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Review

Optimizing strength training for running and cycling endurance performance: A review

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Here we report on the effect of combining endurance training with heavy or explosive strength training on endurance performance in endurance-trained runners and cyclists. Running economy is improved by performing combined endurance training with either heavy or explosive strength training. However, heavy strength training is recommended for improving cycling economy. Equivocal findings exist regarding the effects on power output or velocity at the lactate threshold. Concurrent endurance and heavy strength training can increase running speed and power output at VO_{2max} (V_{max} and W_{max}, respectively) or time to exhaustion at V_{max} and W_{max}. Combining endurance training with either explosive or heavy strength training can improve running performance, while there is most compelling evidence of an additive effect on cycling performance when heavy strength training is used. It is suggested that the improved endurance performance may relate to delayed activation of less efficient type II fibers, improved neuromuscular efficiency, conversion of fast-twitch type IIX fibers into more fatigue-resistant type IIA fibers, or improved musculo-tendinous stiffness.

The effects of strength training on endurance athletic performance have long been the subject of debate among athletes, coaches, and sport scientists. Strength training includes both explosive strength training and heavy strength training that promote different training adaptations. Heavy strength training can be defined as "all training aiming to increase or maintain a muscle or a muscle group's ability to generate maximum force" (Knuttgen & Kraemer, 1987) and is here equal to training with a load that allows between 1 repetition maximum (RM) and 15 RM. Explosive strength training is here defined as exercises with external loading of 0–60% of 1 RM and maximal mobilization in the concentric phase (0% of 1 RM equals body weight). Performance in most endurance events is mainly determined by the maximal sustained power production for a given competition distance, and the energy cost of maintaining a given competition speed. In shorter endurance events and during accelerations and sprint situations, anaerobic capacity and maximal speed may also contribute to performance. Strength training contributes to enhance endurance performance by improving the economy of movement, delaying fatigue, improving anaerobic capacity, and enhancing maximal speed.

Some of the early studies that investigated the effect of combining endurance and strength training in endurance-trained athletes did not identify any additive effect on endurance performance (Jensen, 1963; Paavolainen et al., 1991; Tanaka et al., 1993). However, recent evidence contradicts the findings of those early studies and points toward an additive effect of combining the endurance and strength training on running and cycling performance (Tanaka & Swensen, 1998). At the time of this review, there was a lack of good studies on already well-trained endurance athletes, especially in cycling. The purpose of this review is to provide an updated synopsis on the effect of combining endurance training with heavy or explosive strength training on endurance performance in endurance-trained runners and cyclists.

The effects of strength training on factors determining endurance performance

Maximal oxygen consumption

Maximal oxygen consumption (VO_{2max}) has long been associated with success in endurance sports (Saltin & Astrand, 1967; Costill et al., 1973; Bassett & Howley, 2000) and is one of the major characteristics that determine endurance performance (Di Prampero, 2003; Levine, 2008). Importantly, the highest VO_{2max} value does not necessarily equate to the best endurance performance, but the best endurance performance typically demands high VO_{2max} values (Saltin & Astrand, 1967;

Costill et al., 1973; Lucia et al., 1998; Bassett & Howley, 2000; Impellizzeri et al., 2005). In addition, VO_{2max} sets the upper limit of intensity for prolonged steady-state exercise.

There is little evidence that strength training should be the primary training mode to improve VO_{2max}, and only a trivial effect of concurrent strength and endurance training on VO_{2max} compared to endurance training alone in trained cyclists (Hickson et al., 1988; Bishop et al., 1999; Bastiaans et al., 2001; Levin et al., 2009; Rønnestad et al., 2010a, b; Sunde et al., 2010; Aagaard et al., 2011), long-distance runners (Johnston et al., 1997; Paavolainen et al., 1999; Spurrs et al., 2003; Turner et al., 2003; Saunders et al., 2006; Mikkola et al., 2007a, 2011; Storen et al., 2008; Taipale et al., 2010), cross-country skiers (Hoff et al., 1999, 2002; Osteras et al., 2002; Mikkola et al., 2007b; Losnegard et al., 2011; Rønnestad et al., 2012), or triathletes (Millet et al., 2002). However, the majority of the training interventions investigating the effects of concurrent training lasted only 8 to 12 weeks. Caution should be used when long-term effects of concurrent training are considered.

