exercise intervention studies, another limitation was a lack of statistical power due to a small sample size. Initially, a sufficient number of participants were recruited but due to scheduling constraints, sickness, injury, and non-compliance, only 16 participants were included. Even though previous studies have justified the use of a smaller sample size ($n=14$) (Lum et al., 2019), it does make for a statistically weaker research study.

During the randomisation of the training groups, age, sex, BMI, training speeds, and VO_2 max values were all strictly controlled. 1RM was not one of the variables that was prospectively controlled. This resulted in the RST group having a 1RM more than 20kg greater than the HWT. Albeit not statistically significant, this difference could have affected the group-by-time statistic in the linear mixed-effect model analysis.

Lastly, not all participants followed the controls that were put in place. Some altered their diets which may have affected their weight, some ran races on days leading up to testing, and some significantly changed their training load. Even though the average

datasets did not significantly change over time, it does make a practical difference to how those individuals performed across the intervention and testing period. This therefore could have influenced our overall results. Due to an already small sample size, these infringements to the experimental protocol did not result in the participants' exclusion from the study.

Chapter Seven: Conclusion

Although this study did not achieve one of its aims of unpacking the mechanistic pathways underlying concurrent training in runners, it still yielded valuable findings. These findings showed that RST was superior to HWT, and that TT performance improved linearly over 10 weeks. Novelty, this study also showed the ability of RST to improve 1RM in the back squat – a possible mechanistic factor to be investigated in future. By periodising this easy, low-cost, time-efficient, and low-intensity RST program into an athlete's schedule, one can significantly improve athletes' race finish times by more than a minute. However, these findings must be understood in relation to the findings of previous research discussed in Chapter One. Readers should be cognisant of the fact that the improvements seen from complex training (combination of both RST and HWT) as well as in training programs over longer periods may produce even better results. What this study does add to the complex training discussion is how and why RST-focused complex training may be the most beneficial concurrent training protocol for long-distance runners. Future research investigating the mechanisms underpinning RST and complex training will help refine and improve the way athletes, coaches, and conditioning professionals prescribe and implement concurrent training into their endurance running programs.

Reference List

- Abboud, G.J., Greer, B.K., Campbell, S.C. & Panton, L.B. 2013. Effects of load-volume on EPOC after acute bouts of resistance training in resistance-trained men. *Journal of Strength and Conditioning Research*. 27(7):1936–1941. DOI: 10.1519/JSC.0B013E3182772EED.
- Ache-Dias, J., Dellagrana, R.A., Teixeira, A.S., Dal Pupo, J. & Moro, A.R.P. 2015. Effect of jumping interval training on neuromuscular and physiological parameters: a randomized controlled study. <https://doi.org/10.1139/apnm-2015-0368>. 41(1):20–25. DOI: 10.1139/APNM-2015-0368.
- Ache-Dias, J., Pupo, J.D., Dellagrana, R.A., Teixeira, A.S., Mochizuki, L. & Moro, A.R.P. 2018. Effect of Jump Interval Training on Kinematics of the Lower Limbs and Running Economy. *Journal of Strength and Conditioning Research*. 32(2):416–422. DOI: 10.1519/JSC.0000000000002332.
- Alcaraz-Ibañez, M. & Rodríguez-Pérez, M. 2018. Effects of resistance training on performance in previously trained endurance runners: A systematic review. *Journal of Sports Sciences*. 36(6):613–629. DOI: 10.1080/02640414.2017.1326618.
- Ambrosini, L., Presta, V., Goldoni, M., Galli, D., Mirandola, P., Vitale, M. & Gobbi, G. 2021. Are we able to match non sport-specific strength training with endurance sports? A systematic review and meta-analysis to plan the best training programs for endurance athletes. *Applied Sciences (Switzerland)*. 11(16). DOI: 10.3390/APP11167280.
- Andrade, D.C., Beltrán, A.R., Labarca-Valenzuela, C., Manzo-Botarelli, O., Trujillo, E., Otero-Farias, P., Alvarez, C., Garcia-Hermoso, A., et al. 2018. Effects of plyometric training on explosive and endurance performance at sea level and at high altitude. *Frontiers in Physiology*. 9(OCT). DOI: 10.3389/fphys.2018.01415.
- Andrade, D.C., Flores-Opazo, M., Peñailillo, L., Delgado-Floody, P., Cano-Montoya, J., Vásquez-Gómez, J.A. & Alvarez, C. 2021. Similar Adaptations to 10 Weeks Concurrent Training on Metabolic Markers and Physical Performance in Young, Adult, and Older Adult Women. *Journal of clinical medicine*. 10(23). DOI: 10.3390/jcm10235582.
- Arazi, H., Asadi, A., Mahdavi, S.A. & Nasiri, S.O.M. 2014. Cardiovascular responses to plyometric exercise are affected by workload in athletes. *Postepy w Kardiologii Interwencyjnej*. 10(1):2–6. DOI: 10.5114/pwki.2014.41458.

- Balsalobre-Fernández, C., Santos-Concejero, J. & Grivas, G. V. 2016. Effects of Strength Training on Running Economy in Highly Trained Runners: A Systematic Review with Meta-Analysis of Controlled Trials. *Journal of Strength and Conditioning Research*. 30(8):2361–2368. DOI: 10.1519/JSC.0000000000001316.
- Balsalobre-Fernández, C., Agopyan, H. & Morin, J.B. 2017. The validity and reliability of an iPhone app for measuring running mechanics. *Journal of Applied Biomechanics*. 33(3):222–226. DOI: 10.1123/jab.2016-0104.
- Barnes, K.R., Hopkins, W.G., Mcguigan, M.R., Northuis, M.E. & Kilding, A.E. 2013. Effects of resistance training on running economy and cross-country performance. *Medicine and Science in Sports and Exercise*. 45(12):2322–2331. DOI: 10.1249/MSS.0b013e31829af603.
- Barrie, B. 2020. Concurrent Resistance Training Enhances Performance in Competitive Distance Runners: A Review and Programming Implementation. *Strength and Conditioning Journal*. 42(1):97–106. DOI: 10.1519/SSC.0000000000000528.
- Barrio, E.D., Fernández-Landa, J., Negra, Y., Ramirez-Campillo, R. & de Alcaraz, A.G. 2023. DOI: 10.26582/k.55.2.11.
- Beattie, K. 2019. Strength Training for Endurance Runners. In *Concurrent Aerobic and Strength Training*. M. Schumann & B.R. Ronnestad, Eds. Springer International Publishing. 341–355. DOI: 10.1007/978-3-319-75547-2_23.
- Beattie, K., Carson, B., Lyons, M., Rossiter, A. & Kenny, I. 2017. The Effect of Strength Training for Distance Runners. *Journal of Strength and Conditioning Research*. 31(1).
- Bernard, O., Ouattara, S., Maddio, F., Jimenez, C., Charpenet, A., Melin, B. & Bittel, J. 2000. Determination of the velocity associated with VO₂max. *Medicine and science in sports and exercise*. 32(2):464–470. DOI: 10.1097/00005768-200002000-00031.
- Berryman, N., Maurel, D. & Bosquet, L. 2010. Effect of plyometric vs. Dynamic weight training on the energy cost of running. *Journal of Strength and Conditioning Research*. 24(35):1818–1825.
- Berryman, N., Mujika, I., Arvisais, D., Roubex, M., Binet, C. & Bosquet, L. 2017. Strength training for middle- and long-distance performance: A meta-analysis. *International Journal of Sports Physiology and Performance*. 13(1):57–63. DOI: 10.1123/ijsp.2017-0032.
- Blagrove, R.C., Howatson, G. & Hayes, P.R. 2018. Effects of Strength Training on the Physiological Determinants of Middle- and Long-Distance Running Performance: A

Systematic Review. *Sports Medicine*. 48(5):1117–1149. DOI: 10.1007/s40279-017-0835-7.

Blagrove, R.C., Howe, L.P., Cushion, E.J., Spence, A., Howatson, G., Pedlar, C.R. & Hayes, P.R. 2018. Effects of Strength Training on Postpubertal Adolescent Distance Runners. *Medicine and Science in Sports and Exercise*. 50(6):1224–1232. DOI: 10.1249/MSS.0000000000001543.

Bogataj, Š., Pajek, M., Hadžić, V., Andrašić, S., Padulo, J. & Trajković, N. 2020. Validity, reliability, and usefulness of my jump 2 app for measuring vertical jump in primary school children. *International Journal of Environmental Research and Public Health*. 17(10). DOI: 10.3390/ijerph17103708.

