Strength Training for Endurance Athletes: Theory to Practice

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ABSTRACT

THE PURPOSE OF THIS REVIEW IS TWOFOLD: TO ELUCIDATE THE UTILITY OF RESISTANCE TRAINING FOR ENDURANCE ATHLETES, AND PROVIDE THE PRACTITIONER WITH EVIDENCED-BASED PERIODIZATION STRATEGIES FOR CONCURRENT STRENGTH AND ENDURANCE TRAINING IN ATHLETIC POPULATIONS. BOTH LOW-INTENSITY EXERCISE ENDURANCE (LIEE) AND HIGH-INTENSITY EXERCISE ENDURANCE (HIEE) HAVE BEEN SHOWN TO IMPROVE AS A RESULT OF MAXIMAL, HIGH FORCE, LOW VELOCITY (HFLV) AND EXPLOSIVE, LOW-FORCE, HIGH-VELOCITY STRENGTH TRAINING. HFLV STRENGTH TRAINING IS RECOMMENDED INITIALLY TO DEVELOP A NEUROMUSCULAR BASE FOR ENDURANCE ATHLETES WITH LIMITED STRENGTH TRAINING EXPERIENCE. A SEQUENCED APPROACH TO STRENGTH TRAINING INVOLVING PHASES OF STRENGTH-ENDURANCE, BASIC STRENGTH, STRENGTH, AND POWER WILL PROVIDE FURTHER ENHANCEMENTS IN LIEE AND HIEE FOR HIGH-LEVEL ENDURANCE ATHLETES.

INTRODUCTION

Conflicts among coaches exist regarding the role of strength training for endurance athletes despite over 25 years of research supporting its efficacy and application (34-36,46,47,58,64,65,67,71,82). Historically, resistance and endurance training have been viewed as training modalities at opposite ends of a continuum with divergent adaptations (17,41). In a recent meta-analysis, Wilson et al. (92) reported an inverse relationship between frequency and duration of endurance training and subsequent changes in hypertrophy, strength, and power. Alternatively, strength training has been shown to have a positive effect on endurance performance (46,49,51,65,73). Previous research reports that concurrent strength and endurance training can increase endurance performance in high-level athletes to a greater extent than endurance training alone (46,47,58,64,65,82). The interference effects between strength and endurance training are outside the scope of this review and have been discussed extensively in previous studies (23,24,44,54,92). Endurance in sport has been defined as the ability to maintain or repeat a given force or power output (80). Endurance training can be further subdivided into low-intensity exercise endurance (LIEE) and high-intensity exercise endurance (HIEE). LIEE can be defined as long-duration endurance activities or the ability to sustain or to repeat low-intensity exercise. HIEE can be defined as the ability to sustain or to repeat high-intensity exercise and has been associated with sustained activities of ≤2 minutes (80). Competitive endurance athletes need more than enhanced aerobic power ($\dot{V}O_2$max) and LIEE (34). Requirements for endurance athletes should also include muscular strength, anaerobic power, and HIEE (34-36,46,58,68,82). Furthermore, strength training has been shown to positively influence both LIEE and HIEE across a spectrum of endurance events with greater effects observed in HIEE (34,46,50,58,82,83).

Strength can be defined as the ability to produce force (76). Strength is a skill, which can be expressed in a magnitude of 0–100% (80). In the current endurance literature, 2 primary forms of strength training have been investigated: maximal, high-force, low-velocity, strength training (HFLV) and explosive, low-force, high-velocity strength training (LFHV). Previous studies have examined the effectiveness of concurrent endurance and circuit resistance training, but have demonstrated inferior results (49,73,84). Maximum strength can be defined as the maximal amount of force a muscle or group of muscles can exert against an external resistance and corresponds with the high-force, low-velocity portion of the concentric force-velocity relationship (15,81). The term "explosive strength training" has been used in previous studies in reference to low-force, high-velocity training (0–60% 1 repetition maximum [RM] loads) with maximal movement intent

KEY WORDS:
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(59,69). The use of this terminology is misleading, as explosive strength (alternatively defined as rate of force development [RFD] or power output) (15,81), can be developed across a continuum of loads (0–100% 1RM) (19).

In fact, HFLV training has been shown to elicit improvements in explosive ability (measured as power output) across a larger spectrum of loads compared with LFHV training in weak subjects (20). The ability to improve power output across a larger spectrum of loads, among other reasons, likely explains why HFLV and endurance training may provide superior alterations in endurance performance compared with concurrent LFHV and endurance training for weak endurance athletes (9,60,73). Thus, explosive strength training performed in previous research on endurance performance is alternatively defined here as LFHV training.

Previous research on untrained and recreationally trained individuals has demonstrated that concurrent strength and endurance training can augment LIEE and HIEE, aerobic power, maximal strength, muscle morphology, and body composition (27,28,32,34,42,47,49,71,85). There is also research demonstrating HFLV and LFHV strength training enhance performance in high-level endurance athletes (58,59,61,64,66,72,73). In a recent review of the literature, Beattie et al. (10) reviewed results from 26 studies examining the effects of strength training on endurance performance of well-trained athletes (10). Their findings showed that strength training is effective for improving movement economy, velocity at $\dot{V}O_2max$ ($v\dot{V}O_2max$), power output at $\dot{V}O_2max$ ($w\dot{V}O_2max$), maximal anaerobic running test velocity (V_{MART}), and time trial performance, and suggested that HFLV strength be developed before LFHV strength in endurance athletes with limited strength training experience. Considering these findings, this article focuses primarily on studies examining the effects of HFLV and LFHV strength training on HIEE and LIEE of moderate to high-level endurance athletes. The purpose of this review is twofold: to elucidate the utility of resistance training for endurance athletes, and provide the practitioner with evidenced-based periodization strategies for concurrent strength and endurance training for competitive endurance athletes.

EFFECTS OF STRENGTH TRAINING ON ENDURANCE PERFORMANCE AND UNDERLYING MECHANISMS

CONCURRENT HFLV STRENGTH AND ENDURANCE TRAINING

In one of the earliest studies examining the effects of concurrent strength and endurance training on HIEE, Hickson et al. (34) had moderately trained ($\dot{V}O_2max$: 60 $mL^{-1}\cdot kg^{-1}\cdot min^{-1}$) runners and cyclists perform 10 weeks of endurance and HFLV strength training (>80% 1RM). They reported improvements in treadmill running (13%) and ergometer biking (11%) to exhaustion at maximal work rates (4–8 minutes) and cycling to exhaustion (20%) at 80% $\dot{V}O_2max$ (33). In addition, there were no statistical changes in muscle fiber cross-sectional area or thigh girth, although 1RM leg strength increased on average by 30%, which suggests primarily neural contributions.

