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# Resistance Training and Running Performance and Economy: A Literature Review

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**Resistance Training and Running Performance and Economy: A Literature Review**

by

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An undergraduate honors thesis submitted in partial fulfillment of the  
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### **Abstract**

Running performance is largely determined by maximal oxygen uptake ( $\text{VO}_2 \text{ max}$ ), velocity at  $\text{VO}_2 \text{ max}$ , fractional utilisation of  $\text{VO}_2 \text{ max}$  and running economy. Running economy is relatively under-researched and could be improved by resistance training because of its neuromuscular underpinnings. However, existing research on this topic is quite unorganised and inconclusive and is yet to prove a direct linkage between resistance training, running economy and performance. This literature review aimed to provide an organised overview of the existing literature, identify and address confounding variables and provide recommendations for future research. A search for studies was conducted via Google Scholar and the National Strength and Conditioning Association database. The inclusion criteria were: the participants are between 18 and 60 years of age and run at least three times per week; the article is peer reviewed and published no earlier than 2005; the study either measures running economy (as “the oxygen or metabolic cost to run at a given submaximal velocity” (Blagrove et al., 2018a, p. 1133)) or running performance (as a time-time trial); and the study contains a resistance training intervention and a control condition, or is a literature review. This review did not find sufficient evidence to definitively conclude that resistance training improves running economy or performance, but instead recommends steps to conduct more consistent and controlled future research.

### **Resistance Training and Running Performance and Economy: A Literature Review**

There are four overarching determinants of running performance (RP): maximal oxygen uptake ( $\text{VO}_2 \text{ Max}$ ), velocity at  $\text{VO}_2 \text{ Max}$  ( $v\text{VO}_2 \text{ Max}$ ), fractional utilisation of  $\text{VO}_2 \text{ Max}$ , and running economy (RE). Most of these have been extensively researched, except for RE: “the oxygen or metabolic cost to run at a given submaximal velocity” (Blagrove et al., 2018a, p. 1133). Being underpinned by neuromuscular characteristics, RE has the potential to be improved by resistance training (RT). However, it remains unclear whether changes in RE leads to meaningful improvements in RP. There is a lack of consistency in research on this topic resulting from no uniform definition or measurement of RE and standardised protocols to investigate it. Since RT has the potential to provide athletes with additional performance improvements beyond their  $\text{VO}_2 \text{ max}$  capacity, the lack of consistency in the findings creates the demand for further research into this relationship.

This paper examines RE as a mechanism through which RT could improve RP in a concurrent training program. A concurrent training program is one consisting of simultaneous resistance and endurance training (ET). The goal of this paper is to investigate, through a literature review, the hypothesis that two or more RT sessions per week in adult runners who run three or more times per week results in an improvement in RE and performance. The null hypothesis is that no such effect exists. The lack of consistency and clarity in the literature will then be explored and recommendations to address this in future literature provided.

For this literature review, 19 articles were gathered via Google Scholar. The criteria for inclusion were as follows: the participants are between 18 and 60 years of age and run at least three times per week; the article is peer reviewed and published after 2005. These studies measured RE (as “the metabolic or oxygen cost of running at a given speed” (Blagrove et al., 2018a, p. 1133)), or RP (as a time-time trial); and contained a RT intervention and a control condition or were a literature review.

