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Does maximal strength training improve endurance performance in highly trained cyclists: A systematic review

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ABSTRACT

Muscle strength may play an important role in endurance road cycling events. By increasing lower body strength and power, the anaerobic energy production and maximal levels of muscular force required during races to climb hills, perform repeated surges in pace, or in the final sprint may improve. While strength training is often performed by highly trained cyclists, the scientific literature supporting this practice is subject to a number of methodological limitations and potentially confounding variables that raise doubts over the efficacy of strength training to enhance performance in this population. The purpose of this review is therefore to identify and evaluate original research examining the influence of strength training on road cycling endurance performance in highly trained cyclists. Using relevant databases and keywords, nine training studies met the inclusion criteria and were reviewed. Grade B-level evidence indicated that following performance of strength training, highly trained road cyclists can significantly improve performance variables such as lactate power profile, oxygen cost or consumption, cycling economy, work or exercise efficiency, as well as peak and mean power outputs during time trials lasting between 30-seconds and 4-kilometres. Grade C evidence also suggests mean and average power outputs during time trials ranging from 40 to 60 minutes, and time to exhaustion at maximal aerobic power or 80-85% VO_2max are improved. However, the physiological mechanisms responsible for these improvements are unclear. Future research is also necessary to determine what is the best form(s) of strength training for these athletes, and how best to incorporate such training into their annual periodized training plan.

Keywords: concurrent training; endurance athlete; resistance training.

INTRODUCTION

Professional road cycling is a physiologically demanding sport. The training volumes required to compete internationally are extremely large, with elite cyclists performing 27,000 – 39,000 km a year [1] (Jeukendrup). Further, in professional cycling's highest profile stage races, the Tour de France, Vuelta Espana and Giro d Italia, cyclists complete 3000-4000 km of racing over 21-23 days, in stages ranging between 7km (prologue) and 250km [2] (Lucia). Successful performance in these events attracts worldwide media attention, and is therefore associated with considerable financial benefits for the cyclists and sponsors of the teams competing in these events. Consequently, identifying training interventions that improve competitive performance, and the physiological and metabolic adaptations associated with these forms of training, are of high importance to these athletes, their coaches, and sponsors [3] (Paton and Hopkins).

The physiological/metabolic demands of road races vary depending on factors such as the type of race e.g. mass start, time trial, or criterion, race duration, environment/terrain, strategy, competitive level, and the influence of drafting techniques [4] (Fernandez-Garcia) [5] (Lucia) [6] (Padilla). Successful performance is determined by the interaction of three main factors: maximum oxygen uptake (“VO_2max”), performance oxygen uptake, i.e. the percentage of VO2max at the lactate threshold, and mechanical efficiency or economy i.e. oxygen uptake required to perform at a given velocity [7] (Bassett). However, high anaerobic power outputs, and breathing patterns/ventilation efficiency are also considered important determinants of endurance cycling performance [8] (Faria) [3] (Paton and Hopkins). In mass start road racing, the aerobic energy system, with a high reliance on both glycolytic and lipolytic components, is predominant with 72-95% of these events spent at exercise intensities below or between 70 and 90% of VO_2max [9] (Hawley) [5] (Lucia) [10] (Rauch) [11] (Vogt). Although the percentage time spent at intensities ≥90% of VO_2max accounts for no more than 5% of the race, high power outputs ranging between 9.8 and 12.3W/kg for 5 second efforts have been observed in professional road cycling events. As such, the outcomes of races are often determined by the ability to produce high levels of anaerobic energy and supra-maximal levels of muscular force during short hill climbs, repeated surges in pace, or in the final sprint [12] (Ebert) [13] (Laursen) [14] (Quod). Mass start road racing is therefore best characterized as a dynamic event where aerobic and anaerobic energy production both play important roles [15] (Palmer) [14] (Quod).

Training for these events therefore has traditionally included both long duration/low intensity aerobic training, and phases of higher intensity anaerobic interval training, with appropriate recovery and tapering [16] (Laursen) [17] (Laursen). More recently, trainers and coaches are also now including resistance training in the programmes of elite road cyclists, with a view to improving the energy systems and muscular adaptations required to produce the short sustained high power outputs required during races. The physiological compatibility of simultaneously performing strength and endurance training, often referred to as concurrent training, has been widely investigated in recent times. Concurrent training has resulted in improvements in work economy in endurance sports such as cross-country skiing and running [18] (Hoff) [19] (Osteras) [20] (Storen). Similarly, studies evaluating measures of cycling performance in previously untrained or moderately trained subjects have demonstrated improved cycling economy, time to exhaustion, and reductions in energy expenditure following performance of concurrent training [21] (Hansen) [22] (Loveless) [23] (Marcinik) [24] (Minahan). However, few studies have evaluated the influence of concurrent training in high level endurance athletes. In a recent review, Yamamoto et al. [25] identified equivocal findings in the research on the effects of concurrent training on endurance performance in endurance cyclists. Unfortunately, only five studies were reviewed, and subjects in the studies included ‘club level’ cyclists or athletes who had performed as little as seven hours or 150km of cycle training per week over a six month period. Where elite road cyclists are characterized by their extremely high VO_2max values, performance VO2, and cycling economy, and often train between 500-700km per week over a sustained number of years, the results of Yamamoto et al’s [25] review does not clarify the influence of concurrent training on long term endurance capacity in high level endurance cyclists.