Bogataj, Š., Pajek, M., Andrašić, S. & Trajković, N. 2020. Concurrent validity and reliability of my jump 2 app for measuring vertical jump height in recreationally active adults. *Applied Sciences (Switzerland)*. 10(11). DOI: 10.3390/app10113805.

Bonacci, J., Green, D., Saunders, P.U., Franettovich, M., Blanch, P. & Vicenzino, B. 2011. Plyometric training as an intervention to correct altered neuromotor control during running after cycling in triathletes: A preliminary randomised controlled trial. *Physical Therapy in Sport*. 12(1):15–21. DOI: 10.1016/j.ptsp.2010.10.005.

Brazier, J., Maloney, S., Bishop, C., Read, P.J. & Turner, A.N. 2019. Lower Extremity Stiffness: Considerations for Testing, Performance Enhancement, and Injury Risk. *Journal of Strength and Conditioning Research*. 33(4):1156–1166. DOI: 10.1519/JSC.0000000000002283.

Burgomaster, K.A., Heigenhauser, G.J.F. & Gibala, M.J. 2006. Effect of short-term sprint interval training on human skeletal muscle carbohydrate metabolism during exercise and time-trial performance. *Journal of Applied Physiology*. 100(6):2041–2047. DOI: 10.1152/jappphysiol.01220.2005.

do Carmo, E.C., Barroso, R., Gil, S., da Silva, N.R., Bertuzzi, R., Foster, C. & Tricoli, V. 2021. Can plyometric training change the pacing behaviour during 10-km running? *European Journal of Sport Science*. DOI: 10.1080/17461391.2021.2013952.

do Carmo, E.C., Barroso, R., Gil, S., da Silva, N.R., Bertuzzi, R., Foster, C. & Tricoli, V. 2023. Can plyometric training change the pacing behaviour during 10-km running? *European Journal of Sport Science*. 23(1):18–27. DOI: 10.1080/17461391.2021.2013952.

- Chelly, M.S., Hermassi, S. & Shephard, R.J. 2015. Effects of in-season short-term plyometric training program on sprint and jump performance of young male track athletes. *J Strength Cond Res.* 8(29):2128–2136. Available: www.nscs.com.
- Chtara, M., Chamari, K., Chaouachi, M., Chaouachi, A., Koubaa, D., Feki, Y., Millet, G.P. & Amri, M. 2005. Effects of intra-session concurrent endurance and strength training sequence on aerobic performance and capacity. *British Journal of Sports Medicine.* 39(8):555–560. DOI: 10.1136/bjism.2004.015248.
- Chtara, M., Chaouachi, A., Levin, G.T., Chaouachi, M., Chamari, K., Amri, M. & Laursen, P.B. 2008. Effect of concurrent endurance and circuit resistance training sequence on muscular strength and power development. *Journal of Strength and Conditioning Research.* 22(4):1037–1045. DOI: 10.1519/JSC.0b013e31816a4419.
- Coffey, V.G. & Hawley, J.A. 2017. Concurrent exercise training: do opposites distract? *Journal of Physiology.* 595(9):2883–2896. DOI: 10.1113/JP272270.
- Conley, D. & Krahenbuhl, G. 1980. Running economy and distance running performance of highly trained athletes. *Med Sci Sports.* 12(5):357–360.
- Coyle, E.F. 1999. Physiological determinants of endurance exercise performance. *Journal of Science and Medicine in Sport.* 2(3):181–189. DOI: 10.1016/S1440-2440(99)80172-8.
- Damasceno, M. V., Lima-Silva, A.E., Pasqua, L.A., Tricoli, V., Duarte, M., Bishop, D.J. & Bertuzzi, R. 2015. Effects of resistance training on neuromuscular characteristics and pacing during 10-km running time trial. *European Journal of Applied Physiology.* 115(7):1513–1522. DOI: 10.1007/s00421-015-3130-z.
- Daniels, J.T., Yarbrough, R.A. & Foster, C. 1978. Changes in VO₂ max and running performance with training. *European Journal of Applied Physiology and Occupational Physiology.* 39(4):249–254. DOI: 10.1007/BF00421448/METRICS.
- Dankel, S.J., Mattocks, K.T., Mouser, J.G., Buckner, S.L., Jessee, M.B. & Loenneke, J.P. 2018. A critical review of the current evidence examining whether resistance training improves time trial performance. *Journal of Sports Sciences.* 36(13):1485–1491. DOI: 10.1080/02640414.2017.1398884.
- Davies, C. & Sargeant, A. 1975. Effects of exercise therapy on total and component tissue leg volumes of patients undergoing rehabilitation from lower limb injury. *Ann Hum Biol.* 2:327–337.

- Denadai, B.S., de Aguiar, A.R., de Lima, L.C., Greco, C.C. & Caputo, F. 2017. Explosive Training and Heavy Weight Training are Effective for Improving Running Economy in Endurance Athletes: A Systematic Review and Meta-Analysis. *Sports Med.* 47:545–554. DOI: 10.1007/s40279-016-0604-z.
- Doma, K. & Deakin, G. 2015. The Acute Effect of Concurrent Training on Running Performance Over 6 Days. *Research Quarterly for Exercise and Sport.* 86(4):387–396. DOI: 10.1080/02701367.2015.1053104.
- Doma, K. & Deakin, G.B. 2013. The effects of strength training and endurance training order on running economy and performance. *Applied Physiology, Nutrition, and Metabolism.* 38(6):651–657. DOI: 10.1139/APNM-2012-0362.
- Doma, K. & Deakin, G.B. 2014. The acute effects intensity and volume of strength training on running performance. *European Journal of Sport Science.* 14(2):107–115. DOI: 10.1080/17461391.2012.726653.
- Doma, K., Deakin, G.B., Schumann, M. & Bentley, D.J. 2019. Training Considerations for Optimising Endurance Development: An Alternate Concurrent Training Perspective. *Sports Medicine.* 49(5):669–682. DOI: 10.1007/s40279-019-01072-2.
- Ducrocq, G.P., Hureau, T.J., Meste, O. & Blain, G.M. 2019. Similar Cardioventilatory but Greater Neuromuscular Stimuli With Interval Drop Jump Than With Interval Running. *International journal of sports physiology and performance.* 15(3):330–339. DOI: 10.1123/IJSPP.2019-0031.
- Dudley, G.A. & Djamil, R. 1985. Incompatibility of endurance- and strength-training modes of exercise. <https://doi.org/10.1152/jappl.1985.59.5.1446>. 59(5):1446–1451. DOI: 10.1152/JAPPL.1985.59.5.1446.
- Dumont, N.A., Wang, Y.X. & Rudnicki, M.A. 2015. Intrinsic and extrinsic mechanisms regulating satellite cell function. *Development (Cambridge, England).* 142(9):1572–1581. DOI: 10.1242/DEV.114223.
- Eihara, Y., Takao, K., Sugiyama, T., Maeo, S., Terada, M., Kanehisa, H. & Isaka, T. 2022. Heavy Resistance Training Versus Plyometric Training for Improving Running Economy and Running Time Trial Performance: A Systematic Review and Meta-analysis. *Sports Medicine - Open.* 8(1):1–21. DOI: 10.1186/s40798-022-00511-1.
- Eihara, Y., Takao, K., Sugiyama, T., Maeo, S., Kanehisa, H. & Isaka, T. 2024. The effects of plyometric versus resistance training on running economy and 5-km running time in

middle-aged recreational runners. *European Journal of Sport Science*. DOI: 10.1002/ejsc.12197.

Ellery, S.T., Keogh, J.W.L. & Sheerin, K.R. 2012. Does maximal strength training improve endurance performance in highly trained cyclists: A systematic review. *European Journal of Sports and Exercise Science*. 1(3):90–102. Available: <http://scholarsresearchlibrary.com/archive.html>.

Farrell, A., Wilmore, J.H., Coyle, E.F. & Billing, J.E. 1979. Plasma lactate accumulation and distance running performance. *Med. Sci. Sports*. 11(4):338–344.

Faude, O., Kindermann, W. & Meyer, T. 2009. Lactate Threshold Concepts How Valid are They? *Sports Medicine*. 39(6):469–490. DOI: 0112-1642/09/0006-0469/\$49.95/0.

