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Human Kinetics
BRIEF REVIEW

Effects of Strength Training on Olympic Time-Based Sport Performance: A Systematic Review and Meta-Analysis of Randomized Controlled Trials

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Purpose: To evaluate the effect of strength training on Olympic time-based sports (OTBS) time-trial performance and provide an estimate of the impact of type of strength training, age, training status, and training duration on OTBS time-trial performance. ***Methods:*** A search on 3 electronic databases was conducted. The analysis comprised 32 effects in 28 studies. Posttest time-trial performance of intervention and control group from each study was used to estimate the standardized magnitude of impact of strength training on OTBS time-trial performance. ***Results:*** Strength training had a moderate positive effect on OTBS time-trial performance (effect size = 0.59, $P < .01$). Subgroup meta-analysis showed that heavy weight training (effect size = 0.30, $P = .01$) produced a significant effect, whereas other modes did not induce significant effects. Training status as factorial covariate was significant for well-trained athletes (effect size = 0.62, $P = .04$), but not for other training levels. Meta-regression analysis yielded nonsignificant relationship with age of the participants recruited ($\beta = -0.04$; 95% confidence interval, −0.08 to 0.004; $P = .07$) and training duration ($\beta = -0.05$; 95% confidence interval, −0.11 to 0.02; $P = .15$) as continuous covariates. ***Conclusion:*** Heavy weight training is an effective method for improving OTBS time-trial performance. Strength training has greatest impact on well-trained athletes regardless of age and training duration.

Keywords: running, cycling, swimming, rowing, resistance training

The performance in Olympic time-based sports (OTBS) such as long- and middle-distance running, cycling, swimming, rowing, and sprint kayaking is a multifactorial phenomenon. In such sports, energy expenditure is determined by aerobic and anaerobic pathways.[1–4] Although maximum oxygen consumption and anaerobic capacity might differ between different tiers of sportsmen (eg, well trained vs elite), these physiological factors might not be good predictors among athletes of the same tier or competitive level as it yields lower variability. Conversely, movement economy displays a higher degree of variability among individuals and has been shown to be an important predictor of endurance performance.[5–7] Movement economy can be defined as the steady-rate oxygen cost of a standard power output or movement speed.[8,9] Movement economy is dependent on anthropometric features and physiological, biomechanical, and neuromuscular factors.[10–12]

The role of neuromuscular factors in improving movement economy and, therefore, performance in OTBS has been extensively studied in recent years.[13–21] Multiple studies have been conducted to investigate the relationship between strength and OTBS performance.[22–25] These studies showed that there was a moderate correlation between isometric squat peak force and running economy ($r = .57$),[22] a moderate to large correlation between 30-second Wingate cycling and track cycling split time with isometric midthigh pull peak force ($.78 \le r \le .86$ and $-.49 \le r \le -.55$, respectively), and small to large correlation between upper-body strength and sprint kayak (200- to 1000-m) performance ($-.47 \le r \le -.97$).[23,25] Findings from these studies suggest that improving the strength of muscles involved in the movement of the respective sport might lead to performance enhancement. One explanation as to why the increase in muscular strength and power might improve OTBS performance and movement economy is because, with increased strength, there would be a reduction in relative load to the working muscles and possibly more optimal activation of motoneurons.[12] Thus, reducing the energy cost of movement. In addition, the reduction in relative load would also reduce the rate of local muscular fatigue so that athletes would be able to maintain an optimal movement velocity for a longer period of time,[19] which would enable to achieve a faster race time.

Many studies investigating the effects of heavy weights and explosive strength have shown improved OTBS performance with increased muscular strength or power also.[19,26–30] Therefore, strength training seems to be an efficient and practical method for enhancing OTBS performance. Some systematic reviews and only a few meta-analyses have provided partial evidence that strength training is beneficial to OTBS, such as endurance running,[15–16] cycling,[13–21] competitive swimming,[14] and rowing.[18] However, there is currently no systematic review on the effect of strength training on the performance of multiple OTBS within one review study and hence, enabling comparisons across sports. Moreover, there is no meta-analysis published in the literature with a meta-analysis consolidating the evidence gathered in all these OTBS, providing a wider and quantitative insight on the effects of strength training in performance.

Several factors such as age, training status, and duration of training can affect endurance performance and movement economy.[15–16,31] Meta-analysis by Allen and Hopkins[31] showed that there is a wide range of peak performance ages of elite athletes due to the differences in the attributes required for success in different sporting events. For example, early specialization might have allowed swimmers to acquire the efficient aquatic motion necessary

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for a successful swim; hence, the early peaking phenomenon observed in swimmers.[31] By contrast, aerobic capacity and movement economy required for ultraendurance events increases progressively with increasing training history.[31] Thus, this is the reason why better performing athletes in such events tend to be older. However, the impact of age on the effects of strength training on OTBS performance remains unclear. Meta-analyses by Berryman et al[15] and Denadai et al[16] noted that longer strength training programs resulted in greater improvements in endurance performance and running economy. Denadai et al[16] showed that effects of strength training on running economy did not differ between runners of different training status. However, both studies did not report the impact of athletes' age on the effects of strength training on endurance performance. Furthermore, there is currently no meta-analysis conducted to clarify the impact of these factors (age, training status, and duration of training program) on how strength training affects performance in other OTBS.

The main aim of this study was to systematically review the current body of knowledge on the effects of strength training on OTBS time-trial performance (ie, endurance running, cycling, swimming and rowing). The second aim was to conduct a meta-analysis providing an estimate of the contributions by several factors to the improvement in OTBS time-trial performance (such as age, training status, and duration of training program).

Methods

Literature Search

A systematic search of randomized controlled trials on the effects of strength training on OTBS time-trial performance was conducted. Original research and review articles up to December 28, 2018 were searched and retrieved from electronic searches on PubMed, SPORTDiscus, and Google Scholar databases. PICO (P—patient, problem, or population; I—intervention; C—comparison, control, or comparator; O—outcomes) search strategy was conducted based on the Boolean technique presented in Table 1.

Inclusion and Exclusion Criteria

Figure 1 depicts the PRISMA flow diagram identifying, screening, checking eligibility, and inclusion of the studies. Studies were considered for review if they met the following inclusion criteria: (1) randomized controlled trials, (2) available in English, (3) studies which included time trial of an OTBS as performance measure, and (4) studies that included any modes of strength training (including isotonic, isometric, isokinetic, plyometric, variable resistance, and calisthenics). Studies were excluded for the following reasons: (1) not randomized controlled trials, (2) reported only physiological measures and no performance outcome, and (3) participants were not at least recreational athletes of the respective sports.