It is also well established that adaptations resulting from training are highly specific to the mode of activity performed, and the genetic and molecular mechanisms of adaptation induced by resistance and endurance training are distinct [9] (Hawley) [26] (Nader). Resistance and endurance training activate or repress different genes and cellular signaling pathways, i.e. resistance training stimulates the myofibril proteins responsible for muscle hypertrophy culminating in gains in maximal strength [27] (Fry) [28] (Tesch). In contrast, endurance training increases muscle fiber mitochondrial content and respiratory capacity, slows rates of utilization of muscle glycogen and blood glucose, increases reliance on fat utilization, and reduces lactate production during sub-maximal exercise [29] (Coffey) [9] (Hawley) [30] (Holloszy). Performing concurrent training potentially interferes with the development of aerobic capacity by inducing hypertrophy and increases in the cross sectional area of both Type I and Type II fibres [31] (Putman). Muscle fibre hypertrophy reduces the mitochondrial volume density of both Type I and Type II fibres [32] (Always) [33] (Chilibeck). This has a negative effect on muscle oxidative capacity by reducing the activity of oxidative enzymes, when enzyme activity is expressed relative to protein content [34] (Tesch). Therefore, although a strong relationship exists between maximum strength and power and performance in sprint cycling events, it is unclear if concurrent training induces favorable training adaptations for endurance cycling performance [35] (Stone).

It is possible though, that concurrent training may result in adaptations that could improve performance in endurance cycling events. For example, resistance training may improve cycling economy or efficiency by decreasing the proportion of maximal force required for each pedal stroke, and increasing the strength of Type I muscle fibres [36] (Coyle) [37] (Horowitz). In addition, resistance training may also cause transformation of Type IIX fibres to more oxidative Type IIA myosin isoform expressions, potentially enhancing the oxidative capacity of the trained muscle fibres [38] (Adams) [39] (Andersen) [40] (Hather) [31] (Putman). Theoretically, higher power outputs at sub-maximal lactate concentrations and increases in time to exhaustion would result from improving Type I muscle fibre strength and transforming Type IIX to Type IIA isoform expressions [41] (Hausswirth) [42] (Hickson). It has also been also suggested that resistance training improves the lactate power profile by enhancing the capacity of skeletal muscle to buffer hydrogen ions during exercise [43] (Paavolainen). Consequently, cyclists who have been performing concurrent training as part of their periodized training programmes, may have a performance advantage over non-strength trained athletes during endurance road races [13] (Laursen) [44] (Levin).

For highly trained road cyclists, it remains somewhat unclear whether concurrent training will interfere with the development of aerobic capacity, or whether improvements in maximal strength will lead to increased anaerobic capacity and performance in a road race or time trial. The purpose of this review therefore is to identify and evaluate original research examining the influence of maximal strength training on road cycling endurance performance in highly trained road cyclists to identify the influence of this training method on the performance parameters associated with road cycle racing.

Literature Search Methods

A search of Medline (Pub/Med), CINAHL, SPORTDiscus, ProQuest 5000 International and Google Scholar was performed using the key words *maximal strength or resistance training, cycling, elite or highly trained or competitive cyclists, endurance performance,* and various combinations of these words. Additional search strategies included using the 'related articles' option in PubMed and examining the reference lists of articles identified in the initial search. Inclusion and exclusion criteria used to narrow the focus of this review are listed in Table I. Review articles or articles examining the effects of strength or resistance training on untrained subjects were not included in the review.

Table I: Inclusion and exclusion criteria

Inclusion	Exclusion
Human subjects	Not human subjects
Highly trained or competitive male cyclists or triathletes – over 1 year cycle training with $VO_2max > 50$ $ml.kg^{-1}min^{-1}$; or highly trained or competitive female cyclists or triathletes – over 1 year cycle training with $VO_2max > 47$ $ml.kg^{-1}min^{-1}$	Untrained recreational male cyclists or triathletes with $VO_2max \leq 50$ $ml.kg^{-1}min^{-1}$; or Untrained recreational male cyclists or triathletes with $VO_2max \leq 47$ $ml.kg^{-1}min^{-1}$
Outcome measure included parameters of endurance cycling performance i.e. time trial, time to exhaustion or similar	Outcome measure exclusively 1RM, Vo2max or similar
Strength training was either performed exclusively off the bike or as part of a concurrent training programme including both off the bike resistance training and short duration high intensity supra-maximal intervals on the bike	Strength training performed exclusively on the bike i.e. short duration high intensity supra-maximal cycling intervals

