Concurrent training can be described as simultaneously training for both strength and endurance adaptations (1,18). Endurance athletes train to maximize endurance adaptations, while utilizing strength training as a supplemental method to enhance performance. The current literature suggests that strength training can be utilized to enhance endurance performance, if appropriate volume and intensity are administered (3,5,8,10,14,15). The ideal form of strength training would result in performance improvements, while minimizing muscular hypertrophy, and avoiding undesired increases in body mass and subsequent cellular alterations (i.e., decreased capillary density) (1,18). Furthermore, the ideal form of strength training would reduce the likelihood of overtraining, which has been observed when comparing concurrent training to strength or endurance training alone (18). Therefore, it can be argued that endurance athletes should attempt to identify the most efficient manner in which to strength train, without compromising their endurance training program or their performance. Considering that endurance sports generally incorporate higher training volumes, particularly within competition periods, emphasizing resistance training that facilitates increased strength and power serves an important role within the training process, and can aid in optimal recovery and efficiency of training (1,29,31). This article will examine the scientific basis for concurrent training and extend this science by emphasizing the delivery of practical recommendations for potential applications.

**STRENGTH TRAINING ADAPTATIONS**

There are certain hallmark adaptations associated with strength training such as increases in maximal strength (measured by one-repetition maximum [1RM]), skeletal muscle cross-sectional area (CSA), and power measures (27). These adaptations are primarily the product of neuromuscular alterations, skeletal muscle plasticity, and metabolic improvements. Neuromuscular alterations include increases in rate of force development (RFD), motor unit synchronization, frequency modulation, and autogenic inhibition, as well as a reduced antagonist inhibition (27). Skeletal muscle plasticity refers to increases in the size of individual muscle fibers, muscle fiber type transitioning, and structural alterations. Finally, metabolic improvements stimulated by chronic strength training include increases in muscle glycogen stores, as well as increases in enzymes associated with the adenosine triphosphate and phosphocreatine (ATP-PC) and glycolytic systems, respectively (27). Other adaptations include increases in bone mineral density (BMD), and increases in connective tissue stiffness (27).

**ENDURANCE TRAINING ADAPTATIONS**

Endurance training adaptations can be broadly described as improvements in cardiovascular, muscular, and metabolic function. Cardiovascular adaptations to endurance training include increases in maximal stroke volume (SV) and cardiac output (due to the increased SV), along with a decreased heart rate at a given submaximal intensity (4). Muscular alterations include muscle fiber transitioning, during which type II muscle fibers become...
increasingly more oxidative, which ultimately alters the ratio of type Ila to Ilx (4). Additionally, endurance training elicits increases in mitochondrial volume and density, which improves fat and glucose oxidation, as well as capillary density (4). Capillaries assist in oxygen delivery and clearance of metabolites, lactate, and heat, which can contribute to the milieu associated with muscular fatigue (4).

**CONCURRENT TRAINING ADAPTATIONS**

The concept of concurrent training interference was originally developed by Hickson, which occurs when simultaneously training for adaptations associated with strength and endurance (12). Since Dr. Hickson's initial findings, there has been a substantial amount of research examining the effects of concurrent training on strength and endurance outcomes (2,3,5,9,11,13,14,15,16,19,20,21,22,23,24,25,26,28,30,31,32,33,35,37,38,39,40,41). Currently, there is a growing body of literature supporting the theory that high-intensity strength training (e.g., loads of greater than 80% 1RM) combined with explosive, high-velocity movements can enhance endurance performance (14,15,20,21,23,24,25,32,35).

Concurrent training utilizing high-intensity strength training can improve short-term (i.e., less than 15 min) and long-term (i.e., more than 30 min) endurance performance in well-trained, highly-trained, and recreationally-trained endurance athletes; this observation has been reported in cyclists, runners, cross-country skiers, and triathletes (2,3,5,6,8,9,10,13,14,15,16,19,23,24,25,26,27,28,29,30,31,32,33,36,37). Hoff proposed that strength training improved endurance performance through an increase in maximal strength and RFD (i.e., improved neural function), as well as through increases in the percentage of type Ila muscle fibers and muscle tendon stiffness (14).

Nevertheless, there are concerns when introducing additional training stimuli into a high-volume sport (18,42). Excessive training on a short-term basis is referred to as overreaching, which is postulated to be a product of high volume, high intensity, and/or high frequency training bouts (17,18). Recovery from overreaching can be quickly achieved within a few days (18). However, chronic overreaching can lead to the development of overtraining, which can result in performance decrements (17,18). Therefore, optimal recovery and efficiency of strength training is of vital importance when supplementing an endurance training program with strength training.

