Volume 28, Number 3, pages 44–53

Keywords: strength; high intensity exercise endurance; low intensity exercise endurance

Maximum Strength and Strength Training—A Relationship to Endurance?

Michael H. Stone, PhD; Meg E. Stone
East Tennessee State University, Johnson City, Tennessee

William A. Sands, PhD
United States Olympic Committee, Colorado Springs, Colorado

Kyle C. Pierce, EdD
USA Weightlifting Development Center, Louisiana State University–Shreveport, Shreveport, Louisiana

Robert U. Newton, PhD, CSCS
Edith Cowan University, Perth, Australia

G. Gregory Haff, PhD, CSCS
West Virginia University, School of Medicine, Morgantown, West Virginia

Jon Carlock, MS
United States Olympic Committee, Colorado Springs, Colorado

summary

Endurance can be defined as the ability to maintain or to repeat a given force or power output. The sport performance–endurance relationship is a multi-factorial concept. However, evidence indicates that maximum strength is a major component. Conceptually, endurance is a continuum. The literature indicates that (a) maximum strength is moderately to strongly related to endurance capabilities and associated factors, a relationship that is likely stronger for high intensity exercise endurance (HIEE) activities than for low intensity exercise endurance (LIEE); (b) strength training can increase both HIEE and LIEE, the effect being greater for HIEE; (c) the volume of strength training plays a role in endurance adaptation; and (d) mechanical specificity and training program variables also play a role in the degree of adaptation.

Most coaches and athletes would argue that endurance is a factor that can affect sports performance. However, definitions of endurance vary from sport to sport. For this discussion, *endurance* is defined as the ability to maintain or repeat a given force or power output.

Although explaining the performance–strength relationship in sports is a multi-factorial concept, evidence indicates that maximum strength is likely a key component (37, 39, 52). The purpose of this discussion is to consider briefly the association of measures of maximum strength and the effects of strength training in relation to short- and long-duration endurance and endurance-related factors. Particular attention was given to sports performance related-endurance factors. Evidence from different types of reviewed cross-sectional and longitudinal research was considered; in conceptual areas for which few reviewed publications could be found, theses, abstracts, and observational information were considered in conjunction with reviewed articles. Semi-isokinetic device research was not extensively reviewed for two reasons: first, questions have been raised as to the external validity of these devices and second, coaches and athletes do not typically have access to these devices and they are not commonly used in the training or testing and monitoring of athletes (53). Collectively, the information indicates that the association between maximum strength and sports performance-related endurance factors is stronger than might be expected.

In order to better understand the strength/endurance relationship, a definition of strength is necessary. *Strength* can be defined as the ability to produce force (48, 50). Thus, the measurement of strength is, in effect, a measure of an ability or skill. Because force is a vector quantity, the display of strength would have the characteristics of magnitude (0–100%) and a direction. Furthermore, the generation of force can be isometric or dynamic and has a rate of development. The characteristics of force production are determined by a number of factors, including the type of contraction and the magnitude, rate, and degree of muscle activation. The direction of force production is related to the motor unit and muscle activation patterns and to anatomical factors. Thus, the conditions for measurement of strength must be defined carefully.

The importance of force production can be ascertained from Newton's second law:

$$F = ma$$

Thus acceleration (a) of a mass (m), such as body mass or an external object, depends directly upon the ability of the musculature to generate force (F). Because acceleration is derived from velocity, the velocity an object attains during movement is a function of the applied force. Force must be applied for a certain time, thus creating an impulse that leads to a change in velocity of the object. Furthermore, power production, which is the product of force and velocity, is likely the most important factor in determining success in most sports. For both short- and long-duration endurance activities, it can be argued that the average power, often derived from many cyclic repetitions, is a deciding factor in winning or losing (37, 39, 52). Therefore, the ability to generate force (strength), which is an integral part of power production, may be a key component in determining athletic success (52, 53). However, the degree to which these factors, particularly maximum strength, influence endurance is still not totally clear.

Formerly, the endurance–strength relationship was viewed as a primary function of the muscular system and was described with the term *muscular endurance*. The effects of maximum strength on muscular endurance were simplistically divided into observations of absolute and relative "mechanisms":

- Absolute muscular endurance: the number of repetitions performed at an absolute submaximal resistance is a function of maximum strength—a stronger person has an advantage, especially as the load approaches maximum.
- Relative muscular endurance: at a given percentage of maximum strength, the maximum numbers of repetitions that weaker or stronger individuals are able to perform are (typically) approximately equal and produce equal amounts of "relative" work (23, 47). However, some studies indicate that the weaker person has an advantage in muscular endurance as a result of less work being performed in the same time frame (3).

Although these 2 ideas can be used to explain much of the association between maximum strength and endurance capabilities, these concepts are really more observational descriptions rather than mechanistic descriptions. Furthermore, these observations do not necessarily explain the actual underlying mechanisms associated with increases in endurance resulting from strength gains for all situations. Whereas some sports or events, such the shot put, discus, and track cycling, depend more upon absolute strength capabilities, others, such as road cycling and sprinting, depend more upon strength in relation to body mass (54, 55). However, in sports and daily living, it can be argued that absolute loads are encountered regularly. Indeed, there may be few, if any, instances where loads relative to maximum strength actually are encountered. Fundamentally, these 2 observations/mechanisms (absolute and relative muscular endurance) do not consider additional underlying mechanistic possibilities.