Data Analysis

To enable the formulation of recommendations from the research identified, the methodological design of each study was evaluated using the critical evaluation methods of Megens and Harris [45] and Sackett [46], with two additional criteria; randomisation and control also added (see Table II). Each study reviewed was categorized using a four point scale. Level I studies were large randomized controlled trials using more than 100 participants, in which the levels of Type I and Type II errors were likely to be low. Level II studies were smaller randomized controlled trials using less than 100 subjects, where the possibility of Type I and Type II errors was greater. Level III studies were non-randomized, concurrent or cohort studies. Level IV studies were quasi experimental or case series studies where no comparison or control group was included. Recommendations were as follows: Grade A recommendations required the support of at least one Level I study, Grade B recommendations required the support of one Level II study, and Grade C recommendations required the support of one Level III or IV study [45] [46]. Statistically significant within group differences identified in Level I or II studies are classified as Grade C recommendations.

Table II: Scientific rigour of the reviewed studies

Study	Inclusion/Exclusion Criteria clearly stated	Training Protocol Described	Reliable Outcome Measures	Valid Outcome Measures	Subject/ Assessor Blinding	Subjects Accounted For	Randomisation	Control	Level – 5 Point Scale
Bastiaans et al (2001)	Inclusion Y Exclusion Y	Y	Y	Y	?	Y	N	Y	III
Bishop et al (1999)	Inclusion Y Exclusion Y	Y	Y	Y	?	Y	Y	Y	II
Hausswirth (2009)	Inclusion Y Exclusion N	Y	Y	?	Assessor ? Subjects Y	Y	Y	Y	II
Hickson et al (1988)	Inclusion N Exclusion N	Y	N	N	?	Y	N	N	IV
Levin et al (2009)	Inclusion Y Exclusion Y	Y	Y	?	?	Y	Y	Y	II
Paton & Hopkins (2005)	Inclusion Y Exclusion N	Y	Y	N	?	Y	Y	Y	II
Ronnestad et al (2009)	Inclusion Y Exclusion Y	Y	Y	Y	N	Y	N	Y	III
Ronnestad, et al., (2010)	Inclusion Y Exclusion Y	Y	Y	Y	N	Y	N	Y	III
Sunde et al (2009)	Inclusion Y Exclusion Y	Y	N	N	?	Y	Y	Y	II

Key:

- Level I Studies: large randomized trial, defined as those with more than 100 participants, in which level of false positives or false negatives would be low;
- Level II Studies: smaller randomized controlled trials, defined as those with less than 100 participants, where greater chance for false positives or negatives to occur;
- Level III Studies: non randomized, concurrent, cohort comparisons;
- Level IV Studies: non-randomized studies;
- Level V Studies: case series or studies

RESULTS

Nine eligible studies were identified that investigated the influence of concurrent training on endurance performance in highly trained road cyclists (see Table III). Five of the studies are categorized as Level II [48] (Bishop) [41] (Hausswirth) [44] (Levin) [49] Paton) [50] (Sunde), three as Level III [47] (Bastiaans) [51] (Ronnestad) [52] (Ronnestad) , and one as Level IV [42] (Hickson). Eight studies observed significant within-group improvements in determinants of road cycling performance for cyclists performing strength training in addition to their normal endurance training [42] (Bastiaans) [41] (Hausswirth) [42] (Hickson) [44] (Levin) [49] (Paton) [52] Ronnestad) [51] (Ronnestad) [50] (Sunde). Five studies also observed significant between-group improvements in determinants of road cycling performance i.e. for cyclists who performed strength training in addition to their normal endurance training compared to control groups of cyclists who performed endurance training alone [42] (Bastiaans) [44] (Levin) [49] (Paton) [51] (Ronnestad) [50] (Sunde). Only one study failed to identify either significant within or between group improvements in determinants of road cycling performance for cyclists performing strength training in addition to their normal endurance training [48] (Bishop).

Table III: Changes in cycling performance associated with a strength training programme

