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Review article

Effects of resistance training on cycling performance-related variables: brief review

Efeitos do treinamento resistido nas variáveis relacionadas ao desempenho no ciclismo: breve revisão

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ABSTRACT

Introduction: In elite cyclists, improving the efficiency and economy of cycling occurs after long periods of endurance training. Thus, the association of this with other training methods is interesting for the improvement of the performance of these athletes. **Objective:** To analyze the effects of the endurance and resistance training on VO_{2max}, cycling economy and efficiency, and maximal and submaximal power output. **Methods:** The search was conducted in the follow databases: PubMed, Bireme, and SciELO using "cycling", "strength training", "resistance training", "power training", "plyometric training", "weight training", "concurrent training" as keywords. The inclusion criteria were: randomized studies carried out between 2007-2019. The exclusion criteria were: studies that did not meet the inclusion criteria, participants with some clinical condition (disease) or rehabilitation training characteristics, and duplicate studies. To assess the methodological quality of the studies, the PEDro scale was used. **Results:** Nine studies were included in this review, which demonstrated that resistance training combined with specific training for cycling promotes improvements in athletes' performance parameters, such as: maximum strenght (nine studies +17.8 ± 7.1%), VO_{2max} (one study +13.34%), cycling economy (one study +6.9%), anaerobic power (two studies 5,1± 3,5%), power as a parameter of performance/Endurance (four studies 8,4 ± 4%), when compared to specific training alone. **Conclusion:** In conclusion, adding resistance training to the cyclist training program improves efficiency and economy, as well as aerobic peak and mean anaerobic power.

Keywords: cycling; resistance training; performance.

RESUMO

Introdução: Em ciclistas de elite, a melhoria da eficiência e economia do ciclismo ocorre após longos períodos de treinamento de resistência. Assim, a associação deste com outros métodos de treinamento é interessante para a melhoria do desempenho destes atletas. **Objetivo:** analisar os efeitos do treinamento de endurance e resistência no $VO_{2máx}$, na economia e eficiência do ciclismo e na produção de potência máxima e submáxima. **Métodos:** Foram utilizadas as seguintes bases de dados: PubMed, Bireme e SciELO, utilizando palavras-chave como "ciclismo", "treinamento de força", "treinamento de resistência", "treinamento de potência", "treinamento pliométrico", "treinamento de peso" e "treinamento concorrente". Os critérios de inclusão foram estudos randomizados realizados entre 2007 e 2019. Os critérios de exclusão incluíram estudos que não atendiam aos critérios de inclusão, participantes com alguma condição clínica (doença) ou características de treinamento de reabilitação e estudos duplicados. Para avaliar a qualidade metodológica dos estudos, foi utilizada a escala PEDro. **Resultados:** Nove estudos foram incluídos nesta revisão, que demonstraram que o treinamento de resistência combinado com treinamento específico para o ciclismo promove melhorias nos parâmetros de desempenho dos atletas, como: força máxima (nove estudos +17,8 ± 7,1%), $VO_{2máx}$ (um estudo +13,34%), economia de ciclismo (um estudo +6,9%), potência anaeróbica (dois estudos 5,1 ± 3,5%), potência como parâmetro de desempenho/endurance (quatro estudos 8,4 ± 4%), quando comparado ao treinamento específico sozinho. **Conclusão:** Adicionar o treinamento de resistência ao programa de treinamento do ciclista melhora a eficiência e economia, assim como o pico aeróbico e a potência média anaeróbica.

Palavras-chave: ciclismo; treinamento resistido; performance.

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Introduction

The capacity to generate mechanical energy is essential to overcome external resistance, which forces the cyclist to produce power and speed to carry out the displacement[1]. The interaction between aerobic and anaerobic metabolic systems is linked with power output production during cycling [1,2]. Thus, high-level road cyclists have highly developed energy systems, which is very important during the races. In this sense, training strategies are necessary to develop the aerobic and anaerobic capacities, resulting in higher power output and higher performance [3].

Scientific evidence shows that endurance training promotes physiological adaptations related to higher aerobic performance, such as higher Hemoglobin mass, stroke volume, VO_2 consumption and mitochondrial density. However, a growing body of evidence shows that the endurance training associated with resistance training improve the pedaling economy, rate force development, lactate threshold and Maximal power output [4]. Moreover, Muscle contractile capacity, activation of agonist muscles, diminished coactivation of antagonist muscles, and improved motor unit recruitment and firing rate [5] are recognized as neural adaptations induced by resistance training that contribute to endurance performance.

Rønnestad *et al*. [6] demonstrated that endurance training associated with heavy resistance training for ten weeks increased maximal isometric half squat value, mean power for 30 seconds. Wingate sprint test, and a slightly improvement power output at 4 mmol.l-1 . In another study, Rønnestad *et al*. [7], demonstrated that heavy resistance training also improves also the mean power output during 40-min all-out trial.

In agreement, recent studies have shown that resistance training can improve in mitochondrial functions related to cellular respiration, ATP production and the action of oxidative enzymes in skeletal muscle [8-10]. However, it is still necessary clarify and quantify the possible effect of different resistance training programs and periodization on endurance performance determinants (VO_{2max}, cycling economy and efficiency, maximal and submaximal power output) to maximize the athlete's performance. Thus, this review aims to analyze the effects of the endurance and resistance training on VO_{2max}, cycling economy and efficiency, and maximal and submaximal power output.

Methods

For this brief review, we adopted the following databases: PubMed, Bireme, and SciELO. The following descriptors were used: "cycling", "strength training", "resistance training", "power training", "plyometric training", "weight training", "concurrent training", were used in combination with the Boolean operators OR and AND. To refine the search, PRISMA recommendations were employed [11]. The terms were searched in the title, keywords, and abstract, and after meeting all the criteria, the entire text was read. Only articles in the English language were used.

