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Strength Training for Middle- and Long-Distance Performance: A Meta-Analysis

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Purpose: To assess the net effects of strength training on middle- and long-distance performance through a meta-analysis of the available literature. ***Methods:*** Three databases were searched, from which 28 of 554 potential studies met all inclusion criteria. Standardized mean differences (SMDs) were calculated and weighted by the inverse of variance to calculate an overall effect and its 95% confidence interval (CI). Subgroup analyses were conducted to determine whether the strength-training intensity, duration, and frequency and population performance level, age, sex, and sport were outcomes that might influence the magnitude of the effect. ***Results:*** The implementation of a strength-training mesocycle in running, cycling, cross-country skiing, and swimming was associated with moderate improvements in middle- and long-distance performance (net SMD [95%CI] = 0.52 [0.33–0.70]). These results were associated with improvements in the energy cost of locomotion (0.65 [0.32–0.98]), maximal force (0.99 [0.80–1.18]), and maximal power (0.50 [0.34–0.67]). Maximal-force training led to greater improvements than other intensities. Subgroup analyses also revealed that beneficial effects on performance were consistent irrespective of the athletes' level. ***Conclusion:*** Taken together, these results provide a framework that supports the implementation of strength training in addition to traditional sport-specific training to improve middle- and long-distance performance, mainly through improvements in the energy cost of locomotion, maximal power, and maximal strength.

Keywords: concurrent training, endurance, running, swimming, cycling, cross-country skiing

It is well established that maximal oxygen uptake (VO_2max), the energy cost of locomotion (EC), and aerobic endurance (AE) are crucial factors in middle- and long-distance performance.[1] Together, these factors explained 72% of the performance variability among 36 runners who participated in the 1983 Geneva marathon.[2] Athletes involved in middle- and long-distance competitions have traditionally trained and improved such performance-determining factors through continuous low- to moderate-intensity and intermittent high-intensity methods, called aerobic training as intensities are often described as a percentage of VO_2max or maximal heart rate.[3,4] In recent years, however, convincing evidence has emerged indicating that strength training may also have a positive impact on middle- and long-distance performance (running, cycling, cross-country skiing) and its key determinants for different competitive levels.[5–7] More particularly, it appears that incorporating a strength-training protocol to an ongoing endurance-training program could represent an advantageous method to improve EC.[8–10] In addition to these benefits, improvements in AE were reported.[5]

However, such a training method might be counterintuitive. Indeed, strength and long-distance events were presented at opposite ends of a performance duration/energy metabolism continuum,[11] which could provide some support against the implementation of strength training by middle- and long-distance athletes. The observation that muscle hypertrophy resulting from a strength-training intervention was associated with a reduction of mitochondrial density and distribution in muscle fibers[12] could, at least partially, support such an argument. It appears that when strength and aerobic training are presented simultaneously in a mesocycle (ie, training block with a specific training purpose, usually lasting ~3–6 wk), no detrimental effects are observed on VO_2max in comparison with an aerobic-only training regimen.[13] Furthermore, it seems that the potential negative effects of muscle hypertrophy on aerobic performance could, conceptually, be prevented if the focus of strength-training interventions is oriented toward central (neural) adaptations.[14,15] Moreover, it was recently suggested that, along with improved neural function, peripheral changes such as a shift in muscle-fiber distribution (from fast-twitch type IIb toward fatigue-resistant type IIa) and increases in muscle–tendon stiffness could explain the positive effects of combined strength and aerobic training on middle- and long-distance performance.[16]

Nevertheless, not all studies agree on the positive effects of strength training on middle- and long-distance performance.[17,18] Such discrepancies may be related to the fact that different strength-training strategies were employed in different sport disciplines. In addition to this observation, the athletes' training history, modality of aerobic training, and intervention duration might represent important variables potentially explaining that some differences could be observed in studies interested in combined strength and aerobic training.[19] Considering these methodological aspects, it is difficult to prescribe discrete and specific training recommendations.

The objective of this study was to assess the net effects of strength training on middle- and long-distance performance (ie, athletic events and/or performance tests lasting more than 75 s) through a meta-analysis of the available literature. We also carried out subgroup analyses to determine whether the strength-training load (ie, intensity, duration, and frequency) and other moderators relative to the characteristics of the population (performance level, age, sex, and sport discipline) were outcomes that might influence the magnitude of the effect. We hypothesized that strength training

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would improve middle- and long-distance performance more than sport-specific aerobic training alone. We also hypothesized that gains in performance would be associated with improvements in EC and AE, whereas VO_2max would not be altered.

