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The Impact of Resistance Training on Distance Running Performance

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Contents

Abstract

Traditionally, distance running performance was thought to be determined by several characteristics, including maximum oxygen consumption ($\dot{V}O_{2max}$), lactate threshold (LT), and running economy. Improvements in these areas are primarily achieved through endurance training. Recently, however, it has been shown that anaerobic factors may also play an important role in distance running performance. As a result, some researchers have theorised that resistance training may benefit distance runners. Because resistance training is unlikely to elicit an aerobic stimulus of greater than 50% of $\dot{V}O_{2max}$, it is unlikely that resistance training would improve $\dot{V}O_{2max}$ in trained distance runners. However, it appears that $\dot{V}O_{2max}$ is not compromised when resistance training is added to an endurance programme. Similarly, LT is likely not improved as a result of resistance training in trained endurance runners; however, improvements in LT have been observed in untrained individuals as a result of resistance training. Trained distance runners have shown improvements of up to 8% in running economy following a period of resistance training. Even a small improvement in running economy could have a large impact on distance running performance, particularly in longer events, such as marathons or ultra-marathons. The improvement in running economy has been theorised to be a result of improvements in neuromuscular characteristics, including motor unit recruitment and reduced ground contact time. Although largely theoretical at this point, if resistance training is to improve distance running performance, it will likely have the largest impact on anaerobic capacity and/or neuromuscular characteristics. The primary purpose of this review is to consider the impact of resistance training on the factors that are known to impact distance running performance. A second purpose is to consider different modes of resistance exercise to determine if an optimal protocol exists.

Distance runners have traditionally focused their training on improving cardiovascular and muscular endurance. The principle of training specificity suggests improvement in endurance performance may be achieved most effectively through aerobic training, which, for the distance runner may include long distances at a moderate pace, or shorter distance but high intensity interval work (e.g. 1600m), or some combination of both. This type of aerobic training has been shown to impact several factors which are thought to determine success in distance running.[1,2] The primary factors known to affect distance running performance include maximum oxygen consumption ($\dot{V}O_{2max}$), lactate threshold (LT), and running economy.[2-7] However, elite distance runners may exhibit similar levels of $\dot{V}O_{2max}$, LT, and running economy, suggesting other factors may contribute to success at the elite level. Evidence suggests that anaerobic work capacity may be a determining factor in performance for well-trained distance runners.[8] Further, Noakes[9] suggests muscle power factors may limit endurance performance and may be better predictors of success than $\dot{V}O_{2max}$ when comparing elite aerobic athletes.

The idea that anaerobic capacity, muscle strength, and/or muscle power impact running performance challenges the idea that training for runners should be limited to aerobic activities. While resistance training may not commonly be promoted for distance runners, evidence suggests running performance may be positively impacted by the addition of resistance training to the aerobic training regimen.[10,11] If resistance training is to be useful for distance runners, it likely must impact the variables thought to be responsible for running performance ($\dot{V}O_{2max}$, LT, running economy, and/or anaerobic factors) [see table I for a summary of studies].

The purpose of this article is to explore resistance training as it relates to $\dot{V}O_{2max}$, LT, running economy, anaerobic factors and any other variables that may impact running performance. Additionally, different types of resistance training will be addressed, including circuit weight training, traditional heavy resistance training, and high velocity, or explosive, resistance training (i.e. Olympic weightlifting and plyometrics). It is intended that some conclusion can be drawn regarding the value of resistance training for distance runners.

For the purposes of this article, the generic term ‘resistance training’ will refer to any training specifically designed to increase muscular strength, power, muscular endurance, and/or promote neural adaptations. Specific types of resistance training will be described throughout the text.

1. Maximum Oxygen Consumption

$\dot{V}O_{2max}$ refers to the highest rate at which the body can consume and utilise oxygen.[7] $\dot{V}O_{2max}$, also referred to as aerobic power, is recognised as one of the key predictors of success in endurance running.[2,3,7,9] While the highest $\dot{V}O_{2max}$ value does not necessarily equate to the best performance in a running event, athletes who perform well in endurance activities typically possess high $\dot{V}O_{2max}$ values.[3,7,9,27] Therefore, a goal of many distance runners is to improve $\dot{V}O_{2max}$.