## Literature Review

Throughout the articles, there is agreement on the existence of an ‘interference effect’ (Beattie et al., 2017) between resistance exercise and ET, and its importance when planning a concurrent training program. “The interference effect” (Beattie et al., 2017) is when one mode of training has an impact on the other and its outcomes. However, the mechanism and magnitude of this effect is less clear, and so several different hypotheses have been proposed to explain it. Doma and Deakin (2015) studied the acute effects of RT on RP and presented complementary acute and chronic hypotheses. The chronic hypothesis holds that the physiological responses to RT and to ET are antagonistic. The acute hypothesis suggests that residual fatigue from one mode of training effects the other. In one direction, residual fatigue from running would impair RT sessions and adaptations, and in the other, neuromuscular fatigue from RT would impair subsequent ET (Chtara et al., 2005). Blagrove et al. (2018a) give a more specific cellular mechanism for this chronic hypothesis: a resistance or ET session upregulates cellular pathways, activating or suppressing genes to promote adaptation. In response to RT, insulin-like growth factor 1 (IGF-1) is secreted, upregulating protein synthesis. In response to ET, the IGF-1 pathway is inhibited, suppressing the upregulation of protein synthesis, impairing hypertrophy. This bi-directional effect is seldom acknowledged by other authors.

Managing fatigue is an important consideration when planning a concurrent training program; however, the interference effect also has positive implications for a runner. Hypertrophy would be undesirable for a distance runner as an increase in the cross-sectional area of muscles would decrease capillary density and increase diffusion distances (Rønnestad & Mujika, 2014), and reduce mitochondrial and oxidative enzyme density (Blagrove et al., 2018a). Vikmoen et al. (2016) found that the capillarisation of the m. vastus lateralis in 19 female endurance athletes was not affected, despite some hypertrophy, and loss of

capillarisation should not be a concern to an endurance athlete undertaking a heavy RT. The excess body mass that accompanies the hypertrophic response would likely be determinantal to a runner's performance (Blagrove et al., 2018a). In a 40-week study of 20 competitive distance runners, Beattie et al. (2017) found that there were no significant changes in total body, lean or fat mass in a concurrent training group compared to an ET group. Some studies did find that hypertrophy occurred within a concurrent training program, but without any negative physiological implications (Vikmoen et al. 2016; Blagrove et al., 2018b). Overall, there is consensus that the interference effect within a concurrent training program appears to restrict the hypertrophic effect that normally accompanies resistance exercise alone. As is evident by a lack of change in capillarisation and body composition variables. This agrees with a review conducted by Blagrove et al. (2018a).

The relative frequencies and volumes of RT and ET are important considerations in a concurrent program design to best mediate the interference effect and maximise neural and strength gains with minimal hypertrophy and fatigue. Balsalobre-Fernández et al. (2016) argue that the correct balance between ET and RT is critical to the success of a concurrent training program. In their review and meta-analysis, they determined that all studies in highly trained runners which found improvement in RE had RT comprising approximately 30% of total training volume. This percentage of total volume or a ratio of training sessions could serve as a crude method to quantify the interference effect. A possibility exists that the interference effect is stronger during periods when ET volume is higher, such as a base training or off-season phase (Blagrove et al., 2018a; Blagrove et al. 2018b). Štohanzl et al. (2018) found that minimal dose of 30-minutes of bodyweight circuit training in a study of 41 female athletes improved time to exhaustion (TTE) in a maximal treadmill test, compared to ET only. Moreover, a greater improvement in TTE was seen in circuit training twice per week (22.7%) compared to once per week (13.5%). Hence, the volume and frequency allow

for the management of overall load and mediation of the interference effect in a concurrent program.

Consideration of the sequencing in a concurrent training program is foundational to mediating the interference effect. In a 12-week study of 48 male sports students Chtara et al. (2005) found that performing ET immediately prior to RT resulted in a 13.6% improvement in maximal oxygen consumption ( $\text{VO}_2$  max) compared to a 10.6% improvement in the opposite sequencing. The rest period in between modes of training is also important: Blagrove et al. (2018a) recommends that at least a three-hour rest period in between ET and RT, rather than the immediate sequencing of Chtara et al. (2005). In a literature review investigating the acute response of runners to RT, de Carvalho e Silva et al. (2022) found that RT increased delayed onset muscle soreness (DOMS), creatine kinase levels, participants ratings of perceived exertion (RPE), and decreased peak torque. Although they did not measure performance directly, this suggests that there could be a short-term harmful effect of RT on ET. Contrary to this, Doma and Deakin (2015) found that there was impairment of maximal RP, not submaximal, for six days following RT. They propose that this is a result of localised energy depletion and neuromuscular fatigue. Regardless of differences, a lack of understanding surrounding the short-term effects of RT on RP means that sequencing and timing between sessions is important.