Exercise economy

Exercise economy has been defined as the oxygen consumption required at a given absolute submaximal exercise intensity (Jones & Carter, 2000; Saunders et al., 2004). There is substantial interindividual variability in exercise economy in both running and cycling despite a similar VO_{2max} (Conley & Krahenbuhl, 1980; Horowitz et al., 1994). The importance of exercise economy is underlined by the close relationship with endurance performance in trained individuals with homogenous VO_{2max} (Costill, 1967; Conley & Krahenbuhl, 1980; Horowitz et al., 1994). Accordingly, it is likely that any improvement in exercise economy will be associated with improved long-term endurance performance.

Numerous studies have reported improved running economy after 8–14 weeks of concurrent heavy strength and endurance training, while no substantial changes were observed in the control groups (Johnston et al., 1997; Hoff & Helgerud, 2002; Millet et al., 2002; Storen et al., 2008; Guglielmo et al., 2009; Taipale et al., 2010). Improved running economy is also evident after 6–12 weeks of combined explosive strength and endurance training in runners (Paavolainen et al., 1999; Spurrs et al., 2003; Turner et al., 2003; Saunders et al., 2006; Taipale et al., 2010). Mikkola et al. (2007a) replaced some of the endurance training of young distance runners with only one session a week of explosive strength training and did not find changes in running economy. Given that running economy can be improved by 2–3 strength training sessions per week, it seems a threshold of (explosive) strength training volume and frequency has to be overcome to achieve improved running economy. When cycling economy is measured by the same traditional method used in running (i.e., short, 3–5 min, submaximal bouts of exercise), it appears there is little change after combining heavy strength or explosive strength training with endurance training (Bastiaans et al., 2001; Rønnestad et al., 2010a, b; Aagaard et al., 2011). However, adding heavy strength training to endurance training can improve cycling economy after only 8 weeks (Sunde et al., 2010). The reasons for this discrepancy remain unclear, but the lower performance level of the cyclists in the latter study may have affected the outcome of strength training. On the other hand, by using a nontraditional protocol to measure cycling economy during 5-min periods every half hour throughout 3 h of submaximal cycling, a superior improvement was observed during the last hour after a period of concurrent heavy strength and endurance training (Rønnestad et al., 2011). Lowered heart rate at the end of 2 h of submaximal cycling has also been observed after 5 weeks of heavy strength training in triathletes (Hausswirth et al., 2010). Thus, divergent findings are evident on whether performing heavy strength training together with ordinary endurance training improves cycling economy. This shortcoming may relate in part to methodological differences between studies. Nevertheless, there are no reports of a negative effect of heavy strength and explosive strength training on either cycling or running economy.

Lactate threshold

The fraction of VO_{2max}, which can be sustained during a performance bout (performance VO_2), is associated with the degree of blood lactate accumulation during exercise (Farrell et al., 1979; LaFontaine et al., 1981; Tanaka & Seals, 2008). Several methods have been devised to express the relationship between blood lactate concentration ($[la^-]$) and fraction of VO_{2max} (Bentley et al., 2007; Faude et al., 2009). A common term is lactate threshold, which describes an estimation of a breakpoint on the $[la^-]$ curve as a function of exercise intensity (Tokmakidis et al., 1998). Lactate threshold expressed as a percentage of VO_{2max} is largely unaffected by exercise economy and VO_{2max}, which might explain the small correlation between lactate threshold expressed as % VO_{2max} and time trial cycling performance in cyclists (Støren et al., 2012). There are numerous ways to determine the power output or speed at the lactate threshold, resulting in diverse "thresholds" on the $[la^-]$ vs power/speed curve, which all seem to correlate well with long-term endurance performance (Tokmakidis et al., 1998). Any rightward movement of the $[la^-]$ curve results in improved power output/velocity at the lactate threshold regardless of how the lactate threshold has been determined (Tokmakidis et al., 1998). A higher velocity/power output at the lactate threshold theoretically means that an athlete can maintain a higher velocity/power output during extended exercise. Numerous studies report a high relationship between long-term performance and velocity/power output at the lactate threshold in both cycling and running, and the latter is useful for predicting endurance performance in both runners and cyclists (e.g. Farrell et al., 1979; Coyle et al., 1988, 1991; Grant et al., 1997; Bishop et al., 1998; Lucia et al., 1998; Impellizzeri et al., 2005; Slattery et al., 2006).