Study	**Subjects**	**Resistance Training Programme Design**				**Changes in Performance**			
		Training	**Sets & Reps**	**Frequency**	**Duration**	**Time Trial/TTE**	**Short Term Power**	**Vo2max/ Lactate Threshold**	**1 RM**
Bastiaans et al. (2)	E: 6 M cyclists 8.8+/-1.8 h/wk ET, Vo2max not stated	FW/Machines (high repetition/low weight explosive RT)	2 x 30	Not stated	9 weeks NP	1hr TT – MPO +7.9%*	30-s Erg test +4.3%*α PPO during ICE test +6.3%	Vo2max & LT measure used in calculation of GE& DE GE +1.1% DE +4.3%	NT
	C: 8 M cyclists 8.9 +/- 1.7h/wk ET, Vo2max not stated	-	-	-	-	MPO +5.9%*	30-s Erg test –5% PPO during ICE test +4.4%	GE + 0.7% DE + 2.2%	
Bishop et al. (3)	E: 14 F cyclists 110.2+/-29.4k/wk, peak Vo2 48.2 $ml.kg^{-1}min^{-1}$	FW	Periodized incl. 5x6-8RM or 4x4-6RM or 3x2-4RM	2/wk	12 weeks P	1.hr TT – APO +0.9%		LT +3%	+35.9%* α
	C: 7 F cyclists 123.6+/-35.8k/wk, peak Vo2 48.3 $ml.kg^{-1}min^{-1}$	-	-	-	-	1.hr TT – APO +2.7%		+0.4%	+3.7 %
Hausswirth et al. (8)	E:7 M triathletes 11.7+/-3.7h/wk ET; Vo2max 69.9 $ml.kg^{-1}min^{-1}$	FW/Machines	3-5 x 3-5RM	3/wk	5 weeks	2.hr cycle test @ constant power output - no significant between group difference in Vo2max; HRmax; Pmax; Vo2,HR, power values measured to VT1 and VT2 before and after; significant within group decrease in HR for periods 2 and 3	PPO during ICE test +1.7%	No significant difference in Vo2max; HRmax; Pmax; Vo2,HR, power values measured to VT1 and VT2 during 2.hr cycle test before and after	+6.6 %*
	C: 7 M triathletes 11.9+/-3.1h/wk ET; Vo2max 68.4 $ml.kg^{-1}min^{-1}$	-	-	-	-	No significant difference in Vo2max; HRmax; Pmax;	PPO during ICE test -1.7%	No significant difference in Vo2max; HRmax; Pmax; Vo2,HR, power values measured to	-4.1% *

						Vo2,HR, power values measured to VT1 and VT2 before and after		VT1 and VT2 during 2.hr cycle test before and after	
Hickson et al. (10)	E: .8 cyclist/runner s (6 M 2 F); Vo2max 54.4 ml.kg^{-1}min^{-1}	FW/Machine s	3-5 x 5RM and 3 x 25 (toe raises)	3/wk	10 weeks NP	TTE (min) @ 80-85% V02max +18.8%*	TTE @ max work rates +11%*	Vo2max L/min No change LT No change	+30 %*
Levin et al . (18)	E: 7 M cyclists/ triathletes 274+/-84k; 526+/-85min p/wk ET; Vo2max 62.4 ml.kg^{-1}min^{-1}	FW/Machine s/ Plyometric	3 x 6 or 3 x 12 or 4 x 5 repetition s	3/wk	6 weeks P	30k TT No within group difference in time to completion or mean W produced	PPO/APO during 250m & 1k sprints in 30kTT No difference s in PPO/APO during sprints PPO +4% first 250m &1k sprint PPO +6%14k 250m sprint PPO - 5% final sprint PPO during ICE test -1.7%	Vo2max No change	1RM squat +26 %*
	C:. 7 male cyclists/triathlet es 278+/- 34k;613+/- 78min ET; Vo2max 63.1 ml.kg^{-1}min^{-1}	-	-	-	-	Within group time to completion + 0.3% and MAP +0.7%	No difference s in PPO/APO during sprints PPO +13%, +7%, +11% in final 3 sprints*α PPO during ICE test -1.1%	V02max +0.01%	+ 6.1%
Paton & Hopkins (26)	E: 9 M cyclists 11.6 +/- 2.1h/wk ET; Lactate power profile 68.3%, Vo2max not stated	Plyometrics	3 x maximal effort explosive jumps, 3 x 20	2-3/wk	4-5 weeks NP	4k MPO +8.1%*α	30-second power +9%*α 1km MPO + 8.7%*α	LT + 3.7%*α oxygen cost +3%*α	

			explosive step ups 5 x 30 sec bike sprints,				PPO during ICE test +6.8%*α		
	C: 9 M cyclists 12.9 +/- 3.3 h/wk ET; Lactate power profile 67%, Vo2max not stated	-	-	-	-	4k MPO + 0.3%	30-second power not stated 1k MPO no change PPO during ICE test -0.1%	LT +1.7% oxygen cost +0.3%	
Ronnestad et al. (27)	E: 11 M cyclists 151+/-13hrs ET; Vo2max 66.8 ml.kg^{-1}min^{-1}	FW/Machines	3 x 4-10RM	2/wk	12 weeks P	185min sub-maximal cycling @44% W.max: Last hour Vo2 +2.2%*α HR + 6.5%*/*α LT +14.9%*/*α	5-min TT MPO after 185.min sub max cycling +7.2%* / *α PPO during ICE test +4.2%	V02max +3..3+/-1.4% LT + 7.1%	+26 %*/*α
	C: 9 cyclists (7 M 2 F) 138+/-13hrs ET; Vo2max 65.9 ml.kg^{-1}min^{-1}					Last hour Vo2 +1.9% HR +0.3% LT +11.3%	5 min TT MPO decreased PPO during ICE test +1.9%	Vo2max + 6.0% LT +3.1%	No change
Ronnestad et al. (28)	E: 11 M cyclists 151+/-13hrs ET; Vo2max 66.8 ml.kg^{-1}min^{-1}	FW/Machines	3 x 4-10RM	2/wk	12 weeks P	40min TT MPO +6.0%*	Wingate 30-second test: MPO +1.7% PPO + 9.4%*/*α	ICE: V02max + 3..3%* W/max + 4.3%* RER No change HR No change LT+ 7.1%	IRM +21. 2%*/*α
	C: 9 cyclists (7 M 2 F) 138+/-13hrs ET; Vo2max 65.9 ml.kg^{-1}min^{-1}					MPO +4.6%*	MPO - 1.9% PPO - 0.5%	ICE: Vo2max +6.0% * W/max +1.9*% RER No change HR No change LT+ 3.7%	No change
Sunde et	E.	FW	4 x 4RM	3/wk	8 weeks	CE at 70%	TTE at	VO2max +0.7%	1RM