The inconsistent findings throughout the literature could be due to the lack of a uniform definition and measurement of RE. Blagrove et al. (2018a) use the definition of RE as “as the oxygen or energy cost of sustaining a given sub-maximal running velocity... underpinned by a variety of anthropometric, physiological, biomechanical, and neuromuscular factors.” (p. 1118). Beattie et al. (2017) defined RE as “metabolic cost to cover a given distance at a constant velocity.” (p. 9). These definitions highlight that there is ambiguity in whether it is measured as either the energy or the oxygen cost, or which submaximal velocity is chosen to

take the measurement. The oxygen cost is typically calculated by taking the average  $\text{VO}_2$  over a given time running at a given submaximal speed on a treadmill, a very practical and accessible method. However, in a literature review, Blagrove et al. (2018a) state that the energy cost quantification of RE is more reliable and valid because it is a true measurement of the cost of running rather than an estimation, but of their 24 included studies, only three used the energy cost quantification. Similarly, in the current review, most studies use the oxygen cost method, while only two used some form of energy cost quantification: Blagrove et al. (2018b) and Marcello et al. (2017). Blagrove et al. (2018b) expressed RE as the energy cost of running one kilometre, using the respiratory exchange ratio (RER) and the mean oxygen consumption ( $\text{VO}_2$ ) at the lactate turn point and one and two kilometres per hour slower. Marcello et al. (2017) calculated energy expenditure in a similar manner using the RER at 60% and 80% of participants peak  $\text{VO}_2$ . Another point of variation is the velocity at which RE is measured, regardless of whether the energy or oxygen cost quantification is used. Some studies use the same absolute velocities for all the participants, such as Li et al. (2021) who used 12, 14 and 16km/h, and Štohanzl et al. (2018) who used 7 and 9km/h. Combined with the heterogeneity of participants, this is problematic because a given velocity could be higher intensity for one person, but lower for another (Blagrove et al., 2018a). Also, different training backgrounds should be considered because runners tend to be more economical at the speed which they practice at most (Blagrove et al., 2018a). Subsequently, many studies use relative speeds to measure RE. For example, Piacentini et al. (2013) used three different percentages of each person's marathon pace, and Marcello et al. (2017) used speeds corresponding to 60% and 80% of each participant's  $\text{VO}_2$  peak output. While using the energy cost quantification and relative paces to measure RE is more valid and reliable, there is little consistency in doing so.



In theory, improved RE means that a lower relative effort is required to sustain the same pace, which should translate to improved performance. This link has not been directly proven, rather inferred from observing simultaneous improvements in RE and performance. There are several proposed mechanisms for this, broadly grouped into; musculotendinous stiffness changes, neuromuscular changes, (such as improved motor unit recruitment, firing frequency and coordination), and changes in peak power or maximal force production. Blagrove et al. (2018a) and Li et al. (2021) note that lower limb musculotendinous stiffness has a strong correlation with RE, despite different methods being used to measure leg stiffness. The translation of leg stiffness to RE is hypothesised to be the result of enhanced elastic energy storage in the musculotendinous system during ground contact. This elastic energy storage allows for less muscle activation during the push-off phase (Vikmoen et al., 2016). It appears there are benefits to having stiffer or more compliant tendons in different cases (Rønnestad & Mujika, 2014). Vikmoen et al. (2016) propose that stiff Achilles tendons and compliant patellar tendons are desirable, but that RT could stiffen the latter. They found that heavy RT elicited no beneficial change in patellar tendon properties, RE or RP in well-trained female endurance athletes. The research into the link between RT, musculotendinous stiffness and RE and performance has provided little clarity. Blagrove et al. (2018a) found that leg stiffness could be improved with plyometrics, but Lum et al. (2019) found that plyometric training improved 10-kilometre performance in 14 male distance runners with no change in RE. Similarly, Barnes et al. (2013) also found RE improved under a heavy RT, but not when plyometrics was added to the protocol for 43 Division 1 collegiate cross-country runners over 13 weeks. Conversely, in Piacentini et al. (2013) maximal RT did not improve RE, but RT and the control did. This suggests that the improvements in performance were not a result of changes in RE, and that there are possibly other mechanisms responsible.