Thus far, improvements in $\dot{V}O_{2max}$ have been shown to be best achieved through prolonged bouts of running at a moderate to high intensity (approximately 65–85% of $\dot{V}O_{2max}$) or shorter, repeated bouts of running at a high intensity (80–100% of $\dot{V}O_{2max}$).[1,2,28-31] Prolonged bouts may last between 30 and 120 minutes depending on the intensity, while high intensity intervals usually last 5 minutes or less.[1,2,28-31] These methods of training challenge the oxidative system in such a way as to induce an adaptation in the body that results in greater oxygen consumption. Adaptations that may occur as a result of these training methods include, but are not limited to, increased blood volume, increased oxidative capacity of the muscle through increased mitochondrial volume and density, and increased concentration

Table I. Comparison of resistance training programmes on endurance performance variables

Study	Subjects	Volume	Frequency and duration	Mode of endurance exercise	Results		
					$\dot{V}O_{2max}$	LT	running or work economy
Traditional resistance training							
Johnston et al.[11]	12 trained female distance runners	2–3 sets of 6–20 RM	3 d/wk for 10 wks	Running	↔		↑4%
Hickson et al.[12]	9 healthy untrained males	3–5 sets of 5 RM	5 d/wk for 10 wks	None	↑4% L/min on cycle ↔ on treadmill		
Hurley et al.[13]	13 untrained males	1 set of 8–12 RM	3–4 d/wk for 16 wks	None	↔		
Hickson et al.[14]	8 trained males and females	3–5 sets of 5 RM	3 d/wk for 10 wks	None	↔	↔	
Marcinik et al.[15]	18 healthy untrained males	3 sets of 8–20 RM	3 d/wk for 12 wks	None	↔	↑12%	
Hennessy et al.[16]	56 club rugby players	2–6 sets of 5–10 reps	3 d/wk for 8 wks	Running	↔		
Bishop et al.[17]	16 active, untrained males	3–6 sets of 1–15 reps	3–4 d/wk for 6 wks	Unknown	↔		
Bishop et al.[18]	21 trained female cyclists	3–5 sets of 2–8 RM	2 d/wk for 12 wks	Cycling	↔	↔	
McCarthy et al.[19]	30 untrained males	2 sets of 6 RM	3 d/wk for 10 wks	Cycling	↑10% (mL/kg/min)		
Gettman et al.[20]	41 untrained males	2 sets of 15 reps; circuit training	3 d/wk for 20 wks	None	↑3.5% (mL/kg/min)		
Gettman et al.[21]	77 untrained males and females	3 sets of 12–15 reps; circuit training	3 d/wk for 12 wks	None	↑12% (mL/kg/min)		
Haennel et al.[22]	32 untrained males	3 sets of 15–20 reps; circuit training	3 d/wk for 9 wks	None	↑11.3% (mL/kg/min)		
Kaikkonen et al.[23]	90 sedentary males and females	3 sets of variable reps; circuit training	3 d/wk for 12 wks	None	↑10.4% (mL/kg/min)		
Explosive resistance training							
Paavolainen et al.[10]	22 elite male cross-country runners	15–90 min/session	9 wks	Running	↔	↔	↑8.1%
Paavolainen et al.[24]	15 elite male cross-country skiers	15–90 min/session	6 wks	Cross-country ski training	↔		
Stone et al.[25]	9 sedentary males	3–5 sets of 10 reps	5 wks	None	↑7.5% (mL/kg/min)		
Sport-specific resistance training							
Hoff et al.[26]	15 trained female cross-country skiers	3 sets of 6 RM	3 d/wk for 9 wks	Cross-country ski training	↔	↔	↑22%

LT = lactate threshold; **reps** = repetitions; **RM** = repetition maximum; **sedentary** = no activity prior to study; **untrained** = no regular exercise programme prior to study; $\dot{V}O_{2max}$ = maximum oxygen consumption; ↑ = increase; ↔ = no change.

of oxidative enzymes, and increased capillary density.[2,30,32]

Resistance training, on the other hand, may increase body mass, promote the use of non-endurance, fast twitch muscle fibres, or decrease the activity of oxidative enzymes, any of which may hinder endurance performance by negatively impacting relative $\dot{V}O_{2max}$.[33-39] Resistance training may also result in a reduction in mitochondrial volume density or a decrease in capillary density.[35,37,38,40] These alterations have the potential to decrease an individual's ability to deliver and/or effectively utilise available oxygen. Consequently, distance runners may choose to avoid resistance training for fear of reduced aerobic performance. However, the question remains whether these changes occur to the same magnitude when resistance training is added to a distance running programme and whether $\dot{V}O_{2max}$ is negatively impacted.

According to the literature, improvements in $\dot{V}O_{2max}$ as a result of most forms of resistance training are unlikely to occur in aerobically trained or untrained individuals.[10-18,24,26] For example, Hickson et al.[12] had untrained subjects ($\dot{V}O_{2max}$ = 47.8 mL/kg/min) perform heavy resistance training exercises with the lower body (3–5 sets × 5 repetitions at 80% of one repetition maximum (RM) 5 days a week for 10 weeks. Following the training period, there were significant improvements in strength; however, no improvements were found in relative $\dot{V}O_{2max}$ (mL/kg/min) performed on a treadmill or a cycle ergometer.[12] A small (4%) increase in absolute $\dot{V}O_{2max}$ (L/min) was found when subjects were tested on a cycle ergometer. Hickson et al.[14] performed a similar study using aerobically trained individuals ($\dot{V}O_{2max}$ = 60 mL/kg/min) and found that heavy resistance training with the lower body did not improve relative or absolute $\dot{V}O_{2max}$ measured on a treadmill and cycle ergometer.