The inclusion criteria were randomized studies carried out between January 2007 until December 2019, described in the methodology the variables related to the training program (intensity and volume, such as the load, number of repetitions, number of sets, interval time between sets and exercises; focused on strengthening the lower limbs); adult subjects (≥ 18 years old) who practice cycling, control group performing endurance training through cycling and intervention group performing concurrent training (endurance training + resistance training). The studies should evaluate and analyze the strength, power, VO_{2max}, economy and efficiency. The exclusion criteria were studies that did not meet the inclusion criteria, participants with some clinical condition (disease) or where the training had rehabilitation characteristics, and duplicate studies (Figure 1). To assess the methodological quality of the studies, the PeDro scale was used [12,13].

Results

Studies description

The number of potential studies found during the database search totaled 2499. Figure 1 summarizes the process of searching and selecting potential studies. Nine studies [6,7,14-20] contemplated the inclusion criteria and were then included in this brief review. After the selection, the PeDro scale was used to emphasize the quality of the studies.

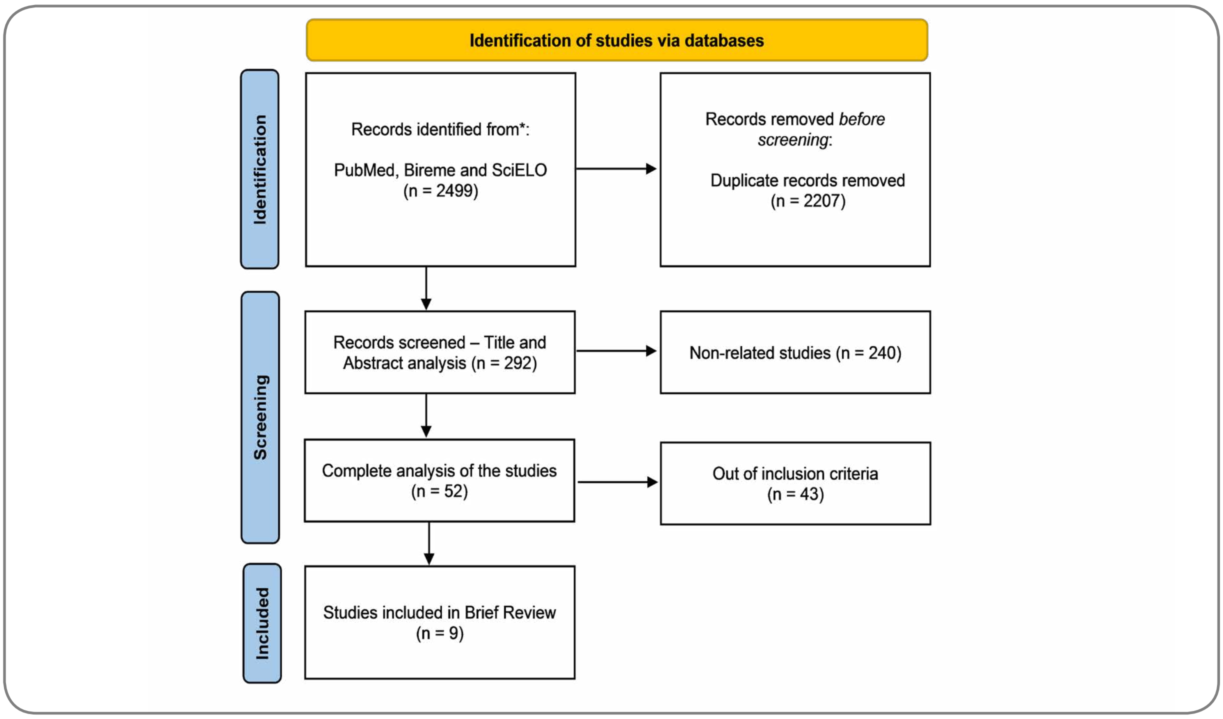

Figure 1 - Process of searching, screening, and selection of studies

PEDro scale score

The individual scores of the studies on the PeDro scale can be seen in Table I, alongside the characteristics of the participants. The study scores ranged from 4 to 7. All of them had points deducted regarding blinding the participants, trainers, and assessors with respect to the interventions and outcomes. Differences in the study scores were attributed to factors such as the lack of explanation of the randomization process of participants, significant differences in key outcomes between groups before the intervention, and the failure to explicitly state whether key outcomes were achieved in at least 85% of participants initially allocated to the groups.

Study characteristics

The study results demonstrated that strength training with endurance training significantly improved the following variables: strength [6,7,14–20] , VO_{2max} [18], cycling economy and efficiency [6,7, 20], maximal and submaximal power output [7,14,18].

Participant's characteristics

The summary of the general participant's characteristics is presented in Table I. There are 141 participants (128 men and 13 women), aged between 19 and 47 years. The samples of the studies consisted of elite cyclists [6,7,14,19], triathletes [15], trained cyclists who belonged to clubs [16], well-trained cyclists and triathletes [17] and finally, well-trained cyclists [18,20].

Training characteristics

The summary of the training program characteristics, including the design and frequency of resistance training, exercises, variables description (intensity, volume, interval) and number of hours per week of endurance training, can be seen in Table II.

All nine studies performed exercises focused on the lower limbs. However, four of them [15-18] mentioned having included in their training core exercises. One study [16] had two intervention groups performing different training. Only three [6,15,19] reported having had some professional follow-up in at least some period of resistance training.

Among the studies, the number of series performed varied from 2 to 5, the number of repetitions ranged from 3 to 20, the number of intervention weeks from 5 to 25 and the weekly frequency of strength training ranged from a session until 3 times a week.

All studies utilized machines in the execution of exercises. Two studies [16,17] indicated the execution of exercises on machines and with free weights. One study [20] utilized only one machine, while six studies [6,714,15,18,19] did not provide clear information related to exercise execution. Furthermore, six studies [6,7,14,15,18,19] employed linear periodization, one [17] used undulating periodization, and two

[15,20] implemented a maximal strength characteristic training. All nine studies conducted resistance training focused on cycling; however, three of them [15,18,19] engaged in other activities such as swimming, running, or cross-country skiing during a fraction of the training period.