Study Selection

Eighty-five relevant studies were retained from the search of the electronic databases and examination of the reference lists. Forty-one articles were excluded based on study design (n = 9), studies were off topic (n = 11), studies were either reviews or book chapters (n = 18), and studies were not written in English (n = 3). Forty-four articles were read in full and 28 articles were included in the meta-analysis (Figure 1).

Quality of the Studies

Quality of the 28 studies included were assessed based on the Physiotherapy Evidence-Based Database (PEDro) scale as this method of assessment has been shown to be reliable for rating quality of randomized controlled trials.[32] In addition, previous systematic reviews and meta-analysis have also used this method to assess the quality of studies that investigated on the effects of strength training on endurance sports.[16,21] The scale pertains to the internal validity and data analysis of a research study. Maximal total score is 11 points, with higher scores indicating better quality. Components of the PEDro scale include (1 point per item): (1) eligibility criteria were specified; (2) subjects were randomly allocated to groups; (3) allocation was concealed; (4) groups were similar at baseline regarding the most important prognostic indicators; (5) blinding of all subjects; (6) blinding of all therapists who administered the therapy; (7) blinding of all assessors who measured at least 1 key outcome; (8) measures of at least 1 key outcome were obtained from more than 85% of the subjects initially allocated to the groups; (9) all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least 1 key outcome was analyzed by "intention to treat"; (10) results of between-group statistical comparisons are reported for at least 1 key outcome; and (11) the study provides both point measures and measures of variability for at least 1 key outcome.

Characteristics of Studies Included

Thirty training effects from 28 studies were included in the meta-analysis. The scope of these studies is summarized in Table 2. Total number of subjects in these 28 studies was 568 (310 assigned to experimental groups and 258 to control groups). Subjects were recreational, well trained, highly trained, and adolescents in 4, 12,

Table 1 PICO Process and Boolean Search Technique

Population	Intervention	Comparison (ie, design)	Outcome
Human*	Strength training	Randomized controlled trial	Performance
Subject*	Resistance training		Time trial
Athlete*	Concurrent training		Power
Participant*	Plyometric training		Velocity
Male*			Economy
Female*			Running
Adolescent*			Cycling
			Rowing
			Kayaking
			Swimming

Note: Asterisks denote truncation to retrieve words with different endings.

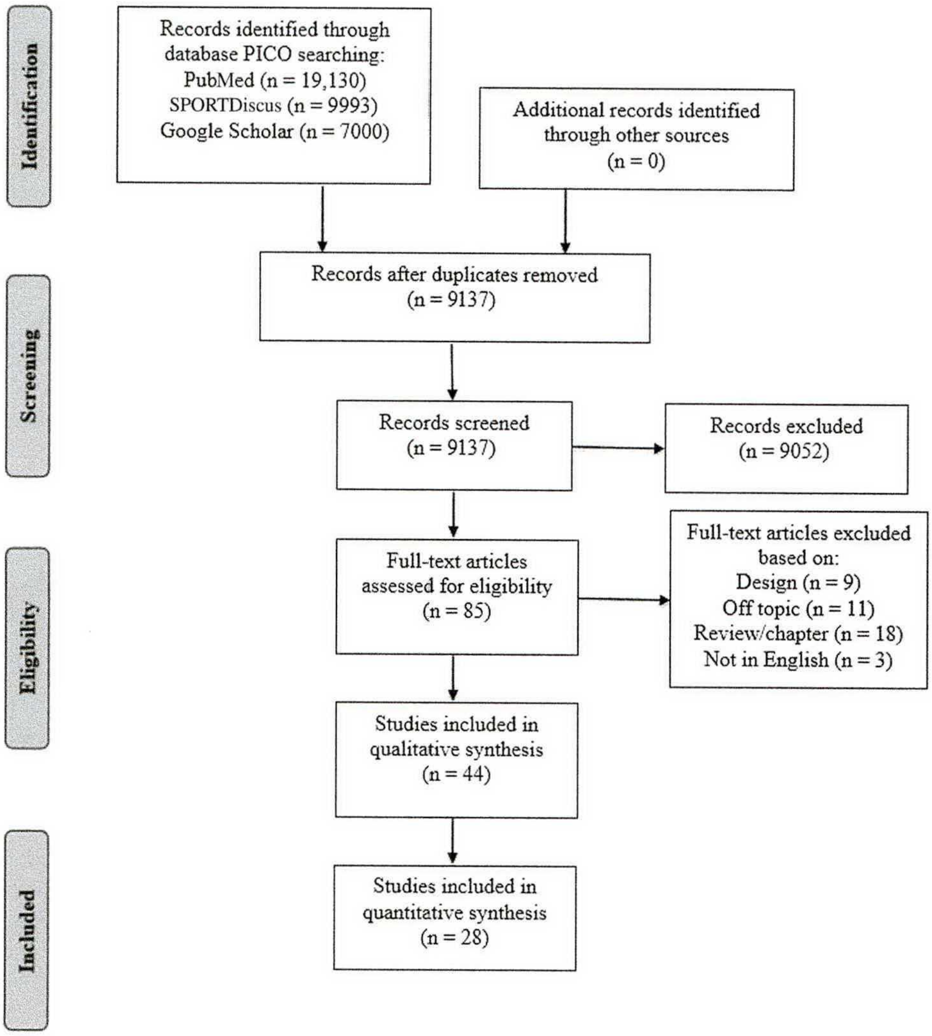

Figure 1 — Summary of PRISMA flow for search strategy.

7, and 5 studies, respectively. Subjects were categorized into respective training status based on the description stated by the authors of each study. Subjects in "recreational" included those described as recreational, "well trained" included those described as well trained or competitive, "highly trained" included those described as highly trained and elite, and adolescents included those below the age of 18 years old. It was assessed running, cycling, swimming, and rowing in 10, 10, 8, and 1 of the studies, respectively. Type of strength training selected included heavy weights training (HWT), plyometric training (PT), endurance weights training (EWT) and mixed heavy weights, and plyometric training (HPT) in 15, 10, 4, and 2 studies, respectively (Table 3).

Data Analysis

All data are reported as mean ± 95% confidence interval (CI). The posttest time-trial running, swimming, and rowing velocity, and cycling average power, of intervention and control group from each study was used to estimate the standardized magnitude of impact of strength training on OTBS time-trial performance. Better time-trial performance is represented by faster running, swimming, and rowing velocity, and higher cycling average power. The weight of each study was computed as variance of the posttest velocity and average power.