Similar studies that considered the effect of resistance training on $\dot{V}O_{2max}$ have varied in the duration of the training programme (6–16 weeks), the specific type of resistance training (traditional resistance training, explosive training), or the fitness level of the subjects.[10,11,13,15,16,24,26] The data appear to be consistent across the studies, indicating that resistance training alone is not a sufficient aerobic stimulus to improve $\dot{V}O_{2max}$. This lack of improvement in $\dot{V}O_{2max}$ may be explained by the finding that an acute bout of resistance training elicits oxygen consumption values of less than 50% of maximal capacity.[13,34,41-43] In fact, an upper and lower body resistance training workout consisting of 8–12 exercises was shown to result in an average oxygen consumption that was similar to that of walking on a treadmill at approximately 6.4 km/h.[13,42] This is hardly a substantial stimulus for improving aerobic capacity in all but the most sedentary of people.

A few studies have found that subjects who performed 8–10 weeks of resistance training showed significant improvement in $\dot{V}O_{2max}$.[19,25] One study employed traditional resistance training exercises including parallel squats,[19] while Stone et al.[25] utilised Olympic-style lifting. Both studies used subjects with relatively low initial levels of cardiovascular fitness ($\dot{V}O_{2max}$ <40 mL/kg/min) and found improvements of less than 10%.

Circuit weight training has consistently resulted in improvements in $\dot{V}O_{2max}$ in untrained individuals, perhaps due to a high heart rate response (approximately 80% maximum heart rate) during exercise.[20-23] This type of training usually involves 20–30 minutes of resistance training in which recovery time between sets is limited to 15–20 seconds. Several studies have found up to 12.5% increase in $\dot{V}O_{2max}$ in subjects following circuit weight training programmes lasting between 9–20 weeks.[20-23] Again, the subjects used in these studies were sedentary and aerobically unfit ($\dot{V}O_{2max}$ <40 mL/kg/min). While these results may be valuable for aerobically unfit individuals, or individuals unable to perform aerobic exercise, they would have little value for aerobically trained individuals, who would likely not see this improvement in $\dot{V}O_{2max}$.

When resistance training has been performed in conjunction with aerobic training, $\dot{V}O_{2max}$ has not been shown to improve beyond values achieved by aerobic training alone.[11,13,14,16,18,19,24,26,27,44] Female distance runners who combined traditional resistance training with a running programme for 10 weeks showed improvements in strength. However, when compared with a sample that performed a similar running programme without resistance training, the two groups showed no difference in $\dot{V}O_{2max}$.[11] Similar results were found in a trained group of runners who maintained their running programme while adding heavy resistance training (parallel squats, knee extensions, knee flexions, toe raises) for a period of 10 weeks. Following the 10-week period, subjects demonstrated an increase in leg strength but no improvement in $\dot{V}O_{2max}$.[14] Failure to improve $\dot{V}O_{2max}$ as a result of adding resistance training to an aerobic training programme has also been reported for cyclists,[14,18] and cross-country skiers.[10,26]

Combining resistance training with endurance training has been shown to attenuate strength gains in most, but not all, situations.[16,44-47] In contrast, although resistance training may not be useful to a distance runner for improving $\dot{V}O_{2max}$, results are consistent in showing that $\dot{V}O_{2max}$ is not compromised when resistance training is combined with an endurance programme.[10,14,15,19,24,26,44-46,48,49] Hickson et al.,[14] in the study described in the previous paragraph, suggested that the addition of heavy resistance training to an existing endurance programme (running or cycling) had no negative effect on endurance performance, as measured by $\dot{V}O_{2max}$ or time to exhaustion. These studies seem to confirm that resistance training should not impair endurance performance.

The value of resistance training for improving $\dot{V}O_{2max}$ in distance runners remains unclear. Few resistance-training studies have been performed on elite, or even sub-elite distance runners. In general, the available data suggest that distance runners will not improve $\dot{V}O_{2max}$ as a result of resistance training.[10,11] The stimulus to the aerobic system is insufficient to impact the highly trained runner.[13,34,41-43] However, the literature seems to dispel the myth that resistance training will hinder aerobic performance since all the endurance athletes studied performed resistance training without causing a reduction in $\dot{V}O_{2max}$[10,11,14,18,24] or other endurance performance measures.[10,14] It appears that adding resistance training to an endurance training programme should not impair endurance performance, and therefore may be valuable to distance runners for reasons other than improving $\dot{V}O_{2max}$.

2. Lactate Threshold

LT refers to the point at which blood lactate accumulates above resting values during increased exercise intensity. It is commonly accepted that LT is an important factor in predicting distance running performance.[4,7,50] A runner with a high LT is able to run at a high percentage of $\dot{V}O_{2max}$ before the lactate production rate exceeds lactate removal rate.