Other potential mechanisms arising from increased strength and strength training include central or peripheral blood flow and vascular effects, muscle fiber recruitment alterations, and changes in movement economy. For example:

- Certain types of resistance training (high volume) may result in small but significant increases in $\dot{V}O_2max$, which could contribute to enhanced endurance (56), particularly among those with low or average aerobic power.
- Although typical strength training has minimal effects on $\dot{V}O_2max$, it may be possible that stronger athletes are more efficient or economical in their movements, leading to enhanced endurance capabilities as a result of performing less work to accomplish a given task (21, 34, 63). These observations indicate that gaining strength can have profound effects on motor control attributes that may lead to an increased economy of movement. Basically, this means that an athlete would use less energy for the same distance traveled, compared with a less movement-efficient athlete. Alterations in movement efficiency may be a primary mechanism underlying performance enhancement among well-trained endurance athletes, as a result of resistance training (40).

- Increases in strength often are accompanied by increases in power and rate of force development (1); it is possible that these adaptations may increase endurance by reducing the relative force (percentage of maximum) applied at similar loads, thus maintaining a greater blood flow, or by reducing the time of restricted blood flow during a muscle contraction, which in turn reduces the limitations to muscle oxygenation and exchange of substrates/metabolites (39).
- As a result of strength training that can affect all motor unit types, the use (or recruitment) of type 1 motor units may be enhanced and use of type 2 motor units reduced per movement at submaximal loads (13, 19, 35). Additionally, strength training has been shown to reduce the amount of muscle activated for a given load (42), thus there could be a smaller metabolic demand for the same force output. This also may indicate that as motor units become stronger or more powerful, fewer motor units will be recruited for a given force output/work rate, thus creating a motor unit reserve available for additional work.
- Another potential mechanism for increased endurance deals with the possible increase in number (and size) of type IIa fibers (MHC IIa). Type IIa fibers have high glycolytic and oxidative potential and are relatively fatigue resistant. Resistance training can result in an increased number of type IIa fibers with a concomitant decrease in the proportion of type IIx fibers. Greater proportions of type IIa fibers may allow a greater tolerance for high-intensity exercise. leading to greater endurance (10, 14). Interestingly, motor unit type may influence fatigue resistance as a result of postactivation potentiation (PAP). PAP may contribute to the ability to generate a given force at a lower adenosine triphosphate expenditure, thus enhancing endurance capabilities (17). Evidence also indicates that a larger proportion of type IIa fibers may enhance the effects of certain types of PAP, resulting in force restoration and maintenance during strength training and strength/power sports, a type of endurance termed *high intensity exercise endurance* (HIEE) (10).
- Some evidence also suggests that fatigue resistance can be improved through strength training as a result of prolonged membrane excitation and enhanced ionic regulation (5, 33).
- Endurance depends upon both aerobic and anaerobic mechanisms—enhancement of anaerobic capacity as a result of strength training also can contribute to enhanced endurance (40).
- The lactate threshold (LT) also can be modified markedly through resistance training (31). Perhaps, using appropriate resistance training, it may be possible to maintain the LT at higher values during periods of primarily aerobic training in which the anaerobic system is not being taxed.

As can be ascertained from the foregoing discussion, there are several potential reasons why strength training may enhance endurance. The discussion dealing with the effects of strength/strength training on endurance is divided into two parts. Part 1 deals with HIEE, which can be defined as the ability to sustain or to repeat high intensity exercise and has been associated with sustained activities of ≤2 minutes (57). Part 2 deals with strength training and long-duration endurance activities, a type of endurance that may be termed low intensity exercise endurance (LIEE). Therefore, LIEE would be the ability to sustain or to repeat low intensity exercise.

The degree to which each of these potential mechanisms contributes to various types of endurance along a high-to-low endurance continuum, particularly among advanced and elite athletes, is not well understood. Certainly, the ability of the coach and athlete to appropriately integrate resistance training into the training process will have a great deal of influence on the degree of endurance enhancement.

As with any type of training goal (i.e., maximum strength, power, endurance), the impact of the training program depends upon training factors including mechanical specificity, the training volume and intensity factors, rest period length, and the trained state.

Maximum Strength Strength Training for Strength and Power Sports

Effects of Enhanced Maximum Strength Correlational Studies

A correlation represents the strength of the relationship among variables—the correlation coefficient (symbolized as r) ranges from –1.0 to 1.0; the closer the coefficient is to 1.0, the stronger the relationship. A positive correlation between 2 variables would mean they increase together, whereas a negative correlation would mean an inverse relationship. Hopkins (22) has ranked correlations according to the following r values: 0.0 (trivial); 0.1 (small); 0.3 (moderate); 0.5 (strong); 0.7 (very strong); 0.9 (nearly perfect); and 1.0 (perfect).

By multiplying the correlation coefficient by itself (r^2), the shared variance can be determined. The shared variance is an estimation of how much of the variability in one variable is explained by the variance in another variable.

Using previously strength-trained subjects (n = 33), Robinson et al. (44) showed that high volume strength training for 5 weeks could increase power output and HIEE. Power and HIEE were measured by fifteen 5-second maximum effort cycle rides with 5-second rest intervals (0.1 kg × body mass).

Robinson et al. (44) showed that maximum strength as measured by the 1 repetition maximum (RM) squat had strong and increasing correlations with cycle peak power (PP), the average PP (APP15) over 15 rides, and the average work accomplished (ATW15) over 15 rides. Pre r values were 0.62 (PP), 0.67 (APP15), and 0.64 (ATW15). Post r values were 0.74 (PP), 0.72 (APP15), and 0.75 (ATW15). This correlational information indicates that maximum strength is associated with both power output and HIEE and that the relationship gets stronger with training (44).