The interference effect in a concurrent training program dampens the hypertrophic response, meaning that RT adaptations are observed primarily in the neuromuscular motor unit changes to sustain the same output, but at a lower metabolic cost (Blagrove et al. 2018a). Piacentini et al. (2013) found that the maximal RT group showed a 6.17% improvement in RE and a 17% increase in 1-repetition-maximum (1RM) for the horizontal leg press, which was greater than the RT and control groups. This improvement in maximal strength was not accompanied by a change in fat-free mass, so they theorise that this improvement in RE resulted from the increase in strength because fewer of motor units need to be recruited to sustain the same movement. Rønnestad and Mujika (2014) found that both concurrent running and heavy or explosive RT improve RE and performance. Focusing on the difference between muscle fibre types, they hypothesise that increased strength of type I fibres will prolong their time to exhaustion, and therefore delay the point where the less efficient type II fibres are recruited. Additionally, RT could promote the conversion of type II-X fibres, replicating the functions of the more fatigue-resistant type II-A fibres. Combined, this would result in more efficiency and delay the onset of fatigue in muscle fibres being recruited (Rønnestad & Mujika, 2014). Similarly, Blagrove et al. (2018b) and Barnes et al. (2013) both attribute improvements in RE to neuromuscular adaptations. Overall, there is considerable support for improvements in RE and subsequently performance resulting from neuromuscular adaptations.

There are also studies that have found improvements in RP in the absence of changes in RE, proposing changes in peak power or maximal force production as potential mechanisms. Li et al. (2021) found that maximal strength had no correlation with RE, noting that maximal muscle activation and 1RM have little specificity to distance running. This opposes the findings of Rønnestad and Mujika (2014), Blagrove et al. (2018b), Barnes et al. (2013), Piacentini et al. (2013) and Blagrove et al. (2018a). Specifically, Barnes et al. (2013) present

peak running speed as a composite measurement of maximal muscle power and neuromuscular characteristics, and hence a valid indicator of distance running. Lum et al. (2019) found that RP improved in the absence of any change in RE and suggested that the performance gains were likely the result of greater peak power output. This suggests that there may be another mechanism linking neuromuscular adaptations and peak power to performance. Similarly, Roschel et al. (2015) and Štohanzl et al. (2018) also found no changes in RE, but the latter did find an improvement in performance. Overall, most authors believe that RT has the potential to benefit RP by enhancing RE via greater musculotendinous stiffness and neuromuscular adaptations; however, this linkage is not conclusive nor well understood.

There is considerable variation in the types of RT and specific exercises used in these studies. The four main types of RT that appear are: heavy or maximal, explosive, plyometric, and circuit training. Heavy RT is characterised by high loads and low repetitions (1-10RM), improving motor unit recruitment (Rønnestad & Mujika, 2014). Explosive RT is concerned with high concentric velocity, promoting stiffer tendons (Beattie et al., 2017). Plyometric training involves the activation of the stretch-shortening cycle through rapid eccentric and concentric movements, also improving musculotendinous stiffness (Lum et al., 2019). It is possible that different types of RT could elicit greater gains in RP as they are more specific to running. Improvements elicited in interventions using heavy RT are inconsistent: 2.5% improvement in a 10-km time trial (Damasceno et al., 2015); 6.17% improvement in RE in masters athletes (Piacentini et al., 2013); and no effect on female RP in a 40-minute maximal effort (Vikmoen et al., 2016). Blagrove et al. (2018b) utilised explosive and reactive RT and found a 3.2 – 3.7% improvement in RE which could possibly be beneficial. Concurrent plyometric training has been shown to improve 10-km time-trial performance by approximately 4.2% (Lum et al., 2019), which is similar to the improvement seen in heavy

