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Effects of High-intensity Training on Performance and Physiology of Endurance Athletes

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Most endurance athletes use high-intensity training to prepare for competitions. In this review we consider the effects of high-intensity interval and resistance training on endurance performance and related physiological measures of competitive endurance athletes. METHODS. There were 22 relevant training studies. We classified training as intervals (supramaximal, maximal, submaximal) and resistance (including explosive, plyometrics, and weights). We converted all effects on performance into percent changes in mean power and included effects on physiological measures that impact endurance performance. FINDINGS. All but one study was performed in non-competitive phases of the athletes' programs, when there was otherwise little or no high-intensity training. Endurance performance of the shortest durations was enhanced most by supramaximal intervals (~4%) and explosive sport-specific resistance training (4-8%). Endurance performance of the longest durations was enhanced most by intervals of maximal and supramaximal intensities (~6%), but resistance training had smaller effects (~2%). Interval training achieved its effects through improvements of maximum oxygen consumption, anaerobic threshold, and economy, whereas resistance training had benefits mainly on economy. Effects of some forms of high-intensity training on performance or physiology were unclear. CONCLUSIONS. Addition of explosive resistance and high-intensity interval training to a generally low-intensity training program will produce substantial gains in performance. More research is needed to clarify the effects of the various forms of high-intensity training on endurance performance, to determine whether prescribing specific forms of resistance training can improve specific deficits of an endurance athlete's physiology, and to determine the effects of combining the various forms in periodized programs. KEYWORDS: aerobic, anaerobic threshold, economy, plyometrics, resistance, strength.

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INTRODUCTION

Endurance in relation to athletic performance has been defined in various ways. In this article we have reviewed effects of high-intensity training not only on athletic endurance performance but also on underlying changes in the aerobic energy system. Endurance for our purposes therefore refers to sustained high-intensity events powered mainly by aerobic metabolism. Such events last ~30 s or more (Greenhaff and Timmons, 1998).

Training for endurance athletes generally emphasizes participation in long-duration low- or moderate-intensity exercise during the base or preparation phase of the season, with the inclusion of shorter-duration high-intensity efforts as the competitive phase approaches. The effects of low- to moderate-intensity endurance training on aerobic fitness are well documented (see Jones and Carter, 2000 for review), but reviews of high-intensity training on endurance performance have focused only on describing the effects of resistance training (Tanaka and Swensen, 1998), the effects of resistance training with runners (Jung, 2003), and the different types of interval training used by athletes (Billat, 2001a) and studied by researchers (Billat, 2001b). Furthermore, previous reviews have included the effects of high-intensity training on untrained or recreationally active subjects, so findings may not be applicable to competitive athletes. The purpose of this review was therefore to describe the effects of high-intensity training on performance and relevant physiological characteristics of endurance athletes.

METHODS

Selection of Studies

We identified most relevant publications through previous reviews and our own reference collections. We found 22 original-research peer-reviewed articles that identified competitive endurance athletes as the subjects in a study of effects of high-intensity training on performance or related physiology. We excluded studies of recreationally active subjects or of subjects whose characteristics were not consistent with those of competitive athletes, including Daniels et al. (1978), Hickson et al. (1988), Tabata et al. (1996), Franch et al. (1998), and Norris and Petersen (1998). We did not perform a systematic search of SportDiscus or Medline databases for theses or for non-English articles, and we did not include data from chapters in books.

Analysis of Training

We assigned the training to two categories:

- Resistance training: sets of explosive sport-specific movements against added resistance, usual or traditional weight training (slow repeated movements of weights), explosive weight training, or plyometrics and other explosive movements resisted only by body mass (Table 1).
- Interval training: single or repeated intervals of sport-specific exercise with no additional resistance (Table 2).

Classification of some resistance-training studies was difficult, owing to the mix of exercises or lack of detail. In particular, all the studies we classified under explosive sport-specific resisted movements probably included some non-explosive resisted movements and some plyometrics.

We classified the duration and intensity of intervals in Table 2 as follows: supramaximal (<2 min), maximal (2-10 min) and submaximal (>10 min), where "maximal" refers to the intensity corresponding to maximum oxygen consumption (VO_2max). The supramaximal intervals will have been performed at or near all-out effort; the maximal intervals will have started at less than maximum effort, but effort will have approached maximum by the end of each interval; the submaximal intervals can be considered as being close to

Table 1: Experimental and control training in studies of the effects of high-intensity resistance training on endurance performance in competitive athletes.