An important consideration is whether significant relationships can be established between variables in high level athletes. Stone et al. (52) reported an investigation of the relationship between the 1RM parallel squat and tests of agility, jumping capabilities, and endurance using international level Scottish badminton players (n = 13). This study was part of the ongoing sports testing-sports science program initiated by the Scottish Institute of Sport. The results (52) indicated that the 1RM squat was correlated strongly with both weighted and unweighted countermovement and static vertical jumps, as well as with tests of agility (r = 0.65–0.87). Additionally, the 1RM was correlated with a test of agility-endurance. A badminton-specific agility test was designed to simulate the change-of-direction and metabolic demands of badminton (X-test; M. Glaister; 52), and this test could be repeated to add an endurance component to the test protocol. Its test-retest reliability was excellent. The X-test was repeated 15 times with a 14-second rest interval for males and a 16-second rest interval for females (simulating the rest intervals between volleys during a badminton match, as measured from video). The correlation between the 1RM squat and the repeated X-test (average time) was r = –0.69. These results indicate that maximum strength (as measured by the 1RM squat and 1RM squat per kg body mass) has significant relationships with power-, speed-, and speed-endurance–related variables.

Additional studies indicate that greater maximum strength can be related to increased power and endurance in various activities, including sprint swimming (11, 12, 46) and sprint cycling (55). These types of studies, dealing with trained subjects, including high level athletes, indicate that maximum strength is related strongly to HIEE.

The studies discussed so far indicate a relationship between maximum strength and endurance. However, cross-sectional and correlational data do not necessarily imply cause and effect.

Effects of Enhanced Maximum Strength Longitudinal Studies

It has been well established that stronger athletes have a greater absolute endurance capability (3). However, it is not uncommon for these athletes to undergo periods of strength-endurance training (high volume strength training) or power-endurance training (high volume power training). Typically, these types of high intensity endurance training programs take place during the general and specific preparation phases and occasionally for very short periods occurring 4–8 weeks before major competitions. Part of the reason for using a strength-endurance or power-endurance phase is the belief that HIEE will be enhanced beyond that of typical strength training. Only a few studies have directly addressed this issue.

McGee et al. (32) compared 3 different training groups consisting of low (Gp-L), moderate (Gp-V), and high volume (Gp-H) strength training groups. The Gp-L group (n = 8) performed 1 set of 8–12RM to failure, with one light warm-up set. The Gp-V group (n = 9) comprised multiple set variations: 2 weeks at 3 × 10RM, 3 weeks at 3 × 5RM, and 2 weeks at 3 × 3RM. The Gp-H group (n = 10) performed 3 × 10RM. Both the moderate and high volume groups performed 3 warm-up sets that progressed from light to moderate intensity.

The subjects trained using large muscle mass exercises and emphasized leg and hip strength-endurance. Training was $3d{\cdot}wk^{-1}$ for 7 weeks. Squats and pressing movements were performed $2d{\cdot}wk^{-1}$ (Monday and Friday) and pulling movements were performed $1d{\cdot}wk^{-1}$ (Wednesday). Total volume of work was quite different among the 3 groups. For example, the total planned repetitions (squats: 2 $times{\cdot}wk^{-1}$) at the target sets were approximately Gp-L = 140; Gp-V = 246; and Gp-H = 420. Considering that reasonable training loads were used, the 3 groups accomplished very different total amounts of work. All the subjects were trained in the same manner for 2 weeks prior to the study. Endurance was measured by 2 methods: cycle ergometry to failure (<5 minutes) at a constant load (4.5 KP) and parallel squats to failure with increasing loads. Pre- and posttesting found that although all groups improved, the greatest percentage of improvement for both tests was Gp-H > Gp-V > Gp-L. Additionally, it was noted that although the greatest improvements were specific (i.e., squats), considerable improvement in cycle endurance also occurred. The authors concluded that the degree of strength training–induced adaptations in HIEE was to a large extent volume-dependent, agreeing with the general observations and conclusions of Stone and Coulter (58).

It is commonly believed that shortening the rest interval between sets enhances the HIEE training effect. Unfortunately, very little study has been conducted that actually addresses this belief. The available current research does not support a strong association between strength training rest interval and HIEE. Robinson et al. (44) used moderately trained subjects and investigated rest interval effects on HIEE. Three different interset rest periods were studied, group 1 (n =

11) used 3-minute rest, group 2 (n = 11) used 1.5-minute rest, and group 3 (n = 11) used 0.5-minute rest. The subjects trained 4d·wk^{-1} for 5 weeks using exercises that emphasized the legs and hips. All subjects performed 5 × 10 repetitions for all major exercises; only the rest intervals were different. Pre- and posttests included the vertical jump (VJ), 1RM squat, and fifteen 5-second maximum effort cycle rides with 1-minute rest intervals (0.1 kg × body mass). Groups 1 and 2 showed nonsignificant improvements in the VJ, whereas group 3 showed a nonsignificant decrease, and group 1 significantly increased in the squat compared with group 3. All three groups improved significantly on the cycle tests, with no differences between groups. The authors (44) concluded that shortening the rest intervals did not produce an advantage for developing HIEE, agreeing with the observations of Nimmons (36) and Kulling et al. (28).

In an unpublished master's thesis, Nimmons (36) trained 2 groups for 9 weeks with exercises emphasizing the leg and hip musculature. Both groups performed a high volume training program using 3 × 10 repetitions at a target load, plus light and moderate warm-up sets of 10 repetitions. However, different rest periods between sets were used: group 1 (n = 8) rested 3 minutes between sets and group 2 (n = 6) rested 30 seconds between sets. Training data indicated that group 1 used substantially higher loads, a higher relative intensity, and performed more work over the 9 weeks, compared with group 2. Maximum strength (1RM squat) increased 13.1% in group 1 and 8.8% in group 2 (effect size, group 1 = 2.29; effect size, group 2 = 1.80). Repetitions to failure at 85% of the 1RM improved 152% in group 1 and 77% in group 2 (effect size, group 1 = 4.89; effect size, group 2 = 3.33). The results (36) indicated that short rest periods did not offer an advantage for increasing HIEE; indeed, the observed tendency was for short rest periods to produce inferior effects.

