

## **Resistance training for distance running: a brief update**

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### **Abstract**

The positive effects of resistance training on distance-running performance through enhanced running economy are well established. However, few practical recommendations exist to aid coaches in planning resistance training to supplement a distance-running program. This article reviews literature in this area and offers practical applications for the athletics coach.

**Keywords:** concurrent strength and endurance training; intersession recovery; periodization; plyometrics; running economy

## **Resistance training for distance running: a brief update**

Combining strength and power with endurance training is difficult because of the conflicting demands of each type of activity and the possible antagonism of the training responses they elicit (33). The contrasting physiological demands of strength and endurance training may lead to interference, meaning that the training effect from one type of training negates the other (13, 42). It has been suggested that concurrent strength and endurance training (CSET) impedes strength development (7, 14, 34). In contrast, increases in strength after CSET have also been reported (3, 26–28), with others (13) reporting improvements in upperbody but not lower-body strength. However, a common conclusion from the above studies was that endurance training adaptations were not affected, leading to the notion that concurrent resistance and endurance training did not affect  $\dot{V}O_{2\max}$  (negatively or positively).

From the large body of CSET literature, it appears that distance runners or participants in endurance sports that require a significant amount of running (i.e., team sports) appear to gain the most advantage from resistance training (20). In distance running (operationally defined for this article as races greater than 5,000 m), although aerobic energy requirements play a predominant role, events involving an anaerobic contribution (i.e., sprint finishes, hill climbs, surges in pace) suggest that including anaerobic forms of training in a distance runners' program may have some benefit. Resistance training may also be beneficial in regard to injury prevention, based on the assumption that stronger tissues from resistance training sustain damage less often (12). However, it is the use of resistance training for improving endurance factors related to performance, such as running economy (RE), that provides the stronger argument for the inclusion of strength training in a distance runners'

program. The more important issue, therefore, is what specific resistance training is required and how both types of training should be structured to enhance endurance performance. The purpose of this article is to examine the influence of resistance training on distance-running performance and how the distance-running athlete should implement a resistance-training program.

## **Resistance training and distance-running performance indicators**

“Running Economy (RE) is typically defined as the energy demand for a given velocity of submaximal running, and is determined by measuring the steady state consumption of oxygen ( $\dot{V}O_2$ ) and the respiratory exchange ratio” (35). RE is one of the most important physiological determinants of endurance performance, in addition to maximum oxygen consumption ( $\dot{V}O_{2max}$ ) and lactate threshold (LT). Indeed, the strong association between RE and distance-running performance suggests that RE may be a better predictor of performance than maximum oxygen uptake in elite runners with similar  $\dot{V}O_{2max}$  (35). Runners with good RE use less energy and therefore less oxygen than runners with poor RE at the same velocity (35). Hence, performance can be improved through running a set distance at a higher velocity or being able to run longer at a set velocity.

The effect of resistance training on other markers of endurance running ability (LT and  $\dot{V}O_{2max}$ ) remains ambiguous, as few studies have been performed on elite or subelite distance runners. LT has only been shown to be enhanced from resistance training when untrained subjects are involved (25). In a review of the impact of resistance training on distance running performance (18), it was reported that supplementary resistance training does not improve  $\dot{V}O_{2max}$  in the highly-trained runner. However, the results of several studies suggest that  $\dot{V}O_{2max}$  would not be hindered by 8–16 weeks of resistance training (18).

The negligible effects of resistance training on  $\dot{V}O_{2max}$  is understandable, given that insufficient stimulus is provided by this type of training to make an impact on  $\dot{V}O_{2max}$ . In elite athletes, the trainability of  $\dot{V}O_{2max}$  with endurance training alone is limited anyway (15), with only small gains likely from active recovery to preparation phases of an annual cycle. Indeed, a 5-year case study on an elite female distance runner (17) found that improvements in 3,000-m race performance were accompanied by small declines in  $\dot{V}O_{2max}$ , but improvements in submaximal physiological variables, such as LT and RE, and the estimated running speed at  $\dot{V}O_{2max}$  were evident.