Methods

Literature-Search Strategy

The databases Scopus (1970 to December 7, 2015), SPORTDiscus with full text (1975 to December 7, 2015) and Web of Science (1945 to December 7, 2015) were searched using the terms [TOPIC: (“strength training” OR “weight training” OR “resistance training” OR “power training” OR “plyometric training” OR “concurrent training” OR “combined strength and endurance training” OR “concurrent strength and endurance training”) AND TOPIC: (“energy cost” OR “caloric cost” OR “metabolic cost” OR “energetic cost” OR “mechanical efficiency” OR “maximal oxygen consumption” OR “maximal oxygen uptake” OR “maximal oxygen intake” OR “VO2max” OR “aerobic power” OR “aerobic capacity” OR “aerobic endurance” OR “endurance performance” OR “cardiovascular performance” OR “lactate threshold” OR “anaerobic threshold” OR “running performance” OR “running economy” OR “running time” OR “running speed” OR “energy cost of running” OR “running efficiency” OR “running endurance” OR “cycling endurance” OR “cycling economy” OR “cycling performance”) AND TOPIC: (locomotion OR running OR cycling OR “cross country skiing” OR marathon OR triathlon OR swimming OR rowing OR soccer OR biathlon)] for English-language and French-language articles. The reference lists of the articles obtained were searched manually to obtain further studies not identified electronically.

Selection Criteria

Studies were eligible for inclusion if they implemented a strength-training intervention in addition to a sport-specific aerobic-training regimen; the outcome included tests and measures of performance, muscle fitness, and aerobic fitness in healthy humans; the paper reported the number of participants and all the necessary data to calculate effect sizes; and middle- and long-distance performances (time trials, constant-duration or time-to-exhaustion tests) were longer than 75 seconds, as the contribution of the aerobic pathway is then considered predominant.[20] Studies were excluded if they presented results reported in a previous publication, the article was a literature review, they presented data only for symptomatic patients, the training program was inadequate (eg, only strength training, overtraining studies, etc), no performance tests were described, no performance factors were available, and participants were reported to be using ergogenic aids.

Study Coding

Two independent reviewers (M.R. and C.B.) who were blinded to authors, affiliations, and the publishing journal read and coded each included study using the following moderators: strength-training intensity (maximal force, maximal power, submaximal force, combination), strength-training frequency (1 session/wk, 2 sessions/wk, ≥3 sessions/wk), duration of strength-training intervention (<24 sessions and ≥24 sessions), performance level (international, national, or regional), sex (male, female, both), and age (<18 y, 18–45 y, 46–64 y, and ≥65 y). Regarding strength-training intensity, maximal force included sets of 1 to 5 repetitions of isoinertial contractions at 80% of 1-repetition maximum (RM) or more.[21] Maximal power included plyometric training, sprint training, and sets of 4 to 6 repetitions at the load that elicits maximal power during a specific isoinertial movement.[22] Finally, submaximal force included sets of 6 to 25 repetitions of isoinertial contractions between 60% and 80% of 1RM.[21] Tests and measures used to assess maximal force, maximal power, and submaximal force were the same as those retained in a previous meta-analysis from our research group.[23] Measures of VO_2max and EC had to be obtained during a maximal graded exercise test and during a 6- to 10-minute submaximal constant-intensity test, respectively. Measures of AE included direct measures such as the relative performance (% of maximal aerobic power) during a constant-duration, constant-distance, or constant-intensity test and indirect measures such as the percentage of VO_2max corresponding to lactate or ventilatory thresholds.[24] An interval scale was used for the coding of performance and measures of muscle and aerobic fitness, while a nominal scale was used for the coding of the other moderators. Any disagreement between the 2 reviewers was discussed in a consensus meeting, and unresolved items were taken to a third reviewer (N.B.) for resolution.