In a similar investigation, reported in an abstract, Kulling et al. (28) indicated that longer interset rest periods facilitated HIEE adaptations. They (28) found that training with 90-second rest periods, compared with 30 seconds, resulted in more repetitions to failure in bench presses at a percentage of body mass (60% for men and 40% for women) after 12 weeks of training. The longer rest periods allowed a higher training intensity, which facilitated adaptations in strength and endurance. These data (28, 36, 44) indicate that if interset rest periods are too short (<90 seconds) then training intensity (i.e., average load) and subsequent adaptations can be compromised. Collectively, these observations bring into question the practice of using circuit resistance training or other short interset rest period programs to enhance strength and strength-endurance. Short interset rest intervals often are used to increase the average metabolic expenditure. However, the short rest periods can compromise resistance exercise loading parameters and subsequent adaptations to training. Clearly, more investigation is needed in this area.

The effects of short interset rest intervals during resistance training on LIEE are not known. However, other types of high-intensity training using short intervals have been shown to substantially alter metabolic variables, including $\dot{V}O_2$max, and positively affect endurance (29, 30, 45). Thus it is possible that short interset rest period resistance training protocols may positively affect aspects of LIEE.

Although not all studies agree, the data presented indicate that:

- Although specificity is evident, strength training can produce adaptations in endurance, which are transferable (i.e., adaptations can take place in exercises not used in the strength training program). For example, weight training transfers to cycle exercise endurance alterations.
- Higher volume training can affect measures of endurance to a greater extent than low volume training.
- Within the context of strength training, short rest periods (≤90 seconds) do not enhance endurance beyond using typical rest periods (3–5 minutes) and can compromise strength and power gains. If rest periods are too short (≤30 seconds), loading could be compromised sufficiently to result in smaller gains in strength power and possibly HIEE.
- A great deal of research is still necessary to clarify these relationships.

Maximum Strength-Strength Training For Endurance Sports

Among coaches and athletes, the type and amount of strength training necessary for LIEE has been controversial (43, 59). Also controversial is the degree to which strength training affects LIEE. Recently, data from several longitudinal studies have indicated that strength-power training can enhance long-duration endurance (i.e., LIEE). This brief review will deal with those studies.

Correlational-Descriptive Studies

Strength or power measures have been associated with endurance performance in several studies in various sports. For example, studies have shown strong correlations between swimming performance up to 400 m and maximum strength/power of the upper body (11, 12, 18, 46, 61). Among road cyclists, anaerobic power has been shown to be a major factor separating higher and lower ranked athletes (60). Anaerobic power was a critical factor determining success among cross-country runners with similar $\dot{V}O_2$max values (8). Additionally, evidence indicates that distance runners with more powerful muscles are more likely to succeed (37). These data indicate the potential for strength training and increased maximum strength to enhance endurance.

Longitudinal Studies

Several longitudinal studies have noted an association between increased strength and increased anaerobic power and measures of endurance as a result of strength training in untrained or minimally endurance trained subjects (20, 24, 31, 38, 41, 45, 49, 56), including middle-aged and older subjects (25).

Strength training also has been shown to produce increases in endurance among trained subjects and well-trained athletes. Hickson (19) studied the effects of adding strength training to the overall training programs of endurance trained subjects (8 men, 2 women, *n* = 10). The subjects were moderately endurance-trained (>50 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$). Ten weeks of strength training ($3d{\cdot}wk^{-1}$) emphasizing leg and hip strength resulted in marked gains in maximum strength (20–38%). Although there was little change in $\dot{V}O_2max$, incremental treadmill and cycle times were increased significantly, as was time to exhaustion on a cycle ergometer at a constant work rate (80–85% of $\dot{V}O_2max$). From a practical standpoint, 10-km running time decreased from 42:27 ± 1:59 to 41:43 ± 1:45 (*n* = 9).

Paavolainen et al. (40) investigated the effects of "explosive strength training" on the performance capabilities of 18 well-trained male orienteers ($\dot{V}O_2max$ = 65 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$). In an attempt to partially control for training volume differences, endurance training time was replaced with strength training (32% of total time) so that the total approximate training time was equal between experimental (GpE, *n* =10) and control (GpC, *n* = 8) groups. Training lasted 9 weeks. Interestingly, GpE showed a small decrease in $\dot{V}O_2max$ over the training period. However, GpE showed superior gains compared to the control group in maximum strength (isometric leg press) a 20-m sprint, jumping ability, anaerobic capacity (VMART), running economy, and most importantly, 5-km time.

Strength training also has been shown to have beneficial effects on endurance factors associated with road cycling. An important aspect of road cycling success is the ability to maintain high average power outputs during a race (4). However, the ability to develop and to maintain reasonable levels of power can be diminished by endurance activities, such as road cycling training, and may be related to hormonal alterations (26). Therefore, interventions allowing power development and maintenance may beneficially affect LIEE. Bastiaans et al. (4), using 14 male competitive road cyclists, investigated the effects of explosive strength training on endurance-related factors. As with Paavolainen et al. (40), endurance training time was replaced with strength training (37% of total time) so that the total approximate training time was equal between experimental (GpE, *n* = 6) and control (GpC, *n* = 8) groups. Although the addition of strength training resulted in small increases in power output and riding efficiency, the major effect dealt with power development and "short-duration performance." Short-term performance was measured by calculating mean power output at a fixed pedal rate (60 rpm) during a 30-second ergometer test. It was shown that GpC lost mean power and GpE showed small increases over the 9-week period. The authors (4) suggested that the data indicated strength training attenuated the commonly observed loss in power and sprint ability associated with long-duration endurance training. Furthermore, GpE showed slightly greater improvement in work accomplished during a 1-hour ergometer time trial, compared with GpC. These data indicate that replacing a portion of endurance training with explosive strength training can preserve or can enhance the ability to maintain high power outputs, at least for short periods, and that this can translate into factors associated with enhanced LIEE (based on the 1-hour time trial).