Study	Experimental training	Control training[a]
Explosive sport-specific resisted movements		
Hoff et al. (1999)	Skiing-specific, 3x 6RM, 7%; general strength, 2%; endurance, 70%; total 8.5 $h.wk^{-1}$	Endurance, 72%; general strength, 13%; total 9.2 $h.wk^{-1}$ in basic preparation phase
Hoff et al. (2002)	Skiing-specific, 3x 6RM, 7.5%, plus endurance; total 9.6 $h.wk^{-1}$	Mainly endurance with strength endurance; total 10.1 $h.wk^{-1}$ in pre-season phase
Osteras et al. (2002)	Skiing-specific, 3x 6RM, 5% of total of 15 $h.wk^{-1}$	Endurance + strength-endurance weights, total 15 $h.wk^{-1}$ in pre-competition phase
Paavolainen et al. (1991)	Skiing-specific, 34-42%; endurance, 66-58%; total 6-9 sessions wk^{-1} in base preparation phase	Endurance running & roller skiing (83%) + strength-endurance weights (17%); total 6-9 sessions wk^{-1} in base preparation phase
Paavolainen et al. (1999)	Running-specific, 32%; endurance and circuit, 68%; 2-3 $session.wk^{-1}$; total 9.2 $h.wk^{-1}$	Endurance running and circuit, 97%; running-specific explosive strength, 3%; total 9.2 $h.wk^{-1}$ in post-competition phase
Sport-specific resisted movements		
Toussaint and Vervoorn (1990)	Swimming sprints against resistance for 30 min, 3 wk^{-1} for 10 wk in competition phase, plus usual (?) swim training	Same as experimental group but without additional resistance during sprint training
Explosive non-sport-specific weight training		
Bastiaans et al. (2001)	4x sets of 30 reps each of squats, leg presses, single-leg step ups for 3.3 $h.wk^{-1}$, plus 5.5 $h.wk^{-1}$ of control endurance cycling	8.9 $h.wk^{-1}$ endurance cycling in pre-competition phase
Plyometrics		
Spurrs et al. (2003)	2x 10 reps of 3-4 jumps, bounding and hops, plus 60-80 km. wk^{-1} endurance running	60-80 km. wk^{-1} endurance running; training phase not stated
Turner et al. (2003)	6 sets of jumps, 3 wk^{-1} for 6 wk, plus usual low-intensity endurance running	Minimum 3 sessions and 16 $km.wk^{-1}$ running; unspecified intensity and training phase
Usual weight training		
Bishop et al. (1999)	3-5 sets of 2-8RM squats, plus usual endurance cycling	Endurance cycling in off-season, unspecified weekly duration
Johnston et al. (1997)	2-3 sets of 6-20RM, plus 32-48 $km.wk^{-1}$ endurance running	32-48 $km.wk^{-1}$ endurance running in pre-competition phase
Millet et al. (2002)	3-5 sets of 3-5RM of 6 lower-limb exercises, 2 wk^{-1} for 14 wk, plus control endurance training	20 $h.wk^{-1}$ endurance running, cycling, swimming at <70 $\%VO_2max$ in winter non-competition phase

RM, repetitions maximum.
[a]"Endurance training" is presumably long sessions below submaximal intensity (below anaerobic threshold).

anaerobic threshold pace (a pace that can be sustained for ~45 min), and effort will have risen to near maximum by the end of each interval.

A major concern with all but one of the studies we reviewed is that the high-intensity training interventions were performed in the non-competitive phases of the athletes' season, when there was otherwise little or no intense training. Authors who have monitored endurance athletes throughout a season have reported substantial improvements in performance and changes in related physiological measures as athletes progress from the base training to competitive phases (Barbeau et al., 1993; Lucia et al., 2000; Galy et al., 2003). Indeed, our own unpublished observations show that well-trained cyclists ordinarily make improvements in power output of ~8% in laboratory time trials as they progress from base through competitive phases of their season. The large improvement in performance as the competitive phase approaches occurs because athletes normally include higher intensity endurance training as part of a periodized program. It therefore seems unlikely that the large improvements reported in studies performed during a non-competitive phase would be of the same magnitude if the studies were performed in the competitive phase, when the athletes ordinarily include higher intensity training in their program. Indeed, in the only training study we could find performed during the competitive phase of a season, Toussaint and Vervoorn (1990) found that 10 weeks of sport-specific resistance training improved race performance time in national level competitive swimmers by ~1%. Though such improvements appear small, they are important for elite swimmers (Pyne et al., 2004), and the estimated change in power of ~3% is certainly greater than the ~0.5% that is considered important in other high-level sports (Hopkins et al., 1999).

Table 2: Experimental and control training in studies of the effects of high-intensity **interval training** on endurance performance in competitive athletes.

Study	Experimental training	Prior and/or control training[a]
Submaximal intervals		
Sjodin et al. (1982)	Running at anaerobic threshold, 1x 20 min, 1 session.wk^{-1} for 14 wk, plus usual training	No control; usual winter training, ~6.5 h.wk^{-1}
Maximal intervals		
Acevedo and Goldfarb (1989)	Running, ?x ? min, 1 session.wk^{-1}, plus Fartlek (presumably mainly max) sessions (8-19 km, 2 session.wk^{-1} for 8 wk	No control; endurance training runs (8-19km) for 3-4 session.wk^{-1}
Billat et al. (1999)[b]	Running, 5x 3 min, 1 session.wk^{-1}, plus 2x 20 min (submax), 1 session.wk^{-1} replacing usual training	No control; low-intensity base phase training, unspecified weekly duration
Laursen et al. (2002b)	Cycling, 8x 2.4 min with 4.8-min recoveries, 2 session.wk^{-1}, plus usual training? Cycling, 8x 2.4 min with 2- to 3-min recoveries, 2 session.wk^{-1}, plus usual training?	~10 h.wk^{-1} of endurance training in off and pre-competition phases
Lindsay et al. (1996)	Cycling, 6-8x 5 min with 1 min recoveries, 1-2 session.wk^{-1} replacing ~15% of usual training	No control; usual base-phase endurance training, ~300km.wk^{-1}
Smith et al. (1999)	Running, 5-6x 2-3 min, 2 session.wk^{-1} for 4 wk plus 1x 30 min.wk^{-1} at 60% of VO_2max	No control; prior training unclear
Stepto et al. (1999)[c]	Cycling, 4x 8 min, 8x 4 min, or 12x 2 min with 1- to 3-min recoveries, 2 session.wk^{-1}, plus usual training	No control; usual endurance training, unspecified training phase, 230 km.wk^{-1}
Westgarth-Taylor et al. (1997)	Cycling, 6-9x 5 min with 1 min recoveries, 2 session.wk^{-1} replacing 15% of usual training	No control; usual base-phase endurance training, unspecified weekly duration
Weston et al. (1997)	Cycling, 6-8x 5 min with 1 min recoveries, 1-2 session.wk^{-1} replacing 5% of usual training	No control; usual base-phase endurance training, ~290 km.wk^{-1}
Supramaximal intervals		
Creer et al. (2004)	Cycling, 4-10x 30-s, 2 session.wk^{-1} for 4 wk plus 5 h.wk^{-1} endurance training	8 h.wk^{-1} endurance training
Laursen et al. (2002a)	Cycling, 12-19x 1 min, 2 session.wk^{1} plus 8 h.wk^{-1} base training	Low intensity in base phase, ~10 h.wk^{-1}
Laursen et al. (2002b)	Cycling, 12x 30 s with 4.5-min recoveries, 2 session.wk^{-1} plus usual training?	~10 h.wk^{-1} of endurance training in off and pre-competition phases
Stepto et al. (1999)[b]	Cycling, 12x 30 s with 4.5-min recoveries or 12x 1 min with 4-min recoveries, 2 session.wk^{-1} plus usual training	No control; usual endurance training, unspecified training phase, 230 km.wk^{-1}