Since the majority of studies reported improved running economy in response to a period of concurrent strength and endurance training in endurance-trained individuals, it would be reasonable to expect an improvement in the exercise velocity or intensity associated with the lactate threshold. This expectation is based on the assumption that the main determinants of the lactate threshold velocity are VO_{2max} and exercise economy (Di Prampero et al., 1986), and that VO_{2max} is not compromised while concurrently performing strength and endurance training. However, the endurance training literature comprises equivocal findings: some studies report little change in the lactate threshold of runners (Paavolainen et al., 1999; Hoff & Helgerud, 2002; Mikkola et al., 2011; Støren et al., 2012), while others observed substantial improvements in velocity at the lactate threshold (Mikkola et al., 2007a, 2011; Guglielmo et al., 2009; Taipale et al., 2013). Some studies report improved power output at a certain [la^-] (Koninckx et al., 2010; Rønnestad et al., 2010a, b), while others report no additional effect of performing strength training (Bishop et al., 1999; Sunde et al., 2010; Aagaard et al., 2011). Importantly, none of the studies on long-distance runners and cyclists report a negative effect of strength training on velocity or power output at the lactate threshold.

Other factors important for endurance performance

The key performance and physiological measures of VO_{2max}, lactate threshold, and exercise economy explain >70% of the between-subject variance in long-duration endurance performances (Di Prampero et al., 1986). Other factors contribute to endurance performance including running speed and power output at VO_{2max} (V_{max} and W_{max}, respectively) predict endurance performance in endurance-trained runners and cyclists, respectively (Morgan et al., 1989; Noakes et al., 1990; Hawley & Noakes, 1992; Yoshida et al., 1993; Billat & Koralsztein, 1996; Bentley et al., 1998; Lucia et al., 1998; Balmer et al., 2000; Stratton et al., 2009). Both W_{max} and V_{max} distinguish the endurance performance in well-trained cyclists and long distance runners, making them a useful marker of endurance performance (Noakes et al., 1990; Lucia et al., 1998). W_{max} and V_{max} are influenced by VO_{2max} and exercise economy, but also incorporate anaerobic capacity and neuromuscular characteristics (Jones & Carter, 2000). Anaerobic power and neuromuscular characteristics are also involved in long-duration endurance performance, especially when athletes are matched for aerobic capacity (Bulbulian et al., 1986; Houmard et al., 1991; Paavolainen et al., 1999b; Baumann et al., 2012). Concurrent endurance and heavy strength training can increase W_{max}/V_{max} or time to exhaustion at W_{max}/V_{max} (Hickson et al., 1988; Millet et al., 2002; Rønnestad et al., 2010a, b; Sunde et al., 2010; Taipale et al., 2010, 2013; Mikkola et al., 2011; Støren et al., 2012). However, this positive effect in cyclists was not observed by using explosive strength training (Bastiaans et al., 2001) nor after short-term (6 weeks) strength training (Levin et al., 2009).

Another related factor important for endurance performance is the ability to generate high power output over a short period of time to get a good position at the start of a race, close a gap, make a critical pass, break away from the pack, or win a final sprint. Peak power output is markedly affected by muscle cross-sectional area (Izquierdo et al., 2004) – increased cross-sectional area of the quadriceps muscle was associated with increased peak power output after combined heavy strength training and endurance training in well-trained cyclists (Rønnestad et al., 2010a). Similarly, anaerobic running power can increase substantially after a period of added explosive strength training (Paavolainen et al., 1999; Mikkola et al., 2007a).