Statistical Analysis

Standardized mean differences (SMDs) for each study group were calculated using the Hedges g.[25] In the studies that used multiple measures of muscle performance, a single composite SMD was calculated.[26] Considering that the effect of combined strength and sport-specific aerobic training on performance may differ according to the parameters of training load and other moderators relative to participant characteristics, we decided a priori to use a random-effects model with the DerSimonian and Laird method. Standardized mean differences were weighted by the inverse of variance to calculate an overall effect and its 95% confidence interval (CI). The net treatment effect was obtained by subtracting the SMD of the control group from the SMD of the experimental group. Variance was calculated from the pooled standard deviation of change scores in both groups. The net treatment effect and its variance were calculated for each category within moderator variables, as well as 95% CI to determine whether SMD was different from zero. A Q test based on the analysis of variance was performed to test the null hypothesis that the effect of combined strength and sport-specific aerobic training was similar between the categories of a moderator variable.[26] When the null hypothesis was rejected, pairwise comparisons were performed with a Z test. The results of the Q test were also used to compute the I^2 statistic, which represents for each category of a moderator variable the percentage of the variability between studies that is due to clinical and/or methodological heterogeneity rather than sampling error.[26] The Cohen criteria were used to interpret the magnitude of SMD: <0.2, trivial; 0.2 to 0.5, small; 0.5 to 0.8, moderate; and >0.8, large.[27] All calculations were made with comprehensive meta-analysis (www.meta-analysis.com).

Results

The literature search allowed identification of 554 potentially relevant publications, of which 28 studies met all inclusion criteria. Exclusion criteria are detailed in Figure 1. Sport disciplines included in this meta-analysis are running, cycling, cross-country skiing, and swimming.

Results (Figure 2) indicated that adding a strength-training mesocycle to a sport-specific aerobic-training program was associated with moderate improvements in middle- and long-distance

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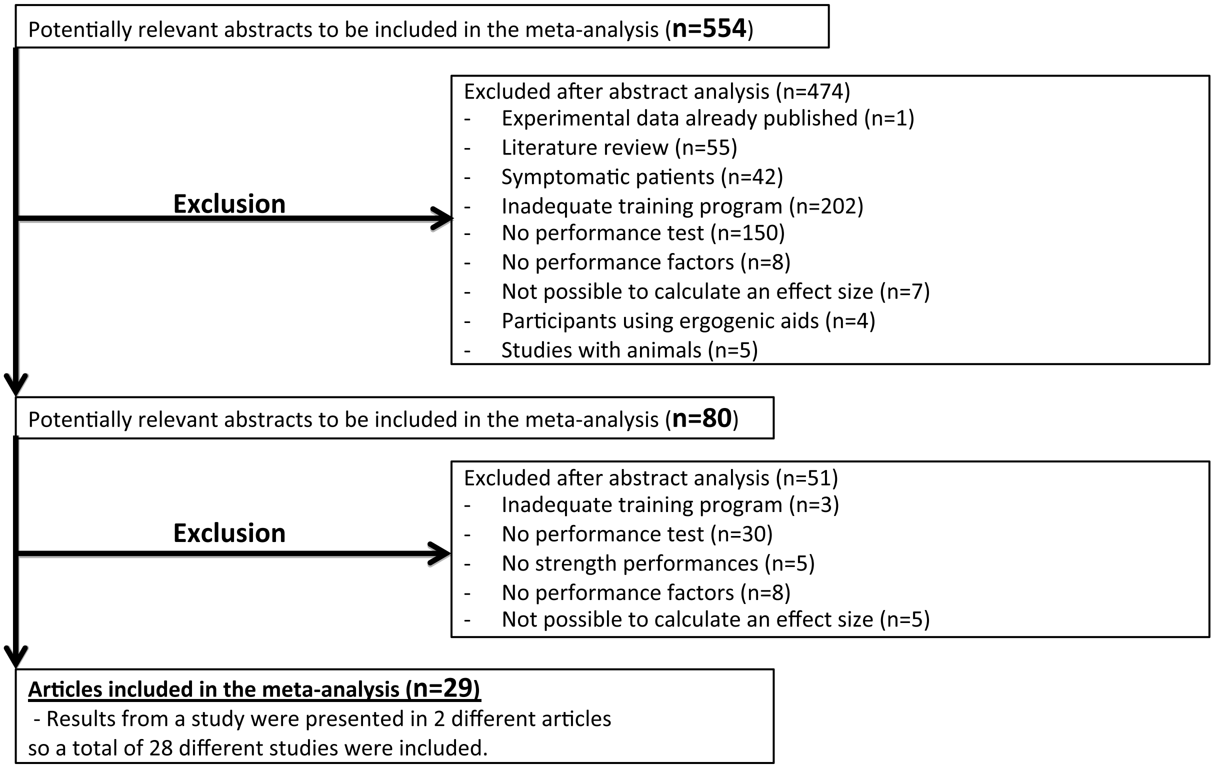

Figure 1 — Flowchart of the study-selection process.