In a more recent investigation by Aagaard et al. (2), highly trained national team cyclists ($\dot{V}O_2max$: 71–75 $mL^{-1}\cdot kg^{-1}\cdot min^{-1}$) performed HFLV strength training (mostly 5–6RM loads) for 16 weeks concurrently with regular endurance training. The strength and endurance training group improved average power output and total distance covered in a 45-minute cycling test (8%), whereas the endurance only group did not. Concomitant increases were found for maximal voluntary isometric contraction (MVIC) of the knee extensors (12%), peak RFD (20%), mean power output in 5 minutes of all-out cycling (3–4%), and mean power output during a 45-minute time trial (8%) with no changes in muscle fiber area, capillarization, and $\dot{V}O_2max$ in the strength and endurance training group (2). The superior LIEE performance in the strength and endurance training group may have been due to a shift in vastus lateralis muscle fiber type from type IIx to type IIa. Increased MVIC as a result of strength training may enhance HIEE and LIEE by decreasing the relative external resistance, which reduces the number of motor units required to produce a given amount of force (13). In addition, improvements in RFD contributed to the improved LIEE performance by reducing time to reach peak concentric forces necessary to produce the desired movement and increasing the length of the eccentric phase lending to greater muscle perfusion and longer capillary mean transit times (1,86).

Strength training has been reported to increase musculotendinous unit stiffness (21,43,51,87). This results in an enhanced ability to store elastic energy in the series and parallel elastic component during eccentric muscle actions, which in turn increases concentric muscle force. This is thought to be one of the reasons why improvements in running economy (35,51,81), cycling economy (8,12,66,83), and cross-country skiing economy (35,36,58) have been observed after a period of HFLV strength and endurance training. However, not all studies show improvements in movement economy as a result of strength training (2,9,14,45,46,64) possibly due to differences in training variables (e.g., mode, volume-load, frequency, duration) and subjects' training status. For example, elite athletes who already possess a high level of efficiency may not further improve movement economy with strength training (64).

The superior performance changes with heavier strength training may be attributed to greater increases in musculotendinous unit stiffness, greater recruitment of high-threshold motor units, and greater capacity to store and release elastic energy, which lead to a right and upward shift in the force-velocity and force-power relationships (58). This does not preclude LFHV strength training for endurance athletes because, although the loads used are typically lighter, there are notable improvements in RFD, which has been linked to greater movement economy and enhanced LIEE and HIEE performance (59,72,85,88).

Furthermore, an increase in musculotendinous stiffness has a greater application to running than cycling because of the greater contribution of the stretch-shortening cycle (69). In contrast, strength training induced improvements on cycling economy and performance are more evident at the end of long cycling tests. Rønnestad et al. (66) found that cycling economy improved more during the final hour of a 185-minute cycling test as a result of HFLV strength with endurance training (3 × 4–10RM, 2 d/wk for 12 weeks) compared with endurance training alone (66). They also reported reduced HR and blood lactate concentrations during the final hour in the strength-trained group. In addition, the subjects completed a 5-minute sprint at the end of the 180 minutes during which the strength-trained group improved average power production, but the endurance only group did not. This "anaerobic reserve" may have been due to increased contractile strength of type I fibers delaying the contribution of the less economical type II fibers, sparing them for the sprint finish (69). The "anaerobic reserve" for late race sprint performance may also be explained by the sparing of substrate stores within a muscle. Goreham et al. (25) reported that 12 weeks of HFLV strength with endurance training (3 × 6–8RM, 3 d/wk for 12 weeks) resulted in greater muscle phosphocreatine and glycogen content, and lower lactate concentrations at the end of a 30-minute cycle at 72% $\dot{V}O_2$max compared with endurance training alone (25).

Previous research has shown that endurance athletes who strength train with loads >70% 1RM exhibit larger changes in movement economy and endurance performance than endurance athletes who strength train with lighter loads (36,48,73). Sedano et al. (73) reported greater magnitudes of change in running economy, countermovement jump (CMJ) height, v$\dot{V}O_2$max, and 3-km time trial performance after 12 weeks of heavy strength training (>70% 1RM) compared with lighter strength training (<40% 1RM) and a control group (circuit training) in Spanish national level runners ($\dot{V}O_2$max >65 $mL^{-1}\cdot kg^{-1}\cdot min^{-1}$) (73). Similarly, Guglielmo et al. (26) found that after only 4 weeks of concurrent running and heavy strength training (3–5 sets at 6RM loads), there were larger magnitudes of change in running economy, 1RM strength, and CMJ height compared with concurrent running and lighter strength training (3–5 sets at 12RM loads) in middle- and long-distance runners ($\dot{V}O_2$max ~61.9 $mL^{-1}\cdot kg^{-1}\cdot min^{-1}$) who competed at the regional and national level (26). Mixed results have been reported for effects of HFLV strength training on cycling economy; however, there are still improvements in LIEE and HIEE performance (2,64,65,83). Furthermore, previous findings suggest that HFLV strength training may exhibit its effects most prominently during high-intensity bouts of endurance events (9,49,66), although there is evidence to the contrary (23,45) (Table 1).

CONCURRENT LFHV STRENGTH AND ENDURANCE TRAINING

LFHV strength training has been reported to elicit improvements in HIEE and LIEE performance (59,74,85); however, research conclusions are mixed (7,45,60) (Table 2). Paavolainen et al. (59) found that LFHV strength training (<40% 1RM) improved 5k run time, running economy, V_{MART}, 20-m sprint speed, and distance covered on a 5-jump test in male cross-country runners ($\dot{V}O_2$max ~64.4 $mL^{-1}\cdot kg^{-1}\cdot min^{-1}$), whereas no changes in these measures were observed in the endurance only group (59). The LFHV strength training involved various plyometric exercises and short sprints (20–100 m), which suggests that although the absolute barbell loads during strength training sessions were relatively light, the forces placed on the musculoskeletal system were much larger than to what the athletes were previously accustomed.

Considering that gaining body mass is a concern for endurance athletes, one of the purported benefits of LFHV strength training is the lower degree of muscle hypertrophy compared with HFLV strength training (28,70), but still being able to achieve increases in strength. In addition, increased muscle fiber cross-sectional area (CSA), maximal strength, and power output can be diminished or fully blunted by concurrent strength and endurance training with the degree of decrement depending on the mode, frequency, and duration of endurance training (2,14,34,42). Rønnestad et al. (64) found that increased CSA of the quadriceps muscle was associated with increased peak power output and cycling time trial performance after combined heavy strength training (twice/week, 3 × 4–10RM) and endurance training in well-trained cyclists without a noticeable change in body mass (64). Therefore, altering the strength to body mass ratio should be more of a concern for endurance athletes than body mass alone. Furthermore, although increases in "nonfunctional" hypertrophy may be detrimental to performance (3,86,91), increases in task specific hypertrophy may be an important factor in enhancing endurance performance, as the typical ectomorphic endurance athlete is unlikely to gain significant amounts of hypertrophy through strength training (89).

It has been suggested that LFHV strength training may provide an additive effect to those elicited by HFLV strength training on HIEE and LIEE performance (85). Taipale et al. (85) tested this hypothesis by dividing endurance runners into 3 groups (LFHV, HFLV, combination) and found no differences between groups in measures of strength (1RM), power (CMJ height), and endurance performance (85). Considering there is a delay between when a training stimulus is implemented and the subsequent effects on performance (90), a sequenced approach may be more appropriate than trying to improve strength, power, and endurance simultaneously (15,81).