[a]"Endurance" training is presumably long sessions below submaximal intensity (below anaerobic threshold).
[b]Shown in Appendices 2-4 as submax and max intervals.
[c]The five training groups in this study were merged into two groups for this review.

Analysis of Performance

Measures of performance in real or staged competitions are best for evaluating the effects of training interventions on competitive athletes (Hopkins et al., 1999). Toussaint et al. (1990) were the only researchers to use competitive performance in a study of high-intensity training. The others have opted instead for laboratory-based ergometer tests or solo field tests, which may not reproduce the motivating effect of competition. Appendix 1 summarizes the effects from sport-specific time trials and constant-power tests, sorted into the same three intensity/duration categories as the interval training. Appendix 2 summarizes the effects on maximum power in incremental tests. To permit comparison of effects, we have converted outcomes in the various performance tests into percent changes in mean or maximum power, using the methods of Hopkins et al. (2001). Footnotes in the appendices indicate which measures needed conversion.

Analysis of Physiological Effects

The remaining tables show the effects of high-intensity training on physiological measures related to endurance performance: maximum oxygen consumption (VO_2max, Appendix 3), anaerobic threshold, exercise economy (Appendix 4), and body mass (Appendix 5). Most endurance events are performed at a nearly constant pace, and for those performed at an intensity below VO_2max mean performance power or speed is the product of VO_2max, the fraction of VO_2max sustained, and aerobic energy economy (di Prampero, 1986). Provided they can be measured with sufficient precision, percent changes in each of these components are therefore worth documenting, because they translate directly into percent changes in endurance power. Of course, training is likely to change more than one of these components, so researchers serious about identifying the mechanism of a change in performance should assess all three.

Most authors of the studies we reviewed measured VO_2max, usually in an incremental test. Some also measured economy (work done per liter of oxygen consumed) from VO_2 measurement either in middle stages of the incremental test or at a fixed work rate in a separate test. Where necessary, we re-expressed percent changes in VO_2max and economy for VO_2 measured in units of $L.min^{-1}$, to avoid difficulties in interpretation arising from changes in mass when VO_2 is expressed as $ml.min^{-1}.kg^{-1}$.

No authors measured the fraction of VO_2max sustained in the endurance test itself (requiring measurement of VO_2 throughout the test), but some measured the anaerobic threshold, usually from an analysis of blood lactate concentration during an incremental test. Depending in its method of measurement, the anaerobic threshold occurs at ~85% of VO_2max, an intensity that an athlete can sustain for ~30-60 min (Jones and Carter, 2000). One can therefore assume that percent changes in the anaerobic threshold will translate directly into percent changes in fractional utilization of VO_2max in a sub-VO_2maximal event. Authors in two studies provided the anaerobic threshold as a power rather than a percent of VO_2max; in this form the measure is effectively already a nett measure of submaximal endurance performance, with contributions from VO_2max, fractional utilization of VO_2max, and economy. We therefore included these measures in Appendix 1 in the subgroup of submaximal tests.

The relevance of changes in anaerobic threshold to changes in endurance performance at maximal and supramaximal intensities is unclear, but for such events (lasting up to ~10 min) anaerobic capacity makes a substantial contribution to performance (Greenhaff and Timmons, 1998). None of the studies we reviewed included critical-power or other modeling of performance to estimate the contribution of changes in anaerobic capacity resulting from high-intensity training. However, a practical and much more reliable measure of anaerobic capacity is performance in sprints lasting ~30 s, which we have included as supramaximal tests in Appendix 1.

Body mass is an important determinant of performance in running [Berg, 2003 #120] and presumably in most other high-intensity endurance sports, depending amongst other things on the distribution of the change in mass between the active limbs and the rest of the body, the power required to continually accelerate and decelerate the limbs, and the power required to move the rest of the body against gravity with each cycle of limb movement and over any undulating terrain or hills. The relationship between changes in body mass and performance is therefore difficult to predict, but it has not been studied empirically for any sport. We have nevertheless included in Appendix 5 the percent changes in body mass from those studies where mass was reported before and after resistance training, because this form of training could increase body mass substantially by increasing muscle mass. None of the studies of interval training provided enough data to estimate changes in body mass, presumably because there were either no substantial changes or the authors did not consider changes in body mass to be an issue with this kind of training.

FINDINGS

The outcomes from individual studies are shown in Appendices 1-5, at the end of this article. Table 3 represents a summary derived from the appendices and justified in the following sections.

Table 3: Summary of effects of high-intensity interval and resistance training on performance and physiology of endurance athletes in a non-competitive (low intensity) phase of training.