A few studies have been performed in which the primary investigation was to determine whether resistance training had any effect on LT. Marcinik et al.[15] had untrained individuals perform common resistance training exercises (e.g. bench press, knee extension, leg press) in a circuit-type session. Following the 12-week resistance-training period the subjects experienced a 12% increase in LT while performing on a cycle ergometer. Therefore, following training, subjects were able to perform at a relative intensity (%$\dot{V}O_{2max}$) that was 12% higher before reaching LT.[15] Additionally, blood lactate levels were lower at submaximal intensities following the resistance-training period. The authors speculated that because limited rest was allowed between exercises, higher than average lactate levels could have been achieved.[15] It is important to note that these subjects were untrained, allowing greater room for improvement compared with a trained population. Additionally, the mode of training (circuit-training) may have generated a sufficient stimulus for the untrained subjects to observe an improvement in LT. A second explanation may also be worth considering. Following a resistance-training programme the muscle fibres are capable of producing more absolute force; therefore, the fibres would work at a lower percentage of maximum strength during endurance exercise, compared with pre-training. This decrease in effort may have resulted in a decrease in anaerobic energy production, resulting in a decrease in blood lactate concentration.[15] Finally, the decrease in relative force production per fibre (i.e. decrease in relative workload) may decrease blood flow occlusion, which may have an effect on lactate production and/or clearance.[15] This study has potential merit for distance runners; however, the results were based on untrained individuals and have yet to be replicated in subsequent studies.

Other studies have also considered the effect of resistance training on LT or blood lactate levels with results in contrast to previous studies.[10,14,18,26] A group of trained, female endurance cyclists performed a periodised parallel squat programme 2 days per week for 12 weeks. The set and repetition scheme changed each week, ranging from three to five sets and two to eight repetitions on any given week. A 3-minute rest period was given between each set. The results revealed no change in LT following the resistance-training programme measured while exercising on a cycle ergometer.[18] It is possible LT was not affected because the subjects were already endurance trained. However, it is also possible that the resistance training sessions were not vigorous enough to impact LT.

A group of trained cross-country skiers added a high intensity resistance-training programme (three sets of six repetitions at 80% of one RM) to their existing endurance training, 3 days per week for 9 weeks. The programme consisted of a single exercise that simulated a cross-country ‘double poling’ motion. The resistance-training programme resulted in no change in blood lactate concentration at $\dot{V}O_{2max}$.[26] Similarly, Paavolainen et al.[10] found that LT was unchanged in trained distance runners following 9 weeks of explosive resistance training.

The effect of resistance training on LT is not conclusive, partially due to a paucity of available literature. Only one known study has found an improvement in LT as a result of resistance training. Subjects in this study were untrained and were not involved in a regular exercise programme.[15] Other studies using trained individuals have failed to find similar improvements in LT.[10,18] This suggests training status may be the critical factor as to whether or not improvements are seen in LT as a result of resistance training.

The evidence seems to suggest that endurance-trained athletes would not improve LT as a result of resistance training.[10,18,26] It is unlikely that resistance training would provide the stimulus necessary to impact LT. However, the evidence is consistent in showing that resistance training does not hinder LT, suggesting distance runners could perform resistance training without a concomitant decrease in LT.[10,15,18,26] This area may benefit from further research because of the lack of available data regarding resistance training and LT.

3. Running Economy

Running economy involves the relationship between $\dot{V}O_{2max}$ and velocity of running, or the oxygen required at a given absolute exercise intensity.[2,5] This concept is easily understood by examining two individuals running at the same velocity. The runner who requires a lower $\dot{V}O_2$ at the given velocity is said to have better economy. Running economy has been shown to influence performance for distance runners.[5,6,51,52] An improvement in running economy would allow a runner to run faster over a given distance or to run longer at a constant speed because of the reduced oxygen consumption.[53,54]

Resistance training has been shown to improve economy in both runners[10,11] and cross-country skiers.[26] A group of trained, female cross-country runners performed 10 weeks of traditional weight training 3 days per week (e.g. parallel squats, knee flexion, arm curls). The resistance-training programme consisted of two to three sets of 6–20 repetitions (depending on the exercise) for 14 different exercises. Following the resistance-training programme, the athletes showed a 4% improvement in running economy.[11] Unfortunately, the authors do not discuss how the change in economy affected race performance. Nonetheless, this is convincing evidence that resistance training may be beneficial to distance runners, since even small improvements in running economy become very important over long distances.