A random effect model (restricted maximum likelihood) was selected because of the wide variation in experimental factor levels in the studies included for synthesis and analysis. Hedges' *g* was selected as standardized effect size (ES). Statistical heterogeneity was assessed by Cochran's Q and I^2. I^2 of 25%, 50%, and 70% are deemed as low, medium, and high level of heterogeneity, respectively.[55] Subgroup meta-analysis was performed for factorial covariates including training status and type of strength training. Meta-regression analysis was performed for continuous covariates including age of participants and duration of intervention. The statistics of the full model reflect the combined impact of all covariates, whereas statistic of individual covariate reflects the impact of the specific covariate. The standardized magnitude of training induced changes was deemed as[56]: (1) trivial ES, if $0 \leq |ES| \leq 0.2$; (2) small sizes, if $0.2 < |ES| \leq 0.5$; (3) moderate sizes, if $0.5 < |ES| \leq 0.8$; and (4) large sizes, if $|ES| > 0.8$. Data analyses were run on R (metaphor, ggplot2, and OpenMeta packages) ($P < .05$).

Results

Quality of the Studies

The quality of the 28 studies was very similar, with PEDro scores ranging from 5 to 7 (Table 2). All 28 studies did not meet the criteria for the following components: (1) allocation was concealed, (2) blinding of all subjects, (3) blinding of all researchers who administered the intervention program, and (4) blinding of all assessors who measured

Table 2 Characteristics of Studies Included in the Meta-analysis

Authors	Mode	N	Sex	Training status	PEDro scale
Aagaard et al[26]	Cycling	14	M	Highly trained	6
Amaro et al[27]	Swimming	21	F and M	Adolescent	7
Aspenes et al[33]	Swimming	20	F and M	Adolescent	7
Bastiaans et al[34]	Cycling	14	M	Well trained	6
Berryman et al[35]	Running	35	M	Well trained	6
Bishop et al[36]	Cycling	21	F	Well trained	6
Bishop et al[37]	Swimming	22	F and M	Adolescent	7
Cossor et al[38]	Swimming	38	F and M	Adolescent	6
Damasceno et al[39]	Running	18	M	Recreational	5
Gallagher et al[17]	Rowing	18	M	Well trained	7
Garrido et al[40]	Swimming	25	F and M	Adolescent	7
Girold et al[28]	Swimming	24	F and M	Well trained	6
Karsten et al[41]	Running	16	F and M	Recreational	7
Kelly et al[42]	Running	16	F	Recreational	6
Naczk et al[43]	Swimming	14	M	Well trained	7
Paavolainen et al[29]	Running	22	M	Highly trained	6
Paton and Hopkins[44]	Cycling	18	M	Well trained	6
Pellegrino et al[45]	Running	22	F and M	Well trained	6
Potdevin et al[46]	Swimming	23	F and M	Adolescent	7
Psilander et al[47]	Cycling	19	M	Well trained	7
Ramirez-Campillo et al[48]	Running	36	F and M	Highly trained	7
Rønnestad et al[49]	Cycling	20	F and M	Well trained	6
Rønnestad et al[30]	Cycling	12	F and M	Well trained	7
Rønnestad et al[50]	Cycling	20	F and M	Highly trained	6
Schumann et al[51]	Running	27	M	Recreational	7
Vikmoen et al[52]	Cycling	19	F	Well trained	7
Vikmoen et al[53]	Running and cycling	19	F	Well trained	7
Vorup et al[54]	Running	16	M	Well trained	6

Abbreviations: F, female; M, male; PEDro, Physiotherapy Evidence-Based Database.

at least one key outcome. Thirteen of the studies did not include eligibility criteria, and 2 studies did not have more than 85% of subjects originally assigned to groups completing the studies.

Effect of Strength Training on Time-Trial Performance

Twenty of the 30 training effects showed improved time-trial performance. The standardized ES of strength training on time-trial performance ranged from –0.81 to 8.74 (Figure 2). Overall, strength training had a moderate positive effect on OTBS time-trial performance (ES = 0.59; 95% CI, 0.22 to 0.96; $Q = 112.04$; $I^2 = 72\%$; $P < .01$). At least 2 studies fell beyond the funnel tunnel of the plot SEs versus standardized mean differences. Removing these 2 studies, the meta-analysis yielded an ES = 0.46 and $I^2 = 62\%$. Therefore, an effect of strength training on performance was noted. Further analysis was required to better understand the high heterogeneity ($I^2 = 72\%$) of the full data set.

The Effect of Training Status and Training Type

The results of the subgroup meta-analysis having training status as factorial covariate was significant for well-trained athletes (ES = 0.62; 95% CI, 0.02 to 1.22; $P = .04$). It was nonsignificant for recreational athletes (ES = 0.21; 95% CI, –0.24 to 0.65; $P = .37$), highly trained athletes (ES = 0.47; 95% CI, –0.03 to 0.97; $P = .06$), and adolescents (ES = 1.61; 95% CI, –0.88 to 4.10; $P = .20$), albeit moderate to large effects in some cohorts (Figure 3A).

Comparing the training type, subgroup meta-analysis was significant for HWT (ES = 0.30; 95% CI, 0.07 to 0.53; $P = .01$). It was nonsignificant for PT (ES = 1.49; 95% CI, –0.21 to 3.19; $P = .09$), EWT (ES = 0.99; 95% CI, –1.96 to 3.95; $P = .51$), and HPT (ES = 0.82; 95% CI, –0.87 to 2.51; $P = .34$), despite again moderate to large effects were noted (Figure 4).

The Effect of Age and Training Duration

Meta-regression analysis yielded a nonsignificant relationship with age of the participants recruited ($\beta = -0.04$; 95% CI, –0.08 to 0.004; $P = .07$) and training duration ($\beta = -0.05$; 95% CI, –0.11 to 0.02; $P = .15$) as continuous covariates. Therefore, training status, age of participants, and training duration have no significant impact on the effects of strength training on OTBS time-trial performance.