	Interval training			Resistance training[a]			
	Sub-maximal	Maximal	Supra-maximal	Explosive sport-specific	Explosive non-sport specific	Plyo-metrics	Usual weights
Performance power							
Submaximal endurance		+++	+++	+	+		+/–
Maximal endurance		+		++		+	
Supramaximal endurance		0	++	++	++++		
Maximum incremental		+++	++	++	+		0
Physiology							
Maximum oxygen uptake	+	++	+	+/–		–	–
Anaerobic threshold	+	+++		++/–			0
Economy	+	+++		++++	++	+++	+
Body mass				+	+	0	+

Key to effects: ++++, 8% or more; +++, 6% (5 to 7%); ++, 4% (3 to 5%); +, 2% (1 to 3%); 0, 0% (-1 to 1%); –, -2% (-1 to -3%).

[a]The study by Toussaint and Vervoorn (1990) of effects of non-explosive resisted movements on swimmers in the competitive phase of training is not included in this summary.

Our interpretation of the appendices was cautious and tentative, because the various kinds of performance and physiological tests are disproportionately represented by the different kinds of training. For example, there has been only one study of purely submaximal interval training, and it did not include a measure of performance power or maximal power in an incremental test (Sjodin et al., 1982). Further, a submaximal performance test was generally included in studies of interval training but not in studies of resistance training, whereas tests of economy are more likely to have been included in studies of resistance training. The reasons for such bias in the use or reporting of tests are unclear.

Authors might have been more likely to include a test or measure that had already been shown to produce a big change. Also, some authors may have chosen not to report non-significant effects, or they may have been instructed to remove them from the manuscript by a misguided reviewer or editor. A formal quantitative meta-analysis can partially improve the interpretation when there are such biases, but we decided against a meta-analysis when we discovered that all but one of the published studies were performed with athletes in the base phase of training. A meta-analysis would not address the real issue for athletes: how does each kind of high-intensity training contribute to performance against a background of other high-intensity training? This review can provide only suggestive evidence.

Endurance Performance

Appendix 1 shows that maximal and supramaximal intervals produced equally impressive gains (3.0-8.3%) on performance at submaximal intensities. The magnitude of the largest improvement (Westgarth-Taylor et al., 1997) is likely to be due to either sampling variation or a computational error, because it is not consistent with the smaller gains (4.6 and 8.3%) in two similar studies by the same group (Lindsay et al., 1996; Weston et al., 1997). Explosive resistance training was less effective (0.3 and 1.0%) over the same time frame as the interval training studies (~4 wk), and even after 9 wk the gains were still not as great (2.9 and 4.0%) as with interval training. In the only study of the effect of usual weight training on submaximal endurance, there were opposing effects on anaerobic threshold power (2.6%) and time-trial power (-1.8%) in the same subjects after 12 wk. The authors suggested that the non-specific movement and speed of the weight training accounted for its failure to enhance time-trial performance (Bishop et al., 1999).

Explosive sport-specific movements produced the greatest gains in maximal endurance tests (1.9-5.2%) after 8-9 wk (Appendix 1). Maximum intervals were less effective (2.8%), although the duration of training was only 4 wk. Plyometric jumps were less beneficial (1.2%).

Not surprisingly, the highest-intensity training produced the greatest enhancements in the supramaximal tests (Appendix 1). The very large gain with explosive weights (11%) was more than twice that with supramaximal intervals and explosive sport-specific resistance (3.0-4.6%). Maximal intervals had little effect (0.4%).

There was only one study of the effects of submaximal intervals (Sjodin et al., 1982), and it did not include measures of performance power. The effects on VO_2max, anaerobic threshold, and economy in that study, if they were additive, would be consistent with ~6% enhancement of submaximal endurance and possibly 2-4% on supramaximal and maximal endurance respectively.

Maximum Incremental Power

Maximum-intensity intervals appear to be the most effective form of high-intensity training for improving maximum incremental power (by 2.5-7.0%; Appendix 2). Gains appear to be smaller with explosive sport-specific resistance training (2.3% and 6.0%) and supramaximal intervals (1.0-4.7%), and possibly smaller still with explosive weights (2.0%). Remarkably, a gain of 4.7% was achieved in only four sessions of supramaximal intervals (Laursen et al., 2002a).

These improvements will transfer to time-trial performance to some extent, because maximum power achieved in an incremental test correlates well with time-trial performance (Noakes et al., 1990; Hawley and Noakes, 1992; Bourdin et al., 2004). Exactly how they will transfer might depend on the duration of the time trial. Most of an incremental test is performed at submaximal intensities, but the last minute or two is maximal and supramaximal. Performance in the test will therefore be determined by a mix of VO_2max, anaerobic threshold, economy, and anaerobic capacity. If the mix does not reproduce that of the time trial, enhancements of one or more components of the mix will produce changes in maximum incremental power that differ from those in time-trial performance.

Maximum Oxygen Consumption

It is evident from Appendix 3 that the largest improvements in VO_2max occurred with maximal-intensity interval training (gains of 2.3-7.1%). Supramaximal intervals were probably less effective (impairment of 0.6% in one study, enhancements of 2.2% and 3.5% in two others). The changes can occur rapidly: Laursen et al. (2002a) recorded an increase of 3.5% after a total of only four supramaximal sessions in two weeks. Explosive weight training can produce smaller gains (up to 2.0%), but the various forms of resistance training had a predominantly negative effect on VO_2max. Improvements in other physiological measures can offset this effect and result in nett improvements in endurance performance following resistance training.