Table I - Characteristics of the Participants and Scores (PEDro scale)

Study	Group	Participants	Age (years)	Height (cm)	Weight (Kg)	Training Status	PEDro Score
Aagaard P *et al.*, 2011	Int Cont	7 (M) 7 (M)	19.5 ± 0.8	180.7 ± 5.4	70.7 ± 5.8	Ciclistas de elite	4
Hausswirth C *et al.*, 2009	Int Cont	7 (M) 7 (M)	30.2 ± 4.3 32.4 ± 4.8	176.3 ± 3 .1 175.0 ± 7 .2	70.4 ± 8.0 69.4 ± 7.8	Triatletas	5
Jackson NP *et al.*, 2007	H-Res H-Rep Cont	7 (M)/2 (F) 8 (M)/1 (F) 3 (M)/2 (F)	31 ± 10 32 ± 9 27 ± 10	ND	25.4 ± 2.1 24.4 ± 2.7 23.1 ± 2.9 (IMC)	Ciclistas em nível de clube	5
Levin GT, McGuigan MR, Laursen PB., 2009	Int Cont	7 (M) 7 (M)	25 (4) 37 (7)	180.5 (9.6) 179.2 (8.0)	78.6 (9.4) 76.2 (8.3)	Ciclistas/Triatletas bem treinados	7
Rønnestad BR, Hansen EA, Raastad T., 2010	Int Cont	6 (M) 6 (M)	ND	ND	ND	Ciclistas bem treinados	5
Rønnestad BR *et al.*, 2016	Int Cont	7 (M) 7 (M)	19.0±1.6 20.1±1.6	179±8 183±9	67.8 ± 7.8 74.3 ± 7.5	Ciclistas de elite	4
Rønnestad BR *et al.*, 2015	Int Cont	9 (ND) 7 (ND)	19.1 ± 1.7 20.1 ± 1.6	178 ± 7 183 ± 9	66.0 ± 8.0 74.3 ± 7.5	Ciclistas de elite	6
Rønnestad BR, Hansen J, Nygaard H, 2017	Int Cont	10 (m)/2 (f) 6 (m)/2 (f)	19 ± 2 20 ± 2	178 ± 9 181 ± 10	67 ± 8 72 ± 9	Ciclistas de elite	6
Sunde A *et al.*, 2010	Int Cont	7 (M)/1 (F) 3 (M)/2 (F)	29.9 ± 7.2 35.8 ± 11.8	178 ± 8 178 ±13	72.5 ± 7.3 75.4 ± 11.2	Ciclistas bem treinados	5

Int = intervention group; Cont = control group; H-Res = intervention group with high loads; H-Rep = intervention group with high repetitions; M = male; F = female; ND = not described; IMC= body mass index

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Table II - Training characteristics

	Group	Training Prescription	Training Classification	Duration (weeks)	Strength training (times per week)	Endurance Training (h/week)
Aagaard P *et al.*, 2011	Int Cont	Resistance exercise: isolated knee extension, incline leg press, hamstring curls and calf raises; week 1: 4 x 10-12 RM; week 2-3: 4 x 8-10 RM; week 4-5: 4 x 6-8 RM; week 6-16: 4 x 5-6 RM; inter: 1-2 min between exercises and 2-3 min between sets.	Linear periodization.	16	2 to 3	10 a 18
Hausswirth C., *et al.*, 2009	Int Cont	Resistance exercise: leg press, leg extension, hamstring curl, and leg curl. 3-5 x 3-5 RM at >90% of 1 RM; inter: 3 min.	Maximum strength.	5	3	Int: 17.1 ± 3.1 Cont: 17.4 ± 3.7
Jackson NP *et al.*, 2007	H-Res H-Rep Cont	Resistance exercise: free weight barbell squats, leg curls, leg press and step up in a Smith machine. H-Res week 1: 2 x 10 reps at 50% of 1 RM; week 2-10: 4 x 4 reps at 85% of 1 RM; H-Rep: week 1: 2 x 10 reps at 50% of 1 RM; week 2-10: 2 x 20 reps at 50% of 1 RM; inter: 2 min	Linear periodization.	10	3	ND
Levin GT, MCGuigan MR, Laursen PB 2009	Int Cont	Resistance exercise: divided into 3 types: strength (4 x 5 reps: lunges, squats, straight-leg deadlift, seated calf raises, inclined crunches); power (3 x 6 reps: jump squats, single-leg jump squat, clean grip deadlift, single-leg calf raises and back extension); hypertrophy (3 x 12 reps: single-leg leg press, knee extension, knee flexion, standing calf raises and abdominal crunches; inter: 2 min.	Ondulatory periodization.	6	3	Int: 526 ± 85 min Cont: 613 ± 78 min
Rønnestad BR, Hansen EA, Raastad T, 2010	Int Cont	Resistance exercise: half squat, recumbent leg press with one leg at a time, standing one-legged hip flexion and ankle plantar flexion; week 1-3: 3 x 10 RM (1st session) and 3 x 6 RM (2nd session); week 4-6: 3 x 8 RM (1st session) and 3 x 5 RM (2nd session); week 7-12: 3 x 6 RM (1st session) and 3 x 4 RM (2nd session); week 13-25: 2 x 5 reps in half squat and recumbent leg press with one leg at a time at 80-85% of 1RM and 1 x 6 RM in one-legged hip flexion and ankle plantar flexion. Inter: 2 min.	Linear periodization.	12 (preparatory) + 13 (competitive).	2 (preparatory). 1 every 7-10 days (competitive)	ND
Rønnestad BR *et al.*, 2016	Int Cont	Resistance exercise: half squat, unilateral leg press, standing unilateral hip flexion and ankle plantar flexion; week 1-10: 3 x 4-10 RM; week 11-25: 3 x 5 reps with 80-85% RM; inter: 2 min.	Linear periodization.	10 (preparatory) + 15 (competitive).	~1 every 8 days	Int: 13.5 ± 1.5 Cont: 13.6 ± 3.2