Discussion

The purpose of this meta-analysis was to evaluate the effects of strength training on OTBS time-trial performance and estimate

Table 3 Effects of Strength Training on the Time Trial of Olympic Time-Based Sport Performance

Authors	Mode	Frequency and duration	Types of training	Time-trial results
Aagaard et al[26]	Cycling	2–3 sessions/wk for 16 wk	HWT: 4 × 5–12 isolated knee extension, incline leg press, hamstring curls, and calf raises	HWT: ↑ 5 (4.8%) and 45 min (8%) all-out cycling mean power
Amaro et al[27]	Swimming	2 sessions/wk for 6 wk	EWT: 3 × 8–15 medicine ball throw, 3 × 10–18 CMJ to 30-cm box, Russian twist, push-ups, and 3 × 6–15 dumbbell flys PT: 3 × 15–25 s medicine ball throw, CMJ to 30-cm box, Russian twist, 3 × 10–20 s push-ups, dumbbell flys (all exercises performed explosively)	EWT: ↑ 50-m swim time (0.3%) PT: ↓ 50-m swim time (5.3%)
Aspenes et al[33]	Swimming	2 session/wk for 11 wk	HWT: 3 × 5 bilateral shoulder extension resistance exercise	HWT: ↓ 400-m swim time (1.4%)
Bastiaans et al[34]	Cycling	3.2 h/wk for 9 wk	EWT: 30 × squats, leg press, and step-up	EWT: ↑ power output during 1-h time trial (11.2%)
Berryman et al[35]	Running	1 session/wk for 8 wk	HWT: 3–6 × 8 semisquat PT: 3–6 × 8 drop jumps (20, 40, and 60 cm)	HWT: ↓ 3000-m run time (4.1%) PT: ↓ 3000-m run time (4.8%)
Bishop et al[36]	Cycling	2 sessions/wk for 12 wk	HWT: 3–5 × 2–8 squats	HWT: ↑ 1-h time trial average power (1.0%)
Bishop et al[37]	Swimming	2 sessions/wk for 8 wk	PT: 1–5 × 1–6 two-foot ankle hop, tuck jump, squat jump, split squat jump, standing jump over barrier, front cone hops, hurdle hops, single-leg bounding, single-leg push-off, multiple box to box jumps, box skip, alternate bounding, double-leg hops, depth jump, depth jump to standing long jump, jump to box, standing jump and reach, standing long jump, and standing long jump with hurdle hop	PT: ↓ time to 5.5 m (15.43%)
Cossor et al[38]	Swimming	3 sessions/wk for 20 wk	PT: 2 × 10–15 fifteen difference plyometric exercises	PT: ↓ 50-m swim time (2.47%)
Damasceno et al[39]	Running	2 sessions/wk for 8 wk	HWT: 2–3 × 3–10 half squat, leg press, plantar flexion, and knee extension	HWT: ↓ 10-km run time (2.5%)
Gallagher et al[17]	Rowing	2 sessions/wk for 8 wk	HWT: 3–5 × 1–5 barbell flat bench press, leg press, dumbbell shoulder press, upright barbell rows, seated row, hamstring curl, barbell biceps curl, barbell incline bench press, barbell deadlift, barbell overhead press, lateral pulldowns, dumbbell bent over rows, hamstring single-leg curls, and triceps extensions EWT: 2–3 × 15–30 (same exercises as HWT)	HWT: ↓ 2000-m rowing time (3.4%) EWT: ↓ 2000-m rowing time (3.1%).
Garrido et al[40]	Swimming	2 sessions/wk for 8 wk	HWT: 2–3 × 6–8 leg extension and bench press, 2–3 × 5 CMJ and CMJ on to box, and 2–3 × 8–10 ball throwing	HWT: ↑ swim velocity for 25 (6.95%) and 50 m (4.77%)
Girold et al[28]	Swimming	3 sessions/wk for 4 wk	HWT: 3 × 6 pull up and draws with pulley	HWT: ↓ 50-m swim time (2%)
Karsten et al[41]	Running	2 sessions/wk for 6 wk	HWT: 4 × 4 Romanian deadlift, parallel squat, calf raises, and lunges	HWT: ↓ 5-km run time (3.5%)
Kelly et al[42]	Running	3 sessions/wk for 10 wk	HWT: 3 × 5 Squats, calf raises, hip extension and flexion, hamstring curl, seated row, and bench press	HWT: ↓ 3-km run time (11.2%)
Naczk et al[43]	Swimming	3 sessions/wk for 4 wk	HWT: 4 × 15 s elbow extension	HWT: ↓ 100-m butterfly swim time (1.83%) and ↓ 50-m freestyle swim time (0.76%)
Paavolainen et al[29]	Running	2–3 sessions/wk for 9 wk	HPT: 5–10 × 20–100 m sprint, 5–20 × alternative jumps, bilateral CMJ, drop and hurdle jump, 1-legged 5 jump test, leg press, knee extensor, and flexor exercise	PT: ↓ 5-km run time (3.1%)

(continued)

Table 3 (continued)

Authors	Mode	Frequency and duration	Types of training	Time-trial results
Paton and Hopkins[44]	Cycling	2–3 sessions/wk for 4–5 wk	PT: 3 × 20 explosive single-leg jumps, 3 × 5 × 30 s high resistance cycling	PT: ↑ 1-km mean power (8.7%) and ↑ 4-km mean power (8.4%)
Pellegrino et al[45]	Running	2–3 sessions/wk for 6 wk	PT: 2–3 × 6–12 squat jump, split scissor jump, double-leg bound, alternate leg bound, single-leg forward hop, depth jump, double-leg hurdle jump, single-leg hurdle jump, single-leg hurdle hop	PT: ↑ VO_2max (5.2%), ↓ 3-km run time (2.6%), and ↓ energy cost of running (1.3%)
Potdevin et al[46]	Swimming	2 sessions/wk for 6 wk	PT: 2–10 × 4–15 double- and single-leg standing jump over barrier, standing long jump, standing long jump with SJ position, single-leg bounding, 2-feet ankle hop, double- and single-leg lateral hop, double- and single-leg depth jump, drop jump, multiple step to step jump, static jump with knees up, combined standing high, and depth and long jumps	PT: ↑ 50-m (3.2%) and 400-m (4.3%) swim velocity
Psilander et al[47]	Cycling	2 sessions/wk for 8 wk	EWT: 6 × 15 leg press	EWT: ↑ 40-min time trial mean power (2.8%)
Ramirez-Campillo et al[48]	Running	2 sessions/wk for 6 wk	PT: 60 × drop jumps (40–60 cm)	PT: ↓ 2.4-km run time (3.9%)
Rønnestad et al[49]	Cycling	2 sessions/wk for 12 wk	HWT: 3 × 4–10 half squat, single-leg leg press, standing 1 legged hip flexion, and ankle plantar flexion	HWT: ↑ 40-min time trial mean power (6%)
Rønnestad et al[30]	Cycling	1–2 sessions/wk for 25 wk	HWT: 2–3 × 4–10 half squat, single-leg leg press, 1–3 × 4–10 standing 1-legged hip flexion and ankle plantar flexion	HWT: ↑ 40-min time trial mean power (14%)
Rønnestad et al[50]	Cycling	2 sessions/wk for 10 wk	HWT: 3 × 4–10 half squat, single-leg leg press, standing 1-legged hip flexion, and ankle plantar flexion	HWT: ↑ 40-min all-out trial power output (3.5%)
Schumann et al[51]	Running	2 sessions/wk for 24 wk	HPT: 5–20 × leg press, bilateral and unilateral knee flexion and calf raises, loaded and unloaded squat jumps, drops jumps, leaps, step-ups, crunches, torso rotation, and lower-back extension	HPT: ↓ 1000-m run time (8.3%), ↑ time to exhaustion (7%), ↑ velocity at blood lactate 4 mmol/L (6%), and ↓ maximal voluntary contraction (6%)
Vikmoen et al[52]	Cycling	2 sessions/wk for 11 wk	HWT: 3 × 4–10 half squat, single-leg leg press, standing hip flexion, and ankle plantar flexion	HWT: ↑ 40-min all-out trial mean power (6.4%)
Vikmoen et al[53]	Running and cycling	2 sessions/wk for 11 wk	HWT: 3 × 4–10 half squat, single-leg leg press, standing hip flexion, and ankle plantar flexion	HWT: ↑ 5-min all-out running distance (4.7%) and cycling average power (7%)
Vorup et al[54]	Running	2 sessions/wk for 8 wk	HWT: 1–4 × 4–10 squat, leg press, and deadlift	HWT: ↑ 400-m run performance (4.8%)