Endurance performance

The traditional way of measuring cycling performance is time trialing lasting between 30 and 60 min. However, the effects of strength training are contradictory with studies variously showing either improvements (Hickson et al., 1988; Koninckx et al., 2010; Rønnestad et al., 2010b; Aagaard et al., 2011) or a trivial effect (Bishop et al., 1999; Bastiaans et al., 2001; Levin et al., 2009). When positive effects are reported, heavy strength training is performed with multiple leg exercises. In contrast, studies failing to show much improvement were typically short term in duration, with a low volume of strength training or using explosive strength training. In contrast, adding both explosive and heavy strength training to endurance training can improve running performance, while no change was observed in the control groups performing endurance training only (Paavolainen et al., 1999; Spurrs et al., 2003; Støren et al., 2012).

Combining heavy strength training and regular endurance training increased mean power output production during a final 5-min all-out sprint after 3 h of submaximal cycling by 7%, while no changes occurred in the endurance training group (Rønnestad et al., 2011). Not all studies, however, have reported that concurrent training results in superior endurance performance, especially in males (Kraemer et al., 2004; Barnes et al., 2013). Nevertheless, there are no reports of negative impacts of concurrent training on endurance performance.

Potential mechanisms

A likely mechanism for improved performance after combined strength and endurance training is (altered) muscle fiber type recruitment pattern. When measuring cycling economy the traditional way, by measuring oxygen consumption during a short period of time at steady-state exercise intensities below the lactate threshold, mainly type I fibers that are activated. In this setting, may the effect of increasing the maximum strength of type I fibers and postponing the activation of the less economical type II fibers be trivial or small. This effect might explain why the literature seems is equivocal on improvements in cycling economy in well-trained cyclists measured the traditional way. Altered muscle fiber recruitment may also explain why improvement of cycling economy in well-trained cyclists after a period of concurrent training is detected first after about 2 h of submaximal cycling (Rønnestad et al., 2011). It is likely that after prolonged cycling will some of the type I fibers be exhausted and the less economical type II fibers gradually increases their contribution to the exercise. It might be suggested that the strength training increases the maximum strength of type I fibers and postpones their time to exhaustion and thereby delaying the activation of type II fibers. Strength training increases maximal force, and therefore peak force or muscle-fiber tension developed in each movement cycle at the same absolute exercise intensity decreases to a lower percentage of the maximal values. A cross-sectional study of cyclists with similar VO_{2max} and W_{max} reported lower EMG activity in the cyclists with higher compared with lower maximal strength (Bieuzen et al., 2007).

Another potentially contributing factor to improved endurance performance is an increased proportion of type IIA fibers and reduced proportion of type IIX fibers. A 16-week study in top-level cyclists combining heavy strength training and endurance training in top-level cyclists examined the proportional redistribution in type II muscle fibers (Aagaard et al., 2011). The increase in the more fatigue-resistant, yet high capability of power output, type IIA fibers may contribute to improved endurance performance. However, there have also been reported no changes in fiber composition in endurance athletes after a period of concurrent strength and endurance training (Bishop et al., 1999). The different findings might be related to differences in initial percentages of type IIX fibres (Bishop et al., 1999).

According to the size principle of motor unit recruitment (Henneman et al., 1965), the following mechanism may be hypothesized: a reduced reliance on the less efficient type II muscle fibers and thus improved exercise economy; slower emptying of glycogen stores; reduced overall muscle fatigue; and a potentially increased capacity for high-intensity performance following prolonged exercise or an increased ability by the athlete to exercise longer until exhaustion (Hickson et al., 1988; Coyle et al., 1992; Horowitz et al., 1994). A 12-week program of heavy strength training resulted in higher phosphocreatine and glycogen content and lower [la$^-$] at the end of 30 min cycling at 72% of VO_{2max}, despite no change in VO_{2max} (Goreham et al., 1999). The performed strength training program was almost identical to the strength training performed in the studies reporting a superior effect of concurrent training in long-term endurance performance, despite the observation of no change in the traditional way of measuring cycling economy (Aagaard et al., 2011; Rønnestad et al., 2011). The studies in which no additive performance effect of concurrent training in cyclists was found performed either explosive strength training with low external load (Bastiaans et al., 2001), low volume of heavy strength training (Bishop et al., 1999), or lasted for a short duration (Levin et al., 2009). Thus, it seems that differences in a strength training program can explain the different findings. Explosive strength training and low-volume heavy strength training can induce inferior strength and hypertrophic responses compared to higher volume of heavy strength (Rønnestad et al., 2007; Holm et al., 2008). Unfortunately, no performance measurements were obtained in the study of Goreham et al. (1999), but the improved aerobic metabolism and conservation of limited glycogen stores are important for long-term endurance performance. Interestingly, they did not observe any change in cycling economy.