Anaerobic Threshold

One cannot draw a firm conclusion about the effect of explosive resistance training on the anaerobic threshold in Appendix 4, given that there were major enhancements in three studies (5.0-7.1%) and substantial impairments in two others (2.0 and 2.1%). In the only study of presumably maximal intervals, the gain was ~5.0%, whereas the gain was less (1.5%) in the only study of submaximal intervals.

Economy

Although the claim of 39% increase in economy from explosive sport-specific resistance training in Appendix 4 is almost certainly erroneous, it is clear from the other studies in the table that explosive resistance training in general produced spectacular beneficial effects (3.5-18%) on this endurance parameter. Plyometrics may be only a little less effective (3.1-8.6%). The effects of interval training were least for submaximal (2.8%) and greater for a mixture of submaximal and maximal (6.5%).

Body Mass

It is reasonably clear from Appendix 5 that explosive resistance training increased body mass by ~1%, presumably via an increase in muscle mass. Any direct harmful effects of this increase in mass on performance were inconsequential, given the large enhancements that this form of training produced in power output of all durations. Usual weight training may produce increases in body mass that are greater (2.8% in one study) and therefore more likely to impair performance in some sports.

CONCLUSIONS AND TRAINING IMPLICATIONS

High-intensity interval and resistance training in an endurance athlete's non-competitive phase can substantially improve performance and related physiological measures. Interval training at intensities around VO_2max (intervals lasting 2-10 min) improves mainly submaximal endurance performance (by ~6%) through improvements of all three components of the aerobic system (VO_2max, anaerobic threshold, economy). Effects of longer intervals at lower intensity have unclear but possibly similar effects on performance, judging by their effects on the components of the aerobic system. Higher intensities of interval training (intervals of <2 min) probably have similar benefit for submaximal endurance and possibly less benefit (~4%) for shorter durations of endurance performance, but the contribution of aerobic components is unclear. Explosive resistance training produces some benefit (~2%) for submaximal endurance, but probably more benefit (4-8%) for maximal and supramaximal endurance. The effects of explosive resistance training are mediated at least partly by major increases in economy, possibly by increases in anaerobic threshold, but probably not by increases in VO_2max. Increases in body mass with this kind of resistance training are not an issue.

Many high-level endurance athletes will already include high-intensity intervals in their training leading up to and including the competitive phase. For these athletes adding more intervals is not necessarily a good strategy, but altering the mix to reduce the volume of lower intensity intervals and increase the volume of higher intensity intervals may be beneficial. Athletes who do not currently include sport-specific explosive resistance training are almost certain to experience substantial gains in performance by adding this form of training to their programs.

A partially selective effect of the different kinds of training on physiological measures raises the possibility of prescribing training to correct weaknesses in these measures. On the basis of the existing research one can tentatively recommend adding or increasing explosive resistance training for an athlete with a poor economy and/or poor anaerobic capacity, and adding or increasing maximal intervals for an athlete with a poor VO_2max.

FURTHER RESEARCH

We need more research aimed at filling voids in the matrix of different kinds of training vs effects on performance and physiology. In particular:

- We need to know more about the effects of non-specific resistance training (especially plyometrics and usual weights) on performance and some aspects of physiology.
- The effects of supramaximal intervals on anaerobic threshold and economy need more research.
- The one study on physiological effects of submaximal intervals needs augmenting with studies that include performance measures.
- High-intensity sport-specific resistance training of the non-explosive variety has not been investigated other than in the one study that was performed in the competitive phase.

This new research will give us a more complete understanding of how each type of high-intensity training in isolation affects endurance performance. More importantly, it will give us a better indication of the possibility of prescribing training to correct deficits in an athlete's physiological profile. Well-designed studies of individualized training prescription will further address this issue.

From the perspective of the athlete and coach, the most important question is how best to combine the various kinds of high-intensity training before and during the competitive phase of the season. There is currently only one study of high-intensity training of athletes in the competitive phase. We need more, and we need studies of periodization of high-intensity training in the phases leading to competition.

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APPENDICES

Appendix 1: Effects of high-intensity training on measures of endurance performance in competitive athletes. Performance is expressed as change in mean power in a sport-specific time trial or its equivalent. Studies ordered approximately by magnitude of effect within each of the intensities/durations of endurance test.