al. (32)	8 cyclists (7 M 1 F) 273+/-288min ET; Vo2max 63.4 ml.kg^{-1}min^{-1}				P	V02 max*/*α MAP + 6.4%*/*α HR +2.7% WE + 4.7%*/*α	MAP + 17.2%*	LT+ 2.02%	+14.2%*/*α
	C: 5 cyclists (3 M 2 F) 588+/-208min ET; Vo2max 58.7 ml.kg^{-1}min^{-1}	-	-	-	-	CE at 70% V02 max * MAP + 0.4% HR +0.7% WE + 1.3%*	TTE at MAP + 5%	VO2max -0.2% LT +1.5%	1 RM +1.9 %

Key : ** = statistically significant within group effect; *α statistically significant between group effect; APO = Average Power Output; C = Control; CE = Cycling Economy; DE = Delta Efficiency; ET = Endurance Training; E = Experimental; F = Female; FW = Free Weights; GE = Gross Efficiency; HR = Heart Rate; HRmax = Heart Rate Maximum; Incl = include; ICE = Incremental Cycle Ergometer; LT = Lactate Threshold; M = Male; MAP = Mean Average Power; MPO = Mean Power Output; NP = Non Periodized; P = Periodized; Pmax = Power Maximum; PPO = Peak Power Output; RM = Repetition Maximum; TT = Time Trial; TTE = Time To Exhaustion; VT1 = Ventilatory Threshold 1; VT2 = Ventilatory Threshold 2; WE = Work Efficiency*

Level II Studies

Five randomized controlled clinical trials were identified that investigated the influence of concurrent training on determinants of road cycling performance in highly trained road cyclists [47] (Bastiaans) [48] (Bishop) [41] (Hausswirth) [44] (Levin) [49] (Paton) [50] (Sunde). Compared to cyclists who performed endurance training alone, cyclists who performed strength training in addition to their normal endurance training demonstrated significant improvements in determinants of road cycling performance such as lactate power profile, oxygen cost, exercise efficiency, cycling economy, and work efficiency at 70% of VO_2max [49] (Paton) [50] (Sunde). Paton and Hopkins [49] also demonstrated improvements in both peak and mean power output values during 30-second, one-kilometre and four-kilometre time trials. Similarly, Levin et al. [44] recorded improvements in peak power outputs during the final three sprints in a 30-kilometre simulated road cycle race. Significant reductions in average heart rate and time to exhaustion at maximal aerobic power were also observed within the concurrent training groups in the Hausswirth et al. [41] and Sunde et al. [50] studies, although these changes were not significant when compared to the control groups.

Level III Studies

Three non-randomized controlled trials were identified that investigated the influence of concurrent training on determinants of road cycling performance in highly trained road cyclists [47] (Bastiaans) [51] (Ronnestad) [52] (Ronnestad). Compared to cyclists who performed endurance training alone, cyclists who performed strength training in addition to their normal endurance training demonstrated significant improvements in determinants of road cycling performance such as heart rate, blood lactate values, and oxygen cost during the last hour of a 185-minute constant workload endurance cycling test [51] (Ronnestad). Strength trained cyclists also demonstrated statistically superior mean power outputs during a five minute all out time trial completed at the conclusion of the 185-minute cycle test [51] (Ronnestad). Baastians et al. [47] also demonstrated significant improvements in maximal and average power outputs during a one hour time trial as well as a 30-second performance test, although these changes were not significant when compared to the control group that performed endurance training alone. Similarly, Ronnestad et al. [52] observed significant improvements in mean power output during a 40-kilometre time trial, and in both maximum power and VO_2max during an incremental cycle ergometer test in the combined strength and endurance trained cyclists, although these improvements were also not statistically significant when compared to the control group.