Several studies have shown the enhancement of RE through resistance training. A study on a group of university female cross-country runners found that 10 weeks of resistance training improved RE through enhanced leg strength (16). In support of this, Millet et al. (27) found that a 14-week combination of endurance training and heavy weight training (>90% of 1 repetition maximum [1RM]) in well-trained (mean pretraining  $\dot{V}O_{2max} = 69.7 \text{ ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ ) triathletes enhanced RE and leg strength and power, and had no negative effect on aerobic capacity. However, both these authors failed to discuss whether this influenced competitive performance (time trial performance).

In summary, RE is an important discriminator of endurance performance in elite athletes, and supplementary weight training in well-trained distance runners' programs can be effective in developing RE. Aerobic capacity is not influenced by weight training and has limited trainability in

elite athletes. The influence of supplementary weight training on LT in distance runners remains unsubstantiated. Therefore, the development of RE is an important reason for focusing on weight training for a competitive endurance athlete.

## **Explosive training and RE**

Some evidence suggests that explosive resistance training may be more beneficial in increasing distance-running performance in trained subjects ( $\dot{V}O_{2\max} > 50 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ) than traditional weight training. Paavolainen et al. (29) found that substituting 33% of endurance training time with explosive activity (i.e., sprints, plyometrics, light resistance [0–40% of 1RM] exercises performed quickly) in elite male crosscountry runners' (orienteers') programs (pretest  $\dot{V}O_{2\max} > 60 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ) for 9 weeks enhanced 5-km run time and RE without a change in  $\dot{V}O_{2\max}$ . These findings indicate that explosive resistance training can improve RE and performance as a consequence of enhanced neuromuscular functioning (29). However, because of the combination of methods used in the experimental group (explosive-strength, endurance, and circuit training), the specific contribution of the individual methods cannot be determined.

Two recent studies have provided support for the notion that plyometrics alone when supplementing a running program improves endurance performance. Turner et al. (38) found that a 6-week plyometric training program improved RE by 4–6% in moderately trained distance runners (mean pretest  $\dot{V}O_{2\max}$  ranging between 50 and 55  $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ). The mechanisms behind this remained unclear because of a range of jump tests showing no significant change. Spurrs et al. (37) have also established that 6 weeks of plyometric training enhances RE by 2–3% in runners of similar ability (mean pretest  $\dot{V}O_{2\max}$  ranging between 57 and 58  $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ). Although gains of the above ranges may appear small, they are likely to have a significant impact on distance-running performance for an elite athlete (38). For instance, in the latter study the 2–3% improvement in RE coincided with a 16-second (2.5%) improvement in mean 3-km running performance.

Potential mechanisms for the enhanced RE could indeed be neuromuscular. Adaptations to the nervous system may allow better intermuscular coordination of all relevant muscles, leading to greater net force (33). Muscular adaptations could also account for enhanced RE, as strength training could cause increased strength of the slow-twitch fibers (16), thus requiring less motor-unit activation to produce a given force, whereas endurance training could modify existing fiber characteristics (31), influencing the oxidative potential of type IIa fibers. Therefore, fast-twitch fibers may be utilized for a longer duration in the race, thus increasing running speed. A more efficient recruitment pattern, whether from neural or muscular adaptations, may require a lower oxygen cost at a given running speed (16). The conversion of Type IIb fibers to Type IIa is a common muscular adaptation of both training methods. This adaptation could potentially improve the oxidative capacity of muscle, as Type IIa fibers are more oxidative. However, this appears to be refuted by previous research (4) as a mechanism behind the improvement in RE from resistance training.

One of the key components of RE is the ability to use the stretch-shortening cycle (SSC) during ground contact (18). The SSC involves improved concentric force and rate of force development following an eccentric contraction when the lower limb joints flex on ground contact. The

mechanisms behind this phenomenon are thought to be neurophysiological, involving potentiation of the concentric contraction by use of the stretch reflex, or mechanical, such as the recoil of the elastic tissues (connective tissue, tendon) stretched during the eccentric phase, providing that a short time period takes place between eccentric and concentric contractions (30). However, there is some argument that the latter is not the exact interpretation of the mechanism; rather, the muscles can build up force prior to the concentric phase, leading to an enhanced concentric performance of the muscles (39). Although it is likely that both neurophysiological and mechanical mechanisms contribute to increased force production during the SSC, the degree to which the two contribute remains speculative.