Abbreviations: EWT, endurance weight training; HPT, mixed heavy weight and plyometric training; HWT, heavy weight training; PT, plyometric training; VO_2max, maximum oxygen consumption.

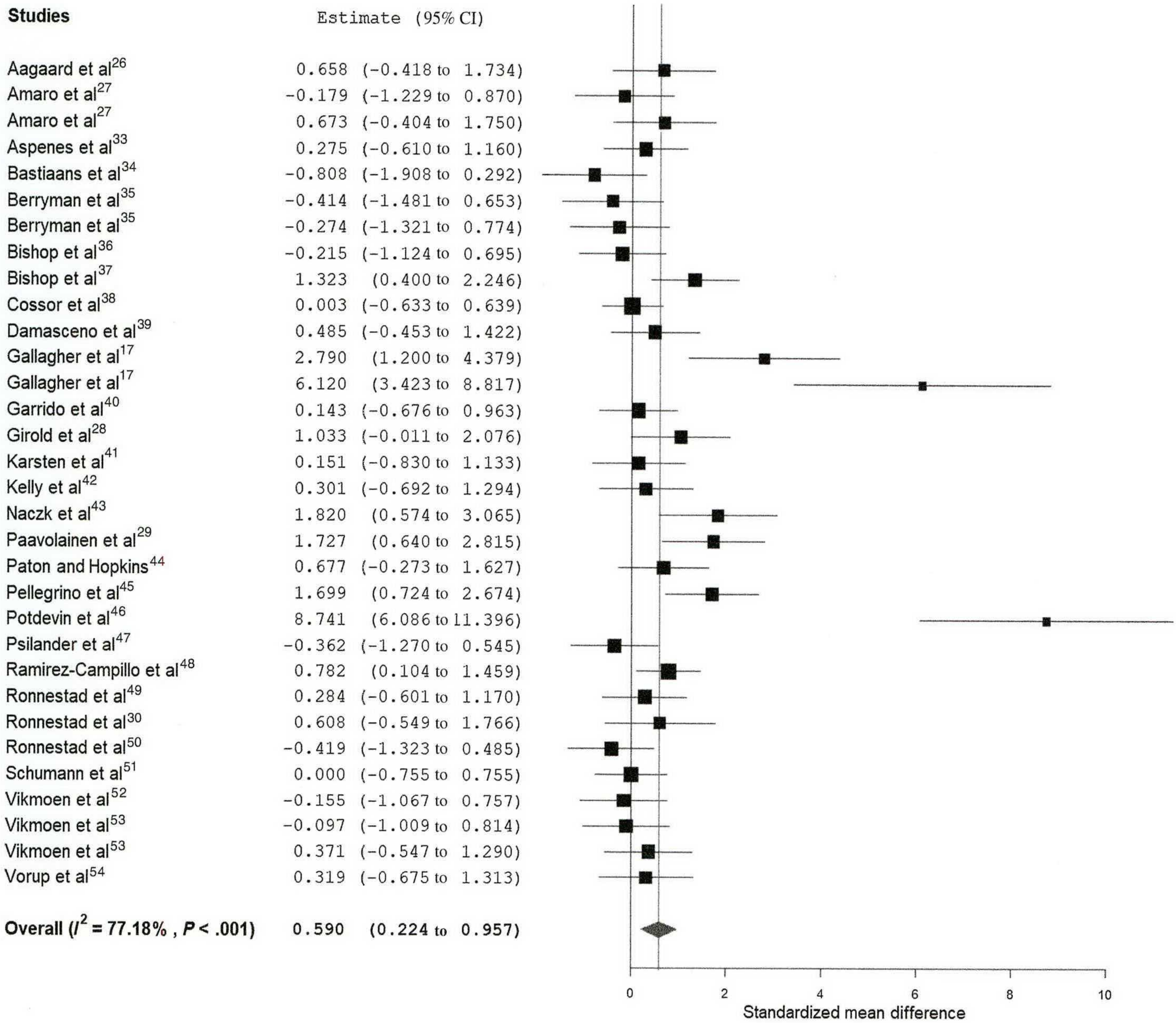

Figure 2 — Standardized mean differences of posttest time-trial performances between intervention and control groups of all included studies expressed as Hedges *g* and 95% CI. CI indicates confidence interval.

the contributions of age, training status, and duration of training program to the improvement in OTBS performance. There is a moderate effect of strength training on time-trial performance of OTBS. Training status, age of participants, and training duration have trivial effects.