Table II - Training characteristics

	Group	Training Prescription	Training Classification	Duration (weeks)	Strength training (times per week)	Endurance Training (h/week)
Rønnestad BR *et al.*, 2015	Int Cont	Resistance exercise: half squat, unilateral leg press, standing unilateral hip flexion and ankle plantar flexion; week 1-3: 3 x 10 RM (1st session) and 3 x 6 RM (2nd session); week 4-6: 3 x 8 RM (1st session) and 3 x 5 RM (2nd session); week 7-10: 3 x 6 RM (1st session) and 3 x 4 RM (2nd session). Week 11-25: 3 x 5 reps with maximal effort in the concentric at 80-85% of 1 RM; inter: 2 min.	Linear periodization.	10 for the development of +15 force for the maintenance of force.	2 (development). ~1 every 8 days (maintenance)	Preparator: Int: 11.3 ± Cont: 1.5 11.7 ± 3.1 Competitive Int: 15.2 ± 3.1 Cont: 15.3 ± 3.9
Rønnestad BR, Hansen J, Nygaard H, 2017	Int Cont	Resistance exercises: half squat, unilateral leg press, standing unilateral hip flexion and ankle plantar flexion; week 1-3: 3 x 10 RMs (1st session) and 3 x 6 RM (2nd session); week 4-6: 3 x 8 RM (1st session) and 3 x 5 RM (2nd session); week 7-10: 3 x 6 RM (1st session) and 3 x 4 RM (2nd session); inter: 2 min.	Linear periodization.	10	2	Int: 11.1 ± 1.8 Cont: 12.3 ± 2.9
Sunde A *et al.*, 2010	Int Cont	Resistance exercise: half-squat in a Smith machine with 4 x 4 RM; inter: 3 min.	Maximum strength.	8	3	ND

Int = intervention group; Cont = control group; H-Res = intervention group with high loads; H-Rep = intervention group with high repetitions; inter = interval; ND = Not described; RM= maximum repetition

Maximum strength

Maximum strength analysis is summarized in the Table III. In general, the intervention groups of all the studies significantly increase in the maximum strength [6,7,14-20].

While in the control groups, there was a significant increase in two studies [17,19], and one that demonstrated a significant reduction [15]. The other studies showed a non-significant difference [6,7,14,18,20]. One study [16] did not report the maximum strength of the control group.

VO_{2max}

VO_{2max} analysis is summarized in Table IV. Overall, it was observed that all intervention groups showed modifications in this variable. One study [18] demonstrated a significant increase in both groups. The remaining studies [7,14] showed a non-significant difference.

Economy and efficiency of the cycling

Cycling economy and efficiency analysis is summarized in Table V. The cycling economy was measured in 5 studies [6,7.14,16,20], all showing differences in pre- and post-intervention. One study [14] demonstrated a significant improvement post-intervention only in the control group. Another study [16] showed no difference in pre-values compared to post-training in the control group and demonstrated a significant improvement in the intervention groups. Two studies [6,7] showed no significant improvement in both groups. One study [20] showed a significant improvement in both groups, being greater in the intervention group.

Table III - Strength Assessment before and after intervention period

Study	Exercise	N	Pre-training (Kg)	Post-training (Kg)	Change (%)
Aagaard P *et al.*, 2011	Maximal isometric quadriceps contraction strength (MVC)	Tel: 7 Cont: 7	Int: 275,3 ± 42,4 N/m Cont: 261,9 ± 45,9 N/m	Int: 307.7 ± 40.4 N/m Cont: 257.9 ± 28.5 N/m	+12* -1.52
Hausswirth C *et al.*, 2009	Leg Press 45º (1 RM)	Int: 7 Cont: 7	Int: 290,7 ± 50,3 Cont: 289,3 ± 38,3	Int: 310.0 ± 55.6 Cont: 277,9 ± 42,1	+6,6 ± 3,9* -4.1 ± 3.0*
Jackson NP *et al.*, 2007	Squat (1RM)	Int: H-Res 9 Int: H-Rep 9 Cont: 5	Int:116 ± 20.1 Você:100 ± 36.9 Cont: ND	Int: 151 ± 29.2 Int:122 ± 26.5 Cont: ND	+30,17*# +22* ND
Levin GT, McGuigan MR, Laursen PB, 2009	Squat (1RM)	Int: 7 Cont: 7	Int: 109±18 Conta: 106±20	Ramal: 137±21 Conta: 113±22	+16,51# +6.79
Rønnestad BR, Hansen EA, Raastad T, 2010	Half squat in a Smith machine (1 RM)	Int: 6 Cont: 6	Int: ND Cont: ND	Int: ND Cont: ND	+23 ± 3* RU
Rønnestad BR *et al.*, 2016	Maximum strength during an isometric half squat on a force plate (MVC)	Int: 7 Cont: 7	Int:1400 ± 378 N/m Cont: 1340 ± 364 N/m	Int: 1726 ± 378 N/m Cont: 1447 ± 394	+23,28*# +7.98
Rønnestad BR *et al.*, 2015	Maximum force through the vertical reaction force in the squat with a jump on a force plate	Int: 9 Cont: 7	Int: ND Cont: ND	Int: ND Cont: ND	20 ± 12* RU
Rønnestad BR, Hansen J, Nygaard H, 2017	Maximum strength during an isometric half squat on a force plate (MVC)	Int: 12 Cont: 8	Int: ND Cont: ND	Int: ND Cont: ND	20 ± 12* +3±3
Sunde A *et al.*, 2010	Half squat in a Smith machine (1 RM)	Int: 8 Cont: 5	Int: 155.0 ± 40.6 Cont: 151,0 ± 36,0	Int: 177.5 ± 50.7 Cont: 154.0 ± 39.3	+14,51*# +1.98

Int = intervention group; Cont = control group; H-Res = intervention group with high loads; H-Rep = intervention group with high repetitions; ND = Not described, *Difference between pre-post, #Difference between intervention group for control group