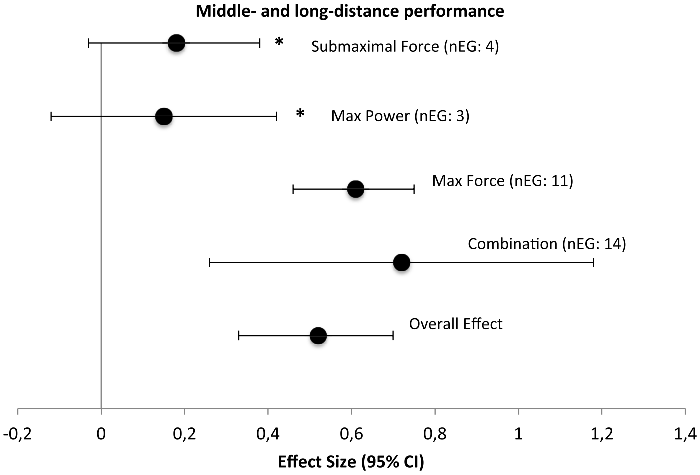

Figure 2 — Strength training for middle- and long-distance performance. *Different from maximal force and combination ($P < .01$). nEG indicates number of experimental groups; CI, confidence interval.

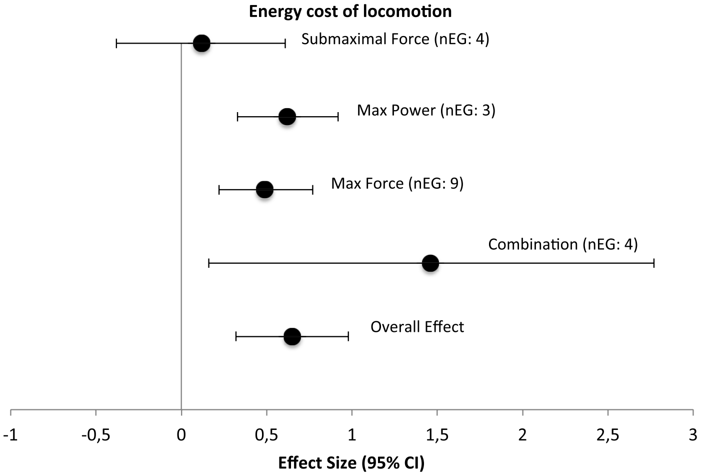

Figure 3 — Strength training and the energy cost of locomotion. nEG indicates number of experimental groups; CI, confidence interval.

performance (net SMD [95%CI] = 0.52 [0.33–0.70], $I^2 = 41\%$). Furthermore, a strength-training-intensity effect was found as maximal strength training and a combination of methods produced greater benefits than submaximal and maximal power training.

Moreover, the implementation of a strength-training program resulted in a moderate improvement in EC (Figure 3) (net SMD [95%CI] = 0.65 (0.32–0.98), $I^2 = 30\%$), while VO_2max (0.03 [–0.16 to 0.23], $P = .75$, $I^2 = 0\%$) and AE remained unchanged (0.03 [–0.19 to 0.25], $P = .82$, $I^2 = 26\%$).

Regarding neuromuscular fitness (Figures 4 and 5), we found a large increase in maximal force (net SMD [95%CI] = 0.99 [0.80–1.18], $I^2 = 46\%$) and a moderate increase in maximal power (0.50 [0.34–0.67], $I^2 = 6\%$) as a consequence of including a strength-training regimen in addition to the sport-specific aerobic-training program. Again, a strength-training-intensity effect was found as submaximal training resulted in less maximal power gain than all other methods.