Performance test	Change in power (%)	Experimental training	Duration of training	Subjects[a]	Reference
Submaximal Tests					
1-h 40-km cycling	12.4?[b]	Max intervals (short recovery)	12 sessions over 6-7 wk	8 M cyclists	Westgarth-Taylor et al. (1997)
1-h 40-km cycling	~8.3	Max intervals (short recovery)	6 sessions over 4 wk	8 M cyclists	Lindsay et al. (1996)
1-h 40-km cycling	4.6 at 2 wk; 6.6 at 4 wk[c]	Max intervals (short recovery)	2 wk^{-1} for 4 wk	8+11 M cyclists	Laursen et al. (2002b)
1-h 40-km cycling	3.2 at 2 wk; 6.2 at 4 wk[c]	Max intervals (long recovery)	2 wk^{-1} for 4 wk	8+11 M cyclists	Laursen et al. (2002b)
1-h 40-km cycling	2.7 at 2 wk; 5.3 at 4 wk[c]	Supramax intervals	2 wk^{-1} for 4 wk	8+11 M cyclists	Laursen et al. (2002b)
Cycling at ventilatory threshold	4.7	Supramax intervals	2 wk^{-1} for 2 wk	7+7 M cyclists	Laursen et al. (2002a)
1-h 40-km cycling	~4.6	Max intervals (short recovery)	6 sessions over 4 wk	6 M cyclists	Weston et al. (1997)
18-min 5-km running	0.3 at 6 wk; 4.0 at 9 wk	Explosive sport-specific movements	9 wk	12+10 M elite runners	Paavolainen et al. (1999)
1-h 40-km cycling	3.4	Supramax intervals	2 wk^{-1} for 3 wk	7 M cyclists	Stepto et al. (1999)
1-h 40-km cycling	3.0	Max intervals	2 wk^{-1} for 3 wk	12 M cyclists	Stepto et al. (1999)
10-km running	3.0	Max intervals	3 wk^{-1} for 8 wk	7 M runners	Acevedo and Goldfarb (1989)
1-h cycling	1.0 at 4 wk; 2.9 at 9 wk	Explosive weights	9 wk	6+8 M cyclists	Bastiaans et al. (2001)
Cycling at D_{max} lactate	2.6	Usual weights	2 wk^{-1} for 12 wk	14+7 F cyclists	Bishop et al. (1999)
20-min running to exhaustion	~1.2[h]	Max intervals	3 wk^{-1} for 8 wk	7 M runners	Acevedo and Goldfarb (1989)
1-h cycling	0.6 at 6 wk; -1.8 at 12 wk	Usual weights	2 wk^{-1} for 12 wk	14+7 F cyclists	Bishop et al. (1999)
Performance test	Change in power (%)	Experimental training	Duration of training	Subjects[a]	Reference
Maximal Tests					
5-min skiing to exhaustion	~5.2[d]	Explosive sport-specific movements	3 wk^{-1} for 9 wk	10+9 M cross-country skiers	Osteras et al. (2002)
5-min skiing to exhaustion	~5.1[e]	Explosive sport-specific movements	3 wk^{-1} for 9 wk	8+7 F cross-country skiers	Hoff et al. (1999)
10-min 3-km running	2.8%	Max intervals	2 wk^{-1} for 4 wk	5 M runners	Smith et al. (1999)
7-min skiing to exhaustion	~1.9[g]	Explosive sport-specific movements	3 wk^{-1} for 8 wk	9+10 M cross-country skiers	Hoff et al. (2002)
10-min 3-km running	1.2	Plyometrics	2-3 wk^{-1} for 6 wk	8+9 M runners	Spurrs et al. (2003)

For footnotes see Appendix 5.

Appendix 1 continued: Effects of high-intensity training on measures of **endurance performance** in competitive athletes. Performance is expressed as change in mean power in a sport-specific time trial or its equivalent. Studies ordered approximately by magnitude of effect.

Performance test	Change in power (%)	Experimental training	Duration of training	Subjects[a]	Reference
Supramaximal Tests					
30-s cycling	10 at 4 wk; 11 at 9 wk	Explosive weights	9 wk	6+8 M cyclists	Bastiaans et al. (2001)
45-s cycling	4.6	Supramax intervals	2 wk^{-1} for 3 wk	7 M cyclists	Stepto et al. (1999)
30-s cycling	3.0	Supramax intervals	2 wk^{-1} for 4 wk	10+7 M cyclists	Creer et al. (2004)
30-s to 2-min 50- to 200-m swimming	~3.0[f]	Sport-specific resistance	3 wk^{-1} for 10 wk	11+11 M & F swimmers	Toussaint and Vervoorn (1990)
45-s cycling	0.4	Max intervals	2 wk^{-1} for 3 wk	12 M cyclists	Stepto et al. (1999)

For footnotes see Appendix 5.

Appendix 2: Effects of high-intensity training on **maximum power in an incremental test** in competitive athletes. Studies ordered approximately by magnitude of effect.

Performance test	Change in power (%)	Experimental training	Duration of training	Subjects[a]	Reference
Cycling	2.1 at 2 wk; 7.0 at 4 wk	Max intervals (short recovery)	2 wk^{-1} for 4 wk	8+11 M cyclists	Laursen et al. (2002b)
Running sprints	0.8 at 3 wk; 3.5 at 6 wk; 6.0 at 9 wk	Explosive sport-specific movements	9 wk	12+10 M elite runners	Paavolainen et al. (1999)
Cycling	3.1 at 2 wk; 5.8 at 4 wk	Max intervals (long recovery)	2 wk^{-1} for 4 wk	8+11 M cyclists	Laursen et al. (2002b)
Cycling	5.3	Max intervals (short recovery)	6 sessions over 4 wk	8 M cyclists	Lindsay et al. (1996)
Cycling	5.0	Max intervals (short recovery)	12 sessions over 6-7 wk	8 M cyclists	Westgarth-Taylor et al. (1997)
Running speed at VO_2max	4.8	Max intervals	2 wk^{-1} for 4 wk	5 M runners	Smith et al. (1999)
Cycling	4.7	Supramax intervals	2 wk^{-1} for 2 wk	7+7 M cyclists	Laursen et al. (2002a)
Cycling	0.7 at 2 wk; 4.0 at 4 wk	Supramax intervals	2 wk^{-1} for 4 wk	8+11 M cyclists	Laursen et al. (2002b)
Cycling	3.5	Max intervals (short recovery)	6 sessions over 28 d	6 M cyclists	Weston et al. (1997)
Running speed at VO_2max	2.9	Submax and max intervals	2 wk^{-1} for 4 wk	8 M runners	Billat et al. (1999)
Cycling	2.5	Max intervals	2 wk^{-1} for 3 wk	12 M cyclists	Stepto et al. (1999)
Running	0.9 at 3 wk; 0.9 at 6 wk; 2.3 at 9 wk	Explosive sport-specific movements	9 wk	12+10 M elite runners	Paavolainen et al. (1999)
Cycling	2.1 at 4 wk; 2.0 at 9 wk	Explosive weights	9 wk	6+8 M cyclists	Bastiaans et al. (2001)
Cycling	1.0	Supramax intervals	2 wk^{-1} for 3 wk	7 M cyclists	Stepto et al. (1999)
Running speed at VO_2max	0.0	Usual weights	2 wk^{-1} for 14 wk	7+8 M triathletes	Millet et al. (2002)

For footnotes see Appendix 5.