Feltner, M.E., Macrae, H.S.H., Macrae, P.G., Turner, N.S., Hartman, C.A., Summers, M.L. & Welch, M.D. 1994. Strength training effects on rearfoot motion in running. *Medicine and Science in Sports and Exercise*. 26(8):1021–1027. DOI: 10.1249/00005768-199408000-00014.

Ferrauti, A., Bergermann, M. & Fernandez-Fernandez, J. 2010. Effects of a concurrent strength and endurance training on running performance and running economy in recreational marathon runners. *Journal of Strength and Conditioning Research*. 24(10):2770–2778. DOI: 10.1519/JSC.0b013e3181d64e9c.

Fiori, L., Castiglia, S.F., Chini, G., Draicchio, F., Sacco, F., Serrao, M., Tatarelli, A., Varrecchia, T., et al. 2024. The Lower Limb Muscle Co-Activation Map during Human Locomotion: From Slow Walking to Running. *Bioengineering*. 11(3). DOI: 10.3390/bioengineering11030288.

Flanagan, E.P. & Comyns, T.M. 2008. The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training. *Strength and Conditioning Journal*. 30(5):32–38. DOI: 10.1519/SSC.0b013e318187e25b.

Fletcher, J.R., Esau, S.P. & MacIntosh, B.R. 2010. Changes in tendon stiffness and running economy in highly trained distance runners. *European Journal of Applied Physiology*. 110(5):1037–1046. DOI: 10.1007/S00421-010-1582-8/FIGURES/6.

Folland, J. & Williams, A. 2007. The adaptations to strength training: Morphological and neurological contributions to increased strength. *Sports Med*. 2(37):145–168.

Gallardo-Fuentes, F., Gallardo-Fuentes, J., Ramírez-Campillo, R., Balsalobre-Fernández, C., Martínez, C., Caniunqueo, A., Cañas, R., Banzer, W., et al. 2016. Intersession and

intrasession reliability and validity of the my jump app for measuring different jump actions in trained male and female athletes. *Journal of Strength and Conditioning Research*. 30(7):2049–2056. DOI: 10.1519/JSC.0000000000001304.

García-Pinillos, F., García-Ramos, A., Ramírez-Campillo, R., Latorre-Román, P. & Roche-Seruendo, L.E. 2019. How Do Spatiotemporal Parameters and Lower-Body Stiffness Change with Increased Running Velocity? A Comparison between Novice and Elite Level Runners. *Journal of Human Kinetics*. 70(1):25–38. DOI: 10.2478/hukin-2019-0036.

García-Pinillos, F., Lago-Fuentes, C., Latorre-Román, P.A., Pantoja-Vallejo, A. & Ramirez-Campillo, R. 2020a. Jump-Rope Training: Improved 3-km Time-Trial Performance in Endurance Runners via Enhanced Lower-Limb Reactivity and Foot-Arch Stiffness. *International Journal of Sports Physiology and Performance*. 15(7):927–933. DOI: 10.1123/IJSPP.2019-0529.

García-Pinillos, F., Jerez-Mayorga, D., Latorre-Román, P., Ramirez-Campillo, R., Sanz-López, F. & Roche-Seruendo, L.E. 2020. How do Amateur Endurance Runners Alter Spatiotemporal Parameters and Step Variability as Running Velocity Increases? A Sex Comparison. *Journal of Human Kinetics*. 72(1):39–49. DOI: 10.2478/hukin-2019-0098.

García-Pinillos, F., Lago-Fuentes, C., Latorre-Román, P.A., Pantoja-Vallejo, A. & Ramirez-Campillo, R. 2020b. Jump-Rope Training: Improved 3-km Time-Trial Performance in Endurance Runners via Enhanced Lower-Limb Reactivity and Foot-Arch Stiffness. *International Journal of Sports Physiology and Performance*. 15(7):927–933. DOI: 10.1123/IJSPP.2019-0529.

Hakkinen, K., Komi, P. V & Alen, M. 1985. Effect of explosive type strength training on isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. *Acta Physiol Scand*. 125:587–600.

Halson, S.L. & Jeukendrup, A.E. 2004. Does overtraining exist? An analysis of overreaching and overtraining research. *Sports Medicine*. 34(14):967–981. DOI: 10.2165/00007256-200434140-00003/FIGURES/1.

Hamilton, R.J., Paton, C.D. & Hopkins, W.G. 2006. *Effect of High-Intensity Resistance Training on Performance of Competitive Distance Runners*.

Haugen, T., Sandbakk, Ø., Seiler, S. & Tønnessen, E. 2022. The Training Characteristics of World-Class Distance Runners: An Integration of Scientific Literature and Results-Proven Practice. *Sports Medicine - Open*. 8(1). DOI: 10.1186/S40798-022-00438-7.

- Hawley, J.A. 2009. Molecular responses to strength and endurance training: Are they incompatible? *Journal of Applied Physiology Nutrition and Metabolism*. 34:355-361 DOI: 10.1139/H09-023.
- Hickson, R.C. 1980. Interference of strength development by simultaneously training for strength and endurance. *European Journal of Applied Physiology and Occupational Physiology*. 45(2-3):255-263. DOI: 10.1007/BF00421333.
- Huiberts, R.O., Wüst, R.C.I. & van der Zwaard, S. 2024. Concurrent Strength and Endurance Training: A Systematic Review and Meta-Analysis on the Impact of Sex and Training Status. *Sports Medicine*. 54(2):485-503. DOI: 10.1007/S40279-023-01943-9/FIGURES/6.
- Jacobs, I., Esbjornsson, M., Sylven, C., Holm, I. & Jansson, E. 1987. Sprint training effects on muscle myoglobin, enzymes, fiber types, and blood lactate. *Med. Sci. Sports Exerc.* 19(4):368-374. DOI: 0195-9131/87/1904-0368\$2.00/0.
- Johnston, R.E., Quinn, T.J., Kertzer, R. & Vroman, N.B. 1997. DOI: 10.1519/00124278-199711000-00004.
- Karsten, B., Stevens, L., Colpus, M., Larumbe-Zabala, E. & Naclerio, F. 2016. The Effects of Sport-Specific Maximal Strength and Conditioning Training on Critical Velocity, Anaerobic Running Distance, and 5-km Race Performance. *International Journal of Sports Physiology and Performance*. 11(1):80-85. DOI: 10.1123/IJSP.2014-0559.
- Katch, V. & Katch, F. 1975. A simple anthropometric method for calculating segmental leg volume. *Res Q*. 45:211-214.
- Kelly, C.M., Burnett, A.F. & Newton, M.J. 2008. The effect of strength training on three-kilometer performance in recreational women endurance runners. *Journal of Strength and Conditioning Research*. 22(2):396-403. DOI: 10.1519/JSC.0B013E318163534A.
- Komi, P. V. 2000. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *Journal of Biomechanics*. 33:1197-1206.
- Kubo, K., Kawakami, Y. & Fukunaga, T. 1999. Influence of elastic properties of tendon structures on jump performance in humans. *Journal of Applied Physiology*. 87(6):2090-2096. DOI: 10.1152/JAPPL.1999.87.6.2090.
- Leveritt, M., Abernethy, P.J., Barry, B.K. & Logan, P.A. 1999. Concurrent strength and endurance training. A review. *Sports Medicine*. 28(6):413-427. DOI: 10.2165/00007256-199928060-00004/METRICS.