These data suggest that (a) maximum strength can be associated with LIEE; (b) strength training can improve LIEE or factors associated with LIEE; and (c) as with strength/power sports, there is a degree of specificity in the endurance adaptations.

Specificity, Training Volume, Hypertrophy, and Lag-Time Issues

Not all studies have shown that strength training enhances endurance (see, for example, references 6 and 7). There are a number of reasons for this.

- One possibility is that strength training has little effect on endurance factors. In the authors' opinions, this factor is unlikely because (a) there are ample studies indicating an effect can occur, and (b) athletes and coaches are very pragmatic. It is the authors' opinions and observations that most coaches, particularly those coaching elite athletes—including endurance athletes—do advocate some form of strength training in the belief that it will enhance performance. Over the long term, it is quite unlikely that athletes and coaches would continue to waste time and effort on training that does not produce reasonable results.
- One of the most important and viable training principles deals with mechanical specificity (53). Mechanical specificity deals with the degree of similarity between training exercises and performance. For example, it is possible that the type of resistance training program used was not specific enough for the sport or event. Bastiaans et al. (4) argued that one possible explanation for Bishop and colleagues' (7) finding no improvement in endurance with strength training deals with the type of contraction used. Bishop et al. (7) used typical heavy slow-velocity strength training, which may not match the characteristics of the task (in this case, high speed endurance cycling). In this context, it is inter-

esting that both Paavolainen et al. (40) and Bastiaans et al. (4) used dynamic explosive moments for the training intervention, which may have matched the characteristics of the performance task better than slower movements. However, Millet et al. (34) used typical heavy strength training procedures and found improvements in movement economy among very well-trained cross-country skiers. Perhaps the task-specificity aspects of cross-country skiing are such that heavy strength training may produce an effect on movement economy or some other factor that enhances endurance.

- Another factor that may affect the outcome of training deals with differences in the trained state. It may be possible that strength training becomes more or less important as the athlete evolves in his or her sport.
- Another factor that may affect the degree of adaptation to training is total training volume. Both Paavolainen et al. (40) and Bastiaans et al. (4) substituted strength training for endurance activities, thus, to a point, maintaining total training volume. Studies adding strength training to existing training regimens may have increased the total volume such that accumulated fatigue interfered with adaptations. One possible mechanism dealing with poor endurance adaptations deals with hormonal alterations. The resting testosterone–cortisol ratio (T:C) has been shown to be a reasonable index of anabolic-catabolic status and to be related to alterations in strength and power (16). More recently, gains in HIEE (51) and LIEE (25) resulting from strength training also have been associated with resting testosterone and the T:C. High volumes of training representing a large training stress can decrease the T:C (9, 15, 16). The additional stress of strength training plus endurance training may alter the T:C such that endurance gains are compromised eventually.
- Lag-time may affect endurance. During strength training, maximum strength, power, and specific performance variables (including endurance) do not adapt at exactly the same rate. Often, additional gains in sports performance may lag behind strength/power gains for several weeks or months. It is possible that the lack of direct correspondence between maximum strength gains and other performance related variables is associated with a lag-time (2, 53). Lag-time deals with a period of time in which the athlete learns how to use training adaptations, particularly increased strength; the lag-time may extend many months in some cases. It is possible that lag-time may be reduced by careful coaching strategies in which the potential link between strength and technique/endurance is pointed out to the athlete. This may partly be accomplished by pointing out similarities between training exercises (i.e., mechanical specificity) and performance exercises.
- Performance gain mismatch may be another factor. It is also possible for increases in strength to continue after the changes in sport performance, including endurance, become asymptotic. This observation may indicate that a change in the type of strength training or types of exercises being used is necessary (25).
- The degree to which hypertrophy and lean body mass gains may influence endurance is unknown. Strength training is often, but not always, accompanied by measurable hypertrophy. It is reasonable to assume that LIEE in which the body mass must be supported would be affected negatively by large gains in body mass, even if the gains were lean body mass. However, typical ectomorphic endurance athletes are not likely to gain appreciable body mass as a result of strength training regimens (62).
- Also of importance is the role of endurance versus recovery. The ability