Similarly, Paavolainen et al.[10] found that 9 weeks of explosive resistance training (plyometrics with and without additional weight, high velocity leg press, knee extension, knee flexion) improved running economy by 8.1% in trained distance runners. This improvement in economy, along with increased muscle power, resulted in a 3.1% improvement in 5km running time, without an increase in $\dot{V}O_{2max}$. The authors claim improved neuromuscular characteristics ultimately led to these improvements.[10]

A key component to running economy is the ability to store and recover elastic energy from the eccentric contraction.[55,56] Resistance training may improve this stretch-shortening cycle, thereby decreasing ground contact time and improving running economy.[10,36,57] The term ‘neuromuscular characteristics’ refers to the interaction between the neural and muscular systems, including neural activation of the muscle fibres through the contraction and relaxation of the fibres. Those neuromuscular characteristics that could affect running economy may include regulation of muscle stiffness, degree of neural input to the muscles, motor unit synchronisation and/or motor unit recruitment.[10,58-60]

Resistance training may improve running economy through several mechanisms. An increase in strength as a result of resistance training may improve mechanical efficiency, muscle coordination, and motor recruitment patterns,[36] which could prove helpful to the distance runner. Kyrolainen et al.[61] suggest that improved coactivation of leg muscles surrounding the joints could aid runners as running speeds increase, due to increased joint stiffness. Johnston et al.[11] propose these improvements in the neuromuscular system may influence running style to enhance running mechanics. Additionally, improved mechanical efficiency and greater muscle coordination may allow for a reduction in relative workload.[26] The combination of improved running mechanics and neuromuscular efficiency may result in a decrease in oxygen consumption, thereby improving economy.[11,26]

Work economy was also improved in elite cross-country skiers who participated in a heavy resistance-training programme.[26] Subjects performed a single exercise that mimicked the double poling action used in cross-country skiing. Three sets of six RMs were performed each of 3 days per week for a period of 9 weeks, which resulted in a 14.5% increase in strength and a 27.0% increase in peak force. Work economy was calculated by dividing oxygen consumption by double-poling speed. Using this calculation, subjects improved their work economy 22%.[26] Time to exhaustion and double poling economy were improved without an increase in $\dot{V}O_{2max}$.[26] These improvements were reportedly due to decreases in relative workload (reduced percentage of maximal force) and time to peak force measured during the double poling action.[26] Because cross-country skiing is a weight-bearing exercise, the results found in this study may potentially be applicable to distance runners.

Running economy has been improved in runners using traditional strength training or explosive, plyometric training.[10,11] Work economy has been improved in cross-country skiers using a movement-specific resistance training programme.[26] Each of these studies showed improvements in economy in 10 weeks or less.[10,11,26] Although more research is needed, these data suggest that any type of resistance training may have a positive effect on economy.

The available data suggest economy can be improved with resistance training, with no deleterious effect to $\dot{V}O_{2max}$ or running performance.[10,11,26] More studies are needed in this area to support this observation in runners. Additionally, each of the studies employed a different mode of resistance training; therefore, more research is required to determine which mode of resistance training might be most effective at improving running economy. Finally, an improvement in race time would be the true indicator of improved performance; therefore, future studies should include a time trial or road race in order to assess improvement in this area.

4. Anaerobic Power, Strength, and Neuromuscular Characteristics

Anaerobic power refers to the ability to convert energy to useful work in the absence of oxygen.[62] Neuromuscular characteristics are related to the activation, recruitment, excitation, properties, and/or performance of the motor unit or muscle group as a whole. These characteristics may include neural activation, motor unit synchronisation, muscle force, stored elastic energy, power, ground contact time, and/or the excitation/contraction coupling sequence.[10,36,57,59,60,63,64] Clearly, resistance training can have a positive effect on anaerobic power and neuromuscular characteristics.[10,36,57,63]

Chronic resistance training may improve anaerobic power through changes in both the nervous and muscular systems.[35,36,39] Changes in the muscle may include increased activity of anaerobic enzymes, increased force production, increased intracellular glycogen, or shifts within major fibre type groups.[35,36,39] Neural adaptations may include improved motor unit recruitment and synchronisation, enhanced rate of force development, improved reflex activity, and improvements in the stretch-shortening cycle.[10,35,36,39] It has been suggested that improvements in endurance performance following resistance training are likely due to neural adaptations.[10] However, some studies have found no improvement in endurance performance following resistance training. This suggests that neural adaptations may not have influenced endurance performance.[17,18] It must be noted that specific adaptations may vary depending on the type of resistance training employed.

What is less clear is the impact of improved anaerobic power and neuromuscular characteristics on endurance performance, particularly distance running performance. If improvements in this area are to benefit distance runners, it is likely that the improvements would be manifested in running economy, since $\dot{V}O_{2max}$ appears not to be affected.

It is becoming more evident that aerobic factors are not the only variables that affect endurance performance. In fact, Green and Patla[59] suggest that any “failure of the excitation-contraction process could prevent full utilisation of available oxygen”, suggesting that, in some cases, the ability to use available oxygen might not be the limiting factor in endurance performance. For example, in an ultramarathon, runners often experience neuromuscular fatigue causing them to slow before oxygen consumption and utilisation are compromised. Evidence is strong to suggest that anaerobic power and neuromuscular characteristics may play a large role in endurance performance, especially when athletes are matched for aerobic capacity.[8-10,64-67]

Bulbulian et al.[8] found that anaerobic work capacity contributed significantly in a three-variable model ($\dot{V}O_{2max}$, ventilatory threshold, and anaerobic work capacity) for predicting race performance in highly fit, male cross country runners. The authors concluded that distance runners who were matched for $\dot{V}O_{2max}$, running economy, and anaerobic threshold would be separated by their anaerobic capacity.[8] It is possible that anaerobic work capacity plays a role in distance running during hill climbing or surging.[68]