Plyometric training enhances the muscles' ability to generate power through exaggerating the SSC. It is suggested that plyometric training improves the ability of the lower limb joints to act stiffer on ground contact, thereby reducing the delay between the eccentric and concentric contractions. This makes the SSC action more efficient during each footfall, leading to a more economical running style (37). In support of this theory, Dalleau et al. (5) have demonstrated through a theoretical study on RE that increasing the stiffness of the propulsive leg provided a lower energy cost per footfall. This would imply that athletes with greater reactive strength are more economical on each stride. Moreover, Spurrs et al. (37) found improvements in countermovement jump, a 5-bounds test, musculotendinous stiffness, and rate of force development during a seated calf raise test along with enhanced RE from plyometric training.

However, it is likely that an optimal level of stiffness exists for enhanced SSC performance. Walshe and Wilson (40) found that subjects with greater musculotendinous stiffness had impaired drop-jump performance at higher drop heights compared to more compliant subjects, but this impairment was not evident at lower drop heights. The decreased performance by stiffer subjects at higher stretch loads was potentially caused by more inhibition from the Golgi tendon organ (40). Distance running is likely to involve lower stretch loads compared to other sports (i.e., jumping); hence, an increased stiffness from resistance training would not impair SSC performance. It is worth noting at this point that a tradeoff between stiffness and running performance may need to be considered. Unnecessarily increased stiffness results in shorter stride length (6), and consequently in decreased running performance. Therefore, although resistance training has the potential to enhance endurance training, care needs to be given to the structure of the training program. To achieve optimal conditions, stiffness must be increased to the point at which it assists the rebound action but does not impede the stride length. Therefore, the combined effects of endurance and resistance training on tendon stiffness may require further investigation.

In summary, there is an increasing amount of literature supporting the use of resistance and plyometric training in distance-running programs to enhance RE and competitive performance (time trials). The additional roles of resistance training for enhancing injury prevention and anaerobic capacity provide further support for the inclusion of resistance training in a distance runner's program. The mechanisms responsible for the enhancement of RE are unclear, but improved efficiency of the SSC during the ground-contact phase has been strongly suggested.

## **Periodization**

Two mechanisms that have previously been proposed to account for the negligible effects of CSET on strength and endurance are the inability of skeletal muscle to adapt to conflicting endurance and resistance training demands, and the residual fatigue from an endurance session, which affects the quality of the subsequent strength training session (23). Therefore, the periodization of resistance and endurance training and the timing between resistance and endurance training sessions are important factors to consider in avoiding interference from each type of training (42).

There is a dearth of literature surrounding the optimal way to periodize CSET programs. Much of the knowledge available to strength and conditioning coaches is anecdotal and not fully examined scientifically. A common fault for distance runners is that the resistance training tends to involve high repetitions at low intensities throughout the year, in fear that muscle mass may be unnecessarily increased and that heavy lifting may hinder  $\dot{V}O_{2\max}$  (9). One study (32) has found that a periodization model termed “reverse linear” (increasing volume/lowering intensity) is more effective than a traditional (linear) or undulating model for improving muscular endurance. However, based on the mechanisms of adaptation to resistance training on RE (see previous section), being able to produce high force quickly and respond to stretch loads imposed on the body during ground contact is more important than local muscular endurance to performance. Also, the level of force produced by the lower body during ground contact relates to running velocity (41).

Zatsiorsky (42) suggests that the solution is to conduct sequential strength and endurance programs, focusing first on strength and then on endurance, and further suggests that “it is less efficient to proceed in the other order.” In relation to distance running, other authors (9, 12) have presented practical advice suggesting the opposite of Zatsiorsky’s view, but following a similar principle of matching the resistance training with the endurance training performed at the same time during the cycle. In essence, the resistance training should parallel the pattern of the running program (9), whereby the off-season involves low-intensity high-volume distance running and as the competitive season approaches a higher quality and lower volume of interval training is performed. Previous research showing improvements in RE from either weight training (16) or plyometric training (37) have shown traditional progression in training intensity and volume over a mesocycle length of training over 10 and 6 weeks, respectively. This provides some support for the adoption of this approach to the resistance- training program for athletes.