We also performed a subgroup analysis of moderator variables (Tables 1–6). Significant differences were observed for strength-training load (intensity and frequency) and AE. Notably,

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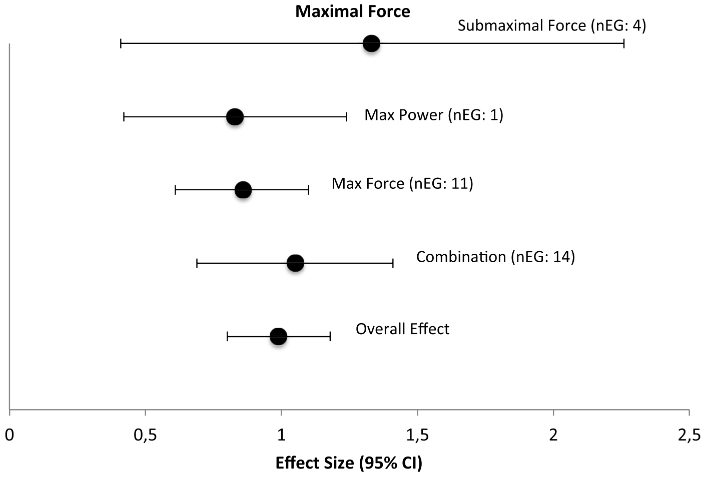

Figure 4 — Strength training and maximal force. nEG indicates number of experimental groups; CI, confidence interval.

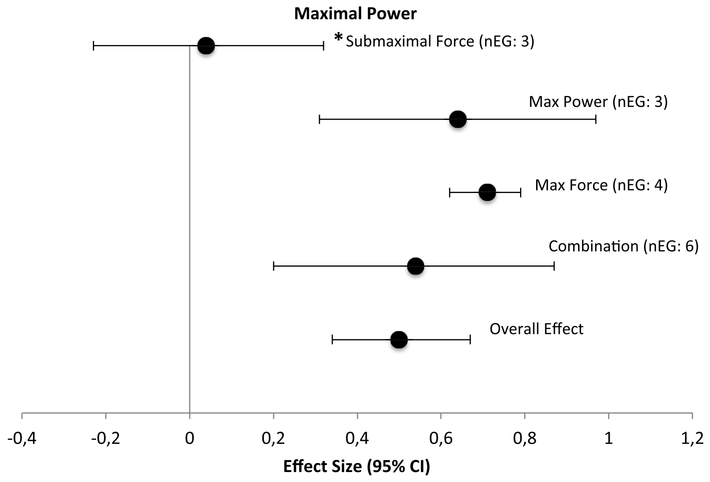

Figure 5 — Strength training and maximal power. nEG indicates number of experimental groups; CI, confidence interval. *Different from all other conditions ($P < .01$).

strength-training volume was associated with EC reductions, whereas protocols including more than 24 sessions led to greater effects on EC than shorter programs. Regional- and national-level athletes seem to particularly benefit from these interventions to improve maximal power and maximal force, respectively. No significant differences were observed for the sport-discipline category, indicating that all sports included in the analyses (running, cycling, cross-country skiing, and swimming) seem to benefit similarly from this training strategy. The possible effect of sex and age could not be tested, since there were not enough studies involving exclusively women or participants with a mean age below 18 or above 46 years to address these issues.

Discussion

The objective of this study was to assess the net effects of strength training on middle- and long-distance performance through a meta-analysis of the available literature. In support of our hypothesis, results from this meta-analysis revealed that such a training strategy moderately improves performances in comparison with sport-specific aerobic training alone, and this irrespective of the athlete's level. Furthermore, these gains in performance could be associated with improvements in EC, whereas no changes in AE and VO_2max were observed.

Table 1 Net Effect of Combined Strength and Aerobic Training on Middle- and Long-Distance Performance According to Strength-Training Load (Frequency and Volume), Performance Level, and Sport Discipline

Moderator	nEG	SMD[a]	95% CI	I^2
Training frequency				
1 session/wk	3	0.43	0.00–0.85	7
2 sessions/wk	18	0.52	0.22–0.82	41
3 sessions/wk	9	0.38	0.12–0.65	0
Training volume				
<24 sessions	10	0.44	0.14–0.73	40
≥24 sessions	20	0.41	0.22–0.60	10
Performance level				
international	2	1.10	–0.61 to 2.80	0
national	11	0.46	0.24–0.67	0
regional/provincial	19	0.50	0.24–0.76	48
Sport				
running	15	0.71	0.31–1.12	34
cycling	11	0.36	0.11–0.61	0
other	6	0.44	0.15–0.73	0

Abbreviations: nEG, number of experimental groups; SMD, standardized mean difference; CI, confidence interval; I^2, percentage of the variability between studies due to clinical and/or methodological heterogeneity rather than sampling error.
[a] <0.2, trivial; 0.2–0.5, small; 0.5–0.8, moderate; >0.8, large.