- Li, F., Wang, R., Newton, R.U., Sutton, D., Shi, Y. & Ding, H. 2019. Effects of complex training versus heavy resistance training on neuromuscular adaptation, running economy and 5-km performance in well-trained distance runners. *PeerJ*. 2019(4). DOI: 10.7717/peerj.6787.
- Li, F., Newton, R.U., Shi, Y., Sutton, D. & Ding, H. 2021. Correlation of eccentric strength, reactive strength, and leg stiffness with running economy in well-trained distance runners. *Journal of Strength and Conditioning Research*. 35(6):1491–1499. DOI: 10.1519/JSC.0000000000003446.
- Lievens, M., Bourgois, J.G. & Boone, J. 2021. Periodization of Plyometrics: Is There an Optimal Overload Principle? *Journal of strength and conditioning research*. 35(10). DOI: 10.1519/JSC.0000000000003231.
- Llanos-Lagos, C., Ramirez-Campillo, R., Moran, · Jason & Sáez De Villarreal, · Eduardo. 2024. Effect of Strength Training Programs in Middle-and Long-Distance Runners' Economy at Different Running Speeds: A Systematic Review with Meta-analysis Key Points. *Sports Medicine*. DOI: 10.1007/s40279-023-01978-y.
- Londeree, B.R. 2012. The Use of Laboratory Test Results with Long Distance Runners. *Sports Medicine* 1986 3:3. 3(3):201–213. DOI: 10.2165/00007256-198603030-00004.
- Lorenzo, S., Minson, C.T., Babb, T.G. & Halliwill, J.R. 2011. Lactate threshold predicting time-trial performance: impact of heat and acclimation. *Journal of Applied Physiology*. 111(1):221. DOI: 10.1152/JAPPLPHYSIOL.00334.2011.
- Lum, D., Tan, F., Pang, J. & Barbosa, T.M. 2019. Effects of intermittent sprint and plyometric training on endurance running performance. 8:471–477. DOI: 10.1016/j.jshs.2016.08.005.
- Lum, D., Barbosa, T.M., Aziz, A.R. & Balasekaran, G. 2023. Effects of Isometric Strength and Plyometric Training on Running Performance: A Randomized Controlled Study. *Research Quarterly for Exercise and Sport*. 94(1):263–271. DOI: 10.1080/02701367.2021.1969330.
- Lundstrom, C.J., Betker, M.R. & Ingraham, S.J. 2017. Effects of Plyometric and Explosive Speed Training on Recreational Marathoners. *Journal of Sports Science*. 5(1). DOI: 10.17265/2332-7839/2017.01.001.
- MacDonald, C.J., Lamont, H.S. & Garner, J.C. 2012. A comparison of the effects of 6 weeks of traditional resistance training, plyometric training, and complex training on measures of

strength and anthropometrics. *Journal of Strength and Conditioning Research*. 26(2):422–431. DOI: 10.1519/JSC.0B013E318220DF79.

Machado, A.F., De Castro, J.B.P., Bocalini, D.S., Figueira Junior, A.J., Nunes, R.D.A.M. & Vale, R.G.D.S. 2019. Effects of plyometric training on the performance of 5-km road runners. *Journal of Physical Education and Sport* ® (*JPES*). 19(1):691–695. DOI: 10.7752/jpes.2019.01099.

Mackey, A.L., Kjaer, M., Charifi, N., Henriksson, J., Bojsen-Moller, J., Holm, L. & Kadi, F. 2009. Assessment of satellite cell number and activity status in human skeletal muscle biopsies. *Muscle and Nerve*. 40(3):455–465. DOI: 10.1002/mus.21369.

Mann, T.N., Lamberts, R.P. & Lambert, M.I. 2014. High responders and low responders: Factors associated with individual variation in response to standardized training. *Sports Medicine*. 44(8):1113–1124. DOI: 10.1007/S40279-014-0197-3/TABLES/1.

Marcinik, E.J., Pottis, J., Schlaback, G., Will, S., Dawson, P. & Hurley, B.F. 1991. Effects of strength training on lactate threshold and endurance performance. *Med. Sci. Sports Exerc*. 23(6):739–743. DOI: 0195-9131/91/2306-0739\$3.00/0.

Martinez, D.B. 2016. The use of reactive strength index, reactive strength index modified, and flight time: contraction time as monitoring tools. *Journal of Australian Strength and Conditioning*. 24(5):37–41.

Matias, A.B., Taddei, U.T., Duarte, M. & Sacco, I.C.N. 2016. Protocol for evaluating the effects of a therapeutic foot exercise program on injury incidence, foot functionality and biomechanics in long-distance runners: A randomized controlled trial. *BMC Musculoskeletal Disorders*. 17(1):1–11. DOI: 10.1186/S12891-016-1016-9/FIGURES/1.

McLaughlin, J.E., Howley, E.T., Bassett, D.R., Thompson, D.L. & Fitzhugh, E.C. 2010. Test of the classic model for predicting endurance running performance. *Medicine and Science in Sports and Exercise*. 42(5):991–997. DOI: 10.1249/MSS.0b013e3181c0669d.

Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D., Raglin, J., Rietjens, G., et al. 2013. Prevention, diagnosis and treatment of the overtraining syndrome: Joint consensus statement of the European College of Sport Science (ECSS) and the American College of Sports Medicine (ACSM). *European Journal of Sport Science*. 13(1):1–24. DOI: 10.1080/17461391.2012.730061.

- Midgley, A.W., McNaughton, L.R. & Jones, A.M. 2007. Training to Enhance the Physiological Determinants of Long-Distance Running Performance. *Sports Medicine*. 37(10):857–880. DOI: 10.2165/00007256-200737100-00003.
- Mikkola, J., Rusko, H., Nummela, A., Pollari, T. & Häkkinen, K. 2007. Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in young distance runners. *International Journal of Sports Medicine*. 28(7):602–611. DOI: 10.1055/S-2007-964849/ID/33.
- Mikkola, J., Vesterinen, V., Taipale, R., Capostagno, B., Häkkinen, K. & Nummela, A. 2011. Effect of resistance training regimens on treadmill running and neuromuscular performance in recreational endurance runners. *Journal of Sports Sciences*. 29(13):1359–1371. DOI: 10.1080/02640414.2011.589467.
- Millet, G.P., Jaouen, B., Borrani, F. & Candau, R. 2002. Effects of concurrent endurance and strength training on running economy and VO₂ kinetics. *Medicine & Science in Sports & Exercise*. 34(8):1351–1359. DOI: 10.1097/00005768-200208000-00018.
- Moore, I.S., Ashford, K.J., Cross, C., Hope, J., Jones, H.S.R. & McCarthy-Ryan, M. 2019. Humans Optimize Ground Contact Time and Leg Stiffness to Minimize the Metabolic Cost of Running. *Frontiers in Sports and Active Living*. 0:53. DOI: 10.3389/FSPOR.2019.00053.
- Morán-Navarro, R., Pérez, C.E., Mora-Rodríguez, R., de la Cruz-Sánchez, E., González-Badillo, J.J., Sánchez-Medina, L. & Pallarés, J.G. 2017. Time course of recovery following resistance training leading or not to failure. *European Journal of Applied Physiology*. 117(12):2387–2399. DOI: 10.1007/S00421-017-3725-7/FIGURES/4.
- Morgan, D.W., Baldini, F.D., Martin, P.E. & Kohrt, W.M. 1989. Ten kilometer performance and predicted velocity at VO₂max among well-trained male runners. *Medicine & Science in Sports & Exercise*. 21(1):78–83.
- Noakes, T.D. 1987. *Lore of Running*. 3rd ed. ed. Cape Town (South Africa): Oxford University Press.
- Noakes, T.D. 1988. Implications of exercise testing for prediction of athletic performance: a contemporary perspective. *Med. Sci. Sports Exerc.* 20:319–330.
- Noakes, T.D., Myburgh, K.H. & Schall, R. 1990. Peak treadmill running velocity during the VO₂ max test predicts running performance. *Journal of sports sciences*. 8(1):35–45. DOI: 10.1080/02640419008732129.

- Nummela, A.T., Paavolainen, L.M., Sharwood, K.A., Lambert, M.I., Noakes, T.D. & Rusko, H.K. 2006. Neuromuscular factors determining 5 km running performance and running economy in well-trained athletes. *European Journal of Applied Physiology*. 97(1):1–8. DOI: 10.1007/S00421-006-0147-3/FIGURES/4.
- Olesen, J., Kiilerich, K. & Pilegaard, H. 2010. PGC-1 α -mediated adaptations in skeletal muscle. *Eur J Physiol*. 460:153–162. DOI: 10.1007/s00424-010-0834-0.
- O’Sullivan, I.J., Johnson, M.I., Hind, K., Breen, S. & Francis, P. 2019. Are changes in running economy associated with changes in performance in runners? A systematic review and meta-analysis. *Journal of Sports Sciences*. 37(13):1521–1533. DOI: 10.1080/02640414.2019.1575177.
- Paavolainen, L., Häkkinen, K., Hämmäläinen, I., Nummela, A. & Rusko, H. 1999. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *Journal of Applied Physiology*. 86(5):1527–1533. DOI: 10.1152/jappl.1999.86.5.1527.
- Paavolainen, L., Nummela, A. & Rusko, H. 2000. Muscle power factors and VO₂max as determinants of horizontal and uphill running performance. *Scandinavian Journal of Medicine & Science in Sports*. 10(5):286–291. DOI: 10.1034/j.1600-0838.2000.010005286.x.
- Patoz, A., Lussiana, T., Breine, B., Mourot, L., Gindre, C. & Hébert-Losier, K. 2023. Concurrent endurance training with either plyometric or dynamic body-weight training both improve running economy with minimal or no changes in running biomechanics. *Sports Biomechanics*. 00(00):1–18. DOI: 10.1080/14763141.2023.2200403.
- Pellegrino, J., Ruby, B.C. & Dumke, C.L. 2016. Effect of plyometrics on the energy cost of running and MHC and titin isoforms. *Medicine and Science in Sports and Exercise*. 48(1):49–56. DOI: 10.1249/MSS.0000000000000747.
- Philp, A., Lee Hamilton, D. & Baar, K. 2011. HIGHLIGHTED TOPIC Signals Mediating Skeletal Muscle Remodeling by Activity Signals mediating skeletal muscle remodeling by resistance exercise: PI3-kinase independent activation of mTORC1. *J Appl Physiol*. 110:561–568. DOI: 10.1152/japplphysiol.00941.2010.-For.
- Piacentini, M.F., Ioannon, G. De, Comotto, S., Spedicato, A., Vernillo, G. & La Torre, A. 2013. Concurrent strength and endurance training effects on running economy in master endurance runners. *Journal of Strength and Conditioning Research*. 27(8):2295–2303.