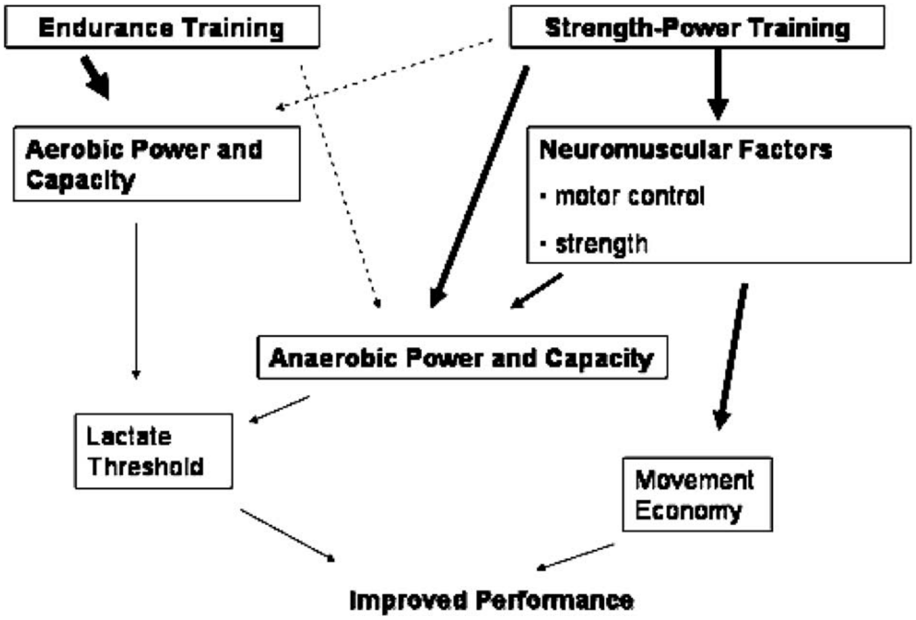

Figure. A representation of a paradigm illustrating the potential interrelated mechanisms that can modify endurance performance. Modified from Paavolainen et al. (40).

to recover is obviously important during repeated bouts of exercise. Although there is little doubt that endurance capabilities and recovery capabilities are related, they are not the same. In this brief review, these 2 aspects are not separately discussed, because the literature does not always distinguish the effects of one aspect independently of the other. It has been the authors' observations that not only are HIEE and LIEE different in nature (performance and underlying mechanisms), but one's ability to recover from HIEE and LIEE also differs. For example, being aerobically fit does not guarantee a rapid recovery from anaerobic activities, particularly heavy resistance training sessions (27). Perhaps there is also a strong degree of specificity of recovery.

- It is also possible that strength training could reduce the injury potential of endurance activities.

Conclusion

Based on this brief review, the authors have several suggestions: (a) maximum strength is associated with endurance factors, a relationship that is likely stronger for HIEE activities than for LIEE; (b) strength training can affect increases in endurance factors for both HIEE and LIEE; (c) the volume of strength training plays a role in the endurance adaptation (i.e., higher volumes generally produce greater gains in endurance); and (d) mechanical specificity and training program variables also play a role in the degree of adaptation. The Figure offers a paradigm illustrating potential interrelated mechanisms that can modify endurance performance (adapted from Paavolainen et al. [40]). ♦

References

1. Aagaard, P., E.B. Simonsen, J.L. Andersen, P. Magnusson, and P. Dyre-Poulsen. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J. Appl. Physiol.* 93:1318–1326. 2002.
2. Abernethy, P.J., and J. Jurimae. Cross-sectional and longitudinal uses of isoinertial, isometric, and isokinetic dynamometry. *Med. Sci. Sports Exerc.* 28:1180–1187. 1996.
3. Anderson, T., and J.T. Kearney. Effects of three resistance training programs on muscular strength and absolute and relative endurance. *Res. Q.* 53:1–7. 1982.
4. Bastiaans, J.J., A.B. van Diemann, T. Venberg, and A.E. Jeukendrup. The effects of replacing a portion of endurance training by explosive strength training on performance in trained cyclists. *Eur J. Appl. Physiol.* 86:79–84. 2001.
5. Behm, D.G., and D.M.M. St.-Pierre. The effect of strength training and disuse on the mechanisms of fatigue. *Sports Med.* 25:173–189. 1998.
6. Bishop, D., and D.G. Jenkins. The influence of resistance training on the critical power function and time to fatigue at critical power. *Aust. J. Sci. Med. Sport.* 28:101–105. 1996.
7. Bishop, D., D.G. Jenkins, L.T. Mackinnon, M. McEniery, and M.F. Carey. The effects of strength training on endurance performance and muscle characteristics. *Med. Sci. Sports Exerc.* 31:886–891. 1999.
8. Bulbubian, R., A.R. Wilcox, and B.L. Darabos. Anaerobic contribution to distance running performance of trained cross-country runners. *Med. Sci. Sports Exerc.* 18:107–118. 1986.
9. Busso, T., K. Häkkinen, A. Pakarinen, C. Carasso, J.R. Lacour, P.V. Komi, and H. Kauhanen. A systems model of training responses and its relationship to hormonal responses in the elite weightlifter. *Eur. J. Appl. Physiol.* 61:48–54. 1990.
10. Chiu, L.Z.F., A.C. Fry, B.K. Schilling, E.J. Johnson, and L.W. Weiss. Neuromuscular fatigue and potentiation following two successive high intensity resistance exercise sessions. *Eur. J. Appl. Physiol.* 92:403–411. 2000.
11. Costill, D., R. Sharp, and J. Troup. Muscle strength: Contributions to sprint swimming. *Swim. World.* 21:29–34. 1980.
12. Davies, J.F. Effects of training and conditioning for middle distance swimming upon various physical measures. *Res. Q.* 30:399–412. 1959.
13. Gollnick, P.D., K. Piehl, and B. Saltin. Selective glycogen depletion pattern in human muscle fibers after exercise of varying pedal speeds. *J. Physiol.* (Lond.). 241:45–57. 1974.
14. Green, H.J. Muscle power fiber type recruitment, metabolism and fatigue. In: *Human Muscle Power*. N.L. Jones, N. McCartney, and A.J. McComas, eds. Champaign, IL: Human Kinetics, 1986. pp. 65–79.
15. Häkkinen, K. Neuromuscular and hormonal adaptations during strength and power training. *J. Sports Med.* 29:9–26. 1989.
16. Häkkinen, K.A. Pakarinen, M. Alen, and P.V. Komi. Serum hormones during prolonged training of neuromuscular performance. *Eur. J. Appl. Physiol.* 53:287–293. 1985.
17. Hamada, T., D.G. Sale, and J.D. MacDougall. Postactivation potentiation in endurance-trained male athletes. *Med. Sci. Sports Exerc.* 32:403–411. 2000.
18. Hawley, J.A., and M.M. Williams. Relationship between upper body anaerobic power and freestyle swimming performance. *Int. J. Sports Med.* 12:1–5. 1991.
19. Hickson, R.C., B.A. Dvorak, E.M. Gorostiaga, T.T. Kurowski, and C. Foster. Potential for strength and endurance training to amplify endurance performance. *J. Appl. Physiol.* 65: 2285–2290. 1988.
20. Hickson, R.C., M.A. Rosenkoetter, and M.M. Brown. Strength training effects on aerobic power and short-term endurance. *Med. Sci. Sports Exerc.* 12:336–339. 1980.
21. Hoff, J., J. Helgerud, and U. Wisloff. Maximal strength training improves work economy in trained fe-