TRAINING THEORY

THE TRAINING PROCESS

The primary goals of any successful training program are to reduce the likelihood of injury and optimize performance (81). Before designing a training

Table 1
Effects of concurrent HFLV strength training and endurance training on HIEE and LIEE

Study	Athletes	$\dot{V}O_2max$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	Strength training	HIEE	LIEE
HFLV ST					
Støren et al. (82)	17 M and F well-trained runners	59.9	4 × 4RM, 3×'s/wk for 8 wk	—	21.3% increase in TE at MAS
Jackson et al. (39)	23 M and F cyclists with >0.5 y competing	52	4 × 4RM, 3×'s/wk for 10 wk	NS for $v\dot{V}O_2max$	NS for 30-km TT
Levin et al. (45)	14 M cyclists with >1 y competing	62.8	4 × 5RM, 3×'s/wk for 6 wk (HFLV)	Control > ST for PP during last 1-km sprint	NS for 30-km TT
Rønnestad et al. (66)	20 M and F well-trained cyclists	66.4	4–10RM, 2×'s/wk for 12 wk	4.2% increase in W_{max}	7% increase in MP during final 5 min of 185 min TT
Rønnestad et al. (64)	20 M and F national level cyclists	66.4	4–10RM, 2×'s/wk for 12 wk	9.4% increase wingate PP, 4.3% increase in W_{max}	6% increase in MP during 40-min TT
Rønnestad et al. (65)	12 M and F national level cyclists	66.3	4–10RM, 2×'s/wk for 25 wk	8% increase in W_{max}, increase wingate PP	—
Rønnestad et al. (68)	17 M national/ international cross-country skiers	66.2	3–5 × 4–8, 4–5 × 3–5RM, 2×'s/ wk for 12 wk	—	NS in 7.5-km rollerski TT
Rønnestad et al. (67)	16 M national/ international cyclists	75.5	4–10RM, 2×'s/wk for 10 wk, 1×/wk for 15 wk	3% increase in W_{max}, earlier peak torque in pedal stroke	6.5% increase in MP during 40 min TT
Sunde et al. (83)	13 M and F competitive cyclists	61.1	4 × 4RM, 3×'s/wk for 8 wk	—	17.2% increase TE at MAP
Aagaard et al. (2)	14 M international level cyclists	72.5	3 × 12, 3 × 10, 3 × 8, 2–3 × 6RM, 2–3×'s/wk for 16 wk	—	8% increase in 45-min TT
Hoff et al. (36)	15 F cross-country skiers, trained 8.8 h/wk	55.3	3 × 6RM (pulldowns), 3×'s/wk for 9 wk	—	137% increase in TE at W_{max}
Hoff et al. (35)	19 M well-trained cross-country skiers	69.4	3 × 6RM (pulldowns), 45 min/wk for 8 wk	—	56% increase in TE at $v\dot{V}O_2max$
Østerås et al. (58)	19 M well-trained cross-country skiers with >5 y competing	61.2	3 × 6RM (pulldowns), 45 min/wk for 9 wk	—	61% increase in TE at $v\dot{V}O_2max$

Table 1 (continued)

Losnegard et al. (46)	19 M and F national level cross-country skiers	64.7	3 × 6–10, 3 × 5–8, 4 × 8, 3 × 4–6RM, 1–2×'s/wk for 12 wk	NS in 20, 40, 60, 80, and 100 m velocity during sprint roller skiing	7% increase in 1.1-km double poling TT, increase in W/kg during 5-min double poling
Millet et al. (51)	15 elite/international level triathletes	68.7	3 × 5, 4 × 5, 5 × 5RM, 2×'s/wk for 14 wk	2.6% increase in $v\dot{V}O_2max$	—
Hausswirth et al. (31)	14 M regional/national level triathletes	69.2	3–5 × 3–5RM, 3×'s/wk for 5 wk	—	Maintenance of FCC during last hour of 2-h cycling test
Sedano et al. (73)	18 M national level runners	69.5	Leg exercises 3 × 7 at 70% 1RM, 2×'s/wk for 12 wk (HFLV group)	increase in $v\dot{V}O_2max$ (ES: 0.87)	HFLV > LFHV > control for 3 km TT ($P < 0.05$)
Guglielmo et al. (26)	16 M regional/national level runners	61.9	3–4 × 6RM, 2×'s/wk for 4 wk (HFLV group)	6.7% increase in vOBLA	—
Barnes et al. (7)	42 M and F collegiate cross-country runners	63.8	2–4 × 6–15, 4 × 5–10, 4 × 4–8, 2 × 3–6RM, 2×'s/wk for 7/10 wk (HFLV group)	10% increase in PF during 5-jump test, 1.6% increase in $v\dot{V}O_2max$	Mean 5k times were worse than control for men, but better than control for women

ES = effect size; F = female; FCC = freely chosen cycling cadence; HFLV = high force low velocity; HIEE = high-intensity exercise endurance; LFHV = low force high velocity; LIEE = low-intensity exercise endurance; M = male; MAP = maximal aerobic power; MAS = maximal aerobic speed; ME = movement economy; MP = mean power; NS = no statistical change; OBLA = onset of blood lactate accumulation; PF = peak force; PP = peak power; TE = time to exhaustion; TT = time trial performance; V_{MART} = maximal velocity in maximal anaerobic running test; $\dot{V}O_2max$ = maximal oxygen uptake; W_{max} = peak power at $\dot{V}O_2max$.

program, however, the coach and the athlete must understand that training is a comprehensive process that harmonizes a myriad of factors to foster athlete development. Figure 1 depicts some of these factors that affect athletic performance. Therefore, the sport coaches, strength and conditioning staff, and sports medicine professionals each play an important role within their own disciplines to contribute to an athlete's development. In addition, the management of external stressors in the athlete's daily life is also an important component in the optimization of performance. To achieve this objective, however, training variables must be integrated in a sequence over the course of the training process (79). The training process is traditionally organized into 3 basic levels: macrocycles, mesocycles, and microcycles (79). A macrocycle is a long-duration training cycle, typically classified as 12 months of training, which are composed of multiple mesocycles. Mesocycles are moderate-length periods of training, which can focus on developing specific fitness characteristics within the macrocycle. Finally, each mesocycle is composed of shorter training periods referred to as microcycles (79). The tool used to structure each phase of training within a macrocycle is referred to as an "annual training plan" (15).

More specifically, the annual plan is a long-term training template used to guide the coach and athlete in the design and implementation of various training phases (15). The annual training plan can be separated into phases: the general preparatory phase, competitive phase, peak phase, and active rest (Figure 2). For a detailed description of each phase, the reader is encouraged to examine the work of Bompa and Haff (15).