RT. Blagrove et al. (2018a) reports that all three of these types likely result in performance benefits, and the addition of any of them to a program is advisable. In a different approach, Štohanzl et al. (2018) found that low volume bodyweight circuit training twice per week improved RP on a maximal treadmill test by an average of 22.7% in time to exhaustion in 41 female recreational runners, with no significant changes found in the ET-only condition. There are many confounding variables that should be considered when trying to draw any conclusion from variation in results that is seen with different training types, including sample size, intervention length and participant characteristics.

The combination of different types of RT, does not necessarily have a compounding effect on the adaptations, but could however, have a deleterious effect. Barnes et al. (2013) found that the addition of plyometric training to a concurrent program already containing heavy RT had a deleterious effect on performance and laboratory measures compared to concurrent heavy RT only. In a 40-week periodised program, Beattie et al. (2017) found that a focus on developing maximal strength in the first 20 weeks resulted in about a 4.8% improvement in RE, while a shift to developing explosive and reactive strength while maintaining maximal strength only yielded little further improvement. Overall, it appears that combining different types of RT is not automatically more beneficial but could be mediated by other factors such as periodisation and overall load.

Beyond the type of RT employed, there is variance in the specific exercises used, and the velocities at which they are performed. An exercise that is used by many studies is the leg press or squat in a Smith machine, including Doma et al. (2015), Vikmoen et al. (2016). In fact, the half-squat in a smith machine was the only exercise used in the study by Roschel et al. (2015). The use of machine weights, such as plantar flexion in a smith machine (Damasceno et al., 2015; Vikmoen et al., 2016), knee extension (Damasceno et al., 2015; Doma et al., 2019) and leg curls (Doma et al., 2019). While this is useful in that it provides

consistency for comparison between different studies, Blagrove et al. (2018a) has noted that multi-joint exercises using free weights that target force generation in the lower leg extensor muscles are have the greatest biomechanical specificity to running, so machine weights may not elicit the greatest possible improvements in RE and performance. Barnes et al. (2013) programmed exercises that utilise the lower-limb muscles associated with running, use free weights, and are multi-joint: back squat, single-leg calf raises, dumb-bell military press, lateral pull-down, box step-up, dead lift, dumb-bell incline bench press, resisted monster walk, pull-up, and Bulgarian split squat. Similarly, Blagrove et al. (2018b) included back squats, Romanian deadlifts, single-leg press and calf raises in their study. The velocity that exercises are performed at is important to ensuring specificity to running. Roschel et al. (2015) proposes that the absence of change in RE in their study could have resulted from the slow movement velocity of the exercises, meaning that the stretch-shortening cycle was not utilised and hence there was no translation to RE. However, other studies using non-plyometric exercises that do not rely heavily on the stretch-shortening cycle have still found improvements in RE, such as Piacentini et al. (2013) where participants lifted at 80-90% of 1RM. It should be noted that many authors do concern themselves with controlling the velocity of the movement, such as Vikmoen et al. (2016) who instructed participants to focus on a 2-3 second eccentric phase followed by a 1-second concentric contraction to develop the rate of force development. Despite this, they also found no change in RE, even though the exercises had a greater movement velocity than Roschel et al. (2015). Hence, the lack of specificity of different exercises to running and the velocity at which they are performed is a point of considerable inconsistency in the literature.

## **Discussion**

Based on this literature review, it is difficult to reject the null hypothesis that two or more RT sessions per week in adult runners who run three or more times per week does not

result in an improvement in RE or performance. However, there is also no definitive evidence that RT is detrimental to a runner. This inconclusiveness stems from inconsistencies within the literature, such as small sample sizes, heterogeneous participant characteristics and methodological differences.