Quality of the Studies

The PEDro quality for the 28 studies was 6.46 ± 0.57 and ranged from 5 to 7 (Table 2). The criteria that all studies did not fulfill were concealing of group allocation, blinding of all subjects to intervention, blinding of all researchers who administered the intervention program, and blinding of all assessors who measured at least one key outcome. As these studies involved performance of physical activities, it is challenging to conceal the group allocation and blinding the subjects and researchers to the intervention program. However, it is possible to blind the assessors who conduct the tests (if the study involves more than one investigator). Therefore, in view of this, the quality of the research methodologies of the 28 studies is considered acceptable. That said, even not considering the 3 abovementioned items, studies had room to improve the research design from an average of 6.46 ± 0.57 to at least 8 scores. For instance, future research designs should consider finding ways of blinding the assessors who conduct the tests, clearly note eligibility criteria in the article, and tackle issues with dropout rates.

Effect of Strength Training on Time-Trial Performance

Our data showed that strength training has a moderate effect (ES = 0.65) on time-trial performance as compared with OTBS sports

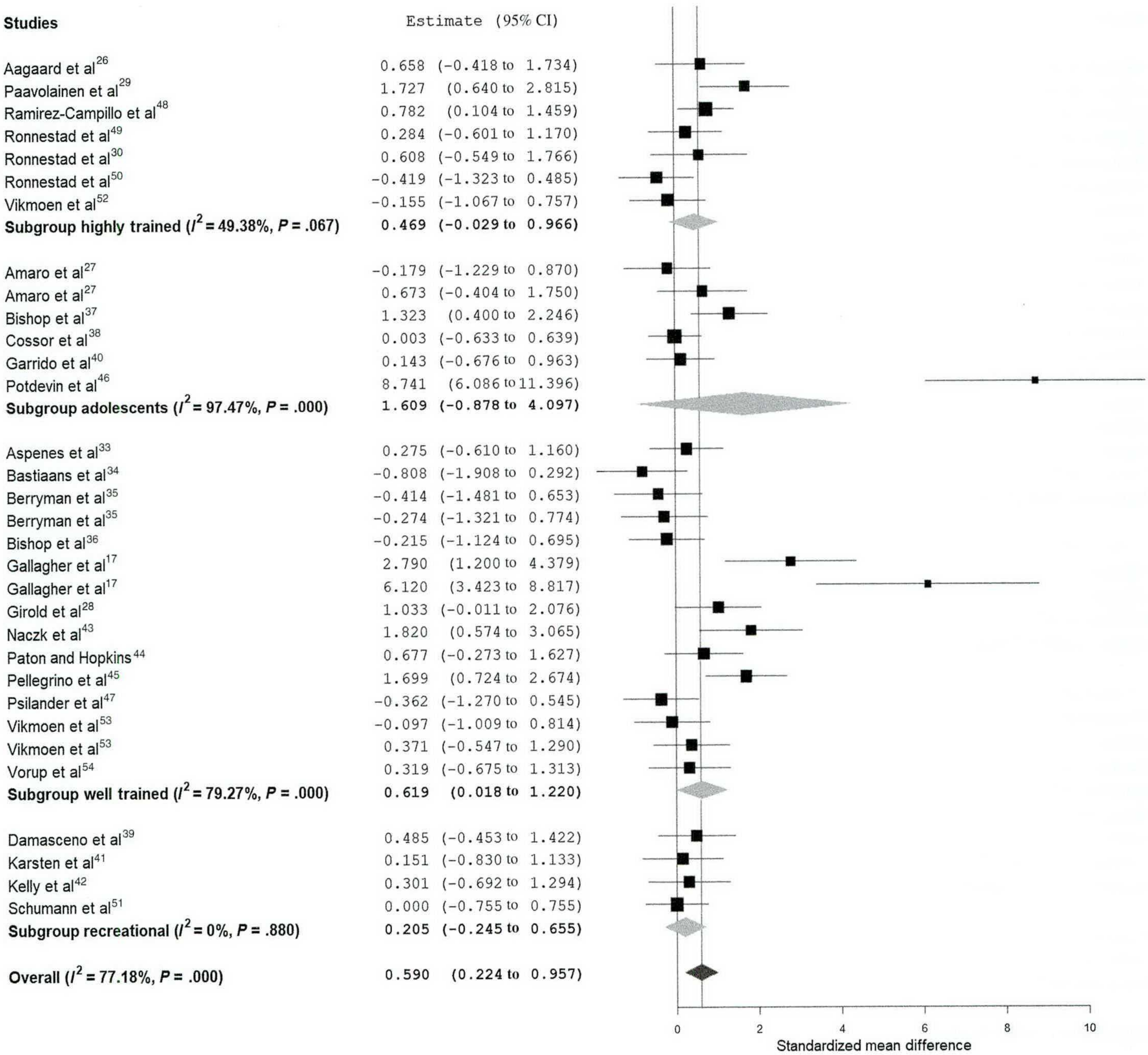

Figure 3 — Subgroup meta-analysis for training status. CI indicates confidence interval.

training alone. However, 2 studies resulted in extreme values.[17,46] When these 2 studies were removed, the meta-analysis resulted in a slightly smaller effect (ES = 0.46) but much lower heterogeneity ($I^2 = 62\%$). It has become a standard procedure in sport sciences and elite performance to have a goal for an improvement of at least ES = 0.2.[57] Practitioners, analysts, and academics in these scientific fields assume that an ES ≥ 0.2 is already meaningful, with an impact on the athletes' performance. Therefore, an ES = 0.65 (and even ES = 0.46) is deemed as very impactful.

Converting an ES = 0.65 into percentile gain, it yields an improvement of 24 points. Likewise, an ES = 0.46 yields an improvement of 18 percentile points. Let's assume that an athlete is ranked 50th in the world's top 100. After going under a strength training program, one can expect that the athlete will move up to rank 24th (if ES = 0.65) or 32nd (if ES = 0.46). As such, strength training has a meaningful impact on the performance of OTBS.

A possible reason for the large ES observed in the studies by Gallagher et al[17] and Potdevin et al[46] is the difference in preintervention rowing velocity and diving velocity, respectively, between the intervention and control groups. In both studies, the preintervention and postintervention performances of intervention groups were better than the postintervention performance of the control groups. However, both studies did not report any significant difference in preintervention performance between groups. Improvement to the methodology of the studies could be accomplished by matching subjects for performance level prior to randomly assigning them to different groups (ie, selecting a counter-balanced randomized research design).