To our knowledge, this is the first comprehensive meta-analysis assessing the net effects of such a concurrent training paradigm on middle- and long-distance performance, its physiological determinants, and its effects on neuromuscular fitness, all in relation to the characteristics of the training intervention and the performance level of the participating athletes. The present results are in line with a recent publication presenting a beneficial effect of strength training on EC in a sample of runners. Indeed, it was shown that explosive and maximal strength training significantly reduced EC by 4.83% (± 1.53%) and 3.65% (± 2.74%), respectively.[10] A significant relationship was also found between training duration and EC improvements, suggesting that, even if 6 to 8 weeks of strength training could lead to a reduction in EC, longer training protocols (up to 14 wk) might be more beneficial. In agreement with this outcome, our subgroup analysis revealed a significant effect of the duration of the strength-training intervention, where protocols including more than 24 sessions led to greater reductions in EC than did protocols of less than 24 sessions.

With regard to other physiological determinants of middle- and long-distance performance, it appears that both VO_2max and AE were unaltered. While these results for VO_2max were expected,[13] a recent review of the literature suggested a positive effect of strength training on AE.[5] Interestingly, even if no significant overall effect was found for AE, our subgroup analysis revealed that strength-training intensity is an important variable. Indeed, it appears that a combination of strength-training methods, encompassing a range of training intensities and loads, might be beneficial for AE. Moreover, strength-training frequency was a significant

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Table 2 Net Effect of Combined Strength and Aerobic Training on Peak Oxygen Uptake According to Strength-Training Load, Performance Level, and Sport Discipline

Moderator	nEG	SMD[a]	95% CI	I^2
Training intensity[b]				
maximal force	11	0.14	−0.17 to 0.46	0
maximal power	3	−0.17	−0.46 to 0.11	0
submaximal force	4	−0.17	−0.44 to 0.10	0
combination	14	0.02	−0.22 to 0.26	31
Training frequency				
1 session/wk	2	0.02	−0.22 to 0.26	0
2 sessions/wk	19	0.07	−0.09 to 0.23	21
3 sessions/wk	9	0.14	−0.19 to 0.47	0
Training volume				
<24 sessions	10	−0.06	−0.23 to 0.11	0
≥24 sessions	20	0.18	−0.04 to 0.39	0
Performance level				
international	2	−0.54	−1.41 to 0.34	0
national	11	−0.01	−0.23 to 0.21	0
regional/provincial	19	0.11	−0.13 to 0.36	0
Sport				
running	15	0.03	−0.16 to 0.23	30
cycling	11	0.11	−0.20 to 0.42	0
other	6	−0.16	−0.57 to 0.25	7

Abbreviations: nEG, number of experimental groups; SMD, standardized mean difference; CI, confidence interval; I^2, percentage of the variability between studies due to clinical and/or methodological heterogeneity rather than sampling error.

[a] <0.2, trivial; 0.2–0.5, small; 0.5–0.8, moderate; >0.8, large. [b] Maximal force included sets of 1–5 repetitions at 80% of 1-repetition maximum (RM) or more; maximal power included plyometric training, sprint training, and sets of 4–6 repetitions at the load that elicits maximal power during a specific isoinertial movement; submaximal force included sets of 6–25 repetitions at 60–80% of 1RM.

Table 3 Net Effect of Combined Strength and Aerobic Training on Aerobic Endurance According to Strength-Training Load, Performance Level, and Sport Discipline

Moderator	nEG	SMD[a]	95% CI	I^2
Training intensity[b]				
maximal force	4	−0.17	−0.60 to 0.25	0
maximal power	3	−0.35[c]	−0.64 to −0.06	0
submaximal force	2	−0.36[c]	−0.91 to 0.19	0
combination	9	0.34	0.03–0.65	32
Training frequency				
1 session/wk	2	−0.26	−0.62 to 0.10	0
2 sessions/wk	9	0.32[d]	0.00–0.64	32
3 sessions/wk	5	−0.45	−0.68 to −0.22	9
Training volume				
<24 sessions	7	−0.13	−0.36 to 0.09	0
≥24 sessions	10	0.14	−0.27 to 0.55	34
Performance level				
international	1	0.13	−0.35 to 0.60	0
national	3	0.12	−0.62 to 0.85	6
regional/provincial	14	0.00	−0.25 to 0.24	32
Sport				
running	11	0.09	−0.22 to 0.39	34
cycling	5	−0.12	−0.55 to 0.31	6
other	2	0.13	−0.44 to 0.70	0

Abbreviations: nEG, number of experimental groups; SMD, standardized mean difference; CI, confidence interval; I^2, percentage of the variability between studies due to clinical and/or methodological heterogeneity rather than sampling error.