Another putative mechanism explaining improvement in endurance-related measurements after concurrent training is increased maximum force, and/or increased rate of force development (RFD) facilitating better blood flow to exercising muscles (Hoff et al., 1999, 2002; Sunde et al., 2010; Aagaard et al., 2011; Støren et al., 2012). Increases in RFD is often caused by increased neural activation and both heavy strength training with maximal velocity in the concentric phase of the lift and explosive strength training can increase neural activation (Mikkola et al., 2011). Superior improvement in maximum force and RFD was accompanied by superior improvement in exercise economy (Heggelund et al., 2013). Improvement in maximum force and/or RFD might lower the relative exercise intensity and induce less constriction of the blood flow. Alternatively, improved RFD may reduce time to reach the desired force in each movement cycle. A shorter contraction time or shorter time with relative high force production in working muscles may increase blood flow to the muscles by reducing time where blood flow is restricted. Whether blood flow is enhanced after a period of concurrent training has not been thoroughly investigated, but in theory, an increase in blood flow will increase delivery of O_2 and substrates to the working muscles – contributing to enhanced endurance performance (but not necessarily improved exercise economy). On the other hand, a recent study on moderately trained cyclists by Barrett-O'Keefe et al. (2012) showed that 8 weeks of heavy strength training improved work economy at a cadence of 60 rpm, reduced muscular blood flow, while maintaining muscular arterial-venous oxygen difference. The latter indicates that improvement in muscular efficiency is an important mechanism behind improved work economy and improved endurance performance.

Magnetic resonance imaging indicates that increased maximum strength reduces the amount of activated muscle mass to generate the same absolute submaximal power (Ploutz et al., 1994). If less muscle mass generates the same power after increased maximum strength, metabolic strain is concentrated on fewer fibers and obviates the effect of increased maximum strength. In the opposite direction, activated muscle fibers might exercise at the same relative intensity due to the increase in maximum strength. If that is the case, then the strength training would presumably not affect exercise economy directly, measured as oxygen consumption, but potentially increase the endurance performance via increasing the quantity of fresh muscle mass available when the final sprint is approaching. In a time trial setting, where the objective is to cover a certain distance as fast as possible, this adaptation could theoretically result in superior performance due to increased power output per unit muscle mass.

One of the distinct differences between cycling and running is the stretch-shortening cycle in running, while the leg movements in cycling are mainly composed of concentric muscle actions. Thus, cyclists are not able to store energy during an eccentric phase and utilize it in the subsequent concentric phase to the same extent as runners. It is estimated that storage and return of elastic energy during running approximates about half of the mechanical work performed during the eccentric phase of a running stride (Cavagna et al., 1964). In accordance with the latter assertion, stiffness of the musculoskeletal system in the lower body is associated with enhanced running economy in a wide range of runners (Craib et al., 1996; Jones, 2002; Trehearn & Buresh, 2009). Muscle-tendon system is able to increase its stiffness through both explosive strength training (Fouré et al., 2011) and heavy strength training (Kubo et al., 2001, 2002). Furthermore, stiffness increases in the muscle-tendon system of the lower body after adding both heavy strength training (Millet et al., 2002) and explosive strength training (Spurrs et al., 2003) to the ongoing endurance training. Importantly, it is likely that there may be an individual optimal stiffness in the muscle-tendon system. There are apparent advantages of stiff tendons in some cases and compliant tendons in other cases (Fletcher et al., 2010). Improved utilization of elastic energy in the muscle-tendon system in the lower body would reduce the demand of adenosine triphosphate production even at low submaximal running intensities, thus improving running economy as observed in the majority of the presented studies. This mechanism is unlikely to be equally important when cycling due to the lack of pronounced eccentric phase from which the elastic energy can be utilized.

