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Should Endurance Athletes Supplement Their Training Program With Resistance Training to Improve Performance?

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summary

This review examines the influence of concurrent strength and endurance training on performance and physiological variables, including maximal oxygen uptake, the lactate threshold, economy of motion, changes in fiber type, and muscle stiffness. Practical recommendations for the strength and conditioning practitioner based on this information are also presented.

A controversial issue concerning athletic trainers and coaches is whether or not strength training should be added to the training regimen of the endurance athlete. This uncertainty arises from the well-known separate adaptive effects that conventional strength and endurance training modes induce when performed independently (for recent reviews, see Tanaka and Swensen [28] and Jung [16]). Strength training typically involves high loads (often near maximal) and low repetitions that enhance the anaerobic energy production and force capacity of those specifically recruited muscle fibers. Conversely, regular endurance training typically involves low-load, high-repetition exercises that enhance the aerobic energy capacity of specifically trained muscle fibers. At face value, for athletes seeking to enhance their endurance capabilities, it would appear that resistance training violates the basic principle of specificity.

Despite the aerobic energy requirements of endurance events, anaerobic aspects also play an important role in the performance success of the highly trained endurance athlete (5). At critical moments during endurance events, such as hill climbs, surges in pace, and sprint finishes, endurance athletes may gain an advantage over their competitors by possessing a developed anaerobic energy system. Indeed, Bulbulian et al. (5) have shown that anaerobic capacity plays an important role in endurance running performance. Therefore, in order to be successful in endurance events, where performance is separated by the slimmest of margins (12), endurance athletes may benefit from the addition of a well-trained anaerobic energy system.

Considerable research has been carried out in relation to the effect that resistance training and endurance training in isolation have on exercise performance and associated physiological variables (for related reviews, see Jones and Carter [15] and McComas [21]). In contrast, data describing the compatibility of these two training modes are relatively sparse. Making matters more confusing, in the few studies that have examined concurrent strength and resistance training, performance improvements have been found in well-trained runners (24) and cross-country skiers (11), but not in cyclists (3).

The nature of the adaptive response to training is always specific to the training stimulus. This makes it challenging, therefore, to determine the influence that resistance training may have on endurance performance and associated physiological variables. Of particular interest is how resistance training impacts what are considered to be the primary factors known to affect endurance performance, namely maximum oxygen uptake ($\dot{V}O_2max$), the lactate threshold, and running economy (15, 18). Jeopardizing any of these factors is likely to have a detrimental effect on the individual's performance outcome. The influence that resistance training has on altering both the physiological composition of muscle fibers (i.e., muscle fiber type) and neural factors (i.e., motor unit function) is also of interest. Investigations into these physiological responses provide useful information to assist the conditioning coach in understanding the effect that resistance training may have on an individual's endurance performance. The purpose of this review, therefore, is to examine the relevant literature pertaining to the influence that concurrent resistance and endurance training has on endurance performance and associated physiological variables, including $\dot{V}O_2max$, the lactate threshold, economy of motion, muscle fiber type, and muscle stiffness.

Maximum Oxygen Uptake ($\dot{V}O_2max$)

$\dot{V}O_2max$ refers to the highest rate at which the body can consume and utilize oxygen, and is well recognized as one of the main predictors of successful endurance performance for the broad population (15). $\dot{V}O_2max$ is limited by both the ability of the heart to pump blood to working muscles and by the ability of the muscles to extract oxygen from the delivered blood (13). Endurance athletes normally possess high $\dot{V}O_2max$ values, and typically train to increase this variable (17). Improvements in $\dot{V}O_2max$ are associated with increases in cardiac output and blood volume, which serve to increase the delivery of oxygen to the working muscles (15). The typical physiological adaptations occurring from resistance training include an increase in body mass, an increase in the size of fast-twitch fibers, and a decrease in the activity of oxidative enzymes (27). These alterations have the potential to hinder endurance performance by adding body mass and decreasing an individual's ability to effectively use available oxygen. Consequently, many endurance athletes may choose to avoid resistance training for fear of hindering their performance.