The generalisability of the findings of these studies is harmed by most of them having small sample sizes, for example: 5 (Marcello et al., 2017); 10 (Doma et al., 2019); 14 (Lum et al., 2019); 15 (Roschel et al., 2015); 16 (Piacentini et al., 2013); 18 (Damasceno et al., 2015); and 19 (Vikmoen et al., 2016). A possible explanation for these low number of participants could be difficulty attaining funding for larger studies in an under-researched and -represented area in sport and exercise science. Another factor may be that studies involve adherence to a concurrent training program and testing over a specific number of weeks, which is a large time commitment for participants and researchers. Some studies do have larger sample sizes, such as Chtara et al. (2005), Štohanzl et al. (2018) and Barnes et al. (2013), who had 48, 41 and 42 participants respectively; however, this is far from the norm. Chtara et al. (2005) and Štohanzl et al. (2018) both used participants with limited ET, which is a larger pool of participants to draw from, while Barnes et al. (2013) was able to work with a collegiate cross-country team. Outside of conducting studies with larger sample sizes, aggregation of findings from different studies into a larger cumulative participant pool would be desirable, but this is impeded by the considerable variation in the participants and methodologies of different studies in this area.

In conjunction with small sample sizes, the generalisability of findings is harmed by heterogeneity in terms of participant age, sex, and ET and RT backgrounds. It becomes difficult to solely examine the relationship between RT and RE and performance when these characteristics become confounding variables. There was a considerable range of ages covered by this literature review, from masters athletes aged around 44 years (Piacentini et

al., 2013) to post pubescent adolescent distance runners aged 15-18 years (Blagrove et al. 2018b). This can prove problematic as age is known to interact with performance and training adaptations. There is a noticeable decline in performance after 30 years (Piacentini et al., 2013), which would mean that any effect of RT on RP may be difficult to detect and quantify in older age groups. In adolescents there is evidence that RT elicits additional gains beyond that expected from maturation (Blagrove et al. 2018b), but because each athlete matures at a different rate it could be difficult to discern the magnitude of the improvement attributable to RT.

The presence of both males and females in the body of literature gathered for the present study also becomes a potentially confounding variable. Some studies are exclusively on men or women, while others include both, which is concerning when there is evidence that those female tendons reacted differently to mechanical loading, having a lower rate of new connective tissue formation (Magnusson et al., 2007). Stiffer or more compliant tendons have been associated with improved RE, possibly because of greater return of elastic energy (Rønnestad & Mujika, 2014; Vikmoen et al., 2016). This means that a lower rate of new connective tissue formation in female tendons could be an advantage or disadvantage over males, depending on the tendon. For example, Vikmoen et al. (2016) observed no change in RP or RE in females; however, Barnes et al. (2013) found that RT was beneficial to RE in females, but possibly harmful in men.

Participants' ET background varies between and within studies based on the events or distance for which they are training and their level of training for these specific distances prior to and during the RT intervention. Additionally, recreational runners may train for health and fitness rather than for a specific event. Authors use broad and loosely defined descriptors for participants ET background, such as 'moderately', 'recreational' and 'elite'. 'Moderately trained' was defined as both running at least three times and 20 kilometres per

week (Lum et al., 2019) while recreational runners are defined as having a 10-kilometre best of 35-40 minutes (Damasceno et al., 2015). The use of 'recreational' within the definition of 'moderately trained' becomes confusing as other studies define their subjects as 'recreational'. 'Recreational runners' were defined as either running two to four times per week and 10-20 kilometres (Štohanzl et al., 2018) or having 10-kilometre bests around 41 minutes (Roschel et al., 2015). There were also multiple definitions for the abilities of participants who were 'collegiate' runners: 5,000-10,000-metre runners with a minimum of four years distance running experience (Li et al., 2021); running at least six days per week for 50-100 miles per week (80-160km) (Marcello et al., 2017); or having five to seven years of training and running 60-110 kilometres per week. Beattie et al. (2017) included 'collegiate' in their definition of 'competitive distance runners': collegiate and national level 1,500-10,000-metre runners with mean  $\text{VO}_2$  max values of 61.3mL/kg/min, opting to not give insight to their training volume and frequency like other studies. Overall, there are considerable inconsistencies in the participant's ET background and its descriptions across studies, which are only worsened by broad and inconsistent definitions.