PERIODIZATION

To reduce the likelihood of injury and maximize athletic performance, strength and conditioning professionals should organize training adaptations in a logical manner to minimize fatigue and highlight technical and fitness characteristics (e.g., strength, speed, endurance, etc.) at

Table 2
Effects of concurrent LFHV strength training and endurance training on HIEE and LIEE

Study	Athletes	$\dot{V}O_2max$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	Strength training	HIEE	LIEE
LFHV ST					
Paavolainen et al. (59)	18 M elite cross-country runners	67.7	Jumps (unilateral and bilateral, drop, hurdle), short sprints (20–100 m), 5–20 reps/set at 0–40% 1RM for 9 wk	3.4% increase in 20-m velocity, increased V_{MART} ($P < 0.05$)	5.1% increase in 5-km TT
Spurrs et al. (74)	17 M trained runners	57.6	Plyometric drills, progressed from 60–180 contacts, 2×'s/wk for 6 wk	—	2.7% increase in 3-km TT
Mikkola et al. (48)	25 M and F, high school runners	62.1	Short sprints (30–150 m), 2–3 × 6–10, 3×'s/wk for 8 wk	NS 1.2% increase in $v\dot{V}O_2max$, 3% increase in V_{MART}	—
Berryman et al. (12)	28 M provincial standard runners	56.9	Drop jumps and concentric squat jumps, 1×/wk for 8 wk	Increase in $v\dot{V}O_2max$ (ES: 0.43)	Increase in 3-km TT (ES: 0.37)
Bastiaans et al. (9)	14 M competitive cyclists (>6 y)	—	2–4 × 30, squats, leg press/pull, step-ups, midsection 3×'s/wk for 9 wk	4.7% increase in W_{max}	7.9% increase in 60 min TT
Mikkola et al. (50)	19 M national cross-country skiers	66.5	Double pole sprints (10 × 10 s), leg exercises 3 × 6–10, sprints, jumps, pogos, 3×'s/wk for 8 wk	NS 2-km poling velocity, 1.4% increase in 30-m double poling	—
Guglielmo et al. (26)	16 M regional/ national level runners	61.9	3–4 × 12RM, 2×'s/wk for 4 wk	1% increase in $v\dot{V}O_2max$	—
Sedano et al. (73)	18 M national level runners	69.5	Leg exercise 3 × 20 at 40% 1RM, 2×'s/wk for 12 wk	Increase in $v\dot{V}O_2max$ (ES: 0.61)	Small improvement in 3k TT ($P < 0.05$)

ES = effect size; F = female; FCC = freely chosen cycling cadence; HFLV = high-force low velocity; HIEE = high-intensity exercise endurance; LFHV = low force high velocity; LIEE = low-intensity exercise endurance; M = male; MAP = maximal aerobic power; MAS = maximal aerobic speed; ME = movement economy; MP = mean power; NS = no statistical change; OBLA = onset of blood lactate accumulation; PF = peak force; PP = peak power; ST = strength training; TE = time to exhaustion; TT = time trial performance; V_{MART} = maximal velocity in maximal anaerobic running test; $\dot{V}O_2max$ = maximal oxygen uptake; W_{max} = peak power at $\dot{V}O_2max$.

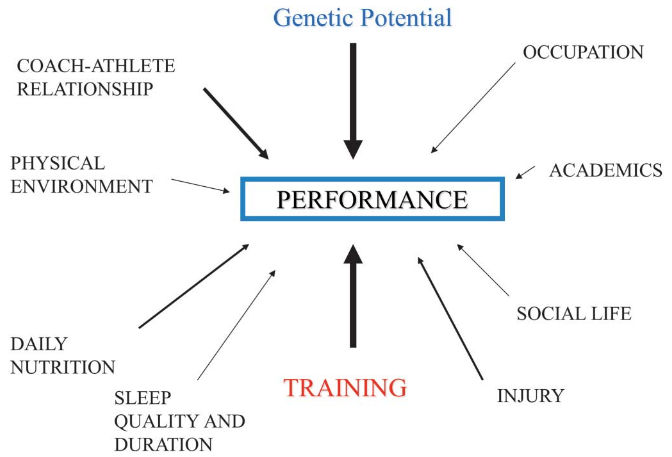


Figure 1. Factors affecting athletic performance, modified from Stone et al. (81). Adapted, with permission, from M.H. Stone, M. Stone, and W.A. Sands, 2007, *Principles and practice of resistance training* (Champaign, IL: Human Kinetics), 203.

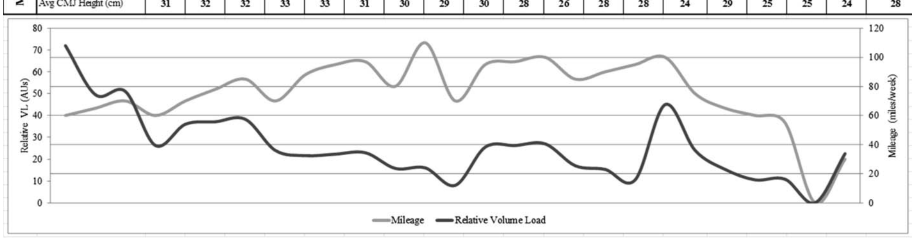
precise times of the training year "to increase the potential to achieve specific performance goals" (79). This process of chronologically manipulating physiological adaptations is referred to as periodization. Although varying definitions of this term have been proposed, periodization has been most recently defined as, "The strategic manipulation of an athlete's preparedness through the employment of sequenced training phases defined by cycles and stages of workload" (22). Furthermore, if the training stimuli are sequenced appropriately, each phase of training will enhance or "potentiate" the next training phase (15,79,81). This concept, referred to as phase potentiation, is essential in the development of endurance-specific performance characteristics.

THE IMPORTANCE OF POWER IN ENDURANCE SPORTS

The development of high-power outputs and high RFDs are vital to success in most sporting events (76) and can differentiate levels of athletic performance (5,6,29). Maximal power output and RFD have conventionally been viewed as fitness characteristics that are less important for endurance sports. This is misguided, however, because there is evidence indicating that

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Competition and Annual Plan	Annual Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Starting Monday Date	3-Jun	10-Jun	17-Jun	24-Jun	1-Jul	8-Jul	15-Jul	22-Jul	29-Jul	5-Aug	12-Aug	19-Aug	26-Aug	2-Sep
	Competitions	Summer Break													
	Importance														
	Laboratory Testing	X													
Running Training	Training Phase	General Preparation								Specific Preparation					
	Mesocycle	General Endurance/Speed				Aerobic/Anaerobic Support				Aerobic/Anaerobic Support				CL	Active Rest
	Sessions	6	6	6	6	7	8	8	8	8	9	9	9	9	6
	Mileage	60	65	70	60	70	78	85	70	88	95	80	80	110	70
	Workouts	distance runs, long runs, fartlek, ext. tempo, strides				distance runs, long distance runs, fartlek, ext. tempo, hill accelerations				distance runs, long distance runs, fartlek, ext. tempo, hill running, accelerations				distance, long distance, progression, fartlek	
Strength Training	Mesocycle	Strength Endurance				Strength				Strength/Power				Active Rest	
	Sessions per week	3	3	3	3	3	3	3	3	3	3	3	3	2	2
	Sets x Reps	3x10	3x10	3x10	2x10	3x5	3x5	3x5	2x5	3x3	3x3	3x3	3x2	2x5	1x5
	Day 1	Clean tech, BS, WL, OHP				Snatch Tech, BS, SU, PP				PS, HS (BS wu), SUJ, PJ				FS, OHP	FS, OHP
	Day 2	Snatch Tech, SP, MTSP, BOR				Clean Tech, CP, MTCP, CU				PC, CPK, CU, HE				MTSP, DBR	MTSP, DBR
	Day 3	Clean Tech, FS, MTCP, WPU				Snatch Tech, FS, SS, WPU				PS, OHS, PU (expl)					
	Avg Weekly Intensity	80.0%	82.5%	85.0%	87.5%	80.0%	82.5%	85.0%	80.0%	80.0%	82.5%	85.0%	87.5%	80.0%	80.0%
	Sets	3	2	2	1	3	3	3	2	3	3	3	3	2	1
	Reps	10	10	10	10	5	5	5	5	3	3	3	2	5	5
Monitoring	Relative Volume Load	72	49.5	51	26.25	36	37.125	38.25	24	21.6	22.275	22.95	15.75	16	8
	Mileage	60	65	70	60	70	78	85	70	88	95	97	80	110	70
	Avg CMJ Height (cm)	31	32	32	33	33	31	30	29	30	28	26	28	28	24