Table IV - VO_{2max} evaluation before and after the intervention period

Study	n	Pre-training	Post-training	Change (%)
Aagaard P *et al.*, 2011	Int: 7 Cont: 7	Int: 73,5 ± 8,2 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 71,5 ± 6 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$	Int:75 ± 6 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 73 ± 2,3 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$	+2.04 +2.09
Hausswirth C *et al.*, 2009	Int: 7 Cont: 7	Int: 69,9 ± 6,3 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 68,4 ± 10,7 ml·kg-1·$^{min-1}$	Int: 70,8 ± 5,5 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 68,3 ± 10,1 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$	+1.28 -0.14
Jackson NP *et al.*, 2007	Int: H-Res 9 Int: H-Rep 9 Cont:5	Int: 47.9 ± 7. $ML{\cdot}kg^{-1}{\cdot}min^{-1}$ Int: 52.8 ± 4.7 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 55,3 ± 3,5 ml·kg-1·$^{min-1}$	Int: 49,3 ± 6,5 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Int:56.3 ± 4.1 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 58,9 ± 2,9 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$	+2.92 +6.62 +6.5
Levin GT, MCGuigan MR, Laursen PB., 2009	Int: 7 Cont: 7	Int:62.4 (5.4) $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 63,1 (1,8) $ml{\cdot}kg^{-1{\cdot}min-1}$	Int: 62,3 (3,2) $ml{\cdot}kg^{-1}$·min-1 Cont: 62,5 (2,7) $ml{\cdot}kg^{-1}{\cdot}min^{-1}$	-0.16 -0.95
Rønnestad BR, Hansen EA, Raastad T., 2010	Int: 6 Cont: 6	Int:65,2 ± 2,2 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 67,3 ± 2,7 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$	Int: 73,9 ± 3,2 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 73,4 ± 3,1 ml·kg-1·$^{min-1}$	+13,34* +9,06*
Rønnestad BR *et al.*, 2015	Int: 7 Cont: 7	Int: 77,59 ± 6,01 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 73.26 ± 5,43 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$	Int: 76,61 ± 8,13 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 74,68 ± 6,59 ml·kg-1·$^{min-1}$	-1.26 +1.11
Rønnestad BR *et al.*, 2015	Int: 9 Cont: 7	Int: 78 ±6 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 73,26 ± 5,43 ml·kg-1·min^{-1}	Int: 80 ±6 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 75 ± 7 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$	+2.56 +2.66
Rønnestad BR, Hansen J, Nygaard H, 2016	Int: 12 Cont: 8	Int: 77 ± 6 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 72 ± 7 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$	Int: 75 ± 8 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 70 ± 7 $ml{\cdot}kg^{-1{\cdot}min-1}$	-2.29 -2.77
Sunde A *et al.*, 2010	Int: 8 Cont: 5	Int: 63,4 ± 6,0 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 58,7 ± 8,8 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$	Int: 63,9 ± 5,6 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ Cont: 58,0 ± 10,8 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$	+0.78 -1.19

Int = intervention group; Cont = control group; H-Res = intervention group with high loads; H-Rep = intervention group with high repetitions; ND = Not described; *Difference between pre-post

Table V - Cycling Economy (CE) and efficiency analysis before and after the intervention period

Study	Test	Used term	Parameter	n	Pre-training	Post-training	Change (%)
Aagaard P *et al.*, 2011	Steady-state four-step incremental cycling	CE	(Watt/kg) / (mLO_2/min/kg) obtained at 75% of the VO_{2max}	Int:7 Cont:7	Int: 0.204 ± 0.025mLO_2/J# Cont: 0.223 ± 0,015mLO_2/J	Int: 0.199 ± 0.014mLO_2/J Cont: 0,207±0,008mLO_2/J	-2.45 +7.17*
Jackson NP *et al.*, 2007	Lactate Profile Test	Economy	VO_2 values at fixed loads (300 W)	Int:H-Res 9 Int:H-Rep 9 Cont:5	Int:46.4 ± 62.2 Int:48 ± 3.7 Cont: 52.6 ± 2,1	Int:48.3 ± 5.4 Int:49.4 ± 2.2 Cont: 52.7 ± 0,6	+4.09 +2.91 +0.19
Rønnestad, BR *et al.*, 2015;	ND	Fractional utilization of the VO_{2max} at the power of 4 mmol·L-1 [la-]	ND	Int:9 Cont:7	Int:78 ± 3% Cont: 80 ± 3%	Int: 80 ± 3% Cont: 81 ± 6%	+2 +1
Rønnestad BR, Hansen J, Nygaard H, 2017	ND	Fractional utilization of the VO_{2max} at the power of 4 mmol·L-1 [la-]	ND	Int:12 Cont:7	Int:79 ± 3% Cont: 81 ± 4%	Int:80 ± 4% Cont: 83 ± 1%	+1 +2
Sunde A *et al.*, 2010	Incremental protocol of VO_{2max}	CE	At power equivalent to 70% of VO_{2max}	Int:8 Cont:5	Int:217 ± 26 (V) Cont: 215 ± 57 (W)	Int:232 ± 36 (V) Cont: 216 ± 65 (W)	+6.9* +0.46

Int = intervention group; Cont = control group; ND = Not described; CE= cycling economy; *Difference between pre-post

Anaerobic power

Anaerobic power was measured in four studies [6,7,18,19], and was summarized in Table VI. All studies demonstrated an increase in peak anaerobic power in the intervention groups, however only one [18] showed a significant increase. Two studies [7,19] showed a non--significant decrease in peak power in the control groups. In the intervention groups, two studies [6,19] demonstrated a non-significant increase in the mean anaerobic power, while the other two [7,18] did not show differences in this parameter after the intervention. On the other hand, in the control groups, three studies [6,7,19] demonstrated a decrease, while one study [18] did not show a difference after the intervention period. Overall, after the intervention period, only one study [18] showed a significant difference in peak power, and no study showed a significant difference in the mean.