male cross-country skiers. *Med. Sci. Sports Exerc.* 31:870–877. 1999.
22. Hopkins, W. A new view of statistics. Internet Society for Sport Science Web site. Available at: http://www.sportsci.org/resource/stats/. Accessed December 28, 2005.
23. Huczel, H.A., and D.H. Clarke. A comparison of strength and muscle endurance in strength-trained and untrained women. *Eur. J. Appl. Physiol.* 64:467–470. 1992.
24. Inbar, O., P. Kaiser, and P. Tesch. Relationships between leg muscle fiber type distribution and leg performance. *Int. J. Sports Med.* 2:154–159. 1981.
25. Izquierdo, M., K. Häkkinen, J. Ibanez, A. Anton, M. Garrues, M. Ruesta, and E.M. Gorostiaga. Effects of strength training on submaximal and maximal endurance performance capacity in middle-aged and older men. *J. Strength Cond. Res.* 17:129–139. 2003.
26. Izquierdo, M., J. Ibanez, K. Häkkinen, W.J. Kraemer, and M. Gorostiag. Maximal strength and power, muscle mass, endurance and serum hormones in weightlifters and road cyclists. *J. Sports Sci.* 22:465–478. 2004.
27. Kang, J., J.R. Hoffman, J. Im, B.A. Spiering, N.A. Ratamess, K. Rundell, S. Nioka, J. Cooper, and B. Chance. Evaluation of physiological responses during recovery following three resistance exercise programs. *J. Strength Cond. Res.* 19:305–309. 2005.
28. Kulling, F.A., B.H. Hardison, B.H. Jacobson, and S.W. Edwards. Changes in muscular endurance from different rest periods between sets in a resistance training program [supplement abstract 437]. *Med. Sci. Sport Exerc.* 31(5):S116. 1999.
29. Linossier, M.T., C. Denis, D. Dormois, A. Geyssant, and J.R. Lacour. Ergometric and metabolic adaptation to a 5-s sprint training programme. *Eur. J. Appl. Physiol.* 67:408–414. 1993.
30. MacDougall, J.D., A.L. Hicks, A.R. MacDonald, R.S. McKelvie, H.J. Green, and K.M. Smith. Muscle performance and enzymatic adaptations to sprint interval training. *J. Appl. Physiol.* 84:2138–2142. 1998.
31. Marcinik, E.J., J. Potts, G. Schlabach, S. Will, P. Dawson, and B.F. Hurley. Effects of strength training on lactate threshold and endurance performance. *Med. Sci. Sports Exerc.* 23:739–743. 1991.
32. McGee, D.S., T.C. Jesse, M.H. Stone, and D. Blessing. Leg and hip endurance adaptations to three different weight-training programs. *J. Appl. Sports Sci. Res.* 6:92–95. 1992.
33. McKenna, M.J., A.R. Harmer, S.F. Fraser, and J.L. Li. Effects of training on potassium, calcium, and hydrogen ion regulation in skeletal muscle and blood during exercise. *Acta. Physiol. Scand.* 156:335–346. 1996.
34. Millet, G.P., B. Jaouen, F. Borrani, and R. Candau. Effects of concurrent endurance and strength training on running economy and $\dot{V}O_2$ kinetics. *Med. Sci. Sports Exerc.* 34:1351–1359. 2002.
35. Morgan, D.W., D.R. Bransford, D.L. Costill, J.T. Daniels, E.T. Howley, and G.S. Krahenbuhl. Variations in the aerobic demand of running among trained and untrained subjects. *Med. Sci. Sports Exerc.* 27:404–409. 1995.
36. Nimmons, M. *High Volume Weight Training With Different Rest Periods and Its Effect on Muscle Hypertrophy* [master's thesis]. Boone, NC, Appalachian State University; 1995.
37. Noakes, T.D. Implications of exercise testing for prediction of athletic performance: A contemporary perspective. *Med. Sci. Sports Exerc.* 20:319–330. 1988.
38. O'Bryant, H.S., R. Byrd, and M.H. Stone. Cycle ergometer and maximum leg and hip strength adaptations to two different methods of weight training. *J. Appl. Sports Sci. Res.* 2(2):27–30. 1988.
39. Osteras, H., J. Helgerud, and J. Hoff. Maximal strength-training effects on force-velocity and force-power relationships explain increases in aerobic performance in humans. *Eur. J. Appl. Physiol.* 88:255–263. 2002.
40. Paavolainen, L., K. Häkkinen, I. Hamalainen, A. Nummela, and H. Rusko. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J. Appl. Physiol.* 86:1527–1533. 1999.
41. Petersen, S.R., G.D. Miller, H.A. Wenger, and H.A. Quinney. The acquisition of muscular strength: The influence of training velocity and initial $\dot{V}O_2$max. *Can. J. Appl. Sport Sci.* 9:176–180. 1984.
42. Ploutz, L.L., P.A. Tesch, R.L. Biro, and G.A. Dudley. Effect of resistance training on muscle use during exercise. *J. Appl. Physiol.* 76:1675–1681. 1994.
43. Reuter, B. Strength training for endurance athletes? *Strength Cond. J.* 22:61–62. 2000.
44. Robinson, J.M., C.M. Penland, M.H. Stone, R.L. Johnson, B.J. Warren, and D.L. Lewis. Effects of different weight training exercise-rest intervals on strength, power and high intensity endurance. *J. Strength Cond. Res.* 9:216–221. 1995.
45. Roda, G., J.L. Ventura, J.A. Cadefau, R. Cusso, and J.A. Parra. A short training programme for the rapid improvement of both aerobic and anaerobic metabolism. *Eur J. Appl. Physiol.* 82:480–486. 2000.
46. Sharp, R.L., J.P. Troup, and D. Costill. Relationship between power and freestyle swimming. *Med. Sci. Sports Exerc.* 14:53–56. 1982.
47. Shaver, L.G. Maximum dynamic strength, relative dynamic endurance and their relationships. *Res. Q.* 42:460–465. 1971.
48. Siff, M. Biomechanical foundations of strength and power training. In: *Biomechanics in Sport.* V. Zatsiorsky, ed. London: Blackwell Scientific Ltd., 2001. pp. 103-139.
49. Smith, D.J. The relationship between anaerobic power and isokinetic torque outputs. *Can. J. Appl. Physiol.* 12:3–5. 1987.