		15	16	17	18	19	20	21	22	23	24	25	26	27
Competition and Annual Plan	Annual Week	15	16	17	18	19	20	21	22	23	24	25	26	27
	Starting Monday Date	9-Sep	16-Sep	23-Sep	30-Sep	7-Oct	14-Oct	21-Oct	28-Oct	4-Nov	11-Nov	18-Nov	25-Nov	2-Dec
	Competitions	8/14 Vanderbilt Invite 5k/8k	8/20 Hokie Invite 6k/8k @ Va. Tech		10/5 Greater Louisville Classic 5k/8k @ Louisville		10/18 Blue Ridge Open 5k/8k @ App State		11/2 Conference Championship 5k/8k @ Lipscomb		NCAA South Regional 6k/10k @ Alabama	NCAA Championships 6k/10k @ Indiana State		
	Importance	7	6		5		4		3		1	2		
	Laboratory Testing	X											X	
Running Training	Training Phase	Specific Preparation			Competition								Transition 1	
	Mesocycle	Direct Endurance/Speed Support			Specific				Taper				Active Rest	
	Sessions	8	8	8	8	8	8	9	7	7	6	6	0	4
	Mileage	95	97	100	85	90	95	100	75	65	60	55	0	30
	Workouts	distance, long distance, LT, RP Intervals, strides			distance, long distance, RP Intervals, fast intervals, race modelling				distance, long distance, progression, RP, fast intervals, strides					
Strength Training	Mesocycle	Strength				Power		CL	Taper				Active Rest	
	Sessions per week	2	2	2	2	2	2	2	2	2	2	2	0	2
	Sets x Reps	3x5	3x5	3x5	2x5	3x3	3x2	5x5	3x5	3x3	3x2	3x2		3x5
	Day 1	PS+OHS, BS, OHP				PSK, JS (BS wu), PP		MTSP, BS, OHP	Snatch, BS, PP		PSK, JS, PJ			MTSP, BS, WPU
	Day 2	PC+FS, SP, PO, HE				PCK, MTSP, SUJ		MTCP,CGSS, CU	Clean, CP, CU		PCK, MTCP, CSR			MTCP, CP, DBR
	Day 3													
	Avg Weekly Intensity	85.0%	87.5%	90.0%	85.0%	85.0%	87.5%	90.0%	80.0%	85.0%	87.5%	90.0%	0.0%	75.0%
	Sets	3	3	3	2	3	3	5	3	3	3	3	0	3
	Reps	5	5	5	5	3	2	5	5	3	2	2	0	5
Monitoring	Relative Volume Load	25.5	26.25	27	17	15.3	10.5	45	24	15.3	10.5	10.8	0	22.5
	Mileage	95	97	100	85	90	95	100	75	65	60	55	0	30
	Avg CMJ Height (cm)	29	25	25	24	28	25	25	23	27	29	31	29	30



Strength Training Abbreviations

BOR	Bent over row	OHS	Overhead squat
BS	Back squat	PC	Power clean
CGSS	Clean grip shoulder shrugg	PCK	Power clean from knee
CP	Clean pull	PJ	Power jerk
CPK	Clean pull from knee	PO	Pullover
CSR	chest supported row	PP	Push press
CU	Chin-up	PS	Power snatch
DBR	Dumbbell row	PSK	Power snatch from knee
FS	Front squat	PU	Pull-up
HE	Hyperextension	SP	Snatch pull
HS	Half squat	SS	Split squat
JS	Jump squat	SU	Step-up
MTCP	Mid-thigh clean pull	SUJ	Step-up jump
MTSP	Mid-thigh snatch pull	WL	Walking lunge
OHP	Overhead press	WPU	Weighted push-up

Figure 2. Cross-country runner macrocycle.

average power output over the course of a long-distance race and maximal power output during the final sprint may be critical factors determining the outcome of the event (56,58,80).

THE IMPORTANCE OF STRENGTH IN THE DEVELOPMENT OF POWER

Power is defined as "the rate of doing work" (40) and is quantitatively expressed as power = force × velocity (55). Therefore, an athlete can either achieve greater power outputs by increasing the force production or by increasing the shortening velocity capabilities of skeletal muscle. It is important to note, however, that skeletal muscle shortening velocities are limited by the activity of myosin ATPase, which ultimately dictates the rate of cross-bridge cycling through ATP dissociation (57). Accordingly, this elucidates the vital role of maximal strength in the development of power (76). Simply put, an increased ability to produce force provides the athlete with the opportunity to enhance power production.

TRAINING SEQUENCING FOR THE ENDURANCE ATHLETE

SEQUENCE AND DURATION OF TRAINING PHASES

Originally proposed by Stone et al. (78), strength and power should be developed by cycling 4 distinct phases of training: strength-endurance, basic strength, strength, and power (78). This model of strength and power development, in addition to the concept of phase potentiation, has since been supported by further evidence (30,52,93) and is also referred to as block periodization (38) or the conjugate-sequencing system (90). A 4-week training phase has been previously suggested, using the first 3 weeks to progressively load the athlete, and the final week as an unloading period to modulate recovery (15,63,81). Although the duration of the phase is dependent on the relative training intensity, training volume, time of the season, needs of the athlete, and other external factors. Regardless of the length of each training cycle, however, it is important for practitioners to remember that the rate of decay, or involution of training effects, seems to be directly proportional to the length of the training period (81,94). Consequently, proper sequencing of training phases with appropriate durations will enhance fitness characteristics from prior stages of training and make them more resilient to decay. In addition, the subsequent training phase can be redirected to focus on another fitness characteristic to further the athlete's preparedness and dissipate accumulated fatigue from the previous training cycle (81).

Although there are a number of schematics to choose from when manipulating these variables, a traditional model fits the previously described sequence of strength and power development (79,81). During the general preparation phase, higher volumes of strength training should be used to enhance work capacity and increase lean body mass (15). Despite concerns over increases in body mass, for many endurance athletes, the general preparation phase is one of the few times during the annual plan where small increases in muscle hypertrophy can be achieved. This in turn will potentiate gains in maximal strength and power in subsequent phases of training. As the athlete progresses from the general preparation period to the specific preparation and competition phases of the macrocycle, strength training volume is progressively diminished while training intensity increases, as strength and power become the primary fitness characteristics of interest, respectively (38). Before a culminating event in the competitive season (e.g., championship race), the peaking phase or taper requires "a reduction of the training load during a variable period of time, in an attempt to reduce the physiological and psychological stress of daily training and optimize performance" (53). After the peaking phase, the athlete transitions into the off-season with a period of active rest consisting of recreational activities in which both intensity and volume are reduced and recovery is the objective (81).