Level IV Study

One prospective quasi-experimental trial involving no control group was identified that examined whether adding strength training to the training programmes of highly trained road cyclists produced positive or negative effects on determinants of road cycling performance [42] (Hickson). Significant within group improvements were demonstrated in time to exhaustion at both 80-85% VO_2max, as well as at maximum work rates.

Grade Recommendations

Based on the results summarized in Table 2, a number of recommendations are proposed:

Grade A Recommendations:
Since none of the studies were randomized controlled clinical trials involving more than 100 participants, no Grade A recommendations could be made [46] (Sackett).

Grade B Recommendations:
Concurrent strength and endurance training in highly trained road cyclists may significantly improve:
- Lactate power profiles, oxygen consumption/cost, exercise efficiency, cycling economy, and work efficiency at 70% of VO_2max [49] (Paton) [50] (Sunde);
- Peak and mean power outputs during sprints and 30-second efforts, and time trials lasting between 1 and 4 kilometers [44] (Levin) [49] (Paton);

Grade C Recommendations:
Concurrent strength and endurance training in highly trained road cyclists may also significantly improve:
- Mean and average power outputs during time trials ranging from 40 to 60 minutes [47] (Bastiaans) [52] (Ronnestad) [51] (Ronnestad);
- Maximal work rates and average heart rates during incremental cycle ergometer testing, and time to exhaustion at maximal aerobic power or 80-85% VO_2max [48] (Bishop) [41] (Hausswirth) [42] (Hickson) [52] (Ronnestad) [51] (Ronnestad) [50] (Sunde).

DISCUSSION

Utilising the rules of evidence described by Sackett [46], some evidence has been identified to support the use of concurrent training in the periodized training programmes of highly trained road cyclists. While no Grade A evidence currently exists, Grade B evidence indicates that in highly trained road cyclists, concurrent training can significantly improve measures of road cycle racing performance such as mean power outputs during time trials ranging between one km and one hour, and anaerobic power as measured by peak power during sprint ($\leq$30 seconds) efforts. These improvements are possibly caused by improving physiological determinants of performance such as the lactate power profile, and cycling or exercise economy. There is also weaker evidence (i.e. Grade C) that concurrent training improves time to exhaustion at maximal aerobic power. In the context of the demands of road cycle racing, where cyclists are often required to produce high aerobic and anaerobic power outputs, and short sustained supra-maximal levels of muscular force throughout the race, improvements in these measures may be highly significant.

To measure the effects of concurrent training on endurance performance, incremental cycle ergometer tests, time to exhaustion, and either distance or time based time trials were the most common outcome measures used in the studies. A number of studies also included analysis of short term power (i.e. 30-second effort mean and peak power) [47] (Bastiaans) [49] (Paton) [52] (Ronnestad). It has been suggested that the most important consideration in selecting the test used to evaluate endurance performance in cyclists, is the relationship between competitive performance and performance in the test [49] (Paton), Paton and Hopkins [53] suggest that currently the best two measures available for predicting competitive time trial performance are peak power measured in a cycle ergometer incremental test ($r = 0.99$) [54] (Balmer); and time or mean power in a simulated 40-kilometre time trial ($r = 0.88$-0.98) [55] (Coyle) [56] (Palmer). By comparison, anaerobic measures such as 30-second testing are less reliable, with co-efficient of variation ranging between 2.2-5.4% [57] (Coggan) [58] (Weinstain). Therefore, the results of studies using time to exhaustion or short term performance indicators may not be as valid or reliable as studies that evaluating performance using a time trial [48] (Bishop). It is also clear that most measures of cycling performance in laboratory tests have random errors $\geq$2%, with this error increasing to 3-4% where tests last several hours [59] (Hopkins). Where performance enhancements of 0.3-0.5% (0.5%-1%) of the typical variation between events make a difference to a highly trained cyclist, the outcome measures used in these studies may be unreliable at tracking the smallest changes in performance that matter to this category of elite athletes [53] (Paton).

Where time to exhaustion was used as an outcome measure; significant between and within group improvements were observed. For example, compared to cyclists performing endurance training alone, a 17.2% improvement in time to exhaustion at mean average power output was observed in cyclists who performed a combination of free and machine weight exercises (4 x 4RM) three times per week for eight weeks (31). Similarly, Hickson et al. [42] observed an 11% within group increase in time to exhaustion at maximal work rates, and an 18.8% improvement in the time spent cycling at 80-85% VO2max, after a single group of cyclists performed a combination of free and machine weight exercises (3-5 x 5RM) three times per week for ten weeks. Although longer cycling tests introduce greater chance of random error, the improvements in time to exhaustion that occurred during progressively longer testing underscores the relevance of completing prolonged tests to better simulate road cycling in studies that evaluate the effectiveness of different training methods [51] (Ronnestad). By comparison, the results of studies using time trials to assess the effect of concurrent strength and endurance training on cycling performance were less conclusive. Although between group improvements' ranging between 7.2-8.7% were noted in mean power outputs in short duration time trials (ranging between one and five km); and within group improvements of 6.0% and 7.9% were observed in longer duration time trials of 40 and 60 minutes [47] (Bastiaans) [49] (Paton) [52] (Ronnestad) [51] (Ronnestad), three studies failed to demonstrate improvements in time trial performance following concurrent training [48] (Bishop) [41] (Hausswirth) [44] (Levin). However, Bishop et al.'s [48] sample included only female participants, and it is possible that gender is a factor influencing whether strength training improves endurance performance in highly trained cyclists; and the 30-kilometre time trial used by Levin et al. [44] including intermittent sprints, has not been validated as an outcome measure for endurance cycling performance.