- Pleša, J., Kozinc, Ž., Smajla, D. & Šarabon, N. 2022. The association between reactive strength index and reactive strength index modified with approach jump performance. *PLOS ONE*. 17(2):e0264144. DOI: 10.1371/JOURNAL.PONE.0264144.
- Plisk, S.S. & Stone, M.H. 2003. Periodization Strategies. *Strength & Conditioning Journal*. 25(6):19-37.
- di Prampero, P.E., Atchou, G., Briickner, J.-C. & Moia, C. 1986. The energetics of endurance running. *Eur J Appl Physiol*. 55:259–266.
- Prieto-González, P., Yagin, F.H., Sánchez-Infante, J. & Ardigò, L.P. 2024. Effectiveness of Maximum, Explosive and Combined Strength Training on Endurance Runners Performance Indicators: A Systematic Review and Meta-Analysis. *Retos*. 58:1030–1049. DOI: 10.20944/PREPRINTS202403.0094.V1.
- Pruyn, E.C., Watsford, M.L. & Murphy, A.J. 2016. Validity and reliability of three methods of stiffness assessment. *Journal of Sport and Health Science*. 5(4):476–483. DOI: 10.1016/J.JSHS.2015.12.001.
- Pugh, J.K., Faulkner, S.H., Turner, M.C. & Nimmo, M.A. 2018. Satellite cell response to concurrent resistance exercise and high-intensity interval training in sedentary, overweight/obese, middle-aged individuals. *European Journal of Applied Physiology*. 118(2):225–238. DOI: 10.1007/s00421-017-3721-y.
- Ramírez-Campillo, R., Álvarez, C., Henríquez-Olguín, C., Baez, E.B., Martínez, C., Andrade, D.C. & Izquierdo, M. 2014a. Effects of plyometric training on endurance and explosive strength performance in competitive middle- and long-distance runners. *Journal of Strength and Conditioning Research*. 28(1):97–104. DOI: 10.1519/JSC.0B013E3182A1F44C.
- Ramírez-Campillo, R., Álvarez, C., Henríquez-Olguín, C., Baez, E.B., Martínez, C., Andrade, D.C. & Izquierdo, M. 2014b. Effects of plyometric training on endurance and explosive strength performance in competitive middle- and long-distance runners. *Journal of Strength and Conditioning Research*. 28(1):97–104. DOI: 10.1519/JSC.0b013e3182a1f44c.
- Ramirez-Campillo, R., Andrade, D.C., García-Pinillos, F., Negra, Y., Boullosa, D. & Moran, J. 2021. Effects of jump training on physical fitness and athletic performance in endurance runners: A meta-analysis: Jump training in endurance runners. *Journal of Sports Sciences*. 39(18):2030–2050. DOI: 10.1080/02640414.2021.1916261.

- Ramirez-Campillo, R., García-Pinillos, F., Nikolaidis, P.T., Clemente, F.M., Gentil, P. & García-Hermoso, A. 2022. Body composition adaptations to lower-body plyometric training: A systematic review and meta-analysis. *Biology of Sport*. 39(2):273–287. DOI: 10.5114/BIOLSPORT.2022.104916.
- Robineau, J., Babault, N., Piscione, J., Lacombe, M. & Bigard, A.X. 2016. Specific training effects of concurrent aerobic and strength exercises depend on recovery duration. *Journal of Strength and Conditioning Research*. 30(3):672–683.
- Rogers, S.A., Hassmén, P., Hunter, A., Alcock, A., Crewe, S.T., Strauts, J.A., Gilleard, W.L. & Weissensteiner, J.R. 2019. The Validity and Reliability of the MyJump2 Application to Assess Vertical Jumps in Trained Junior Athletes. *Measurement in Physical Education and Exercise Science*. 23(1):69–77. DOI: 10.1080/1091367X.2018.1517088.
- Rønnestad, B.R. & Mujika, I. 2014. Optimizing strength training for running and cycling endurance performance: A review. *Scandinavian Journal of Medicine and Science in Sports*. 24(4):603–612. DOI: 10.1111/sms.12104.
- Rønnestad, B.R., Hansen, E.A. & Raastad, T. 2010. Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. *European Journal of Applied Physiology*. 108(5):965–975. DOI: 10.1007/s00421-009-1307-z.
- Rosenblat, M.A., Lin, E., da Costa, B.R. & Thomas, S.G. 2021. Programming Interval Training to Optimize Time-Trial Performance: A Systematic Review and Meta-Analysis. *Sports Medicine*. 51(8):1687–1714. DOI: 10.1007/S40279-021-01457-2.
- Rusko, H., Nummela, A. & Mero, A. 1993a. A new method for the evaluation of anaerobic running power in athletes. *European journal of applied physiology and occupational physiology*. 66(2):97–101. DOI: 10.1007/BF01427048.
- Rusko, H., Nummela, A. & Mero, A. 1993b. A new method for the evaluation of anaerobic running power in athletes. *European journal of applied physiology and occupational physiology*. 66(2):97–101. DOI: 10.1007/BF01427048.
- Russell, R.D., Redmann, S.M., Ravussin, E., Hunter, G.R. & Larson-Meyer, D.E. 2004. Reproducibility of endurance performance on a treadmill using a preloaded time trial. *Medicine and science in sports and exercise*. 36(4):717–724. DOI: 10.1249/01.MSS.0000121954.95892.C8.

- Sáez-Sáez De Villarreal, E., Requena, B. & Newton, R.U. 2010. Does plyometric training improve strength performance? A meta-analysis. *Journal of Science and Medicine in Sport*. 13:513–522. DOI: 10.1016/j.jsams.2009.08.005.
- Saltin, B. & Astrand, P.O. 1967. Maximal oxygen uptake in athletes. *Journal of Applied Physiology*. 23(3):353–358. DOI: 10.1152/jappl.1967.23.3.353.
- Saunders, P.U., Pyne, D.B., Telford, R.D. & Hawley, J.A. 2004a. Reliability and variability of running economy in elite distance runners. *Medicine and Science in Sports and Exercise*. 36(11):1972–1976. DOI: 10.1249/01.MSS.0000145468.17329.9F.
- Saunders, P.U., Pyne, D.B., Telford, R.D. & Hawley, J.A. 2004b. Factors affecting running economy in trained distance runners. *Sports Med*. 34(7):465–485.
- Saunders, P.U., Telford, R.D., Pyne, D.B., Peltola, E.M., Cunningham, R.B., Gore, C.J. & Hawley, J.A. 2006. Short-term plyometric training improves running economy in highly trained middle and long distance runners. *Journal of strength and conditioning research*. 20(4):947–954. DOI: 10.1519/R-18235.1.
- Schober, P. & Schwarte, L.A. 2018. Correlation coefficients: Appropriate use and interpretation. *Anesthesia and Analgesia*. 126(5):1763–1768. DOI: 10.1213/ANE.0000000000002864.
- Schumann, M., Pelttari, P., Doma, K., Karavirta, L. & Häkkinen, K. 2016. Neuromuscular Adaptations to Same-Session Combined Endurance and Strength Training in Recreational Endurance Runners. *International journal of sports medicine*. 37(14):1136–1143. DOI: 10.1055/S-0042-112592.
- Sedano, S., Marín, P.J., Cuadrado, G. & Redondo, J.C. 2013. Concurrent training in elite male runners: The influence of strength versus muscular endurance training on performance outcomes. *Journal of Strength and Conditioning Research*. 27(9):2433–2443. DOI: 10.1519/JSC.0b013e318280cc26.
- Segabinazi Peserico, C., Zagatto, A.M. & Machado, F.A. 2014. Reliability of peak running speeds obtained from different incremental treadmill protocols. *Journal of Sports Sciences*. 32(10):993–1000. DOI: 10.1080/02640414.2013.876087.
- Seo, D. Il, Kim, E., Fahs, C.A., Rossow, L., Young, K., Ferguson, S.L., Thiebaud, R., Sherk, V.D., et al. 2012. Reliability of the one-repetition maximum test based on muscle group and gender. *Journal of Sports Science and Medicine*. 11(2):221–225.
- Skovgaard, C., Christensen, P.M., Larsen, S., Andersen, T.R., Thomassen, M. & Bangsbo, J. 2014. Concurrent speed endurance and resistance training improves performance, running