Although $\dot{V}O_2max$ is a good index of an individual's aerobic capability, it is not a perfect predictor of endurance performance (15). We refer to endurance performance in this context as time to complete a given distance, where time to complete the required distance could range from 2 minutes to 4 hours (8). Hickson and colleagues (10) showed that resistance training (5 $d \cdot wk^{-1}$, 10 wk, 5 sets × 5 repetitions maximum [RM]; parallel squat, leg press, calf raise) significantly improved endurance performance for both cycling (47%) and treadmill running (12%) in 9 untrained subjects, despite no change in $\dot{V}O_2max$ (~48 $mL \cdot kg^{-1} \cdot min^{-1}$). The authors suggested that the performance improvements found were related to increases in muscular strength and power. In a subsequent study, however, Hickson et al. (16) found that cycling and running performances, as well as $\dot{V}O_2max$, were unaltered following a resistance training program (3 $d \cdot wk^{-1}$, 10 wk, 3–5 sets × 5RM; parallel squat, leg press, calf raise) in a group of well-trained male subjects ($\dot{V}O_2max \approx 60$ $mL \cdot kg^{-1} \cdot min^{-1}$). Johnston and colleagues (14) also found no change in $\dot{V}O_2max$ in a group of female distance runners who incorporated resistance training (3 $d \cdot wk^{-1}$, 10 wk, 2 sets, 12–20RM; parallel squat, leg press, hammer curl, weighted sit-up, lunge, bent-leg heel raise, bench press) into their normal endurance training program over 10 weeks. The finding of no change in $\dot{V}O_2max$ following resistance training has been confirmed by Bishop et al. (3), Paavolainen et al. (24), and Hoff et al. (11). It appears convincing, therefore, that when resistance training is performed in conjunction with endurance training in already well-trained individuals, $\dot{V}O_2max$ does not improve beyond values that are achieved by endurance training alone. This is not surprising, considering that an acute bout of resistance training typically elicits oxygen consumption values of less than 50% of $\dot{V}O_2max$ (20), and the stimulus to enhance $\dot{V}O_2max$ would be much greater in the well-trained endurance athlete (17). Thus, if indeed endurance performance is enhanced through the addition of a resistance-training program, it does not appear to occur through increases in $\dot{V}O_2max$. It is important to note, however, that although resistance training will not improve $\dot{V}O_2max$, there is no evidence to suggest that resistance training will hinder one's $\dot{V}O_2max$ or endurance performance.

Lactate Threshold

Lactate threshold refers to the point during exercise above which there is a 1 $mmol \cdot L^{-1}$ increase in blood lactate levels compared with baseline levels (7), and represents the theoretical point during exercise whereby lactate production exceeds its removal (4). Lactate threshold has been shown to be an important predictor of endurance performance over long-duration endurance events (26), because someone with a high lactate threshold has the ability to run at a higher percentage of their $\dot{V}O_2max$ without accumulating excess lactate.

Lactate threshold has been examined following resistance training in untrained and trained subjects. Marcinik et al. (19) implemented a 12-week resistance-training program (3 $d \cdot wk^{-1}$, 12 wk, 3 sets × 10RM; bench press, hip flexor, knee extension, knee flexion, push-up, leg press, lat-pulldown, arm curl, parallel squat, sit-up) in 10 untrained male subjects; 8 untrained men served as controls. The training group demonstrated a 12% increase in their lactate threshold without a change in $\dot{V}O_2$max. Although this study suggests that resistance training may increase one's lactate threshold, unfortunately, these authors did not examine whether changes occurred in the control group. In contrast to these findings, Bishop and colleagues (3) augmented normal endurance training in female cyclists with a periodized parallel squat training program (2 $d \cdot wk^{-1}$, 12 wk, 3 sets × 5–15RM; parallel squat) and found no change in lactate threshold. This disparity of these results to those of Marcinik et al. (19) may be due to differences in training level of the subjects of these studies and/or the fact that the resistance training sessions implemented were not of a high enough intensity to stimulate an increased lactate threshold. Paavolainen et al. (24) also monitored lactate threshold in well-trained distance runners following a resistance training intervention (3 $d \cdot wk^{-1}$, 9 wk, 15–90 min; 5–10 sprints of 20–100 m, alternative jumps, bilateral countermovement, drop and hurdle jumps, 1-legged 5-jump, leg press, knee extensor-flexor exercises), and like Bishop et al. (3), they found no change in lactate threshold.

The effect that resistance training has on lactate threshold and endurance performance remains unclear, partially due to the paucity of available literature. Lactate threshold has the potential to be increased following resistance training, through an enhancement in the capacity of skeletal muscle to buffer H^+ ions (22). Indeed, improved muscle buffering capacity has been shown to be related to improved endurance performance (29), but to our knowledge, muscle buffering capacity has yet to be examined following a resistance training program intervention.