Where mean or peak power were recorded during short anaerobic (≤30 seconds) efforts, improvements ranging between 4.3-9.4% were observed following performance of concurrent training compared to endurance training alone [47] (Bastiaans) [49] (Paton) [51] (Ronnestad). The largest improvements in anaerobic power outputs (9% and 9.4%) were observed following performance of three sessions per week of three sets of maximal effort explosive jumps and step ups over 4-5 weeks, and two sessions of periodized free and machine weight (4-10RM) exercises performed over 12 weeks [49] (Paton) [51] (Ronnestad). Paton and Hopkins [49] suggest that the improvements observed may be due to increases in the firing frequency of muscle motor units from strength training, leading to increases in muscle peak force and rate of force development. These changes in short term cycling power output may be highly significant in the context of the demands of a road cycle race where cyclists are often required to produce high levels of peak and mean power for short durations when climbing hills, surging and in the final sprint. Together with the improvements observed in time to exhaustion and both short and longer time trial measures, these results suggest concurrent training may positively influence both the aerobic and anaerobic determinants of road cycling performance.

As noted, peak power output ("PPO") during incremental cycle ergometer testing is also a reliable measure for evaluating the performance of elite cyclists (co-efficient of variation of 0.9%) [59] (Balmer) [60] (Balmer). However, four of the six studies that evaluated PPO in an incremental cycle ergometer test failed to identify an improvement in this measure after cyclists performed concurrent training programmes [47] (Bastiaans) [41] (Hausswirth) [44] (Levin) [51] (Ronnestad). The 4.3% within group improvement in PPO observed by Ronnestad et al. [52] was also not significant compared to the 1.9% improvement observed in cyclists performing endurance training alone. The only study observing a between group improvement was Paton & Hopkins [49]. The 6.8% increase in PPO observed is large in the context of highly trained cyclists, where enhancements of the magnitude of 0.5-1.0% are considered significant. However, this improvement in performance cannot be attributed to the effects of strength training alone, since subject's alternated explosive resistance training exercises with 30-second sprints on the bike.

The physiological adaptations underlying the improvements in the performance measures identified in this review are not completely clear. Power outputs corresponding to set lactate inflection points (i.e. 1mM or 4 mM) have commonly been suggested to be important determinants of endurance cycling performance [55] (Coyle). The results of this review suggests that concurrent training may improve endurance cycling performance by increasing mean power outputs at the anaerobic threshold and/or other markers of blood lactate accumulation. This potentially reflects increased capacity for high intensity performance such as mean power output over the course of prolonged road races or time trial compared with endurance training alone [61] (Jackson) [52] (Ronnestad) [51] (Ronnestad) [50] (Sunde). Improvements in anaerobic threshold-type measures following concurrent strength and endurance training may be caused by alterations in muscle fiber recruitment patterns that increase the lactate threshold and reduce the reliance on glycogenesis [60] (Balmer) [42] (Hickson) [52] (Ronnestad) [50] (Sunde). Hickson et al. [42] also suggests that an improvement in lactate profiling occurs by delaying recruitment of the more glycolitic type II muscle fibers, allowing cyclists to push greater loads for the same blood lactate response. Since type I muscle fibers are more efficient than type II fibers when performing sub-maximal exercise, increasing the relative recruitment of and the strength of type I fibers may delay activation of less economical type II fibers, resulting in reduced blood lactate levels for the same absolute workload [52] (Ronnestad). The increased strength and/or rate of force development resulting from concurrent strength and endurance training may also improve short-term power output and result in improved performance in sprints performed either in isolation or embedded in a simulated time trial [44] (Levin) [50] (Sunde). However, it is unclear if these effects reflect primarily neural or morphological adaptations to strength training.