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Table VI - Power and anaerobic capacity in the Wingate test before and after the intervention period

Study	Test	n	Pre-training (W)	Post-training (W)	Change (%)
Intervenção					
Rønnestad BR, Hansen EA, Raastad T., 2010	Pico Wingate ($W\cdot kg^{-1}$)	6	18,5 ± 0,4	19,9 ± 0,8	+7,56 *# 0
	Média de Wingate ($W\cdot kg^{-1}$)		10,2 ± 0,3	10,2 ± 0,4	+6,76
	Índice de Fadiga		34 ± 1,2	36,3 ± 3,1	
Rønnestad BR *et al.*, 2016	Pico Wingate ($W\cdot kg^{-1}$)	7	23,51 ± 2,99	23,61 ± 3,29	+0,42 +1,59
	Média de Wingate ($W\cdot kg^{-1}$)		10,65 ± 0,92	10,82 ± 0,45	ND
	Índice de Fadiga		ND	ND	
Rønnestad BR *et al.*, 2015	Pico Wingate ($W\cdot kg^{-1}$)	9	23,6 ± 2,9	24,2 ± 3,4	+2,54* 0
	Média de Wingate ($W\cdot kg^{-1}$)		10,9 ± 0,9	10,9 ± 1,1	ND
	Índice de Fadiga		ND	ND	
Rønnestad BR, Hansen J, Nygaard H., 2017	Pico Wingate ($W\cdot kg^{-1}$)	12	23,2 ± 2,7	24,3 ± 2,8	+3,87 +1,86# ND
	Média de Wingate ($W\cdot kg^{-1}$)		10,7 ± 1,0	10,9 ± 0,9	
	Índice de Fadiga		ND	ND	
Study	**Test**	**n**	**Pre-training (W)**	**Post-training (W)**	**Change (%)**
Controle					
Rønnestad BR, Hansen EA, Raastad T., 2010	Pico Wingate ($W\cdot kg^{-1}$)	6	15,7 ± 1,1	16,0 ± 1,6	+1.91
	Média de Wingate ($W\cdot kg^{-1}$)		9,3 ± 0,6	9,3 ± 0,7	0
	Índice de Fadiga		25,6 ± 3,4	24,6 ± 4,4	-3.9
Rønnestad BR *et al.*, 2016	Pico Wingate ($W\cdot kg^{-1}$)	7	23,07 ± 2,78	22,75 ± 2,11	-1,38
	Média de Wingate ($W\cdot kg^{-1}$)		10,68 ± 0,65	10,49 ± 0,91	-1,77
	Índice de Fadiga		ND	ND	ND
Rønnestad BR *et al.*, 2015	Pico Wingate ($W\cdot kg^{-1}$)	7	22,9 ± 2,4	22,6 ± 1,7	-1,31
	Média de Wingate ($W\cdot kg^{-1}$)		10,7 ± 0,7	10,5 ± 0,9	-1,86
	Índice de Fadiga		ND	ND	ND
Rønnestad BR, Hansen J, Nygaard H, 2017	Pico Wingate ($W\cdot kg^{-1}$)	8	22,1 ± 3,2	22,4 ± 4,0	+1,33
	Média de Wingate ($W\cdot kg^{-1}$)		10,3 ± 1,1	10,1 ± 1,5	-1,94
	Índice de Fadiga		ND	ND	ND

ND = Not described; *= Difference between pre-post; # Difference between intervention group for control group

Power as performance/endurance parameter

The summary of the analysis of short-term power can be seen in Table VII. Average power for short and long durations and peak power, were used as performance/endurance measures. In one study [14], short-term endurance was measured, and a significant increase in average power was observed in both groups, with a more significant increase in the intervention group.

Table VII - Short-term endurance given by the power output before and after the intervention period

Study	Test	Term used	Parameter	n	Pre-training (W)	Post-training (W)	Change (%)
Aagaard P *et al.*, 2011	Maximum of 5 minutes	Short term endurance performance	Average ergometer work rate	Int: 7 Cont: 7	Int: 405.4 ± 53.3 Cont: 388.4 ± 14.1	Int: 425 ± 39.4 Cont: 400,4 ± 33,6	+4.83* +2.98*

Int = intervention group; Cont = control group; *= Difference between pre-post

The summary of the analysis of long-term power, as well as the test used, can be seen in Table VIII. Four studies [6,7,14,18] measured long-term performance/endurance. One study [14] showed a significant increase in power produced by both the intervention and control groups. Two studies [7,18] demonstrated a significant improvement in average power production in the intervention groups, and one study [6] showed a non-significant decrease in the parameter in the control group and an improvement in the intervention group.

Table VIII - Long-term endurance given by the power produced before and after the intervention period

Study	Test	Term used	Parameter	n	Pre-training (W)	Post-training (W)	Change (%)
Aagaard P *et al.*, 2011	45 min time-trial	Endurance performance of long duration	Average work rate (Watts)	Int: 7 Cont: 7	Int:313.7 ± 45.9 Cont:309.5 ± 20.3	Int:340.1 ± 33.1 Cont:321 ± 19.5	+ 8.41*# + 3.39*
Rønnestad BR, Hansen EA, Raastad T., 2010	40-minute maximum test	Average Power	ND	Int: 6 Cont: 6	Int: ND Cont: ND	Int: ND Cont: ND	+ 14 ± 3* + 4 ± 1*
Rønnestad BR *et al.*, 2015	40-minute maximum test	Average Power	ND	Int: 9 Cont: 7	Int: ND Cont: ND	Int: ND Cont: ND	+6.5 ± 5.7* 0
Rønnestad BR, Hansen J, Nygaard H, 2016	40-minute maximum test	Average Power	ND	Int: 12 Cont: 8	Int: ND Cont: ND	Int: ND Cont: ND	+3.5 ± 5.5 -0.8 ± 5.7

Int = intervention group; Cont = control group; ND = Not described; *Difference between pre-post, #Difference between intervention group for control group

The summary of the analysis of studies that evaluated peak power can be seen in Table IX. Seven studies [6,7,15-19] evaluated this variable. One study [15] showed a non-significant increase in the intervention group, and in the control group, there was a non-significant decrease. Another study [16] found a significant and superior increase in peak power in the control group compared to the intervention groups. One study [17] observed a non-significant decrease in both groups. Three studies [6,7,18] assessed peak power through a maximal 40-minute test, where only one [18] demonstrated a significant improvement in the intervention group, while there was a non-significant reduction in the control groups of the 3 studies.