- economy, and muscle NHE1 in moderately trained runners. *Journal of Applied Physiology*. 117(10):1097–1109. DOI: 10.1152/jappphysiol.01226.2013.
- Snow, M.H. 1978. An autoradiographic study of satellite cell differentiation into regenerating myotubes following transplantation of muscles in young rats. *Cell and Tissue Research*. 186(3):535–540. DOI: 10.1007/BF00224941/METRICS.
- Snyder, K.R., Earl, J.E., O'Connor, K.M. & Ebersole, K.T. 2009. Resistance training is accompanied by increases in hip strength and changes in lower extremity biomechanics during running. *Clinical Biomechanics*. 24(1):26–34. DOI: 10.1016/j.clinbiomech.2008.09.009.
- Spurrs, R.W., Murphy, A.J. & Watsford, M.L. 2003. The effect of plyometric training on distance running performance. *European Journal of Applied Physiology*. 89(1):1–7. DOI: 10.1007/s00421-002-0741-y.
- Štohanzl, M., Baláš, J. & Draper, N. 2017. Effects of minimal dose of strength training on running performance in female recreational runners. *The Journal of Sports Medicine and Physical Fitness*. 58(9):1211–1217. DOI: 10.23736/S0022-4707.17.07124-9.
- Støren, Øy., Helgerud, J., Støa, E.M. & Hoff, J. 2008. Maximal strength training improves running economy in distance runners. *Medicine and Science in Sports and Exercise*. 40(6):1087–1092. DOI: 10.1249/MSS.0b013e318168da2f.
- Stratton, E., O'Brien, B.J., Harvey, J., Blitvich, J., McNicol, A.J., Janissen, D., Paton, C. & Knez, W. 2009. Treadmill velocity best predicts 5000-m run performance. *International Journal of Sports Medicine*. 30(1):40–45. DOI: 10.1055/S-2008-1038761/ID/22/BIB.
- Šuc, A., Šarko, P., Pleša, J. & Kozinc, Ž. 2022. Resistance Exercise for Improving Running Economy and Running Biomechanics and Decreasing Running-Related Injury Risk: A Narrative Review. *Sports*. 10(7):98. DOI: 10.3390/SPORTS10070098.
- Taddei, U.T., Matias, A.B., Ribeiro, F.I.A., Bus, S.A. & Sacco, I.C.N. 2020. Effects of a foot strengthening program on foot muscle morphology and running mechanics: A proof-of-concept, single-blind randomized controlled trial. *Physical Therapy in Sport*. 42:107–115. DOI: 10.1016/j.ptsp.2020.01.007.
- Taipale, R.S., Mikkola, J., Vesterinen, V., Nummela, A. & Häkkinen, K. 2013. Neuromuscular adaptations during combined strength and endurance training in endurance runners: Maximal versus explosive strength training or a mix of both. *European Journal of Applied Physiology*. 113(2):325–335. DOI: 10.1007/S00421-012-2440-7/TABLES/3.

- Taipale, R.S., Mikkola, J., Salo, T., Hokka, L., Vesterinen, V., Kraemer, W.J., Nummela, A., Haikkinen, K., et al. 2014. Mixed maximal and explosive strength training in recreational endurance runners. *J Strength Cond Res.* 28(3):689–699. Available: www.nsga.com.
- Trowell, D., Vicenzino, B., Saunders, N., Fox, A. & Bonacci, J. 2020. Effect of Strength Training on Biomechanical and Neuromuscular Variables in Distance Runners: A Systematic Review and Meta-Analysis. *Sports Medicine.* 50(1):133–150. DOI: 10.1007/s40279-019-01184-9.
- Unger, C.L. & Wooden, M.J. 2000. Effect of Foot Intrinsic Muscle Strength Training on Jump Performance. *Journal of Strength and Conditioning Research.* 14(4):373-378.
- Verdijk, L.B., Van Loon, L., Meijer, K. & Savelberg, H.H.C.M. 2009. One-repetition maximum strength test represents a valid means to assess leg strength in vivo in humans. *Journal of Sports Sciences.* 27(1):59–68. DOI: 10.1080/02640410802428089.
- Vikmoen, O., Raastad, T., Seynnes, O., Bergstrøm, K., Ellefsen, S. & Rønnestad, B.R. 2016. Effects of heavy strength training on running performance and determinants of running performance in female endurance athletes. *PLoS ONE.* 11(3):1–18. DOI: 10.1371/journal.pone.0150799.
- De Villarreal, E.S.S., Izquierdo, M. & Gonzalez-Badillo, J.J. 2011. Enhancing jump performance after combined vs. maximal power, heavy-resistance, and plyometric training alone. *Journal of Strength and Conditioning Research.* 25(12):3274–3281. DOI: 10.1519/JSC.0B013E3182163085.
- Vorup, J., Tybirk, J., Gunnarsson, T.P., Ravnholt, T., Dalsgaard, S. & Bangsbo, J. 2016. Effect of speed endurance and strength training on performance, running economy and muscular adaptations in endurance-trained runners. *European Journal of Applied Physiology.* 116(7):1331–1341. DOI: 10.1007/s00421-016-3356-4.
- Willy, R.W. & Davis, I.S. 2011. The effect of a hip-strengthening program on mechanics during running and during a single-leg squat. *Journal of Orthopaedic and Sports Physical Therapy.* 41(9):625–632. DOI: 10.2519/jospt.2011.3470.
- 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. *Journal of Strength and Conditioning Research.* 26(8):2293–2307. DOI: 10.1519/JSC.0b013e31823a3e2d.

- Withers, R.T., Craig, N.P., Bourdon, P.C. & Norton, K.I. 1987. Relative body fat and anthropometric prediction of body density of male athletes. *Eur J Appl Physiol Occup Physiol.* 56(2):191–200.
- Wondem, D.A. & Tegege, Z.M. 2023. Effect of Concurrent Strength and Endurance Training on Distance Running Performances in Well-Trained Athletes. *Sport Mont.* 21(3):101–107. DOI: 10.26773/smj.231016.
- 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. *Journal of Strength and Conditioning Research.* 22(6):2036–2044.
- Yamamoto, L.M., Klau, J.F., Casa, D.J., Kraemer, W.J., Armstrong, L.E. & Maresh, C.M. 2010. The effects of resistance training on road cycling performance among highly trained cyclists: a systematic review. *Journal of Strength and Conditioning Research.* 24(2):560–566.
- Young, W. 1995. Laboratory strength assessment of athletes. *New Stud Athlete.* 10:88–96.
- Zatsiorsky, V.M. & Kraemer, W.J. 2007. *Science and Practice of Strength Training.* Champaign, IL: Human Kinetics.

Appendices

Appendix 1: A guide to exercise selection and prescription for concurrent training for long-distance runners.