One study (8) has enabled speculation that the level of athlete may dictate whether a traditional model or a reverse of this would be more profitable, with athletes having greater pretraining status responding better to a traditional model. However, this research was performed on rowers with moderate  $\dot{V}O_{2\max}$ , and training volume was not matched between experimental groups. Clearly more research is needed to expand on this idea.

### **Intersession recovery between strength and endurance training**

In light of the above with regard to CSET and periodizing, the sequencing of the 2 components must be examined to provide a theoretical base on which a periodized plan can be constructed. Indeed, a large body of research has examined the effects of various modes of endurance activity on strength. Lepers et al. (21) and Gómez et al. (11) examined the effects of prolonged running exercises of 2

hours and a 10-km simulated race, respectively, on strength performance. Lepers et al. (21) concluded that the 2-hour run significantly affected the eccentric force production of the quadriceps muscles immediately after the run, but there was no further postrun measurement point. Gómez et al. (11) also found decreased power of the knee flexors immediately after the 10-km race. However, the runners had almost recovered and returned to their baseline strength and power values 48 hours after the run. They suggested this as an appropriate interval between endurance and strength training sessions. Nevertheless, this may be impractical for the distance-running athlete, as endurance- training sessions usually take place every day.

Abernethy (1), Leveritt and Abernethy (22), and Sporer and Wenger (36) examined the effects of endurance training on strength, and the latter authors additionally investigated recovery periods. Abernethy (1) concluded that his results support the acute fatigue hypothesis, as both running protocols had a negative effect on strength 4 hours after the run. Leveritt and Abernethy (22) had similar findings for high-intensity endurance performance. Finally, Sporer and Wenger (36) supported those findings, as they also identified a decrease in strength performance of the involved muscle groups up to 8 hours after the run. They suggested that 40 minutes of endurance training impairs strength production for 8 hours following that performance.

It is interesting to note that Leveritt et al. (24) found no difference in strength 8 hours after a 50-minute cycling task of comparable exercise intensity to that studied by Sporer and Wenger (36), contradicting all the above-mentioned literature. This study used a non-weightbearing activity (i.e., cycling) as a means of endurance performance, and it merits further examination. Being a non-weightbearing activity, cycling involves no ground contact with the lower limbs. This is in contrast to running, which involves greater SSC activity imposed by ground contact when the impact forces are larger and produce greater stretch loads. Fatigue from SSC exercises, whether of short or long (i.e., marathon running) duration, taxes all major elements: metabolic, mechanical, and neural (19). Furthermore, the recovery is lengthy and bimodal, with delayed muscle damage impairing muscle stiffness regulation (19). This may have important implications for strength training that follows, particularly if it involves further SSC exercise.

The majority of literature investigates the effects of endurance training on subsequent strength performance. Although the chronic effects of resistance training on endurance performance have been well investigated, little research has been conducted into the acute effects of strength training on endurance performance, despite suggestions and recommendations that resistance training should be performed first (36, 42). Fitness-fatigue characteristics for both types of training session will differ; despite being independent of each other, they will have a cumulative effect. This will have important ramifications in designing training programs when the emphasis is on one and not the other physical quality.

In summary, the distance runner's yearly plan should provide the foundation for periodizing concurrent endurance and resistance training. The resistance-training program should follow a traditional periodization model, with the volume and intensity of the resistance training coinciding with the endurance training emphasis at that time in the cycle. The timing between resistance and endurance training sessions is another important consideration in trying to avoid interference effects. The available literature relating to the acute effects of endurance training on strength tends to suggest that at least 8 hours' recovery is required between endurance and resistance training sessions. Ideally, resistance and endurance training should be performed on separate days, but this may be impractical for the distance runner. No research to date is available that has investigated the effects of a resistance

training session on subsequent endurance performance to indicate a required recovery period in this regard.