Noakes[9] also suggests endurance performance may be limited by muscle power factors, such as rate and force of cross-bridge activity. A study of trained distance runners found a correlation between leg power and 10km running time, suggesting that skeletal muscle contractility differs between fast and slow runners.[9] Similarly, differences have been discovered in certain neuromuscular characteristics between high- and low-calibre runners with similar $\dot{V}O_{2max}$ values. High-calibre runners were found to have greater relative pre-activation, decreased relative integrated electromyographic activity, and shorter contact time compared with low-calibre runners during a 10km time trial.[60] The authors suggest these neuromuscular factors may impact distance running performance through force production or more effective use of elastic energy.[60] Further, performance in a 5km run has been shown to be partially determined by neuromuscular characteristics and muscle power.[10,64]

Peak running velocity during a $\dot{V}O_{2max}$ treadmill test ($v\dot{V}O_{2max}$) is equated with muscle power, as it is the peak workload that can be achieved during a treadmill test. Running $v\dot{V}O_{2max}$ has been shown to be a strong predictor of endurance running performance, particularly in trained individuals.[6,9,50,65,69,70] Noakes et al.[65] contend that $v\dot{V}O_{2max}$ is a better predictor of endurance running performance than is

$\dot{V}O_{2max}$, suggesting factors other than oxygen consumption may be involved. This may be particularly true with elite distance runners who may show a plateau at the end of a treadmill $\dot{V}O_{2max}$ test. In such a case, it may be possible to increase treadmill speed without increasing oxygen consumption.[65] Thus, $v\dot{V}O_{2max}$ may reveal more information regarding distance running performance compared with $\dot{V}O_{2max}$. The question that remains is what determines $v\dot{V}O_{2max}$. Noakes[9] contends these factors are likely related to muscle power and/or neuromuscular characteristics.

Peak velocity during a maximal anaerobic running test (V_{MART}) has also been shown to be a good predictor of endurance running performance.[10,64,71] The authors suggest V_{MART} is related to neuromuscular characteristics and that this test can be used as a measure of muscle power.[10,64,71,72] Additionally, V_{MART} has been shown to be highly correlated with 5km performance, further suggesting that neuromuscular characteristics are related to distance running performance.[64] Finally, a test battery used to determine neuromuscular and anaerobic factors revealed that improvements in these factors following explosive resistance training resulted in improved running economy and muscle power.[10] The neuromuscular test battery included ground contact time during a 10km running time trial, a five-jump test, maximal 20m velocity, and V_{MART}. Improvements in these neuromuscular characteristics as a result of resistance training ultimately led to improved 5km running time.[10]

Available evidence suggests that neuromuscular and anaerobic factors play some role in distance running performance, particularly when factors such as $\dot{V}O_{2max}$, running economy, and anaerobic (lactate) threshold are held constant.[8-10,64,65,69] Certainly, resistance training could improve muscle power and neuromuscular characteristics, so if these factors do play an important role in determining distance running performance, we can only assume that resistance training would benefit the distance runner. However, an improvement in distance running performance due to improved neuromuscular factors and muscle power that results from resistance training is largely theoretical, with the exception of the findings from Paavolainen et al.[10] In other words, most of the studies discussed in this section suggest the importance of anaerobic and neuromuscular characteristics in endurance performance, and few would argue that resistance training could benefit these factors. What is lacking is a solid foundation of studies that provide data suggesting that resistance training for distance runners alters neuromuscular and anaerobic characteristics in such a way as to improve endurance performance.

The strongest evidence in this area was presented by Paavolainen et al.,[10] who showed that explosive resistance training improved neuromuscular characteristics. This improvement in neuromuscular characteristics resulted in improved muscle power and running economy, which led to an improved 5km running time in trained distance runners. Improvements in neuromuscular and power factors were observed, in part, as decreased ground contact time and improved V_{MART}. No changes were found in $\dot{V}O_{2max}$, suggesting something other than aerobic factors caused the improved performance.[10]

Contrary to previously mentioned studies, Bishop et al.[17,18] found that increased leg strength as a result of resistance training had no impact on endurance performance in trained female cyclists (LT, $\dot{V}O_{2max}$, 1-hour cycle test) or untrained males (critical power, $\dot{V}O_{2max}$, time to exhaustion). The authors proposed that mechanisms other than strength gains were responsible for improved endurance performance seen in other studies.[17,18] The authors did not consider muscle power or neuromuscular characteristics used in previously mentioned studies. Additionally, it is possible that the mechanisms that allow resistance training to improve distance running performance may not apply to cycling performance.