There are a number of limitations associated with this review. The Grade B evidence identified is based on only five studies, and the strength of the evidence identified in the literature is limited due to a number of design and methodological limitations. For example, four of the studies noting the benefits of strength training did not randomize subjects into either an intervention or control group [47] (Bastiaans) [42] (Hickson) [52] (Ronnestad) [51] (Ronnestad). There are also a number of potential confounding variables that provide alternative explanations for the improvements seen. For example, participants in seven of the studies continued to perform high intensity efforts on the bike during the intervention period [47] (Bastiaans) [48] (Bishop) [41] (Hausswirth) [44] (Levin) [49] (Paton) [52] (Ronnestad) [51] (Ronnestad). Where participants continued to perform high intensity intervals or maximal efforts on the bike during the intervention period, it is impossible to attribute endurance performance improvements to the influence of strength training alone. Paton and Hopkins [49] was also the only study to evaluate concurrent training during the competitive phase of the season. Substantial improvements in performance and changes to related physiological measures are likely to occur as athletes' progress from base to competitive training [3] (Paton). It is therefore unlikely that improvements observed when studies take place in off-season phases would be of the same magnitude if performed during the athletes' competitive phase.

Similarly, where studies added strength training to normal endurance training, it is possible that higher volumes of training, rather than increases in leg strength, are responsible for the improvements in endurance performance observed [48] (Balmer) [42] (Hickson) [44] (Levin) [52] (Ronnestad) [51] (Ronnestad) [50] (Sunde). Further, overtraining and residual fatigue associated with adding strength training to the normal training programmes of endurance road cyclists may be a factor limiting physiological adaptations when performed over longer periods of time than performed in these studies [61] (Jackson). Where high training loads are performed without adequate recovery, impaired performance may result from the continued disturbance to autonomic balance [62] (Billat). It is also interesting that the significant improvements in endurance performance parameters noted in higher level competitive road were not observed when strength training was performed by lower level club cyclists, female cyclists, or trained male cyclists/triathletes [48] (Bishop) [41] (Hausswirth) [44] (Levin). It is therefore possible that the performance/training status of a cyclist may be a significant factor in determining whether they are likely to respond positively to the addition of strength training to their programme. Specifically, lower level cyclists may gain a sufficient training stimulus by performing endurance cycling alone; whereas high-level cyclists who have a long training history of high volume endurance cycling training may need to incorporate additional forms of training (e.g. strength training) if they wish to address their relative weak points that are hindering further gains in performance.

CONCLUSION

Although the short term duration of the studies identified does not allow a definitive answer to the question whether adding strength training to the periodized programmes of highly trained road cyclists is beneficial to performance in the long-term, the results of this review suggest that the inclusion of strength training in their overall training programmes may enhance performance in a range of highly demanding road cycling events. By increasing lower body strength and power, highly trained road cyclists may improve their anaerobic energy production potential during short hill climbs, repeated surges in pace during the race, and in the final sprint. It is therefore suggested that high level road cyclists perform some form of strength training to improve these sport specific performance determinants. This may be even more relevant where cyclists are unable to perform high intensity training on their bike due to inclement weather or where other extrinsic environmental constraints exist.

Future research should be conducted to determine what is the best form(s) of strength training for these athletes, and how best to incorporate such training into their annual periodized training plan. Factors such as the optimal strength training frequency, intensity, duration, and length of recovery periods etc, and the timing of this form of training in relation to other forms of on the bike training sessions and competition events, should be examined. Investigations into whether strength training should be added to or replace on the bike training sessions is also important, since identifying optimal training volume/loads will assist in reducing the risks of overtraining that result from the continued disturbance of autonomic balance. However, based on the research evaluated which involved training durations of a minimum of 8–12 weeks and 3-4 sets of between 3-6RM loads, maximal strength training using high loads and few repetitions, emphasising neural adaptation rather than muscle hypertrophy, may be the most effective method of resistance training to enhance road cycling performance. Although explosive or plyometric resistance training also significantly improved short term performance measures e.g. 30-second power output and mean power output in one and four km time trials, it is unclear if such benefits would transfer to longer duration endurance performance due to the limited role of the stretch-shorten cycle during predominantly concentric activities like cycling. This also raises the question of whether lower body strength training for cyclists should be performed with or without a prior eccentric contraction? It has also been suggested that cyclists must perform a 'conversion phase' so that gains in maximum strength are converted into improvements in muscular endurance of longer duration [63] (Bompa). The exact specifications of the periodization plan to convert maximal strength to strength endurance would therefore also be helpful in identifying the optimal strength training prescription that would provide transferable benefits to highly trained road cyclists.

Bullet Point Summary

- In highly trained road cyclists, concurrent training significantly improves measures of road racing performance such as time to exhaustion at maximal aerobic power, mean power outputs during time trials and anaerobic power as measured by peak power during sprint (≤30 seconds) efforts.

- Two sessions per week of maximal strength training for 8–12 weeks using high loads and few repetitions (3-4 sets of between 3-6RM), emphasising neural adaptation rather than muscle hypertrophy, may be the most effective method of resistance training to enhance road cycling performance.

- Improvements in road-cycling performance are possibly caused by improving physiological determinants of performance such as the lactate power profile, and cycling or exercise economy.

- Future research is necessary to determine the best form(s) of strength training and how best to incorporate such training programmes including factors such as the optimal strength training frequency, intensity, duration, and length of recovery periods etc, and the timing of this form of training in relation to other forms of on the bike training sessions and competition events

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