## **Conclusion**

In recent years strong evidence has emerged as to the positive effects of strength training (in particular explosive strength and plyometric training) on distance- running performance (RE and 3-to 10-km time trials) in trained distance runners ( $\dot{V}O_{2\max} > 50 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ). Although the exact mechanisms remain unclear, it is believed that enhanced storage and release of elastic energy during ground contact is one such mechanism. The resistance training should follow a traditional periodization model, coinciding with the emphasis of the running program at that point in the cycle to avoid interference. Resistance and endurance sessions should be performed on separate days or should at least be separated by 8 hours, with the priority session performed first, to again avoid interference effects.

## **Practical recommendations for athletics coaches**

Providing recommendations for a range of different athletes racing at a variety of distances is not possible. All athletes, regardless of the event, should be subject to a thorough needs analysis prior to design of a resistance-training program. With this in mind, the following section provides an overview of an annual resistance- training program for a 5- to 10- km distance runner with 1 competition phase during the summer track season. This example should be adaptable for any given athlete based on the athlete's needs analysis.

In this example (Table 1), the athlete develops basic aerobic factors in phase 2 through a high volume of endurance running. The restoration of  $\dot{V}O_{2\max}$  (phase 2) to competition levels should not take too long for high-level athletes, and therefore during this phase the endurance and resistance training programs can look to develop other relevant performance factors such as RE and LT. During this phase, the resistance training should aim to elicit some basic strength adaptation (i.e., 3 sets of 10 repetitions at 60–70% of 1RM), rather than muscular endurance, which should be adequately developed through the running program. This load should be appropriate for developing strength in preparation for plyometric training and a higher intensity of weight training during phase 3 (i.e., 3 sets of 6–8 repetitions at above 80% of 1RM), which will be necessary to develop RE and improve anaerobic performance (29, 37, 38). As the competitive season approaches (phase 3), the volume of endurance work decreases but the quality (speed) increases. The resistance training sessions here should be of greater quality (i.e., increased load, lower volume, plyometrics incorporated) aiming to increase strength and power (2, 12) in order to help develop RE. Training studies for plyometric or explosive training indicate 6–9 weeks' duration for development of RE (29, 37, 38) in well-trained athletes, and therefore the annual cycle should incorporate a power mesocycle of at least this length

prior to the competitive season. During phase 4, a maintenance program is required to sustain strength and power to enhance performance and injury prevention.

Table 2 provides sample sessions performed during phases 2, 3, and 4 of the model in order to illustrate the types of exercises and dosages used during each phase. Runners need to develop lower limb strength, as the lower limbs are subject to loads of 4–8 times body weight during ground contact for walking and running, respectively (10). Hence, exercises such as squats and lunges are important core resistance exercises to enhance performance. In addition, assistance exercises such as calf raises and ankle dorsiflexion using elastic resistance should be used to develop strength of the gastrocnemius and tibialis anterior, respectively, to prevent common running injuries such as Achilles tendonitis and shin splints. Upper-body exercises are included in phase 2 to aid upper-body strength for arm and symmetrical movements of the body while running. During phase 3, exercises are selected to enhance strength and power of the lower body (Table 2). The upper body will have some involvement in power exercises such as hang clean and split jerks. Plyometrics should be incorporated during this phase to enhance reactive strength, beginning the phase with lower-intensity drills such as squat jumps and vertical jumps and progressing to more intense exercises such as drop jumps and bounds (Table 2) by the end of this phase. Exercises should be incorporated throughout each phase to develop torso strength to aid postural control while running. These can include sit-ups, back extensions, and oblique exercises as well as various bridging exercises to enhance isometric endurance.

The resistance and endurance training ideally should take place on separate days. If this is impractical, then 8 hours of recovery from the endurance session should be permitted to allow optimal adaptations from the resistance training session. Hence, each session depicted in Table 2 is performed either during the morning or during an evening when the running session has been performed 8 hours previously.