Participants were also varied in their RT backgrounds. Many studies use untrained resistance participants (Doma et al., 2019; Doma & Deakin, 2015; Damasceno et al., 2015; Blagrove et al., 2018b), which is useful as there is no existing influence of RT on their performance. However, they must learn the proper technique associated with RT, which can be time-consuming and limit their initial gains. This may partially explain why the use of machine weights is commonplace. Other studies use individuals with RT experience, often requiring them to not participate in RT for a specified period prior to the beginning of the study, such as 12 months (Vikmoen et al., 2016) and 10 weeks (Barnes et al., 2013). This experience could mean that participants are able to perform more running-specific multi-joint exercises with free weights; however, there is the risk that they have not been taught proper



technique, which can be difficult to rectify, or the prior experience could dampen gains made. Overall, generalisations of the results in these studies are difficult: differing participant characteristics mean that varying results cannot be definitively attributed to the RT interventions and makes comparisons more complicated.

Methodological and protocol disagreements and inconsistencies; pertaining to volume, frequency, periodisation, length of a concurrent program, the biomechanical specificity of strength exercises to running, and measuring RE contribute to the inability of this review to reject the null hypothesis. There is no standardised volume and frequency of either mode of training throughout the literature, likely in part due to the varying training backgrounds of participants. There is some degree of consistency in the frequency of RT, with most studies programming it one to three times per week. However, the volume and frequency of running training varies dramatically, from 20-kilometers (Roschel et al., 2015) to 160-kilometres (Marcello et al., 2017) per week. The ratio quantifying the relative volume and frequency of resistance and ET (Balsalobre-Fernández et al., 2016) highlights the discrepancies between studies. The utilization of this ratio could address the variations resulting from heterogeneous participants, as the relative loads can be kept uniform, although the absolute volumes and frequencies might vary between studies. This could allow for the confounding variable of varying volumes and frequencies of training to be better controlled.

Disagreement on the RT protocols also makes generalisations and meaningful conclusions difficult. The use of the Smith machine to perform many exercises was common (Doma et al., 2015; Vikmoen et al., 2016; Roschel et al., 2015). This is useful in that it ensures consistency within and between studies, is simple for beginners, and requires less supervision. However, this practice brought into question for the lack of biomechanical specificity of running, and presumably lower transferability. Blagrove et al. (2018a) argues that the most useful exercises are those which use free weights and multi-joint movements,

but this is not the norm. Overall, it is hard to determine the potential benefits of RT to a runner's performance when it is uncertain whether the specific exercises that are being performed are those which will have the greatest transferability to running.

The dual periodisation of both the RT and ET and their interactions is an important but often overlooked consideration. The program of an elite runner is commonly divided into an off-season, focusing on aerobic development, and a racing in-season, focusing on speed development and aerobic maintenance. Beattie et al. (2017) was the sole study that considered multiple seasons, focusing on maximal strength during 20-week preseason and reactive and explosive strength during the 20-week in-season. Many studies do not specify when, within an athlete's respective season, their program is conducted, such as Štohanzl et al. (2018). Other studies were conducted in either the off-season or during the racing season only, Lum et al. (2019) and Barnes et al. (2013) respectively. Periodisation may be unaccounted for because studies are typically too short, or participants are not advanced enough in their training level. – Recreational runners typically run for general health and fitness or to peak for a single race rather than a season. Different periodisation models, or lack periodisation altogether, is confounding; varying ET volumes with the respective seasons may alter the magnitude of the interference effect. Similarly, the type of RT may not optimally complement the focus of the running program.