Potential negative outcomes

A potential counterproductive outcome of strength training is that muscle hypertrophy could have a negative impact on weight-bearing endurance events. An increase in myofiber cross-sectional area could reduce capillary to muscle fiber cross-sectional area ratio, thus increasing diffusion distance. In this respect, it is worth mentioning that 8–16 weeks of supplemental strength training failed to increase total body mass nor compromise the development of VO_{2max} in endurance athletes including cyclists (Bishop et al., 1999; Bastiaans et al., 2001; Levin et al., 2009; Rønnestad et al., 2010a, b; Sunde et al., 2010; Aagaard et al., 2011), runners (Johnston et al., 1997; Paavolainen et al., 1999; Spurrs et al., 2003; Turner et al., 2003; Saunders et al., 2006; Mikkola et al., 2007a, 2011; Storen et al., 2008), duathletes and triathletes (Hickson et al., 1988; Millet et al., 2002), and cross-country skiers (Hoff et al., 1999, 2002; Osteras et al., 2002; Mikkola et al., 2007b; Losnegard et al., 2011; Rønnestad et al., 2012).

Even though strength training can be added to endurance training without a concomitant increase in total body mass, there seems to be a small, ~3–6%, increase in measurements of muscle hypertrophy of the main target muscles (Rønnestad et al., 2010a, 2012; Taipale et al., 2010; Aagaard et al., 2011; Losnegard et al., 2011). An impaired hypertrophic response to strength training is likely explained by recent developments within molecular sports science. Endurance exercise may negatively affect intracellular pathways important for myofibrillar protein synthesis (reviewed in Hawley, 2009). Activation of adenosine monophosphate-activated protein kinase by endurance exercise may inhibit mammalian target of rapamycin signaling and suppress strength exercise-induced myofibrillar protein synthesis (Nader, 2006; Hawley, 2009). Consequently, acute intracellular signaling response to concurrent strength and endurance training does not promote ideal activation of pathways responsible for muscle hypertrophy (Coffey et al., 2009). Observations of disparate mRNA response to concurrent strength and endurance training underline the importance of local factors in explaining compromised strength training adaptations to a large volume of concurrent training (Coffey et al., 2009).

The observed impaired or absence of whole muscle or muscle fiber hypertrophy after combining strength training with large volumes of endurance training (Hickson et al., 1988; Bishop et al., 1999; Rønnestad et al., 2010a, b, 2012; Aagaard et al., 2011; Losnegard et al., 2011) greatly reduces the risk of impaired capillary to muscle fiber ratio. In untrained subjects, strength training alone can increase some aspects of the capillaries perfusing skeletal muscle fibers (Hather et al., 1991; Green et al., 1999; McCall et al., 2004). In moderate-trained students, an increase in capillary to fiber ratio has been observed after concurrent strength and endurance training, while no change was evident after strength or endurance training alone (Bell et al., 2000). The only study performed on top-level endurance athletes did not observe a negative effect after 16 weeks of concurrent heavy strength training and endurance training on muscle capillarization (Aagaard et al., 2011). In addition, after a period of concurrent strength and endurance training, there is no impairment of the oxidative enzyme activity in endurance-trained athletes (Hickson et al., 1988; Bishop et al., 1999; Bell et al., 2000). Thus, with regard to muscle vascularization and oxidative potential, there seems to be no indications of negative effect of strength training.