## References

1. ABERNETHY, P.J. Influence of acute endurance activity on isokinetic strength. *J. Strength Cond. Res.* 7:141–146. 1993.
2. AMERICAN COLLEGE OF SPORTSMEDICINE. Progression models in resistance training for healthy adults. *Med. Sci. Sports Exerc.* 34:364–380. 2002.
3. BELL, G.J., S.R. PETERSEN, J. WESSEL, K. BAGNALL, AND H.A. QUINNEY. Physiological adaptations to concurrent endurance training and low velocity resistance training. *Int. J. Sports Med.* 12:384–390. 1991.
4. COYLE, E.F., W.H. MARTIN, S.A. BLOOMFIELD, O.H. LOWRY, AND J.O. HOLLOSZY. Effects of detraining on responses to submaximal exercise. *J. Appl. Physiol.* 59:853–859. 1985.
5. DALLEAU, G., A. BELLI, M. BOURDIN, AND J. LACOUR. The spring-mass model and the energy cost of treadmill running. *Eur. J. Appl. Physiol.* 77:257–263. 1998.

6. DERRICK, T.R., G.E. CLADWELL, AND J. HAMILL. Modelling the stiffness characteristics of the human body while running with various stride lengths. *J. Appl. Biomech.* 16:36–51. 2000.
7. DUDLEY, G.A., AND R. DJAMIL. Incompatibility of endurance- and strength-training modes of exercise. *J. Appl. Physiol.* 59:1446–1451. 1985.
8. EBBEN, W.P., A.G. KINDLER, K.A. CHIRDON, N.C. JENKINS, A.J. POLICHNOWSKI, AND A.V. NG. The effect of high-load vs. high-repetition training on endurance performance. *J. Strength Cond. Res.* 18:513–517. 2004.
9. ERICKSON, T.M. The benefits of strength training for endurance athletes. *NSCA Perform. Training J.* 4(2):13–17. 2005.
10. GIDDINGS, V.L., G.S. BEAUPRE, R.T. WHALEN, AND D.R. CARTER. Calcaneal loading during walking and running. *Med. Sci. Sports Exerc.* 32:627–634. 2000.
11. GÓMEZ, A.L., R.J. RADZWICH, C.R. DENEGAR, J.S. VOLEK, M.R. RUBIN, J.A. BUSH, B.K. DOAN, R.B. WICKHAM, S.A. MAZZETTI, R.U. NEWTON, D.N. FRENCH, K. HÄKKINEN, N.A. ATAMESS, AND W.J. KRAEMER. The effect of a 10-kilometer run on muscle strength and power. *J. Strength Cond. Res.* 16:184–191. 2002.
12. HASEGAWA, H., J. DZIADOS, R.U. NEWTON, A.C. FRY, W.J. KRAEMER, AND K. HÄKKINEN. Periodized training programmes for athletes. In: *Strength Training for Sport*. W.J. Kraemer and K. Häkkinen, eds. Oxford: Blackwell Science, 2002. pp. 69–134.
13. HENNESSY, L.C., AND W.S. WATSON. The interference effects of training for strength and endurance simultaneously. *J. Strength Cond. Res.* 8:12–19. 1994.
14. HICKSON, R.C. Interference of strength development by simultaneously training for strength and endurance. *Eur. J. Appl. Occup. Physiol.* 45:255–263. 1980.
15. JAKEMAN, P.M., E.M. WINTER, AND J. DOUST. A review of research in sports physiology. *J. Sports Sci.* 12:33–60. 1994.
16. JOHNSTON, R.E., T.J. QUINN, R. KERTZER, AND N.B. VROMAN. Strength training in female distance runners: Impact on running economy. *J. Strength Cond. Res.* 11:224–229. 1997.
17. JONES, A.M. A five-year physiological case study of an Olympic runner. *Br. J. Sports Med.* 32:39–43. 1998.
18. JUNG, A.P. The impact of resistance training on distance running performance. *Sports Med.* 33:539–552. 2003.
19. KOMI, P.V. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J. Biomech.* 33:1197–1206. 2000.
20. LAURSEN, P.B., S.E. CHRISWELL, AND J.A. CALLAGHAN. Should endurance athletes supplement their training program with resistance training to improve performance? *Strength Cond. J.* 27:50–55. 2005.