**ENDURANCE PERFORMANCE**

There are three primary factors that account for the interindividual variance in endurance performance (maximal oxygen consumption, exercise economy, and lactate threshold); although other factors can contribute to performance in actual competition (1).

**MAXIMAL OXYGEN CONSUMPTION**

Maximal oxygen uptake (VO\textsubscript{2}\text{max}) can be defined as the highest rate at which oxygen can be transported and utilized by the body during maximal exercise (4). VO\textsubscript{2}\text{max} has long been considered one of the most important factors in determining endurance performance, and is the most commonly utilized measure to determine aerobic fitness (4). VO\textsubscript{2}\text{max} is increased through improvements in central and peripheral mechanisms, which are primarily augmented by a periodized endurance training program that emphasizes training with systematic variations in frequency, duration, and intensity (4,18).

There is currently no literature to suggest that strength training has a significant positive effect on the VO\textsubscript{2}\text{max} of trained endurance athletes. However, it has been thought that improved cardiovascular function can potentially be induced through high-intensity strength training such as a decreased submaximal heart rate at a given exercise intensity.

**EXERCISE ECONOMY**

As defined by Saunders et al., exercise economy is the oxygen consumption required at a given absolute submaximal exercise intensity (34). It has been suggested that exercise economy has the greatest interindividual variation among well-trained endurance athletes (1,18). Costill outlined the similar VO\textsubscript{2}\text{max} values found between well-trained endurance athletes, which led researchers to investigate other determinants of endurance performance (7). Therefore, the importance of exercise economy is emphasized when determining variability in competitions.

Hoff et al. found that heavy strength training with loads of more than 85% of 1RM elicited improvements in sport-specific exercise economy in well-trained cross-country skiers (15). In addition, Hoff and colleagues pointed out that training with an emphasis on maximal mobilization of force in the concentric action should improve exercise economy by improving neuromuscular function (15). Furthermore, Hoff et al. suggested that increases in RFD and maximal strength can decrease the threshold necessary to produce the same absolute force (15). It has been reported that high-intensity strength training induces changes in neuromuscular function, which allows an athlete to produce a greater net force with each stride, primarily as a result of increased motor unit synchronization and firing frequency (15). Therefore, an athlete can produce the same absolute force at a lower relative intensity.

In an earlier study, Hoff et al. observed a training-induced increase in RFD, which would theoretically allow for a shorter propulsion phase for a given overall force output. This shorter propulsion phase would facilitate an extended muscle relaxation phase, which would reduce the time of contraction-induced muscle occlusion (14). Theoretically, this would increase the time for muscle perfusion while increasing the mean capillary transit time (MCTT) during every stride of an endurance event. Furthermore, it has been hypothesized that an increase in MCTT could induce a glycogen sparing effect, due to increasing the time for diffusion for free fatty acids (FFA), which are large in size and would benefit from the increased time for diffusion. Hoff and colleagues argued that this training-induced effect could lead to an enhanced removal of metabolites and a reduced production of lactate (due to the glycogen sparing effect), which could potentially delay fatigue and improve the efficiency of the contracting muscle (14).

Millet et al. found that high-intensity strength training increased muscle-tendon stiffness (measured as running leg stiffness), which has been suggested to improve exercise economy (23). It is postulated that improving force transmission, due to a more optimal muscle-tendon stiffness, could contribute to the aforementioned improved efficiency of the contracting muscle. In this scenario, an increased muscle-tendon stiffness could also...
facilitate an increase in MCTT, as hypothesized by Hoff et al. and Aagaard and Anderson (1,14).

LACTATE THRESHOLD
Lactate threshold (LT) can be described as the fraction of the maximal oxygen uptake at which blood lactate rapidly increases in concentration (4). The LT is generally described as a percentage of VO\textsubscript{2}max, which has been argued to be largely unaffected by resistance training (14,15). However, multiple studies have reported an increase in velocity at the LT during anaerobic running and cycling tests (20,33). Therefore, it can be hypothesized that the LT can be increased by an improvement in work efficiency, if the athlete’s body mass and absolute VO\textsubscript{2}max remain constant.

Mikkola et al. demonstrated an increase in all submaximal running velocities during a maximal anaerobic running test after eight weeks of explosive strength training combined with endurance training (20). This observation has been identified by other research groups through various measures, which include reports of an increased velocity at a given lactate concentration (20). Taipale et al. demonstrated an increase in running speed at the respiratory compensation threshold after the completion of eight weeks of mixed maximal and explosive strength training (38). These results indicate a positive shift in the LT, if it is assumed that the LT is a product of the athletes’ VO\textsubscript{2}max and exercise economy (38).