Table IX - Peak power before and after the intervention period

Study	Test	Term used	Parameter	n	Pre-training (W)	Post-training (W)	Change (%)
Hausswirth C *et al.*, 2010	Incremental to exhaustion	Maximum aerobic power (Pmáx)	Potency associated with VO_{2max}	Int: 7 Cont: 7	Int: 412.9 ± 28.0 Cont: 417.1 ± 51.5	Int: 419.3 ± 29.6 Cont: 410.7 ± 44.8	+1.55 -1.53
Jackson NP *et al.*, 2007	Lactate profile	Maximum power	Higher load on test	Int: H-Res 9 Int: H-Rep 9 Cont: 5	Int: 305.6 ± 39.1 Int:330.6 ± 48.0 Cont: 315.0 ± 51.8	Int: 305.6 ± 37.0 Int 338.9 ± 47.0 Cont: 330.0 ± 41.1	0 +2.51 +4.76
Levin GT, Mcguigan MR, Laursen PB, 2009	Gradual exercise	PPO	Highest average power recorded every second	Int: 7 Cont: 7	Entrada: 361±36 Cont: 352±39	Int: 355±27 Cont: 348±37	-1.66 -1.13
Rønnestad BR, Hansen EA, Raastad T, 2010	40-minute maximum test	Wmáx	ND	Int: 6 Cont: 6	Int:420 ± 15 Cont:401 ± 37	Int: 454 ± 19 Cont: 399 ± 33	+8.09*# -0.49
Rønnestad BR *et al.*, 2015	ND	Maximum aerobic power (Wmáx)	ND	Int: 7 Cont: 7	Int: 5.92 ± 0.51 ($W \cdot kg^{-1}$) Cont: 5.81 ± 0.24 ($W \cdot kg^{-1}$)	Int: 6.04 ± 0.72 ($W \cdot kg^{-1}$) Cont: 5.88 ± 0.45 ($W \cdot kg^{-1}$)	+2.02 +1.02
Rønnestad BR *et al.*, 2015	40-minute maximum test	Wmáx	ND	Int: 9 Cont: 7	Int: ND Cont: ND	Int: ND Cont: ND	+3 ± 3*# +3 ± 6
Rønnestad BR, Hansen J, Nygaard H, 2016	40-minute maximum test	Wmáx	Average power in the last minute of the test	Int: 12 Cont: 8	Int: 6.1 ± 0.5 (W·kg-1) Cont: 5.8 ± 0.5 ($W \cdot kg^{-1}$)	Int: 6.1 ± 0.6 (W·kg-1) Cont: 5.7 ± 0.6 ($W \cdot kg^{-1}$)	0 -1.72

Int = intervention group; Cont = control; ND = Not described; *Difference between pre-post, #Difference between intervention group for control group.ppo: peak power output

Discussion

This review aimed to analyze the effects of resistance training on cycling performance-related variables: maximum strength and power output, VO_{2max}, and cycling economy (EC). The results show a positive impact of resistance training on the performance of cyclists. All the concurrent training groups included in this review evidenced the maximum strength increases. When analyzing the training methodologies applied in the studies, it is remarkable that the predominance of periodization systems culminated in strength training characterized by high loads and moderate repetitions.

Since the study participants are cyclists, they already performed endurance training, which likely provided a strength base, especially for the knees and hip extensors [22]. Although only a few studies have shown increased maximal strength in the control groups, it is possible that performing endurance training had some effect on the increased maximal output in both groups. The variations in terrain and weather conditions, such as hills, mountains, and even the wind in which cyclists usually perform their training, may be responsible for the increased strength in the control groups and may have influenced the gains of the intervention groups. Regardless, it is noteworthy that the increase in maximal strength output was significant and more remarkable in all intervention groups compared to the control groups in the studies. It indicates that applying resistance training is effective in cycling practitioners.

Maximum strength production in these athletes is significant since it contributes to power production [15,18]. Increasing the strength to higher levels reduces the intensity of the exercise with particular loads. Therefore, the adaptations caused by the insertion of the resistance training, as well as the increase in the maximum strength production, tend to allow the increase in the production of the average and the peak of power, either in a short (anaerobic sprint) or long-term (aerobic), which will be discussed later.

VO_{2max}

VO_{2max} defines the maximum aerobic power and capacity [12,23]. Therefore, increasing VO_{2max} is essential for cyclists, as it allows better use of oxygen during the rides performed in their competitions. The results between the studies were contrasting; some showed superior improvement in the intervention group, and others showed superior improvement in the control groups; however, the results between groups were insignificant.

The study conducted by Rønnestad *et al*. [16] demonstrated a significant increase in VO_{2max} in both groups; however, the intervention group showed superior improvement compared to the control group, although there was no significant difference before and after the intervention. Thus, this difference was due to strength training.

The results indicated that the incorporation of strength training in cyclists did not impede the enhancement of their VO_{2max}, which has been elucidated in some prior literature [25,26]. Additionally, the study sample comprised aerobically well-trained athletes with high VO_{2max} values, which may account for the slight changes between pre- and post-values, as they typically have limited room for further improvement in maximum aerobic power and capacity [24].

Economy and efficiency of cycling

Economy and mechanical efficiency are usually dealt with when assessing cyclists' performance because they are essential for performance parameters and are considered endurance-determining aerobic factors. These factors are expected to improve performance [27] due to the improvement of this parameter, which is the decrease in the amount of oxygen used for the same exercise intensity, inferring the decrease in energy expenditure for the intensity in question [25]. Observing the five studies [12,14,18–20] inserted in this review that measured the parameters analyzed here, in general, both groups had improved after the intervention period.

The study by Aagaard *et al.* [12] showed a considerable improvement in the economy and efficiency of the control group; however, the control group was significantly less efficient than the intervention group at the beginning of the study. There was a more significant margin for the development of the economy and efficiency cycling. Corroborating with the last study, Jackson *et al.* [14] demonstrated a significant increase in VO_2 use in both intervention groups and not significant in the control group. In agreement with the authors, the groups had no significant difference. In agreement with that, Sunde *et al.* [20] demonstrated an interesting result. Both groups started from a very close baseline before the intervention. After the period, the intervention group showed a significant improvement in this parameter, higher than the control group, with no significant difference.