Studies	Estimate (95% CI)
Aagaard et al[26]	0.658 (−0.418 to 1.734)
Aspenes et al[33]	0.275 (−0.610 to 1.160)
Berryman et al[35]	−0.274 (−1.321 to 0.774)
Bishop et al[36]	−0.215 (−1.124 to 0.695)
Damasceno et al[39]	0.485 (−0.453 to 1.422)
Gallagher et al[17]	2.790 (1.200 to 4.379)
Garrido et al[40]	0.143 (−0.676 to 0.963)
Girold et al[28]	1.033 (−0.011 to 2.076)
Karsten et al[41]	0.151 (−0.830 to 1.133)
Kelly et al[42]	0.301 (−0.692 to 1.294)
Naczk et al[43]	1.820 (0.574 to 3.065)
Ronnestad et al[49]	0.284 (−0.601 to 1.170)
Ronnestad et al[30]	0.608 (−0.549 to 1.766)
Ronnestad et al[50]	−0.419 (−1.323 to 0.485)
Vikmoen et al[52]	−0.155 (−1.067 to 0.757)
Vikmoen et al[53]	−0.097 (−1.009 to 0.814)
Vikmoen et al[53]	0.371 (−0.547 to 1.290)
Vorup et al[54]	0.319 (−0.675 to 1.313)
Subgroup HWT (I^2 = 1.29%, *P* = .103)	**0.301 (0.069 to 0.534)**
Amaro et al[27]	−0.179 (−1.229 to 0.870)
Bastiaans et al[34]	−0.808 (−1.908 to 0.292)
Gallagher et al[17]	6.120 (3.423 to 8.817)
Psilander et al[47]	−0.362 (−1.270 to 0.545)
Subgroup EWT (I^2 = 95.82%, *P* = .000)	**0.992 (−1.962 to 3.947)**
Amaro et al[27]	0.673 (−0.404 to 1.750)
Berryman et al[35]	−0.414 (−1.481 to 0.653)
Bishop et al[37]	1.323 (0.400 to 2.246)
Cossor et al[38]	0.003 (−0.633 to 0.639)
Paton and Hopkins[44]	0.677 (−0.273 to 1.627)
Pellegrino et al[45]	1.699 (0.724 to 2.674)
Potdevin et al[46]	8.741 (6.086 to 11.396)
Ramirez-Campillo et al[48]	0.782 (0.104 to 1.459)
Subgroup PT (I^2 = 96.24%, *P* = .000)	**1.490 (−0.215 to 3.194)**
Paavolainen et al[29]	1.727 (0.640 to 2.815)
Schumann et al[51]	0.000 (−0.755 to 0.755)
Subgroup HPT (I^2 = 84.71%, *P* = .011)	**0.817 (−0.873 to 2.508)**
Overall (I^2 = 77.18%, *P* = .000)	**0.590 (0.224 to 0.957)**

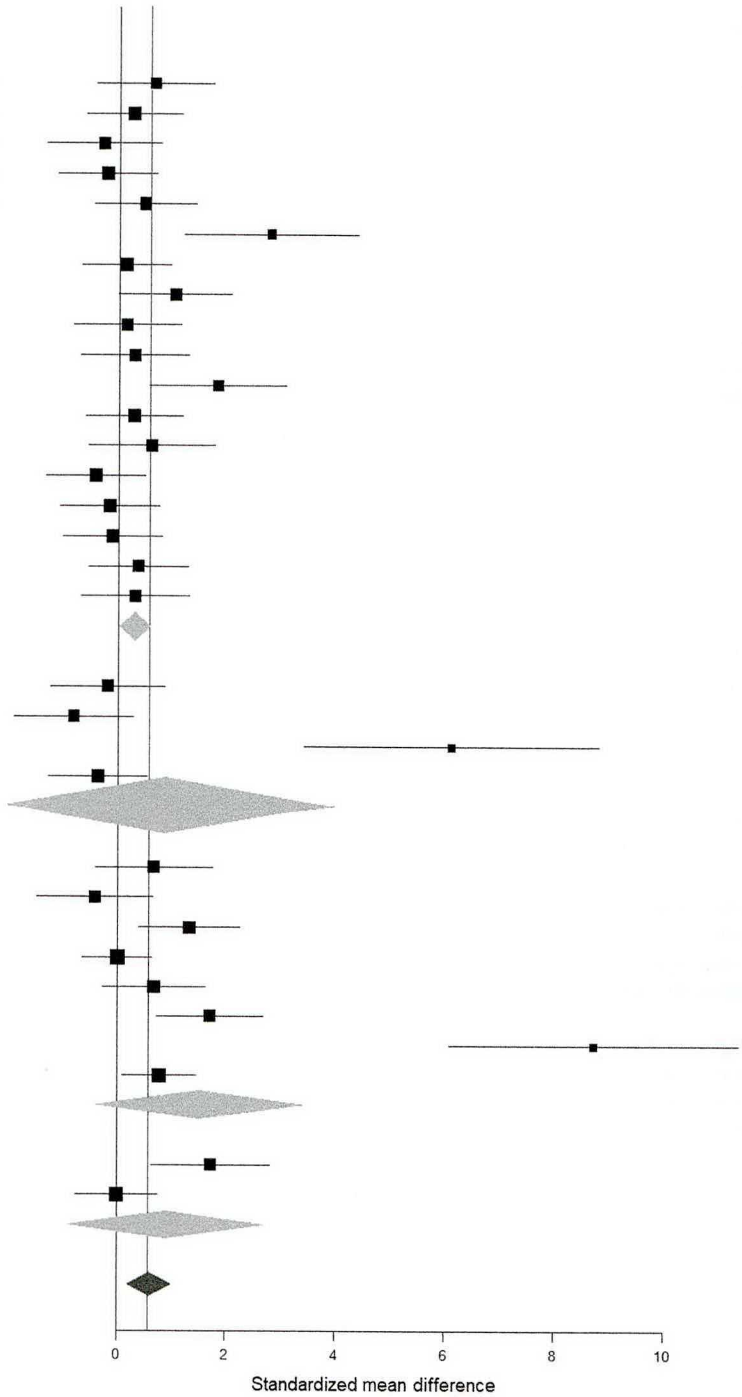

Figure 4 — Subgroup meta-analysis for training type. CI indicates confidence interval.

The Effect of Training Status and Training Type

Subgroup analysis was performed to consider the effects of training status and training type. The results showed that training status has no significant impact on the effects of strength training on OTBS time-trial performance. However, HWT presented a significant small ES on OTBS time-trial performance.

Our meta-analysis showed a trend for a small effect for the highly trained athletes (ES = 0.47, $P = .06$). Again, an ES = 0.47 yields an improvement of 18 percentile points. This finding was somewhat in tandem with Denadai et al[16] findings, which showed that improvement in running economy after concurrent strength and endurance training was similar in individuals of different training levels. Highly trained OTBS athletes could be less responsive to their specific sports training and would require higher volume or duration to make similar magnitude of improvement in time-trial performance or movement economy as athletes of lower-training status.[58] However, highly trained OTBS athletes might not necessarily have more experience in strength training than athletes of lower-training status, as their training regime might include little or no strength training.[13] Hence, the addition of new training stimulus such as strength training could enhance their neuromuscular adaptations to similar magnitude as compared with athletes of lower-training status; thus, improving their time-trial performance.