TRAINING VOLUME AND INTENSITY

The selection of appropriate training volumes and intensities within each training phase is vital in the facilitation of the desired physiological response. For endurance athletes with limited strength training experience, a traditional model is appropriate (79,81). These athletes should begin with building a neuromuscular base using HFLV strength training, and after a certain strength level is achieved, LFHV strength training can then be implemented (10). This is supported by evidence indicating that among well-trained athletes, LFHV is necessary to make further alterations in the high-velocity end of the force-velocity curve (30,77). Thus, HFLV and LFHV strength training are both important components in the endurance athlete's strength and conditioning program provided they are included at the appropriate time and in the correct sequence (Figure 2).

Regarding high-level endurance athletes, however, the use of a traditional model with a single peaking phase is often impractical, as most athletes will compete in multiple significant events throughout the course of a competitive season. Accordingly, manipulating volume and intensity to produce specific physiological adaptations must coincide with this competitive schedule (80). Unlike the traditional model, after the athlete completes the peaking phase and competes in a key event of the season, further planning will be necessary to prepare the athlete for future competitions of importance (80,81). More specifically, if adequate time exists before the next major event, strength training volume may be increased to re-establish strength levels (63,79). Conversely, if time is insufficient, strength training volume should be increased cautiously to avoid undue fatigue before the next contest (63,80,81).

EXERCISE SELECTION FOR THE ENDURANCE ATHLETE

When selecting exercises for specific phases of training, it is important for practitioners and athletes to consider the transfer of training effect. That is, the degree of performance adaptation that can result from a training exercise (11,81). Therefore, choosing exercises with similar movement patterns and kinetic parameters (e.g., peak force, RFD, acceleration, etc.) will result in a greater transfer to performance (11). Although some endurance sport movements have both closed and open kinetic chain sequences, in movements such as running, closed kinetic chain exercises should be prioritized as they have been suggested to require greater levels of intermuscular coordination (76) and result in greater performance enhancement compared with open chain movements (62,75). Traditional squatting and weightlifting movements are primary examples. Moreover, squat strength has been strongly correlated to athletic movements that require relatively high-velocity, high-power outputs and RFD (6,18). Weightlifting exercises and their derivatives have also shown a strong transfer of training to such movements as well (4,16,37). Practically, these exercises may assist with passing an opponent, enhancing movement economy, increasing average power output, and sprinting the final 100 m of a race (56,58,80). Considering the essential role that these exercises play in the development of strength and power and subsequent effects on HIEE and LIEE, squatting and weightlifting movements should be staples throughout the training year for endurance athletes.

PRACTICAL APPLICATIONS

Previous research on concurrent training for endurance athletes suggests that maximum strength is associated with endurance factors, a relationship that is likely stronger for HIEE activities than for LIEE. HFLV strength training can affect increases in HIEE and LIEE through increasing peak force and RFD. LFHV strength training has also been reported to elicit improvements in HIEE and LIEE performance, however, not all studies agree. When considering findings from studies examining changes in endurance performance and related measures after strength training, it seems that concurrent HFLV strength and endurance training may provide superior results compared with LFHV strength and endurance training for relatively weak endurance athletes. For endurance athletes with more strength training experience, a sequenced approach (e.g., block periodized model) may be more appropriate than trying to improve strength, power, and endurance simultaneously.

A limitation to the current research exists in the design and implementation of training protocols. Some studies comparing different strength training modalities fail to control for differences in strength and endurance training volume between experimental conditions. Another limitation, only controlled for in a few studies, is the addition of strength training without a simultaneous reduction in the volume of endurance training. Practically, if applied in an athletic setting, this could result in poor fatigue management and an increased risk of overtraining syndrome. The implementation of an annual training plan where endurance and strength training variables are carefully manipulated will maximize athletic performance while reducing injury risk by more appropriately managing training volume. Future research should examine the effectiveness of monitoring programs in determining when to manipulate training variables throughout a macrocycle and the subsequent effects on endurance performance.

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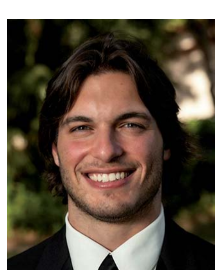

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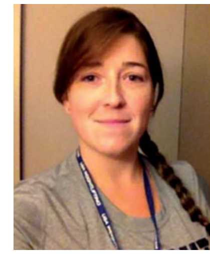

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REFERENCES

1. Aagaard P and Andersen JL. Effects of strength training on endurance capacity in top-level endurance athletes. *Scand J Med Sci Sports* 20(Suppl 2): 39–47, 2010.
2. Aagaard P, Andersen JL, Bennekou M, Larsson B, Olesen JL, Crameri R, Magnusson SP, and Kjaer M. Effects of resistance training on endurance capacity and muscle fiber composition in young

top-level cyclists. *Scand J Med Sci Sports* 21: 298–307, 2011.