In theory, the same motor unit recruitment patterns that occur during the endurance event in question should be trained in the resistance-training program in order to make the appropriate adaptations. To our knowledge, however, this premise has yet to be examined. To date, confounding variables in the pertinent literature, such as differences in endurance training programs, make it difficult to accurately generalize the influence that resistance training has on endurance performance ability. Thus far, the present literature suggests that endurance-trained athletes would not improve lactate threshold as a result of resistance training. Only one known study appears to refute this (19), but subjects in that study were untrained. The research has shown consistently, though, that resistance training does not appear to hinder lactate threshold, suggesting that endurance athletes could perform resistance training without an accompanying decrease in lactate threshold.

Economy of Motion

Economy of motion represents the metabolic requirements for a given exercise intensity (i.e., running speed or power output). Unfortunately, to our knowledge, changes in economy of motion following concurrent strength and endurance training have been examined only in runners and cross-country skiers, making our review of economy of motion limited to studies conducted with runners. Running economy first should be explained in simple terms. If 2 individuals are running at the same speed, the individual who consumes the lower $\dot{V}O_2$ at a given running speed is said to be more economic, or efficient, by consuming less oxygen and thereby producing less metabolic heat at the same running speed as his or her competitor. Both Paavolainen et al. (24) and Johnston et al. (14) have investigated running economy in trained distance runners following a resistance-training program intervention. Paavolainen et al. (24) employed a 9-week plyometric resistance-training program with trained male distance runners and found an 8.1% increase in running economy, with an associated increase in muscle power (+7.1%) and reduced running time over 5 km (−3.1%). The authors speculated that an improvement in neuromuscular characteristics, such as an increase in muscle stiffness and reduced time of the stretch-shortening cycle (see explanation below) caused these results (24). Johnston et al. (14) used a 10-week resistance-training program with their subjects and found a 4% improvement in running economy. Unfortunately, these authors failed to examine whether this change in economy influenced race performance (14), so no meaningful comparisons can be made between the studies. Nonetheless, these results are consistent in suggesting that resistance training may assist in increasing run performance by way of improving running economy, and that the mechanistic explanation for improvements in running economy likely arises from neuromuscular changes (see below). Moreover, it should be noted that running economy improved more in the study by Paavolainen et al. (24) in response to plyometric resistance training, than in the study by Johnston et al. (14) that implemented a more conventional resistance training program.

Neuromuscular Changes

In accordance with the principles of training specificity, resistance training and endurance training induce rather distinct muscular adaptations (15, 21). Endurance training facilitates improvements in aerobic processes (i.e., the delivery and utilization of oxygen), whereas resistance training increases muscular strength, anaerobic power, and muscular endurance (15, 21). It has been suggested that improvements in endurance performance following a resistance training program may be due to the influence of strength training on motor unit recruitment patterns and muscle fiber conversion (14). Moreover, it appears likely that the improvements in running economy and associated improvements in running performance are caused through changes in neuromuscular characteristics, which may include increased muscle stiffness, increased neural input to the muscles, motor unit synchronization, mechanical efficiency, muscle coordination, and/or motor unit recruitment patterns (16). A key component to running economy is the ability to store and to recover elastic energy from an eccentric contraction. Resistance training may improve running economy by increasing the stiffness of the muscle-tendon unit, thereby increasing the elastic energy return (23). Running economy also might be increased through reducing the time of the stretch-shortening cycle mechanism (1). Both neuromuscular changes would serve to decrease ground contact time and to increase stride length per unit of oxygen consumed.

Muscle fiber conversion happens to be one of the few, if not the only, common muscular adaptations that occurs from both resistance training and endurance training; both training modes increase the percentage of Type IIa muscle fibers at the expense of Type IIb fibers (20, 30). Comparatively, Type IIa fibers are more oxidative than Type IIb fibers, so an increase in Type IIa fibers would result in an increase in the oxidative capacity of the muscle, which in turn could lead to an improved endurance performance by increasing the capacity for aerobic energy production. Theoretically this is justifiable; however, research by Coyle and colleagues (6) appears to refute this. Coyle et al. (6) studied 7 endurance-trained subjects at 12, 21, 56, and 84 days after the cessation of training. Running economy was unchanged throughout the detraining period, which occurred despite a large shift from Type IIa to IIb fibers (6). Bishop et al. (3) also found no change in either the fiber type composition or the oxidative potential of skeletal muscle following a 12-week resistance training program in female cyclists. These findings suggest that muscle fiber conversion has little or no impact on oxygen uptake or economy of motion (3, 6).