	Day 1		Day 2		Day 3	
	Exercise selection		Exercise selection		Exercise selection	
	Low training age	High training age	Low training age	High training age	Low training age	High training age
GPP— Mesocycle 1	1. Goblet squat 2. Split squat 3. Hamstring curl machine 4. KB swing 5. CMJ 6. Hurdle hop	1. BB back squat 2. DB walking lunges 3. Nordic hamstring 4. Clean/rack pull 5. CMJ 6. Hurdle hop	1. DL/RDL 2. SL squat 3. PF variation 4. High-effort box jump 5. Pogo jump 6. Drop/depth jumps	1. DL/RDL 2. SL squat 3. PF variation 4. High-effort box jump 5. Pogo jump 6. Drop/depth jumps	1. Leg press 2. SLDL 3. Machine knee extension 4. Jump squat 5. Bounding 6. Tuck jump	1. BB back squat 2. SLDL 3. Bulgarian split squat 4. Jump squat 5. Bounding 6. Tuck jump
GPP— Mesocycle 2	1. Goblet squat 2. Split squat 3. Hamstring curl machine 4. KB swing 5. CMJ 6. Hurdle hop	1. BB back squat 2. DB walking lunges 3. Nordic hamstring 4. Clean/rack pull 5. CMJ 6. Hurdle hop	1. DL/RDL 2. SL squat 3. PF variation 4. High-effort box jump 5. Pogo jump	1. DL/RDL 2. SL squat 3. PF variation 4. High-effort box jump 5. Pogo jump	1. Leg press 2. SLDL 3. Machine knee extension 4. CMJ 5. Bounding	1. BB back squat 2. SLDL 3. Bulgarian split squat 4. CMJ 5. Bounding
SPP— Mesocycle 3	1. Squat variation 2. Hamstring curl 3. KB swing 4. CMJ 5. Hurdle hop	1. BB back squat 2. Nordic hamstring 3. Clean/rack pull 4. CMJ 5. Hurdle hop	1. DL/RDL 2. Split squat 3. Jump squats 4. High-effort box jump 5. Pogo jump	1. DL/RDL 2. Bulgarian split squat or SL squat 3. Weighted BB 1/4 jump squats 4. High-effort	1. Leg press 2. SLDL 3. KB swing 4. CMJ 5. Pogo jump	1. BB back squat 2. SLDL 3. Clean/rack pull 4. CMJ 5. Pogo jump
Maintenance— Mesocycle 4	1. Squat variation 2. Hamstring curl or SLDL 3. KB swing 4. CMJ 5. Hurdle hop	1. BB back squat 2. Nordic hamstring or SLDL 3. Clean/rack pull 4. CMJ 5. Hurdle hop	1. DL/RDL 2. Split squat 3. Jump squats 4. High-effort box jump 5. Pogo jump	1. DL/RDL 2. Bulgarian split squat or SL squat 3. Weighted BB 1/4 jump squats 4. High-effort box jump 5. Pogo jump	—	—
Taper/ peaking— Mesocycle 5	1. Squat variation 2. Hamstring curl or SLDL 3. KB swing 4. CMJ 5. Hurdle hop	1. BB back squat 2. Nordic hamstring or SLDL 3. Clean/rack pull 4. CMJ 5. Hurdle hop	1. DL/RDL 2. Split squat 3. Jump squats 4. High-effort box jump 5. Pogo jump	1. DL/RDL 2. Bulgarian split squat or SL squat 3. Weighted BB 1/4 jump squats 4. High-effort box jump 5. Pogo jump	—	—

BB = barbell; CMJ = countermovement jump; DB = dumbbell; DL = deadlift; GPP = general preparatory phase; PF = plantarflexion; RDL = Romanian deadlift; SL = single leg; SLDL = single-leg deadlift; SPP = specific preparatory phase.

Table 4
Concurrent training prescription for resistance training sessions based on the periodized phase of training for competitive endurance runners

Phase:	GPP	GPP	SPP	Maintenance	Taper/peak
Time frame:	Mesocycle 1 (4–6 wk)	Mesocycle 2 (4–6 wk)	Mesocycle 3 (4–6 wk)	Mesocycle 4 (2–4 wk)	Mesocycle 5 (~2 wk)
Resistance training goal of the phase:	Induce neuromuscular adaptations and accumulate muscular strength	Build maximal force development and accumulate muscular strength	Improve rate of force development, maximal strength development, and increase peak power output	Preserve muscular strength and power output and avoid training loss	Preserve muscular strength and power output and retain performance
Maximal strength development exercise prescription:	3 exercises, 4–6 sets × 6–10 reps @ 70–80% 1RM, 2-min rest intervals	3 exercises, 2–4 sets × 3–6 reps @ 75–85% 1RM, 2- to 3-min rest intervals	3 exercises, 2–4 sets × < 5 reps @ >80% 1RM, 3 + min rest intervals	3 exercises, 1–2 sets × < 5 reps @ >80% 1RM, 2- to 3-min rest intervals	3 exercises, 1–2 sets × < 5 reps @ 50–60% 1RM, 2-min rest intervals
Explosive strength and reactive strength exercise prescription:	Up to 6 exercises, total of 60–100 contacts	3–4 exercises, 100–200 contacts	3–4 exercises, 100–200 contacts	3–4 exercises, 50–100 contacts	3–4 exercises, 50–100 contacts
GPP = general preparatory phase; reps = repetitions; RM = repetition maximum; SPP = specific preparatory phase.					

Source: Barrie (2020)

  
ATTENTION ALL RUNNERS **HPALS**
Health through Physical Activity, Lifestyle and Sport RESEARCH CENTRE

HAVE YOU EVER WONDERED WHAT TYPE OF STRENGTH TRAINING RUNNERS SHOULD BE DOING?

You can be part of a research study to help answer this question if:

- ✓ Run 60-100km per week
- ✓ Recent PB of 3:00 for males
- ✓ Recent PB of 3:20 for females
- ✓ Don't perform regular strength training
- ✓ Are not currently injured

Find out more **Interested?**  

  **Register to participate**

RIZANBEHARDIEN.WIXSITE.COM

Appendix 3: Participation Information Sheet



MSc (Med) Exercise science

Effects of resistance training on physiological and biomechanical factors in marathon runners: Reactive strength vs. heavy weight training

Participation information sheet

Why am I receiving this letter?

My name is Rizaan Behardien, and I am a Masters student in the Division of Physiological Sciences at the University of Cape Town. I will be conducting a study to compare the effects of resistance training on endurance running performance. This letter serves as a means to recruit participants for this study, which will form part of the MSc Exercise Science thesis by dissertation. If this study interests you and you would like to be a part of it, please read further.

What is this study about?

This study aims to explore the differences in training adaptations elicited by different resistance training modalities. This study is specifically looking at how heavy-weight training and reactive-strength training affects your time trial performance, physiological determinants of running (e.g., $VO_2\max$, running economy, etc.), neuromuscular, biomechanical, and body composition factors. This study will span 12 weeks starting from the beginning of 2023. The results from this study will help inform what type of resistance training runners should be using and how this should be prescribed to them most effectively.

Can I participate in this study?

This study is aimed at well-trained long-distance runners of both sexes. Therefore, you will need to:

- Have raced a marathon or half marathon within the last 6 months,
- Train a minimum of 3 times per week
- And not have participated in a consistent strength training program over the last 6 months.

You also need to not:

- Be injured or currently recovering from injury
- Or have a health condition, whereby participating in this study may put your health at risk.

How will the study be structured?

The study will last 12 weeks, which will be split into 2 4-week training blocks, each separated by 4 1-week testing periods. The study will sort participants into 2 groups: heavy-weight training group, and a reactive-strength training group. The participants will engage in 2 training sessions per week. This will be held at the Sports Science Institute of South Africa (SSISA) gym. During the testing periods, you will be required to come into the SSISA running labs and gym 3 times that week. The testing period sessions should last no longer than 30 minutes.

What happens if you decide to participate in the study?

You will need to sign the **consent form** (attached below), confirming that you have read and understand the information regarding the study, and send it to the email address below. In response, we will send you the date of the first meeting we will have at SSISA to explain the procedure in greater detail. During this initial meeting, we will explain how you can share your training logs for the last 4 weeks with us so that we can keep track of your training before, during, and after the study. After this meeting, you will be randomly allocated into one of the three groups (as mentioned above).

You will then observe one deload week of training where you take an active recovery rest from training. During this week you will fill out a short questionnaire each morning. This questionnaire will help us understand your fatigue levels during the training period which helps to detect early signs of overtraining. Once this deload week is complete your baseline testing week will begin, followed by the commencement of the intervention period (as described above).

Potential Risks of this study

Due to the nature of resistance training, we cannot rule out the possibility that you may develop a training-related injury during the training programme. To reduce this risk, the training programme and your performance will be monitored on a weekly basis by Professor Andrew Bosch and the student researcher (Rizaan Behardien) who is also a physiotherapist and personal trainer. The exercise program will gradually increase in training load and intensity to prevent acute and overuse injuries. In the unlikely event that you sustain any bodily injury because of the training, participants from South Africa will be covered by insurance provided by the university. The insurer will cover all reasonable medical costs required to treat your injury, according to the SA Good Practice Guidelines 2006.