3. Abe T, Kojima K, Kearns CF, Yohena H, and Fukuda J. Whole body muscle hypertrophy from resistance training: Distribution and total mass. *Br J Sports Med* 37: 543–545, 2003.
4. Arabatzi F, Kellis E, and Saez-Saez De Villarreal E. Vertical jump biomechanics after plyometric, weight lifting, and combined (weight lifting + plyometric) training. *J Strength Cond Res* 24: 2440–2448, 2010.
5. Baker D. Comparison of upper-body strength and power between professional and college-aged rugby league players. *J Strength Cond Res* 15: 30–35, 2001.
6. Baker D and Nance S. The relation between running speed and measures of strength and power in professional rugby league players. *J Strength Cond Res* 13: 230–235, 1999.
7. Barnes KR, Hopkins WG, McGuigan MR, Northuis ME, and Kilding AE. Effects of resistance training on running economy and cross-country performance. *Med Sci Sports Exerc* 45: 2322–2331, 2013.
8. Barrett-O'Keefe Z, Helgerud J, Wagner PD, and Richardson RS. Maximal strength training and increased work efficiency: Contribution from the trained muscle bed. *J Apple Physiol (1985)* 113: 1846–1851, 2012.
9. Bastiaans JJ, van Diemen AB, Veneberg T, and Jeukendrup AE. 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.
10. Beattie K, Kenny IC, Lyons M, and Carson BP. The effect of strength training on performance in endurance athletes. *Sports Med* 44: 845–865, 2014.
11. Behm DG. Neuromuscular implications and applications of resistance training. *J Strength Cond Res* 9: 264–274, 1995.
12. Berryman N, Maurel D, and Bosquet L. Effect of plyometric vs. dynamic weight training on the energy cost of running. *J Strength Cond Res* 24: 1818–1825, 2010.
13. Bieuzen F, Lepers R, Vercruyssen F, Hausswirth C, and Brisswalter J. Muscle activation during cycling at different cadences: Effect of maximal strength capacity. *J Electromyogr Kinesiol* 17: 731–738, 2007.
14. Bishop D, Jenkins DG, Mackinnon LT, McEniery M, and Carey MF. The effects of strength training on endurance performance and muscle characteristics. *Med Sci Sports Exerc* 31: 886–891, 1999.
15. Bompa T and Haff G. *Periodization: Theory and Methodology of Training*. Champaign, IL: Human Kinetics, 2009.
16. Channell BT and Barfield JP. Effect of Olympic and traditional resistance training on vertical jump improvement in high school boys. *J Strength Cond Res* 22: 1522–1527, 2008.
17. Coffey VG and Hawley JA. The molecular bases of training adaptation. *Sports Med* 37: 737–763, 2007.
18. Comfort P, Bullock N, and Pearson SJ. A comparison of maximal squat strength and 5-, 10-, and 20-meter sprint times, in athletes and recreationally trained men. *J Strength Cond Res* 26: 937–940, 2012.
19. Cormie P, McCaulley GO, and McBride JM. Power versus strength-power jump squat training: Influence on the load-power relationship. *Med Sci Sports Exerc* 39: 996–1003, 2007.
20. Cormie P, McGuigan MR, and Newton RU. Influence of strength on magnitude and mechanisms of adaptation to power training. *Med Sci Sports Exerc* 42: 1566–1581, 2010.
21. Craib MW, Mitchell VA, Fields KB, Cooper TR, Hopewell R, and Morgan DW. The association between flexibility and running economy in sub-elite male distance runners. *Med Sci Sports Exerc* 28: 737–743, 1996.
22. DeWeese BH, Gray HS, Sams ML, Scruggs SK, and Serrano AJ. Revising the definition of periodization: Merging historical principles with modern concern. In: *Olympic Coach*. Colorado Springs, CO: United States Olympic Committee, 2013. pp. 5–19.
23. Docherty D and Sporer B. A proposed model for examining the interference phenomenon between concurrent aerobic and strength training. *Sports Med* 30: 385–394, 2000.
24. Fyfe JJ, Bishop DJ, and Stepto NK. Interference between concurrent resistance and endurance exercise: Molecular bases and the role of individual training variables. *Sports Med* 44: 743–762, 2014.
25. Goreham C, Green HJ, Ball-Burnett M, and Ranney D. High-resistance training and muscle metabolism during prolonged exercise. *Am J Physiol* 276: 489–496, 1999.
26. Guglielmo LG, Greco CC, and Denadai BS. Effects of strength training on running economy. *Int J Sports Med* 30: 27–32, 2009.
27. Hakkinen K, Alen M, Kraemer WJ, Gorostiaga E, Izquierdo M, Rusko H, Mikkola J, Hakkinen A, Valkeinen H, Kaarakainen E, Romu S, Erola V, Ahtiainen J, and Paavolainen L. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol* 89: 42–52, 2003.
28. Hakkinen K, Komi PV, and Alen M. Effect of explosive type strength training on isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. *Acta Physiol Scand* 125: 587–600, 1985.
29. Hansen KT, Cronin JB, Pickering SL, and Douglas L. Do force-time and power-time measures in a loaded jump squat differentiate between speed performance and playing level in elite and elite junior rugby union players? *J Strength Cond Res* 25: 2382–2391, 2011.
30. Harris GR, Stone MH, O'Bryant HS, Proulx CM, and Johnson RL. Short-term performance effects of high power, high force, or combined weight training methods. *J Strength Cond Res* 14: 14–20, 2000.
31. Hausswirth C, Argentin S, Bieuzen F, Le Meur Y, Couturier A, and Brisswalter J. Endurance and strength training effects on physiological and muscular parameters during prolonged cycling. *J Electromyogr Kinesiol* 20: 330–339, 2010.
32. Hennessy LC and Watson AW. The interference effects of training for strength and endurance simultaneously. *J Strength Cond Res* 8: 12–19, 1994.
33. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol Occup Physiol* 45: 255–263, 1980.
34. Hickson RC, Dvorak BA, Gorostiaga EM, Kurowski TT, and Foster C. Potential for strength and endurance training to amplify endurance performance. *J Appl Physiol (1985)* 65: 2285–9220, 1988.
35. Hoff J, Gran A, and Helgerud J. Maximal strength training improves aerobic endurance performance. *Scand J Med Sci Sports* 12: 288–295, 2002.
36. Hoff J, Helgerud J, and Wisløff U. Maximal strength training improves work economy in trained female cross-country skiers. *Med Sci Sports Exerc* 31: 870–877, 1999.
37. Hori N, Newton RU, Andrews WA, Kawamori N, McGuigan MR, and Nosaka K. Does performance of hang power clean differentiate performance of jumping, sprinting, and changing of direction? *J Strength Cond Res* 22: 412–418, 2008.

38. Issurin VB. New horizons for the methodology and physiology of training periodization. *Sports Med* 40: 189–206, 2010.

39. Jackson NP, Hickey MS, and Reiser RF. High resistance/low repetition vs. low resistance/high repetition training: effects on performance of trained cyclists. *J Strength Cond Res* 21: 289–295, 2007.

40. Knudson DV. Correcting the use of the term "power" in the strength and conditioning literature. *J Strength Cond Res* 23: 1902–1908, 2009.

41. Knuttgen HG. Strength training and aerobic exercise: Comparison and contrast. *J Strength Cond Res* 21: 973–978, 2007.

42. Kraemer WJ, Patton JF, Gordon SE, Harman EA, Deschenes MR, Reynolds K, Newton RU, Triplett NT, and Dziados JE. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *J Appl Physiol (1985)* 78: 976–989, 1995.

43. Kubo K, Kanehisa H, and Fukunaga T. Effects of resistance and stretching training programmes on the viscoelastic properties of human tendon structures in vivo. *J Physiol* 538: 219–226, 2002.

44. Leveritt M, Abernethy PJ, Barry BK, and Logan PA. Concurrent strength and endurance training. A review. *Sports Med* 28: 413–427, 1999.

45. Levin GT, McGuigan MR, and Laursen PB. Effect of concurrent resistance and endurance training on physiologic and performance parameters of well-trained endurance cyclists. *J Strength Cond Res* 23: 2280–2286, 2009.

46. Losnegard T, Mikkelsen K, Rønnestad BR, Hallén J, Rud B, and Raastad T. The effect of heavy strength training on muscle mass and physical performance in elite cross country skiers. *Scand J Med Sci Sports* 21: 389–401, 2011.

47. McCarthy JP, Pozniak MA, and Agre JC. Neuromuscular adaptations to concurrent strength and endurance training. *Med Sci Sports Exerc* 34: 511–519, 2002.

48. Mikkola J, Rusko H, Nummela A, Pollari T, and Hakkinen K. Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in young distance runners. *Int J Sports Med* 28: 602–611, 2007.

49. Mikkola J, Vesterinen V, Taipale R, Capostagno B, Hakkinen K, and Nummela A. Effect of resistance training regimens on treadmill running and neuromuscular performance in recreational endurance runners. *J Sports Sci* 29: 1359–1371, 2011.

50. Mikkola JS, Rusko HK, Nummela AT, Paavolainen LM, and Hakkinen K. Concurrent endurance and explosive type strength training increases activation and fast force production of leg extensor muscles in endurance athletes. *J Strength Cond Res* 21: 613–620, 2007.

51. Millet GP, Jaouen B, Borrani F, and Candau R. Effects of concurrent endurance and strength training on running economy and.VO(2) kinetics. *Med Sci Sports Exerc* 34: 1351–1359, 2002.

52. Minetti AE. On the mechanical power of joint extensions as affected by the change in muscle force (or cross-sectional area), ceteris paribus. *Eur J Appl Physiol* 86: 363–369, 2002.

53. Mujika I and Padilla S. Scientific bases for precompetition tapering strategies. *Med Sci Sports Exerc* 35: 1182–1187, 2003.

54. Nader GA. Concurrent strength and endurance training: From molecules to man. *Med Sci Sports Exerc* 38: 1965–1970, 2006.