It has been shown that better trained athletes have improved movement economy and are less responsive to similar training program than athletes of lower-training status.[58] Results from our meta-analysis partially supported this statement, as there is significant moderate effect on the improvement in OTBS performance of well-trained athletes as compared with highly trained athletes, but not for recreational and adolescent athletes. The nonsignificant effect in recreational and adolescents could be because these groups of athletes' baseline performance were at a low level, which could be improved with or without strength training intervention. Conversely, the well-trained athletes had higher performance levels which required higher intensity or volume of the usual OTBS training to induce any form of improvement to OTBS performance. Therefore, the addition of strength training to the intervention groups of well-trained athletes resulted in significant beneficial effect.

Despite the nonsignificant effect in recreational and adolescent athletes, these athletes should be made aware that there would be a diminishing return in training effect from OTBS training alone as their training history increases.[58] In such a situation, the addition of strength training could further enhance their training adaptations and performance. In addition, strength training has been shown to reduce sports injuries and overuse injuries.[59] Therefore, it is still recommended that recreational and adolescent athletes include strength training as part of their overall training program.

The studies included in the meta-analysis have used different modes of strength training to enhance OTBS performances. These included PT, HWT, EWT, and HPT. Although each mode of strength training has been shown to result in different neuromuscular adaptations,[60] it has also been noted to result in similar improvement in strength and power in individuals with no strength training experience.[61] The current meta-analysis showed that HWT resulted in a significant small effect on the improvement in OTBS time-trial performance, whereas there was no significant effect from PT, EWT, and HPT. This suggests that HWT may be the most effective form of strength training in improving OTBS time-trial performance. This only partially supports the findings of the systematic reviews by Berryman et al[15] and Denadai et al[16] as both studies also showed significant effect for PT. The systematic review by Yamato et al[21] also showed that explosive resistance training was effective in improving cycling performance among different modes of strength training. Although the PT has been shown to improve endurance performance in other systematic reviews and meta-analysis,[15,16,21] our meta-analysis only showed a trend for a large effect under PT (ES = 1.49, $P = .09$). That said, even if $P > .05$, an ES = 1.49 can be converted into an improvement in 43 percentile points, which is not negligible as far as coaches, athletes, and analysts is concerned. One possible reason for mixed findings can be due to the different performance measures analyzed in previous reviews and meta-analysis as compared with this study.

The Effect of Age and Training Duration

Meta-regression analyses were performed to consider the effects of participants' age and training duration. The age of participants and training duration have no significant impact on the effects of strength training on OTBS time-trial performance.

The current findings showed that age had no significant impact on the effects of strength training on OTBS time-trial performance. Age of subjects in the studies included in the meta-analysis ranged from 11.7 to 39 years old. The meta-analysis by Denedai et al[16] was not able to determine if age was a factor that impacts the effect of strength training on running economy as there was a high confounding effect between age and training level. In another meta-analysis, Berryman et al[15] were not able to test the effect of age due to the lack of participants within the required age groups. Studies that investigated the impact of age on strength adaptations after a period of strength training have shown no difference in strength gain between younger and older adults.[62,63] This is possibly why the current meta-analysis showed that age had no significant impact on the effects of strength training on OTBS time-trial performance. Currently, no study has compared the impact of strength training on OTBS time-trial performance in athletes of different age groups. As such, further investigation on the impact of age on the effects of strength training on OTBS time-trial performance is required to provide a firm conclusion.

Previous meta-analysis on the effects of strength training on running economy by Denadai et al[16] noted that 6 to 14 weeks of strength training was effective in improving economy in endurance runners, whereas 14 to 20 weeks of strength training would be required to enhance running economy of highly trained runners. In support of this, Berryman et al[15] suggested that longer duration training protocols might be more beneficial for improving energy cost of movement. One possible reason could be that longer training duration might lead to higher magnitude of strength gain due to the higher accumulated volume of work. The increase strength gains further led to greater improvement in energy cost of movement. However, our data showed that training duration has no effect on time-trial performance of OTBS. This difference in findings could be due to the difference in the variables being assessed. Indeed, energy cost of movement is one of the factors affecting time-trial performance; nevertheless, it is not the only factor. For example, the improvement in strength could have allowed individuals to reduce the rate of fatigue, hence, allowing them to sustain high power output for a longer period of time.[19] In summary, in our review we are focused on the main performance outcome (ie, time trial), whereas the other authors have been more focused on the performance determinants.

Research Gaps

Studies included in the meta-analysis were on endurance running, cycling, and swimming and rowing. There are currently a limited number of randomized controlled trial studies investigating the effects of strength training on rowing performance. In addition, there is no randomized controlled trial study on the effects of strength training on other time-based sports such as, for instance, kayaking and canoeing. Therefore, the results of this meta-analysis should not be generalized to other OTBS besides the ones reported in this study.

Future studies in this field should aim to compare the effects of different modes of strength training (isometric, isotonic, eccentric, variable resistance, and plyometric) on various OTBS time-trial performances. In addition, randomized controlled trial studies should provide a deeper insight of the deterministic or mechanistic relationship between neuromuscular adaptations and performance of different OTBS.

Practical Applications

Various strength training methods have been performed to enhance OTBS time-trial performance in running, cycling, and swimming and rowing. The current meta-analysis showed that strength training has a significant moderate effect on endurance performances with a meaningful impact on the percentile gain of ranked athletes.

There seems to be a greater beneficial effect from HWT compared with PT, EWT, and HPT. Studies that included HWT in the intervention had the participants performed heavy resistance exercise at 3- to 12-repetition-maximum load for 1 to 6 sets, and 2 to 3 times per week for 4 to 16 weeks. Therefore, practitioners should consider designing a similar training program.

Improvement in OTBS time-trial performances were independent of age, training status, and duration of intervention. Therefore, a 4 to 16 weeks strength training program should be able to result in improved performance in OTBS athletes regardless of age and training status.

Conclusion

Results from this meta-analysis supported a moderate beneficial effect of strength training on endurance performance. There seems to be a greater beneficial effect going under a HWT. Such improvements are not related to age of the participants, training status, or duration of the intervention.

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