Two studies conducted by Rønnestad *et al.* [18] and Rønnestad *et al.* [19], who used the same method to evaluate economy and efficiency, showed antagonistic results among themselves, where the first [18] showed superiority in the result obtained in the intervention group, and the other [19] in the control group. However, there was no significant difference between the study groups. The intervention period in both studies differs significantly, which may also explain this difference. These two studies mentioned no difference in gross efficiency but did not compare the before and after intervention.

Considering the results presented here, even though the majority of studies demonstrate an improvement in CE in the resistance training group, it is not possible to state with complete certainty the impact of adding resistance training to cyclists on cycling economy and efficiency due to the issues described throughout this section.

Anaerobic power

The mean and peak power are essential in cyclists, as they contribute to power production and decrease the intensity of the exercise with any particular load. The insertion of strength training can be positive for power production in general.

Four studies [16–19] that evaluated anaerobic power demonstrated that the intervention group had some increase in peak power, with significance in only two [16,19]. Only two studies [17,19] showed an increase in the mean but without real significance. In the control groups, two [16,19] showed a non-significant increase in power peak, and the other two [17,18] showed a decrease, while on average, the [16] showed no change, and the other 3 [17–19] showed a decrease in the parameter.

Although in the study by Rønnestad *et al*. [16], the groups did not depart from a close baseline, the intervention group already showed a higher peak power than the control group before the intervention, which would decrease the development margin of this parameter [25]. However, the increase in peak power after intervention was more significant in the intervention group. Despite the increase in peak in both groups, no change in mean power output after the period was shown, which would indicate a greater decline in power output throughout the test in the intervention group, as seen by the increase in fatigue after the intervention period.

The study by Rønnestad *et al*. [18] also presents similar results, where there was an increase in the power peak. However, there was no difference in the average power produced in the intervention group, indicating probable worsening in the fatigue index after the intervention. However, it is not possible to make this point since the study did not present this data. It is also important to note that the control group in this study showed a decline in peak and average power output.

Another study by Rønnestad *et al*. [17] presents exciting results. In the intervention group, the peak power produced increased less than the average, while in the control group, there was a decline in both. In the intervention group, it indicates less performance loss during the test after the training application. However, it is impossible to point this out accurately since the study also does not show the fatigue index.

The latest study by Rønnestad *et al*. [19] demonstrates an increase in power peak and average produced in the intervention group. In contrast, in the control group, there was an increase in power peak and a decline in the average produced. However, it does not expose the fatigue index, making it impossible to make more accurate notes regarding the performance loss during the test.

Based on the data exposed and analyzed here, it is clear that strength training and the consequent increase in maximum force production can increase the peak power output in a maximum-intensity sprint.

Power as a parameter of performance/endurance

The general concepts and the importance of power production in cycling, as well as its relationship with maximal strength production, were previously discussed in the topic regarding anaerobic power.

Only the study by Aagaard *et al*. [12] tested short-term endurance performance in a maximum 5-minute test, and both groups showed an increase in average power output, which was higher in the intervention group, especially when considering variation in groups. Considering this, adding strength training could influence the parameter; however, as it is a single study, it cannot be concluded with certainty that it was responsible for the improvement rather than some specific issue within the study's intervention group.

Among the four studies [12,16,18,19] that measured average power as a long-term performance/endurance parameter, all showed improvement in the intervention group, whereas three [12,16,18] showed significant improvement. In the control groups, two [12,16] showed non-significant improvement and less than the intervention groups; one [18] showed no difference after the intervention period, and one [19] showed a decrease after the intervention period.

The positive and even expressive improvement of this parameter in all intervention groups, contrary to what is shown in the control groups, allows us to infer the impact of strength training on average power production in cyclists. However, it is worth noting that the non-exposure or exposure in graphs that do not allow the absolute values of the average power production before and after the intervention in some studies [16,18,19] makes it challenging to elucidate the actual effect of resistance training in this parameter.

Regarding the peak power produced, among the seven studies [13–19] that measured it, the intervention groups showed some improvement of the parameter, with only one [16] having significant improvement, except for one study [15] that showed a decrease in the peak, and one study [19] that showed no difference after the intervention period. Regarding the control groups of the studies, most showed a decrease in the parameter [13,15,16,19].

The study of Aagaard *et al.* [14] demonstrated a remarkable finding: the intervention group that performed the high repetition training had an increase in the peak power produced. In contrast, the group that used the higher loads had no difference between the previous ones. Post-intervention, the control group showed a better improvement compared to both groups. Here, it is noteworthy that, according to the authors themselves, the participants in the intervention groups imagined that the strength training added to the endurance training they already performed would be something they could not continue.

The study of Rønnestad *et al.* [16] showed a considerably significant improvement in this parameter compared to all studies in his intervention group, unlike his control group, which showed a decrease in the parameter.

In analyzing the studies by Rønnestad *et al.* [16], Rønnestad *et al.* [18] and Rønnestad *et al.* [19], who measured both peak and average power output, the results of the intervention groups are interesting. Two [16,18] showed an increase in peak and average after the intervention period, higher than those found in the control groups, with a more significant increase, indicating a greater capacity to maintain power production constancy throughout the race. These three studies were performed by the same authors and with similar training methodologies; a possible explanation for this difference between the results would be the duration weeks of the studies, which was shorter in only one [19]. The endurance training was performed indoors, which may have interfered with the results, especially considering that both the peak and the average power production tended to decrease in the control group.

Considering all that has been exposed throughout this topic, it is noted that adding resistance training to the cyclist training program can positively impact the average power output, whether short or long-term, as well as the peak of power output.

Conclusion

In conclusion, from a practical standpoint, the results suggest that it may be advantageous to incorporate resistance training 2-3 times per week during the periodization of both amateur and elite cyclists. However, further research is required to explore various training configurations among athlete and amateur cyclist populations.

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Author contributions
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