55. Newton RU and Kraemer WJ. Developing explosive muscular power: Implications for a mixed methods training strategy. *Strength Cond J* 16: 20–31, 1994.

56. Noakes TD. Implications of exercise testing for prediction of athletic performance: A contemporary perspective. *Med Sci Sports Exerc* 20: 319–330, 1988.

57. Nyitrai M, Rossi R, Adamek N, Pellegrino MA, Bottinelli R, and Geeves MA. What limits the velocity of fast-skeletal muscle contraction in mammals? *J Mol Biol* 355: 432–442, 2006.

58. Østerås H, Helgerud J, and Hoff J. 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.

59. Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, and Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol (1985)* 86: 1527–1533, 1999.

60. Paavolainen L, Hakkinen K, and Rusko H. Effects of explosive type strength training on physical performance characteristics in cross-country skiers. *Eur J Appl Physiol Occup Phys* 62: 251–255, 1991.

61. Paavolainen LM, Nummela AT, and Rusko HK. Neuromuscular characteristics and muscle power as determinants of 5-km running performance. *Med Sci Sports Exerc* 31: 124–130, 1999.

62. Palmitier RA, An KN, Scott SG, and Chao EY. Kinetic chain exercise in knee rehabilitation. *Sport Med* 11: 402–413, 1991.

63. Plisk SS and Stone MH. Periodization strategies. *Strength Cond J* 25: 19–37, 2003.

64. Rønnestad BR, Hansen EA, and Raastad T. Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. *Eur J Appl Physiol* 108: 965–975, 2010a.

65. Rønnestad BR, Hansen EA, and Raastad T. In-season strength maintenance training increases well-trained cyclists' performance. *Eur J Appl Physiol* 110: 1269–1282, 2010b.

66. Rønnestad BR, Hansen EA, and Raastad T. Strength training improves 5-min all-out performance following 185 min of cycling. *Scand J Med Sci Sports* 21: 250–259, 2011.

67. Rønnestad BR, Hansen J, Hollan I, and Ellefsen S. Strength training improves performance and pedaling characteristics in elite cyclists. *Scand J Med Sci Sports* 25: 89–98, 2015.

68. Rønnestad BR, Kojedal O, Losnegard T, Kvamme B, and Raastad T. Effect of heavy strength training on muscle thickness, strength, jump performance, and endurance performance in well-trained Nordic Combined athletes. *Eur J Appl Physiol* 112: 2341–2352, 2012.

69. Rønnestad BR and Mujika I. Optimizing strength training for running and cycling endurance performance: A review. *Scand J Med Sci Sports* 24: 603–612, 2013.

70. Sale DG. Neural adaptations to strength training. In: *Strength and Power in Sport*. Komi P, ed. Oxford, UK: Blackwell, 1992. pp. 249–265.

71. Sale DG, Jacobs I, MacDougall JD, and Garner S. Comparison of two regimens of concurrent strength and endurance training. *Med Sci Sports Exerc* 22: 348–356, 1990.

72. Saunders PU, Telford RD, Pyne DB, Peltola EM, Cunningham RB, Gore CJ, and Hawley JA. Short-term plyometric training improves running economy in highly trained middle and long distance runners. *J Strength Cond Res* 20: 947–954, 2006.

73. Sedano S, Marín PJ, Cuadrado G, and Redondo JC. Concurrent training in elite male runners: The influence of strength versus muscular endurance training on

performance outcomes. *J Strength Cond Res* 27: 2433–2443, 2013.

74. Spurrs RW, Murphy AJ, and Watsford ML. The effect of plyometric training on distance running performance. *Eur J Appl Physiol* 89: 1–7, 2003.

75. Steindler A. *Kinesiology of the Human under Normal and Pathological Conditions*. Springfield, IL: Charles C Thomas, 1973.

76. Stone MH, Moir G, Glaister M, and Sanders R. How much strength is necessary? *Phys Ther* 3: 88–96, 2002.

77. Stone MH and O'Bryant H. *Weight Training: A Scientific Approach*. Minneapolis, MN: Burgess Publishing, 1987.

78. Stone MH, O'Bryant H, and Garhammer J. A hypothetical model for strength training. *J Sports Med Phys Fitness* 21: 342–351, 1981.

79. Stone MH, O'Bryant HS, Schilling BK, and Johnson RL. Periodization: Effects of manipulating volume and intensity. Part I. *Strength Cond J* 21: 56–62, 1999.

80. Stone MH, Sands WA, Pierce KC, Newton RU, Haff G, and Carlock J. Maximum strength and strength training- a relationship to endurance? *Strength Cond J* 28: 44–53, 2006.

81. Stone MH, Stone M, and Sands WA. *Principles and Practice of Strength Training*. Champaign, IL: Human Kinetics, 2007.

82. Støren O, Helgerud J, Støa EM, and Hoff J. Maximal strength training improves running economy in distance runners. *Med Sci Sports Exerc* 40: 1087–1092, 2008.

83. Sunde A, Støren O, Bjerkaas M, Larsen MH, Hoff J, and Helgerud J. Maximal strength training improves cycling economy in competitive cyclists. *J Strength Cond Res* 24: 2157–2165, 2010.

84. Taipale RS, Mikkola J, Nummela A, Vesterinen V, Capostagno B, Walker S, Gitonga D, Kraemer WJ, and Hakkinen K. Strength training in endurance runners. *Int J Sports Med* 31: 468–476, 2010.

85. Taipale RS, Mikkola J, Vesterinen V, Nummela A, and Hakkinen K. Neuromuscular adaptations during combined strength and endurance training in endurance runners: Maximal versus explosive strength training or a mix of both. *Eur J Appl Physiol* 113: 325–335, 2013.

86. Tanaka H and Swensen T. Impact of resistance training on endurance performance. A new form of cross-training? *Sports Med* 25: 191–200, 1998.

87. Trehearn TL and Buresh RJ. Sit-and-reach flexibility and running economy of men and women collegiate distance runners. *J Strength Cond Res* 23: 158–162, 2009.

88. Turner AM, Owings M, and Schwane JA. Improvement in running economy after 6 weeks of plyometric training. *J Strength Cond Res* 17: 60–67, 2003.

89. Van Etten LM, Verstappen FT, and Westererp KR. Effect of body build on weight-training induced adaptations in body composition and muscular strength. *Med Sci Sports Exerc* 26: 515–521, 1994.

90. Verkhoshansky U. The long-lasting training effect of strength exercises. *Soviet Sports Rev* 20: 1–3, 1985.

91. Wakahara T, Fukutani A, Kawakami Y, and Yanai T. Nonuniform muscle hypertrophy: Its relation to muscle activation in training session. *Med Sci Sports Exerc* 45: 2158–2165, 2013.

92. Wilson JM, Marin PJ, Rhea MR, Wilson SM, Loenneke JP, and Anderson JC. Concurrent training: A meta-analysis examining interference of aerobic and resistance exercises. *J Strength Cond Res* 26: 2293–2307, 2012.

93. Zamparo P, Minetti AE, and di Prampero PE. Interplay among the changes of muscle strength, cross-sectional area and maximal explosive power: Theory and facts. *Eur J Appl Physiol* 88: 193–202, 2002.

94. Zatsiorsky VM. *Science and Pracitce of Strength Training*. Champaign, IL: Human Kinetics, 1995.