50. Stone, M.H. Explosive exercise. *NSCAJ.* 15:7–15. 1993.
51. Stone, M.H., and A.C. Fry. Increased training volume in strength/power athletes. In: *Overtraining in Sport.* R.B. Kreider, A.C. Fry, and M.L. O'Toole, eds. Champaign, IL: Human Kinetics, 1998. pp. 87–106
52. Stone, M.H., G. Moir, M. Glaister, and R. Sanders. How much strength is necessary? *Phys. Ther. Sport.* 3:88–96. 2002.
53. Stone, M.H., S. Plisk, and D. Collins. Training principle: Evaluation of modes and methods of resistance training—A coaching perspective. *Sport Biomech.* 1:79–104. 2002.
54. Stone, M.H., K. Sanborn, H.S. O'Bryant, M.E. Hartman, M.E. Stone, C. Proulx, B. Ward, and J. Hruby. Maximum strength-power-performance relationships in collegiate throwers. *J. Strength Cond. Res.* 17: 739–745. 2003.
55. Stone, M.H., W.A. Sands, J. Carlock, S. Callan, D. Dickie, D. Daigle, J. Cotton, and S.L. Smith. The importance of isometric maximum strength and peak rate of force development in sprint cycling. *J. Strength Cond. Res.* 18:878–884. 2004.
56. Stone, M.H., G.D. Wilson, D. Blessing, and R. Rozenek. Cardiovascular responses to short-term Olympic-style weight training in young men. *Can. J. Appl. Sports Sci.* 8:134–139. 1983.
57. Stone, M.H., G.D. Wilson, R. Rozenek, and H. Newton. Anaerobic capacity: Physiological basis. *NSCAJ.* 5:30–71. 1984.
58. Stone, W.J., and S.P Coulter. Strength/endurance effects from three resistance training protocols with women. *J. Strength Cond. Res.* 8:231–234. 1994.
59. Suslov, F. How much strength is needed in endurance events? *Modern Coach and Athlete.* 35:9–12. 1997. Translated from *Legkaya atletika* 10. 1992.
60. Tanaka, H., J. Bassett, T.C. Swensen, and R.M. Sampedro. Aerobic and anaerobic power characteristics of competitive cyclist in the United States Cycling Federation. *Int. J. Sports Med.* 14:334–338. 1993.
61. Tousaint, H.M., and K. Vervoorn. Effects of specific high resistance training in the water on competitive swimmers. *Int. J. Sports Med.* 11:228–233. 1990.
62. Van etten, L.M., F.T. Verstappen, and K.R. Westererp. Effect of body build on weight-training-induced adaptations in body composition and muscular strength. *Med. Sci. Sports Exerc.* 26: 515–521. 1994.
63. Wisloff, U., and J. Helgerud. Evaluation of a new upper body ergometer for cross-country skiers. *Med. Sci. Sports Exerc.* 30:1314–1320. 1998.

Michael H. Stone is currently the Exercise and Sports Science Laboratory Director at East Tennessee State University.

Margaret E. Stone is currently a track and field coach at East Tennessee State University.

William A. Sands is the head of Sports Biomechanics and Engineering for the United States Olympic Committee.

Kyle C. Pierce is a professor in the Kinesiology and Health Science Department and is the Director and Coach of the USA Weightlifting Development Center at LSU Shreveport.

Newton

Robert U. Newton is the foundation professor in Exercise, Biomedical and Health Sciences at Edith Cowan University, Perth, Western Australia.

Haff

G. Gregory Haff is currently an assistant professor in the Division of Exercise Physiology in the Department of Human Performance and Applied Exercise Physiology at the West Virginia University School of Medicine in Morgantown, West Virginia.

Jon Carlock is currently the Strength and Conditioning Supervisor at the Olympic Training Center in Lake Placid, New York.