The evidence strongly suggests that there is potential for distance runners to benefit from resistance training by improving muscular power and neuromuscular characteristics. Of the factors known to affect distance running performance (i.e. $\dot{V}O_{2max}$, LT, running economy, anaerobic factors), neuromuscular characteristics seem to be the area most likely affected by resistance training performed by elite distance runners. It is likely that improvements in neuromuscular characteristics and/or power would affect distance running performance by improving running economy. However, more research is needed to clearly define improvements that have been found and determine if those improvements result in enhanced race performance for distance runners.

5. Time to Exhaustion

Several studies have found improvements in endurance performance that were measured in time to exhaustion rather than the previously mentioned, 'classic' endurance characteristics ($\dot{V}O_{2max}$, LT, running economy).[12,14,15,26] Time to exhaustion at a given workload on a treadmill or cycle ergometer is a common method of measuring endurance performance. Time to exhaustion is often performed at 75–80% of $\dot{V}O_{2max}$; however, the test is not limited to this work rate.

Marcinik et al.[15] found that increased leg strength (30–50%), as a result of resistance training, was associated with a 33% increase in time to exhaustion on a cycle-ergometer test performed at 75% of $\dot{V}O_{2max}$. The authors did not claim to understand the cause of improved endurance performance. However, the authors concur with previous studies that suggest the improvement may be due to a decrease in relative force required for each pedal stroke.[14,15] Also, the improvement in time to exhaustion may have been related to improved LT found in these subjects, regardless of improvements in strength.[15]

Hickson et al.[12,14] found increased strength due to resistance training correlated with increased time to exhaustion on both the treadmill and the cycle ergometer, and an increase in short-term running and cycling performance. However, there was no significant improvement in 10km race time.[14] Additionally, these improvements were found in both trained and untrained individuals.[12,14] It was hypothesised that improved time to exhaustion on the cycle resulted from a decrease in the relative quadriceps force required for each pedal stroke, or perhaps an increase in the absolute pedal force if relative effort was held constant. The authors further claimed that resistance training resulted in more efficient recruitment of Type I fibres and delayed recruitment of inefficient Type II fibres, thereby delaying glycogen depletion and fatigue. These factors, combined with increased strength, may have led to the increased time to exhaustion on a cycle ergometer.[14] However, because subjects in one of these studies[14] increased their $\dot{V}O_{2max}$, it is difficult to determine whether the improved time to exhaustion was directly caused by an increase in leg strength or due to improved cardiovascular function. Additionally, it is possible the increase in leg strength did not translate to an increase in pedal force, based on the concept of movement specificity. It has been shown that increased quadriceps strength does not necessarily translate to increased power on a cycle ergometer.[73] Future research may investigate the mechanism for improved time to exhaustion to determine if the authors' theory is correct.

Hickson et al.[14] did suggest that these benefits may not be observed in trained runners because the force generated per stride is much less than the force generated per pedal stroke in cycling. However, the results showed a 13% increase in short-term endurance on a treadmill (time to exhaustion at 100% $\dot{V}O_{2max}$) with no increase in $\dot{V}O_{2max}$. This suggests the improvement in time to exhaustion may be related to improved anaerobic factors and/or neuromuscular characteristics. This finding may have implications for elite milers or other middle distance runners since their races are typically run at a very high percentage of $\dot{V}O_{2max}$. This improvement was reportedly due to increased muscular strength and anaerobic capacity.[14] Additionally, Paavolainen et al.[10] did find improved endurance performance (5km race time) in trained runners following an increase in strength. It has been suggested that stronger muscles may allow runners to exercise longer by reducing the force contribution of each fibre.[68]

Cross-country skiers who increased strength following resistance training were found to have greater work economy and improved time to exhaustion.[26] Economy was reportedly improved as a result of reduced relative workload, as might be expected following strength gains. The authors suggest the improved time to exhaustion resulted from an increased ability to work with high levels of blood lactate.[26]

Each of these studies reported an increase in time to exhaustion following an increase in muscle strength.[14,15,26] It is difficult to assess whether the improvement was due directly to an increase in muscle strength or due to some other factor. Additionally, only one of the studies used running as its mode of exercise. While time to exhaustion may not be the most reliable method of determining improvements in endurance performance, the result of these studies are consistent enough to suggest that resistance training may be beneficial to the endurance athlete. The question is whether performance could be improved in an elite runner. Additionally, it remains unclear whether an improved time to exhaustion is directly due to an increase in strength or due to some other mechanism related to resistance training.

6. Type of Resistance Training and Endurance Performance

In order to fully understand the benefits of resistance training for endurance athletes, a discussion of the impact of different types of resistance training is necessary. Circuit training, which involves a variety of resistance training exercises performed with minimal rest (approximately 30 seconds) between sets, has been shown to improve endurance performance (measured as improvements in $\dot{V}O_{2max}$, time to exhaustion and LT) in untrained individuals.[15,20-23] However, no current evidence suggests that circuit training would improve performance in trained distance runners.