21. LEPERS, R., M.L. POUSSON, N.A. MAFFIULETTI, A. MARTIN, AND J. VAN HOECKE. The effects of prolonged running exercise on strength characteristics. *Int. J. Sports Med.* 21:275–280. 2000.
22. LEVERITT, M., AND P.J. ABERNETHY. Acute effects of high-intensity endurance exercise on subsequent resistance activity. *J. Strength Cond. Res.* 13:47–51. 1999.
23. LEVERITT, M., P.J. ABERNETHY, B.K. BARRY, AND P.A. LOGAN. Concurrent strength and endurance training: A review. *Sports Med.* 28:413–427. 1999.
24. LEVERITT, M., H. MACLAUGHLIN, AND P.J. ABERNETHY. Changes in leg strength 8 and 32 h after endurance exercise. *J. Sports Sci.* 18:865–871. 2000.
25. 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.
26. MCCARTHY, J.P., M.A. POZNIAK, AND J.C. AGRE. Neuromuscular adaptations to concurrent strength and endurance training. *Med. Sci. Sports Exerc.* 34:511–519. 2002.
27. 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.
28. NELSON, A.G., D.A. ARNALL, S.F. LOY, L.J. SILVESTER, AND R.H. CONLEE. Consequences of combining strength and endurance training regimens. *Phys. Ther.* 70:287–294. 1990.
29. 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.
30. POTACH, D.H., AND D.A. CHU. Plyometric training. In: *Essentials of Strength Training and Conditioning* (2nd ed.). T.R. Baechle and R.W. Earle, eds. Champaign, IL: Human Kinetics, 2000. pp. 427–470.
31. POTTEIGER, J.A. Aerobic endurance exercise training. In: *Essentials of Strength Training and Conditioning* (2nd ed.). T.R. Baechle and R.W. Earle, eds. Champaign, IL: Human Kinetics, 2000. pp. 495–509.
32. RHEA, M.R., W.T. PHILLIPS, L.N. BURKETT, W.J. STONE, S.D. BALL, B.A. ALVAR, AND A.B. THOMAS. A comparison of linear and daily undulating periodised programs with equated volume and intensity for local muscular endurance. *J. Strength Cond. Res.* 17:82–87. 2003.
33. SALE, D.G. Neural adaptation to resistance training. *Med. Sci. Sports Exerc.* 20:S135–S145. 1988.
34. SALE, D.G., I. JACOBS, J.D. MACDOUGAL, AND S. GARNER. Comparison of two regimens of concurrent strength and endurance training. *Med. Sci. Sports Exerc.* 22:348–356. 1990.
35. SAUNDERS, P.U., D.B. PYNE, R.D. TELFORD, AND J.A. HAWLEY. Factors affecting running economy in trained distance runners. *Sports Med.* 34:465–485. 2004.

36. SPORER, B.C., AND H.A. WENGER. Effects of aerobic exercise on strength performance following various periods of recovery. *J. Strength Cond. Res.* 17:638–644. 2003.
37. SPURRS, R.W., A.J. MURPHY, AND M.L. WATSFORD. The effect of plyometric training on distance running performance. *Eur. J. Appl. Physiol.* 89:1–7. 2002.
38. TURNER, A.M., M. OWINGS, AND J.A. SCHWANE. Improvement in running economy after 6 weeks of plyometric training. *J. Strength Cond. Res.* 17:60– 67. 2003.
39. VAN INGEN SCHENAU, G.J., M.F. BOBBERT, AND A. DE HAAN. Does elastic energy enhance work efficiency in the stretch shorten cycle? *J. Appl. Biomech.* 13:389–415. 1997.
40. WALSH, A.D., AND G.J. WILSON. The influence of musculotendinous stiffness and drop jump performance. *Can. J. Appl. Physiol.* 22:117–132. 1997.
41. WEYAND, P.G., D.B. STERNLIGHT, M.J. BELLIZZI, AND S. WRIGHT. Faster top running speeds are achieved with greater ground forces, not more rapid leg movements. *J. Appl. Physiol.* 89: 1991–1999. 2000.
42. ZATSIORSKY, V.M. *Science and Practice of Strength Training*. Champaign, IL: Human Kinetics, 1995. pp. 200–220.