Appendix 3: Effects of high-intensity training on maximum oxygen consumption in competitive athletes. Studies ordered approximately by magnitude of effect.

Performance test	Change in VO_2max (%)	Experimental training	Duration of training	Subjects[a]	Reference
Cycling	2.6 at 2 wk; 7.1 at 4 wk	Max intervals (short recovery)	2 wk^{-1} for 4 wk	8+11 M cyclists	Laursen et al. (2002b)
Running	4.9	Max intervals	2 wk^{-1} for 4 wk	5 M runners	Smith et al. (1999)
Cycling	2.0 at 2 wk; 4.4 at 4 wk	Max intervals (long recovery)	2 wk^{-1} for 4 wk	8+11 M cyclists	Laursen et al. (2002b)
Cycling	3.5	Supramax intervals	2 wk^{-1} for 2 wk	7+7 M cyclists	Laursen et al. (2002a)
Cycling	2.3	Max intervals	2 wk^{-1} for 3 wk	12 M cyclists	Stepto et al. (1999)
Cycling	0.8 at 2 wk; 2.2 at 4 wk	Supramax intervals	2 wk^{-1} for 4 wk	8+11 M cyclists	Laursen et al. (2002b)
Running	2.2	Submax intervals	1 wk^{-1} for 14 wk	8 M runners	Sjodin et al. (1982)
Running	2.1	Submax and max intervals	2 wk^{-1} for 4 wk	8 M runners	Billat et al. (1999)
Skiing	2.0	Explosive sport-specific movements	6 wk	7+8 M cross-country skiers	Paavolainen et al. (1991)
Skiing	3.4 to -3.9[j]	Explosive sport-specific movements	3 wk^{-1} for 9 wk	8+7 F cross-country skiers	Hoff et al. (1999)
Skiing	1.4[k]	Explosive sport-specific movements	3 wk^{-1} for 8 wk	9+10 M cross-country skiers	Hoff et al. (2002)
Running	0.7	Max intervals	3 wk^{-1} for 8 wk	7 M runners	Acevedo and Goldfarb (1989)
Running	-0.3	Usual weights	3 wk^{-1} for 10 wk	6+6 F runners	Johnston et al. (1997)
Running	-0.4	Plyometrics	3 wk^{-1} for 6 wk	10+8 F+M subelite runners	Turner et al. (2003)
Cycling	-0.6	Supramax intervals	2 wk^{-1} for 3 wk	7 M cyclists	Stepto et al. (1999)
Running	-2.3[k]	Explosive sport-specific movements	3 wk^{-1} for 8 wk	9+10 M cross-country skiers	Hoff et al. (2002)
Cycling	-2.4	Usual weights	2 wk^{-1} for 12 wk	14+7 F cyclists	Bishop et al. (1999)
Running	-3.0	Plyometrics	2-3 wk^{-1} for 6 wk	8+9 M runners	Spurrs et al. (2003)
Running	-3.2	Usual weights	2 wk^{-1} for 14 wk	7+8 M triathletes	Millet et al. (2002)
Running	0.0 at 3 wk; -3.4 at 6 wk; -4.2 at 9 wk[l]	Explosive sport-specific movements	9 wk	12+10 M elite runners	Paavolainen et al. (1999)
Skiing	-4.7	Explosive sport-specific movements	3 wk^{-1} for 9 wk	10+9 M cross-country skiers	Osteras et al. (2002)

For footnotes see Appendix 5.

Appendix 4: Effects of high-intensity training on **anaerobic threshold** (on oxygen consumption as percent of VO_2max) and on **exercise economy**. Studies ordered approximately by magnitude of effect within each measure.