In addition, it can be theorized that through an improvement in exercise economy, there will be a decrease of energy expenditure for a given amount of work (40). A decreased energy expenditure over a prolonged period of competition could result in a significant overall decrease in energy expenditure for the competition. A decreased energy expenditure could assist in maintaining glycogen stores, delaying fatigue, and ultimately, enhance performance (14,15,40). Additionally, a decrease in energy expenditure could assist in maintaining short- and long-term energy balance, which has been associated with the overtraining milieu (17).

SOME OTHER FACTORS
Running speed (V\textsubscript{max}) and power output (W\textsubscript{max}) at VO\textsubscript{2}max have been shown to predict endurance performance in well-trained endurance runners and cyclists (36). Stratton et al. demonstrated that running velocity on a treadmill at VO\textsubscript{2}max could predict performance in a 5,000-m run (36). V\textsubscript{max} and W\textsubscript{max} are products of VO\textsubscript{2}max and exercise economy, while incorporating significant anaerobic and neuromuscular components (36). High-intensity strength training paired with explosive, high-velocity movements has been shown to increase V\textsubscript{max}, W\textsubscript{max}, and time-to-exhaustion in well-trained, highly-trained, and recreationally-trained endurance athletes (20,21,22,23,30,31,32,33,38,39).

The ability to generate high power output over a short period of time is a vital component of endurance performance. This ability is magnified at certain junctures during endurance competitions such as initial positioning, closing a gap, making a pass, or during the final kick. Ronnestad et al. showed an increase in both mean and peak power output after the completion of heavy lower body strength training (29). Of importance, Ronnestad and colleagues demonstrated that one strength training session per week could partially maintain the training-induced improvements elicited through strength training (29). Therefore, maintaining training-induced alterations can be done in a low volume manner, which would allow for proper recovery during the competition period.

Additionally, Ronnestad et al. found that 25 total weeks (10 weeks of preparatory and 15 weeks of competition) of heavy strength training led to an earlier occurrence of peak torque in the pedal stroke when considering pedal characteristics among cyclists; an occurrence not observed in the endurance training only group (33). Ronnestad and colleagues proposed a hypothesis concerning an increased duration of blood flow due to an extended relaxation phase, which, in theory, would facilitate a greater amount of blood flow to working musculature (6,29). According to this theory, the increased blood flow would increase the delivery of oxygen and substrates to the working musculature, contributing to an increase in power output at a given intensity.

PRACTICAL APPLICATION
Based on the current literature, it is suggested that endurance athletes engage in high-intensity strength training combined with explosive, high-velocity movements in order to best enhance performance (18). It is postulated that this type of training model will enhance performance through an increase in maximal strength and neuromuscular capabilities, which will result in an improvement in exercise economy and anaerobic characteristics (1,18). Furthermore, the research indicates that total training volume can be altered to prevent overtraining, while maintaining a low-volume, high-intensity strength training approach during competition periods (29).

High-intensity strength training, when paired with explosive, high-velocity movements, can elicit an improved exercise economy as a result of an increased velocity at lactate threshold, an improved lactate removal ability, and a possible increase in substrate availability, as well as the ability to maintain stride length and frequency at a given velocity (1,9,18). In addition, high-intensity strength training facilitates muscle fiber transitioning, whereby fast twitch muscle fibers develop an increased oxidative capacity, and thus, increase the oxidative capacity of the type II muscle fibers in the targeted musculature (2,18). These muscular and neuromuscular alterations serve to directly improve endurance performance.

Based on previous research, high-intensity strength training should be performed twice per week during the off-season, or periods of reduced endurance volume (18). However, during periods of competition or heightened endurance training volume, it is suggested that muscular and neuromuscular adaptations elicited by high-intensity strength training can be maintained in only one strength training session per week for a period of up to 14 weeks (29). It is recommended that a preparatory phase of at least six weeks precede the high-intensity strength training, in order to reduce the risk of injury and learn exercise technique (18,29). It can be suggested that an undulating periodized approach could effectively introduce this type of training to the athlete during the
preparatory period, while allowing the athlete to consistently train at high intensities throughout the year.

After the completion of the preparatory phase, it is advised that athletes perform strength training with loads of more than 75% 1RM involving less than six repetitions for at least 2 – 3 sets with approximately 2 – 3 min of rest between sets (18). In addition, athletes are advised to perform at least two sets of explosive, high-velocity movements. Previous research trials have primarily examined the impact of strength training on lower body musculature; however, the most beneficial strategy may be to target all major muscle groups and utilize compound ballistic movements, as generally prescribed to athletes of all sports. When implementing this type of training program, athletes should be monitored for symptoms associated with overreaching such as an extended period of “heavy legs” or “staleness,” as these are commonly associated with decrements in performance (17).