[a] <0.2, trivial; 0.2–0.5, small; 0.5–0.8, moderate; >0.8, large. [b] Maximal force included sets of 1–5 repetitions at 80% of 1-repetition maximum (RM) or more; maximal power included plyometric training, sprint training, and sets of 4–6 repetitions at the load that elicits maximal power during a specific isoinertial movement; submaximal force included sets of 6–25 repetitions at 60–80% of 1RM. [c] Different from combination ($P < .01$). [d] Different from 1or 3 sessions/wk ($P < .01$).

moderator associated with AE: Two strength sessions weekly were related to benefits on AE. However, the mechanisms underpinning these intensity and frequency effects are not clear and cannot be elucidated from the present data set.

The observed enhancements in middle- and long-distance performance were also accompanied by improvements in neuromuscular fitness as a consequence of including a strength-training regimen in addition to the sport-specific aerobic-training program. Indeed, large and moderate effect sizes were reported for maximal force and maximal power, respectively. A smaller effect on maximal power than on maximal strength after a concurrent strength- and aerobic-training cycle could be related to the interference phenomenon, which has been defined as a reduction in strength gains when both aerobic and strength training are presented in the same mesocycle.[14] Indeed, a meta-analysis[13] published in 2012 showed that the interference phenomenon was particularly related to lower-body power. Furthermore, it was shown that running, more than cycling, was detrimental for strength gains.[13] However, our results do not support this sport-discipline effect, as no differences were found among sports in this subgroup analysis.

Although strength-training intensity was not a key factor for improvements in maximal strength, our results revealed that heavy and explosive weight training were particularly effective methods to improve maximal power. These results are in line with some reports showing that novice weight lifters could improve maximal power and maximal strength by implementing a heavy weight-training program[28] and that these eventual gains in maximal strength could later represent an advantage to improve maximal power through traditional explosive strength training.[29] Taken together, these results support the implementation of combined strength and aerobic training to improve neuromuscular fitness in middle- and long-distance athletes, who might be inexperienced with strength training. Our results show that regional- and national-level athletes could particularly benefit with regard to neuromuscular fitness from these strength-training interventions.

Our subgroup analysis showed an effect of strength-training intensity on middle- and long-distance performance. It appears that maximal strength training and a combination of methods (submaximal strength, maximal force, and maximal power) during a mesocycle represent particularly effective strategies to improve athletes' performance. Different mechanisms were suggested to play a key role in this relationship between neuromuscular fitness and middle- and long-distance performance. Improved neural function, greater rate of force development, gains in type I fiber maximum strength, an increased proportion of type IIa fiber at the expense of type IIb fibers, and modifications in tendon stiffness and

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Table 4 Net Effect of Combined Strength and Aerobic Training on the Energy Cost of Locomotion According to Strength-Training Load (Frequency and Volume), Performance Level, and Sport Discipline

Moderator	nEG	SMD[a]	95% CI	I^2
Training frequency				
1 session/wk	2	0.73	0.34–1.12	0
2 sessions/wk	9	0.36	0.03–0.69	25
3 sessions/wk	7	0.48	−0.08 to 1.03	4
Training volume				
<24 sessions	6	0.10	−0.27 to 0.47	2
≥24 sessions	12	0.63[b]	0.29–0.97	9
Performance level				
international	2	1.72	−1.83 to 5.27	0
national	6	0.66	−0.09 to 1.42	7
regional/provincial	12	0.49	0.22–0.77	9
Sport				
running	10	0.83	0.31–1.34	38
cycling	5	−0.20	−0.25 to 0.74	4
other	5	1.17	−0.13 to 1.63	0

Abbreviations: nEG, number of experimental groups; SMD, standardized mean difference; CI, confidence interval; I^2, percentage of the variability between studies due to clinical and/or methodological heterogeneity rather than sampling error.
[a] <0.2, trivial; 0.2–0.5, small; 0.5–0.8, moderate; >0.8, large. [b] Different from <24 sessions ($P < .05$).

Table 5 Net Effect of Combined Strength and Aerobic Training on Maximal Force According to Strength-Training Load (Frequency and Volume), Performance Level, and Sport Discipline.