Practical recommendations

To increase the probability of improved endurance performance subsequent to a strength training period, the strength training exercises should involve similar muscle groups and imitate the sports-specific movements. This advice is underpinned by adaptations in the neural system (like optimal activation of the involved muscles) as well as structural adaptations (like optimizing the number of active cross-bridges in that particular range of motion). An intended rather than the actual velocity appears to determine the velocity-specific training response (Behm & Sale, 1993; Heggelund et al., 2013). This scenario means that even though the actual movement velocity is quite low, RFD might be increased if the athlete focuses on performing the concentric phase of the lift as quick as possible. Superior adaptations in maximal strength and RFD are achievable after 8 weeks of heavy strength training with maximal velocity in the concentric phase compared to moderate velocity in the concentric phase (Heggelund et al., 2013). This superiority was accompanied by superior improvement in exercise economy during single leg knee extension in untrained to moderate-trained persons. Athletes are advised to build up maximal strength in the important muscles during the preparatory period. Two strength training sessions per week, designed as a "daily undulating periodized program" is typically enough to achieve a sufficient increase in strength during a 12-week period. Athletes are advised to perform between 4 RM and 10 RM and 2–3 sets with approximately 2–3 min of rest between sets. Before endurance athletes start lifting heavy loads, they must ensure that they have first developed a proper lifting technique with lighter loads. Note that in the beginning of a strength training period, it is common to get "heavy" and "sore" legs in the first days after the strength training session. Therefore, it is important to commence at low level with the concurrent endurance training during the first 2–3 weeks of a strength training program. One approach to overcome this initial strength training adaptation phase is to conduct it just after the end of a competition season, when endurance training has a lower priority. During the competitive season or in training periods, development of strength is not prioritized, approximately one strength training session per week (low volume) with high intensity seems to maintain the previous strength training adaptations (Rønnestad et al., 2010b, 2011b).

Both explosive and maximal strength training have positive influences on endurance running performance and/or running economy in endurance athletes (e.g., Paavolainen et al., 1999; Millet et al., 2002; Spurrs et al., 2003; Støren et al., 2012). Recently, the enhancing effects of combining endurance training with either heavy or explosive strength training on running performance have been investigated. The studies that report a difference in adaptations after heavy or explosive strength training point toward more favorable adaptations as a result of heavy strength training (Guglielmo et al., 2009; Mikkola et al., 2011; Barnes et al., 2013).

Conclusion

Recent research on highly trained athletes indicates that strength training can be successfully prescribed to enhance endurance performance (Table 1). For cycling performance, heavy strength training with maximal

Table 1. Effects of heavy and explosive strength training on endurance performance

Potential positive physiological and performance effect	Evidence of benefit	Potential negative physiological and performance effect	Evidence of negative outcome
Improved VO_{2max}	No	Increased body mass	No
Improved exercise economy	Yes	Compromised relative VO_{2max}	No
Improved anaerobic capacity	Yes	Increased diffusion distance	No
Improved lactate threshold	Yes	Reduced capillarization	No
Reduced or delayed fatigue	Yes	Reduced oxidative enzyme activity	No
Improved maximal strength	Yes		
Improved rate of force development	Yes		
Improved maximal speed	Yes		
Improved endurance performance	Yes		

velocity during the concentric phase is preferred, while both heavy strength training with maximal velocity during the concentric phase and explosive strength training have additive effects on running performance. The primary explanation for improved endurance performance is most likely adaptations within the strength-trained muscle including postponed activation of less efficient type II fibers, improved neuromuscular efficiency, conversion of fast-twitch type IIX fibers into more fatigue-resistant type IIA fibers, and improved musculo-tendinous stiffness. Importantly, no negative effects of adding strength training to an endurance training program have been reported.

Perspectives

The effects of strength training on endurance athletic performance have been the subject of a long debate among athletes, coaches, and sport scientists. Incorporation of strength training in endurance athletes' preparation has gradually received more attention during the last two decades with studies showing divergent findings. Some of this discrepancy seems to be related to the mode of strength training. In general a coach and athlete can employ with confidence concurrent endurance and strength training to improve athletic endurance performance. To optimize the effect of added strength training to cycling performance, athletes should undertake heavy strength training with maximal velocity during the concentric phase should be the training mode to recommend (instead of explosive strength training), while both explosive- and heavy strength training with maximal velocity during the concentric phase appear to have an additive effect on running performance.

Key words: aerobic capacity, concurrent training adaptations, exercise economy, neuromuscular function, cycling, running.

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