**CONCLUSION**

In conclusion, high-intensity strength training paired with explosive, high-velocity movements is suggested to enhance endurance performance. However, any form of resistance training is theorized to provide an ergogenic effect. It is recommended that a practical approach be taken when implementing this model of strength training, which would involve a thorough preparatory period.

**REFERENCES**


**ABOUT THE AUTHOR**

Marc Lewis is the co-owner of Winston Salem Personal Training, as well as a graduate teaching and research assistant at the University of South Carolina in the Department of Exercise Science. He completed his Bachelor of Science degree in Exercise Science from Wake Forest University, while serving as a research assistant in exercise physiology under Dr. Michael Berry. He has instructed courses covering exercise physiology, clinical exercise physiology, and strength and conditioning. Lewis holds numerous certifications, such as being recognized as a Certified Strength and Conditioning Specialist® (CSCS®) through the National Strength and Conditioning Association (NSCA). He has published peer-reviewed research in exercise physiology, as well as authored guest articles for various fitness professionals. His research interests concern concurrent training and its application for athletic performance.
# TABLE 1. SAMPLE TRAINING SCHEDULE FOR COMPETITIVE DISTANCE RUNNER

<table>
<thead>
<tr>
<th>TIME OF DAY</th>
<th>SUNDAY</th>
<th>MONDAY</th>
<th>TUESDAY</th>
<th>WEDNESDAY</th>
<th>THURSDAY</th>
<th>FRIDAY</th>
<th>SATURDAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning</td>
<td>Long run</td>
<td>Repetition training</td>
<td>Rest/ off</td>
<td>Long run</td>
<td>Program B</td>
<td>Rest/ off</td>
<td>Interval training</td>
</tr>
<tr>
<td>下午/傍晚</td>
<td>Rest/ off</td>
<td>Program A</td>
<td>Rest/ off with active recovery</td>
<td>Active recovery</td>
<td>Active recovery</td>
<td>Tempo/ pace run</td>
<td>Rest/ off</td>
</tr>
</tbody>
</table>

# TABLE 2. SAMPLE PROGRAM A (POST-PREPARATORY PERIOD)

<table>
<thead>
<tr>
<th>EXERCISE</th>
<th>SETS</th>
<th>REPS</th>
<th>INTENSITY</th>
<th>REST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bench presses</td>
<td>3</td>
<td>5</td>
<td>75% 1RM</td>
<td>2 – 3 min</td>
</tr>
<tr>
<td>Back squats</td>
<td>3</td>
<td>5</td>
<td>75% 1RM</td>
<td>2 – 3 min</td>
</tr>
<tr>
<td>Romanian deadlifts (RDL)</td>
<td>3</td>
<td>5</td>
<td>Movement skill*</td>
<td>2 – 3 min</td>
</tr>
<tr>
<td>Lateral lunges (dumbbell)</td>
<td>3</td>
<td>6</td>
<td>Rating of Perceived Exertion (RPE) 14 – 16</td>
<td>2 – 3 min</td>
</tr>
<tr>
<td>Pull-ups</td>
<td>3</td>
<td>6</td>
<td>Use band or machine assistance as necessary</td>
<td>2 – 3 min</td>
</tr>
</tbody>
</table>

*Begin with a medicine ball or kettlebell to learn weight shift, postural alignment, and hip hinge, then progress accordingly with loading.

# TABLE 3. SAMPLE PROGRAM B (POST-PREPARATORY PERIOD)

<table>
<thead>
<tr>
<th>EXERCISE</th>
<th>SETS</th>
<th>REPS</th>
<th>INTENSITY</th>
<th>REST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push presses</td>
<td>3</td>
<td>5</td>
<td>75% 1RM*</td>
<td>2 – 3 min</td>
</tr>
<tr>
<td>High pulls</td>
<td>3</td>
<td>5</td>
<td>Movement skill**</td>
<td>2 – 3 min</td>
</tr>
<tr>
<td>Glute/ham raises</td>
<td>3</td>
<td>5</td>
<td>RPE 14 – 16 with banded resistance and isometric hold</td>
<td>2 – 3 min</td>
</tr>
<tr>
<td>Lunges (dumbbell)</td>
<td>3</td>
<td>6</td>
<td>RPE 14 – 16</td>
<td>2 – 3 min</td>
</tr>
<tr>
<td>Bulgarian split squats (dumbbell)</td>
<td>3</td>
<td>6</td>
<td>RPE 14 – 16</td>
<td>2 – 3 min</td>
</tr>
</tbody>
</table>

*This can be an estimated 1RM from the preparatory period.
**Teach the movement and add weight accordingly while allowing the athlete to move the load with maximal velocity and an appropriate intensity of effort (RPE 14 – 16).