Neuromuscular changes, including a shortening of the stretch-shortening cycle and an increase in muscle stiffness, which aid to increase the recovery of elastic energy from the eccentric phase of muscular contraction during running, appear to be the most plausible explanation for the improvement in running economy and performance following resistance training. Because cycling involves predominantly concentric contractions, this may help to explain why concurrent strength and endurance training has yet to show significant enhancements in performance in cyclists (2, 3). However, many cycling races consist of a series of stochastic surges, completed by a sprint finish (25). Creating improved leg strength, therefore, appears intuitively an advantage, especially for cyclists whose role it is to compete successfully in sprint finishes. Research is needed to examine this premise. One of the authors (P.L.) has observed that many cyclists perform strength-endurance work, using steep hills, large gears, and low cadences to closely mimic the muscular recruitment patterns essential for high-intensity cycling. A recent study of cyclists gives some promise for cyclists who wish to supplement their endurance training regimen with resistance training. Bastiaans et al. (2) compared two 9-week training programs of similar volume ($8.8\ h \cdot wk^{-1}$): endurance training only versus 73% endurance training and 37% explosive strength training (4 sets, 30RM; squats, leg presses, step-ups). Although both groups significantly improved their endurance performance, there was no significant difference between the groups in terms of their change in performance. This is an important finding for those athletes who live in environments that experience significant periods of inclement weather where outdoor training becomes difficult. Thus, on poor weather days, specific explosive resistance training may be substituted without fear of a performance loss from the absence of an endurance training session (2). Although the limited number of studies in this area completed with cyclists would suggest that resistance training might not help to improve cycling performance (3), further research is warranted to determine whether resistance training might assist to facilitate sprint cycling performance.

Conclusion

Although research is limited concerning the influence that resistance training has on endurance performance, findings suggest that resistance training may improve endurance performance in runners through improvements in economy of motion, without significantly influencing $\dot{V}O_2max$ or the lactate threshold. Running economy likely is augmented through neuromuscular adaptations, including a reduced time of the stretch-shortening cycle mechanism, or an increase in muscle stiffness. Resistance training has yet to show improvements in cycling performance or associated physiological variables, although more studies with this population are required before we can rule out that concurrent strength and endurance training is not beneficial in cyclists. An important point that should be emphasized for the strength and conditioning coach is that resistance training has never been shown to have a negative influence on endurance performance and associated variables, but could have many positive neuromuscular effects. Whereas an increase in running economy following resistance training appears to be responsible for the improved running performance, there is no definite explanation at this time of the changes occurring at the neuromuscular level that might be responsible for these improvements, making further research in this area warranted. An increase in muscle stiffness, a reduction in neural input to the muscles, an increase in motor unit synchronization and recruitment, or some combination of these mechanisms, has the potential to contribute to the increase in running economy that has been reported (16). Future research also is required into the type of resistance training that elicits the greatest increase in economy of motion and endurance performance, and whether resistance training can alter positively certain aspects of cycling performance (i.e., sprint cycling).

Practical Recommendations for the Athletic Trainer/Coach

The addition of resistance training to the training program of a well-trained endurance athlete is controversial, but may be warranted if time permits, because anaerobic ability can separate the performance of elite endurance athletes. Distance runners would appear to gain the most advantage from resistance training, but this finding also could be generalized to include sports that require significant amounts of running, such as soccer, field hockey, and Australian-rules football. In endurance runners, various forms of resistance training have been shown to improve running economy and endurance performance (14, 24), but explosive resistance training mimicking the eccentric phase of running (i.e., plyometric training) appears to be most effective (24). This same result has not been found for endurance-trained cyclists (2, 3). The finding of a positive influence on performance, predominantly in runners, suggests that the most significant influence that resistance training makes is an alteration in neuromuscular characteristics, such as a reduction in the time of the stretch-shortening cycle mechanism or an increase in muscle stiffness.

In conclusion, what should be apparent from this review is that the key to designing any weight training program for endurance athletes is to follow the principle of specificity. If performance improvements are to occur from resistance training, they are most likely to arise from resistance training exercises that closely mimic the recruitment patterns witnessed in one's particular sport (principle of specificity). Thus, before training program design begins, the strength and conditioning coach should closely observe athletes performing their sport in the field. What types of muscle forces, velocities, recruitment patterns, and repetitions are involved? Strength and conditioning practitioners should use this information to build appropriate and specific training programs for their endurance athletes. ♦

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