Variation in intervention length also makes it difficult to determine or recommend any optimal program lengths, with studies ranging from 6 weeks (Piacentini et al., 2013) to 40 weeks (Beattie et al., 2017). It is also possible that there is an optimal point past which further gains are minimal, as Beattie et al. (2017) found that almost most of the overall improvement in RE was accounted for by the gains made in the first 20 weeks. However, it is difficult to generalise this, as this was the only study with such structure and length. The minimal improvement past 20 weeks it could be a result of the shift from maximal to

explosive and reactive strength development, or from the change from off-season to in-season running training. There is little justification as to why certain program lengths are chosen, which indicates a lack of clarity and understanding surrounding optimal program lengths. Developing this knowledge and consistency will improve the generalisability of findings and guide future structuring of RT and RE and performance studies.

The lack of consensus defining and measuring RE also makes comparison and generalisation of any findings unwise and raises the question of whether RE should be measured at all. RE is either defined and measured as the more common oxygen cost, or the more valid energy cost via the respiratory quotient (Blagrove et al., 2018a). Additionally, the protocol of using absolute or relative speeds for treadmill testing is not uniform. The use of relative speeds is less common, but more sensitive to RE changes as it accounts for the varying abilities of subjects. However, because RE changes may be speed specific (Blagrove et al., 2018a), relative speeds still may not detect RE changes that manifest outside of a certain percentage effort. Some studies address this by using multiple paces, such as Damasceno et al. (2015), but there is still the risk that the desired pace is outside of this range. It is possible that RE could be measured in different ways, such as analysing changes in biomechanics, tendon stiffness, or enzyme activity, but these have not been sufficiently researched. Overall, if improvements in RE do not translate to meaningful changes in RP, the findings are of little practical use. Therefore, if the difficulties in measuring RE prove to be irreconcilable, it may be more useful to just focus on measuring RP through time trials over a distance that the subject trains for, as this has a great degree of external validity (Blagrove et al., 2018a).

## **Conclusion**

In summary, despite a wealth of anecdotal evidence, the null hypothesis cannot be rejected to definitively conclude that any form of RT improves RE or performance because of

the overwhelming array of confounding variables. These mainly relate to a lack of consistency in participant characteristics, definition and measurement of RE and overall program design. However, the findings are promising and moving forward it may be useful to reframe this null hypothesis to simply focus on whether RT has an impact on RP. Providing greater methodological uniformity in future research will potentially result in more conclusive determinations. For RE to become a more relevant area of study, the confounding variables discussed in this review must be experimentally investigated so that they can be controlled for the true relationship between RT and RE to be understood. Time constraints mean that a limitation of this literature review could be that the number of articles it encompassed was relatively low compared to the volume of research on the topic, and as such the investigation may not be entirely comprehensive, or there may be studies already speaking to the conclusions made.

### **Practical Applications**

Future studies should exercise greater control on the confounding variables highlighted in this review, with a standardised methodology. The ideal specific set of participants would be trained runners at their  $\text{VO}_2$  ceiling with a restricted age range such as their peak age of 25-30. Studies should investigate the different responses of men and women to RT, where the only variable being manipulated is sex. Until this relationship is better understood, it would be pertinent to exclusively use males or females in subsequent studies. Studies should be at least 20 weeks in length, sufficient to consider and complement the periodisation of an elite runner's program. ET should be performed prior to RT and time and frequency ratio of ET to RT in these studies should not stray far from 3:1. Exercises should be more carefully selected to ensure the greatest degree of transferability to running: use free weights to perform multi-joint exercises that mimic running, such as a barbell split squat. For greater practical application and utility future research would be better served to focus on RP

measured via a time trial over an elite athlete's preferred distance. If a direct, causal relationship between RT and RP has been proven, then these confounding variables and RE could be investigated.

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