If you do get injured during the study and the insurer pays for the necessary medical costs, you will be required to accept the insurance payment as a full settlement of the claim for medical costs. However, by accepting the insurance coverage, you still have the right to make a separate claim for other losses based on negligence in a South African court.

You will also be able to contact the student researcher at any time via email if you experience any injuries and he will advise accordingly.

Potential Benefits

As a runner looking to improve your performance, we believe you will benefit from a structured and monitored program that is aimed at supplementing your current running

training. However, if you are placed in the control group, you will also be given the opportunity to receive the intervention training of your choice once the study is completed. On a larger scale, the results will benefit running coaches, high-performance scientists, strength and conditioning practitioners, and the athletes themselves. This information will increase the pool of knowledge of effective training methods aimed at enhancing running performance. These results could help shape and revolutionise the way we understand running training.

Once the study is completed

The information collected during the study will be kept by the researchers in a password-protected file for 5 years. All personal information will be kept confidential. If the study were to be published in a scientific journal, your private information would remain anonymous.

Will the results of the research be shared with you?

Once the study is completed you will be able to access the results if you wish and a summary of the findings will be sent to you.

Principles concerning the research.

It is important to note and fully understand, that your participation in the study is entirely **voluntary**, and you may withdraw at any point, without any consequences. There is also no cost for you to join the study. As a participant, you will receive feedback on your own training and running performance measured during the study. Your personal information (name, surname, and contact details) will always remain private and entirely confidential.

Please do not hesitate to contact student researcher Rizaan Behardien or principal researcher A/Prof Andrew Bosch if you have any questions about the study. If you have any questions regarding your rights and welfare as a participant, you can contact the

Faculty of Health Sciences Human Research Ethics Committee at the University of Cape Town. The contact details are below.

I am interested in being a participant, now what?

Read the informed consent sheet below and click on the link to the questionnaire. Thereafter, if you qualify for the study, you will be cued to provide written consent (as mentioned above).

Muhammed Rizaan Behardien (MSc Student investigator)	bhrmuh003@myuct.ac.za	+27 84 461 9987
A/Prof Andrew Bosch (running coach and study supervisor)	Andrew.bosch@uct.ac.za	+27 21 650 4578
UCT FHS Human Research Ethics Committee	hrecenquiries@uct.ac.za	+27214066338

Appendix 4: Consent Form



MSc (Med) Exercise science

Effects of resistance training on physiological and biomechanical factors in marathon runners: Reactive strength vs. heavy weight training

Consent Form

I _____ (full name and surname), confirm that I have been fully informed and understand the study entitled “**Effects of resistance training on physiological and biomechanical factors in marathon runners: Reactive strength vs. heavy weight training**”, to be conducted by researchers from the Division of Physiological Sciences, Faculty of Health Sciences, at the University of Cape Town.

I have read and understand what my participation in this study means, including the potential risks and benefits associated with participating in this study. I have had the opportunity to ask the questions I have relating to the study, and I am satisfied that they have been answered sufficiently.

I understand that:

1. Participating in this study is entirely voluntary.
2. I can withdraw from the study at any time without any consequences.
3. I may receive my results after the study has been completed.
4. My privacy and anonymity will be maintained throughout the study and all my personal information will be used for purposes of this study.
5. I consent to participate in this research study as described above.
6. I will receive a copy of this informed consent document.

Please select the appropriate block:

- I agree to participate in this study.
- I do not agree to participate in this study.

By placing your signature below, you confirm your informed consent to participate in this study.

Signature: _____ Date: _____



UNIVERSITY OF CAPE TOWN
Faculty of Health Sciences
Human Research Ethics Committee



Room 45 E-52-E-Floor- Old Main Building
Groote Schuur Hospital
Observatory 7925
Telephone [021] 406 6492
Email: hrec-submissions@uct.ac.za
Website: www.health.uct.ac.za/home/human-research-ethics

15 December 2022

HREC REF: 674/2022

A/Prof A Bosch
Department of Human Biology
Physiological Sciences -SSISA
Email: Andrew.bosch@uct.ac.za
Student: bhrmuh003@myuct.ac.za

Dear A/Prof Bosch

PROJECT TITLE: EFFECTS OF RESISTANCE TRAINING ON PHYSIOLOGICAL AND BIOMECHANICAL FACTORS IN MARATHON RUNNERS: REACTIVE STRENGTH VS. HEAVY WEIGHT TRAINING- (MSc CANDIDATE-MR MUHAMMED R BEHARDIEN)

Thank you for submitting your study to the Faculty of Health Sciences Human Research Ethics Committee (HREC) for review.

It is a pleasure to inform you that the HREC has **formally approved** the above-mentioned study.

Approval is granted for one year until the 30 December 2023.

Please submit a progress form, using the standardised Annual Report Form (FHS016) if the study continues beyond the approval period. Please submit a Standard Closure form if the study is completed within the approval period.

(Forms can be found on our website: www.health.uct.ac.za/fhs/research/humanethics/forms)

The HREC acknowledge that the student: Mr Muhammed Behardien will also be involved in this study.

Please quote the HREC REF 674/2022 in all your correspondence.

Please note that the ongoing ethical conduct of the study remains the responsibility of the principal investigator.

Please note that for all studies approved by the HREC, the principal investigator **must** obtain appropriate institutional approval, where necessary, before the research may occur.

Yours sincerely

PROFESSOR M BLOCKMAN
CHAIRPERSON, FACULTY OF HEALTH SCIENCES HUMAN RESEARCH ETHICS COMMITTEE

HREC/ref 674.2022

Federal Wide Assurance Number: FWA00001637. Institutional Review Board (IRB) number: IRB00001938 NHREC-registration number: REC-210208-007
This serves to confirm that the University of Cape Town Human Research Ethics Committee complies to the Ethics Standards for Clinical Research with a new drug in patients, based on the Medical Research Council (MRC-SA), Food and Drug Administration (FDA-USA), International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use: Good Clinical Practice (ICH GCP), South African Good Clinical Practice Guidelines (DoH 2020), based on the Association of the British Pharmaceutical Industry Guidelines (ABPI), and Declaration of Helsinki (2013) guidelines. The Human Research Ethics Committee granting this approval is in compliance with the ICH Harmonised Tripartite Guidelines E6: Note for Guidance on Good Clinical Practice (CPMP/ICH/135/95) and FDA Code Federal Regulation Part 50, 56 and 312.

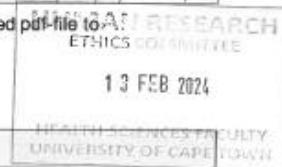
HREC/ref 674.2022



FHS016: Annual Progress Report / Renewal

HREC office use only (FWA00001637; IRB00001938)		
This serves as notification of annual approval, including any documentation described below.		
<input checked="" type="checkbox"/> Approved	Annual progress report	Approved until/next renewal date 28.02.2025
<input type="checkbox"/> Not approved	See attached comments	
Signature Chairperson of the HREC/ Designee		Date Signed 13/2/2024

Note: Please email this form and supporting documents (if applicable) in a combined pdf file to hrec-enquiries@uct.ac.za.
Please clarify your plan for research-related activities during COVID-19 lockdown.
Please use the latest form found on our website:
<http://www.health.uct.ac.za/fhs/research/humanethics/forms>



Comments to PI from the HREC

Thank you for your Study
Deviation 674/2022

HREC Chair Signature
Date: **13/2/2024**

Principal Investigator to complete the following:

1. Protocol information

Date (when submitting this form)	9/2/24		
HREC REF Number	674/2022	Current Ethics Approval was granted until	31/12/2023
Protocol title	Effects of resistance training on physiological and biomechanical factors in marathon runners: Reactive strength vs. heavy weight training		
Protocol number (if applicable)			
Are there any sub-studies linked to this study?	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No	
If yes, could you please provide the HREC Reference number for all sub-studies? Note: A separate FHS016 must be submitted for each sub-study.			
Principal Investigator	A/Prof Andrew Bosch		
Department / Office Internal Mail Address	Andrew.bosch@uct.ac.za		

1.1 Does this protocol receive US Federal funding?	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No
--	------------------------------	--