Traditional resistance training (e.g. squats, bench press) has also been shown to improve endurance performance in both trained and untrained individuals.[11,12,14] Long-term endurance (time to exhaustion at 80% of $\dot{V}O_{2max}$) and short-term endurance (time to exhaustion at 100% of $\dot{V}O_{2max}$) were both improved in both trained and untrained subjects following a period of heavy resistance training with the legs.[12,14] Similarly, a traditional resistance-training regimen improved running economy in trained cross-country runners.[11]

A third type of training involves high intensity movements that are specific to the sport. The concept of movement specificity suggests that the type of resistance training should closely model the movement that will be performed in competition. A group of trained cross-country skiers improved time to exhaustion following a resistance-training programme in which the subjects performed high intensity repetitions using a motion that simulated the double poling action used in cross-country skiing.[26] Other studies have shown that resistance training exercises which resembled a particular movement or motor skill resulted in greater improvements in that particular motor skill.[74] More research is needed to determine the effectiveness of movement specificity as it applies to distance runners.

A final type of resistance training involves explosive movements (e.g. plyometrics, including weighted and unweighted jumps). Perhaps the most convincing evidence in this line of research found that the addition of explosive training to a distance runner's training programme improved running economy and 5km running time.[10] This type of training is most likely to improve the use of stored elastic energy and motor unit synchronisation.[36,57]

The evidence suggests that a variety of types of resistance exercise have potential benefit to distance runners. While the data are convincing, more research is needed to determine which style of resistance training, if any, is more beneficial than any other.

7. Conclusions

The purpose of this review was to consider the benefits of resistance training for distance runners. It was assumed that if some benefit could occur as a result of resistance training, one of the following areas known to influence endurance performance would likely be affected: $\dot{V}O_{2max}$, LT, running economy, or anaerobic factors/neuromuscular characteristics.

The evidence seems to suggest that resistance training may improve $\dot{V}O_{2max}$ and LT in aerobically unfit individuals, but these factors are not likely to be affected by resistance training for the trained endurance runner.[10,11,19,25] The stimulus simply is not intense enough to challenge the aerobic system of the trained endurance athlete; therefore, it should be no surprise that these factors are not affected.[34,41-43] This seems to be the case regardless of the type of resistance training performed.

The limited evidence available suggests resistance training has a significant effect on running economy.[10,11] Cross-country skiers have also been shown to improve economy as a result of resistance training, supporting the idea that performance can be improved in endurance athletes.[26] Whether these changes are a result of increased motor unit firing patterns, improved muscle coordination, improved mechanical efficiency, or simply increased strength requires further investigation.

Perhaps the most intriguing evidence involves changes in neuromuscular characteristics and/or anaerobic factors (including muscular power, strength, and fibre recruitment patterns) and their effects on distance performance. These factors appear to be important in distinguishing endurance athletes who have similar levels of $\dot{V}O_{2max}$, LT, and running economy.[8-10,66,67,69] Resistance training has been shown to improve these neuromuscular characteristics, which in turn leads to improved distance running performance.[10]

Other studies have found increased time to exhaustion as a result of resistance training,[12,14,15,26] usually with no change in $\dot{V}O_{2max}$. It has been suggested that the improved endurance performance is somehow related to improved neuromuscular characteristics, perhaps manifested in improved economy.[10]

Ultimately, the key measurement to determine the success of a resistance-training programme for distance runners is race performance. Studies have found improvements in a laboratory setting and in physiological correlates that are related to distance running performance. However, at the time of this writing, only one study has found improved running time as a result of resistance training.[10]

Improvements in distance running performance appear to be possible with some type of resistance training, whether that is explosive training or more traditional resistance training. These benefits may result from improved neuromuscular characteristics, improved running economy, or improved anaerobic capacity. Finally, it appears that distance runners can participate in a short-term resistance-training programme (<16 weeks) without the concern of a decrease in aerobic performance.

8. Future Research

Future research in this area needs to consider the duration of a resistance-training programme. Many of the previously mentioned studies were performed over a relatively short time period (8–16 weeks). Evidence suggests that many early changes in strength may be attributed to neurological adaptations without a change in muscle size.[36] Runners may be concerned if resistance training led to gains in body mass; therefore, long-term studies might reveal the implications of prolonged resistance training.

Some research provided evidence that adding resistance training may lead to injury in runners. This certainly warrants further investigation to assess the risks versus benefits of resistance training.

Additional research may focus on the best method of resistance training for distance runners. The literature reviewed here revealed benefits to distance runners following both explosive-type and traditional resistance training. However, more studies are needed to support the claims of previous research and to identify the methods that result in the greatest benefit to distance runners.

Perhaps the most important variable to consider is improved race time or time trial performance. While $\dot{V}O_{2max}$, LT, running economy, and neuromuscular characteristics are valuable measurements, they mean very little without an improved race performance.

Finally, researchers often consider only arithmetic group means when determining success of a training programme. It is certainly possible that some distance runners would benefit from resistance training, while others may be non-responders. In order to truly understand the benefits of resistance training for distance runners, investigators must consider the impact on the individual, in addition to arithmetic means.

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