Performance test	Change in measure (%)	Experimental training	Duration of training	Subjects[a]	Reference
Anaerobic threshold					
Skiing VO_2 at 1.8 mM lactate above baseline	7.1[m]	Explosive sport-specific movements	3 wk^{-1} for 9 wk	10+9 M cross-country skiers	Osteras et al. (2002)
Running VO_2 at increase of lactate	6.8[m]	Explosive sport-specific movements	9 wk	12+10 M elite runners	Paavolainen et al. (1999)
Running VO_2 at 2.5 & 4 mM	5.3 & 4.9	Max intervals	3 wk^{-1} for 8 wk	7 M runners	Acevedo and Goldfarb (1989)
Skiing VO_2 at 1.8 mM lactate above baseline	5.0[m]	Explosive sport-specific movements	3 wk^{-1} for 8 wk	9+10 M cross-country skiers	Hoff et al. (2002)
Running VO_2 at 4mM lactate	1.5	Submax intervals	1 wk^{-1} for 14 wk	8 M runners	Sjodin et al. (1982)
Running VO_2 at ventilatory threshold	0.2	Usual weights	2 wk^{-1} for 14 wk	7+8 M triathletes	Millet et al. (2002)
Skiing VO_2 at ~2 and ~4 mM lactate	-2.0[m]	Explosive sport-specific movements	6 wk	7+8 M cross-country skiers	Paavolainen et al. (1991)
Running VO_2 at 1.8 mM lactate above baseline	-2.1[m]	Explosive sport-specific movements	3 wk^{-1} for 8 wk	9+10 M cross-country skiers	Hoff et al. (2002)
Performance test	Change in measure (%)	Experimental training	Duration of training	Subjects[a]	Reference
Economy[n]					
Skiing at VO_2max	39?[o]	Explosive sport-specific movements	3 wk^{-1} for 9 wk	8+7 F cross-country skiers	Hoff et al. (1999)
Skiing at 10.9 $km.h^{-1}$	18	Explosive sport-specific movements	3 wk^{-1} for 8 wk	9+10 M cross-country skiers	Hoff et al. (2002)
Running at 75% VO_2max	15?[p]	Usual weights	2 wk^{-1} for 14 wk	7+8 M triathletes	Millet et al. (2002)
Skiing at anaerobic threshold	13	Explosive sport-specific movements	3 wk^{-1} for 9 wk	10+9 M cross-country skiers	Osteras et al. (2002)
Running at 15 $km.h^{-1}$	7.8 at 3 wk; 7.0 at 6 wk; 8.6 at 9 wk[q]	Explosive sport-specific movements	9 wk	12+10 M elite runners	Paavolainen et al. (1999)
Running at 12, 14 and 16 $km.h^{-1}$	7.6, 6.2 and 4.9	Plyometrics	2-3[-1] wk for 6 wk	8+9 M runners	Spurrs et al. (2003)
Running at 14 $km.h^{-1}$	6.5	Submax and max intervals	2 wk^{-1} for 4 wk	8 M runners	Billat et al. (1999)
Cycling at 50-70% VO_2max	4.1 at 4 wk; 3.5 at 9 wk	Explosive weights	9 wk	6+8 M cyclists	Bastiaans et al. (2001)
Running at 15 $km.h^{-1}$	2.8	Submax intervals	1 wk^{-1} for 14 wk	8 M runners	Sjodin et al. (1982)
Running (mean at various speeds)	3.1	Plyometrics	3 wk^{-1} for 6 wk	10+8 F+M runners	Turner et al. (2003)
Running at 12.8 and 13.8 $km.h^{-1}$	1.7 and 1.2	Usual weights	3 wk^{-1} for 10 wk	6+6 F runners	Johnston et al. (1997)

For footnotes see Appendix 5.

Appendix 5: Effects of high-intensity training on **body mass** in competitive athletes. Studies ordered approximately by magnitude of effect.

Performance test	Change in mass (%)	Experimental training	Duration of training	Subjects[a]	Reference
-	2.8	Usual weights	3 wk^{-1} for 10 wk	6+6 F runners	Johnston et al. (1997)
-	1.7	Explosive sport-specific movements	9 wk	12+10 M elite runners	Paavolainen et al. (1999)
-	~1.5[r]	Explosive sport-specific movements	3 wk^{-1} for 9 wk	10+9 M cross-country skiers	Osteras et al. (2002)
-	1.3[s]	Explosive weights	9 wk	6+8 M cyclists	Bastiaans et al. (2001)
-	0.8	Explosive sport-specific movements	6 wk	7+8 M cross-country skiers	Paavolainen et al. (1991)
-	0.8	Usual weights	2 wk^{-1} for 12 wk	14+7 F cyclists	Bishop et al. (1999)
-	0.6	Explosive sport-specific movements	3 wk^{-1} for 9 wk	8+7 F cross-country skiers	Hoff et al. (1999)
-	0.3	Plyometrics	2-3 wk^{-1} for 6 wk	8+9 M runners	Spurrs et al. (2003)
-	0.2	Explosive sport-specific movements	3 wk^{-1} for 8 wk	9+10 M cross-country skiers	Hoff et al. (2002)

Supramax, supraximal; max, maximal; submax, submaximal; M, male; F, female; VO_2, oxygen consumption.
[a]Numbers are experimental + control.
[b]The value of 12% in the paper appears to be an unrealistic increase (should probably be ~5.3%).
[c]These changes in performance time on the Cateye ergometer need to be inflated by an unknown factor (perhaps 1.5x) to convert them to changes in mean power.
[d]Estimated from 51% increase in time to exhaustion using methods of Hopkins et al. (2001).
[e]Estimated from 50% increase in time to exhaustion using methods of Hopkins et al. (2001).
[f] Estimated from a 0.8- 1.1% decrease in swim time using methods of Hopkins et al. (2001).
[g]Estimated from 26% increase in time to exhaustion using methods of Hopkins et al. (2001).
[h]Estimated from 17% increase in time to exhaustion using methods of Hopkins et al. (2001).
[i] Changes based on VO_2 in $L.min^{-1}$.
[j] Wide inconsistency between VO_2 in $L.min^{-1}$, $ml.min^{-1}.kg^{-1}$ and $ml.min^{-1}.kg^{-0.67}$ probably due to ~3% increase in body mass in resistance group.
[k]Estimated from VO_2 in $ml.min^{-1}.kg^{-1}$ by adding 0.2% change in body mass.
[l] Estimated from VO_2 in $ml.min^{-1}.kg^{-1}$. Value at 9 wk corrected by adding the 1.7% change in body mass. Values at 3 and 6 wk not corrected because change in body mass unknown.
[m]Estimated by combining percent changes in mean VO_2 and mean VO_2max.
[n]Expressed as percent change in work output per liter of oxygen consumed
[o]The value of 39% in the paper is unrealistic.
[p]The increase in economy of 15% is not consistent with an associated *increase* in heart rate and no change in speed at VO_2max; standard deviation of economy consistent with outlier or faulty portable gas analyzer.
[q]Estimated from VO_2 expressed as $ml.min^{-1}.kg^{-1}$. Value at 9 wk corrected by subtracting the 1.7% change in body mass. Values at 3 and 6 wk not corrected because change in body mass unknown.
[r]Estimated by combining data for VO_2 in $L.min^{-1}$ and $ml.min^{-1}.kg^{-1}$.
[s]Change in lean body mass.

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