Moderator	nEG	SMD[a]	95% CI	I^2
Training frequency				
1 session/wk	0	—	—	—
2 sessions/wk	19	1.10	0.76–1.43	34
3 sessions/wk	9	0.72	0.64–0.80	0
Training volume				
<24 sessions	8	0.93	0.59–1.27	20
≥24 sessions	20	0.86	0.72–1.20	52
Performance level				
international	2	0.66	0.10–1.22	0
national	11	1.23	0.95–1.60	3
regional/provincial	17	0.83[b]	0.59–1.07	60
Sport				
running	13	0.84	0.55–1.13	0
cycling	11	1.21	0.84–1.58	58
other	6	1.03	0.41–1.64	17

Abbreviations: nEG, number of experimental groups; SMD, standardized mean difference; CI, confidence interval; I^2, percentage of the variability between studies due to clinical and/or methodological heterogeneity rather than sampling error.
[a] <0.2, trivial; 0.2–0.5, small; 0.5–0.8, moderate; >0.8, large. [b] Different from national athletes ($P < .01$).

stretch-shortening-cycle properties could all contribute to better middle- and long-distance performance.[5,16] However, the most appropriate strength- and aerobic-training periodization still needs to be determined.

Table 6 Net Effect of Combined Strength and Aerobic Training on Maximal Power According to Strength-Training Load (Frequency and Volume), Performance Level, and Sport Discipline

Moderator	nEG	SMD[a]	95% CI	I^2
Training frequency				
1 session/wk	2	0.59	−0.10 to 1.27	0
2 sessions/wk	8	0.32[b]	0.09–0.54	4
3 sessions/wk	5	0.67	0.52–0.82	15
Training volume				
<24 sessions	4	0.62	0.38–0.87	6
≥24 sessions	11	0.41	0.18–0.65	0
Performance level				
international	2	0.59	−0.21 to 1.39	0
national	4	0.21	−0.07 to 0.50	0
regional/provincial	10	0.60[c]	0.42–0.77	11
Sport				
running	11	0.51	0.28–0.73	0
cycling	3	0.59	0.21–0.97	19
other	2	0.32	−0.02 to 0.67	0

Abbreviations: nEG, number of experimental groups; SMD, standardized mean difference; CI, confidence interval; I^2, percentage of the variability between studies due to clinical and/or methodological heterogeneity rather than sampling error.
[a] <0.2, trivial; 0.2–0.5, small; 0.5–0.8, moderate; >0.8, large. [b] Different from other conditions ($P < .01$). [c] Different from the national level ($P < .01$).

We must acknowledge that this study is not without limitations. Indeed, the aerobic energy system is not the only determinant of middle- and long-distance performance. Anaerobic performance seems also critical, especially in shorter events.[16,30] However, to our knowledge, research in this field has so far been mainly conducted on aerobic factors (VO_2max, AE, and EC). Considering the benefits of strength training on anaerobic performance,[31] we recommend that more research be conducted to better understand the relationship between strength training, anaerobic factors, and middle- and long-distance performance. Another limitation regarding this research field is related to the duration of training protocols. Whereas this study reports greater benefits for EC after longer training protocols (>24 sessions), one could argue that the chronic effects of such a training regimen are less understood. Future research should be conducted to study the effects of different long-term periodization strategies, which will be helpful to provide practitioners with more guidelines regarding, for example, the appropriate timing for the implementation of strength development in the annual training plan.

Practical Applications

Results of this meta-analysis support the implementation of strength training in addition to the sport-specific aerobic program to moderately improve performance in middle- and long-distance events. The results suggest that these beneficial effects are similar for running, cycling, cross-country skiing, and swimming, irrespective of athlete level. With regard to training adaptations, this meta-analysis revealed that EC could be improved through such a training strategy, whereas no detrimental effects are reported for both VO_2max and AE. In terms of strength-training intensity, greater effects on performance were found as a result of programs

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including maximal force development. Moreover, a training frequency of 2 strength sessions per week and a protocol duration >24 sessions were associated with greater benefits on EC.

Conclusion

In summary, the objective of this study was to assess the net effects of strength training on middle- and long-distance performance through a meta-analysis of the available literature. Results from this meta-analysis support a moderate beneficial effect of such a training regimen on performance. Future research in this field should be conducted to determine the effects of different periodization strategies, particularly from a long-term perspective.

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