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SYSTEMATIC REVIEW

The Effect of Strength Training on Performance in Endurance Athletes

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Abstract

Background Economy, velocity/power at maximal oxygen uptake ($\mathrm{v}\dot{V}\mathrm{O}_{2\,\max}/\mathrm{w}\dot{V}\mathrm{O}_{2\,\max}$) and endurance-specific muscle power tests (i.e. maximal anaerobic running velocity; vMART), are now thought to be the best performance predictors in elite endurance athletes. In addition to cardiovascular function, these key performance indicators are believed to be partly dictated by the neuromuscular system. One technique to improve neuromuscular efficiency in athletes is through strength training.

Objective The aim of this systematic review was to search the body of scientific literature for original research investigating the effect of strength training on performance indicators in well-trained endurance athletes—specifically economy, $\mathrm{v}\dot{V}\mathrm{O}_{2\,\max}/\ \mathrm{w}\dot{V}\mathrm{O}_{2\,\max}$ and muscle power (vMART).

Methods A search was performed using the MEDLINE, PubMed, ScienceDirect, SPORTDiscus and Web of Science search engines. Twenty-six studies met the inclusion criteria (athletes had to be trained endurance athletes with $\geq$6 months endurance training, training $\geq$6 h per week OR $\dot{V}\mathrm{O}_{2\,\max}$ $\geq$50 mL/min/kg, the strength interventions had to be $\geq$5 weeks in duration, and control groups used). All studies were reviewed using the PEDro scale.

Results The results showed that strength training improved time-trial performance, economy, $\mathrm{v}\dot{V}\mathrm{O}_{2\,\max}/\mathrm{w}\dot{V}\mathrm{O}_{2\,\max}$ and vMART in competitive endurance athletes.

Conclusion The present research available supports the addition of strength training in an endurance athlete's programme for improved economy, $\mathrm{v}\dot{V}\mathrm{O}_{2\,\max}/\mathrm{w}\dot{V}\mathrm{O}_{2\,\max}$, muscle power and performance. However, it is evident that further research is needed. Future investigations should include valid strength assessments (i.e. squats, jump squats, drop jumps) through a range of velocities (maximal-strength ↔ strength-speed ↔ speed-strength ↔ reactive-strength), and administer appropriate strength programmes (exercise, load and velocity prescription) over a long-term intervention period (>6 months) for optimal transfer to performance.

1 Introduction

Endurance sport performance relies on a complex interplay of physiological and biomechanical factors. Cardiovascular capacity has often been thought to be the main limiting factor in endurance performance. Classical measures such as maximal oxygen uptake ($\dot{V}\mathrm{O}_{2\,\max}$) and lactate threshold (LT) have been traditionally used in the laboratory to predict the performance potential of runners, cyclists, triathletes and cross-country skiers [1]. Consequently, physical preparation for these sports has generally focused on developing these two physiological qualities. However, elite endurance athletes with similar $\dot{V}\mathrm{O}_{2\,\max}$ levels can have differing abilities during a race and therefore maximum oxygen uptake cannot fully explain true racing ability. Economy, and assessments that include an endurance-specific muscle power component, such as velocity/power during maximal oxygen uptake ($\mathrm{v}\dot{V}\mathrm{O}_{2\,\max}/\mathrm{w}\dot{V}\mathrm{O}_{2\,\max}$) and maximal anaerobic running velocity (vMART), are now thought to be superior performance indicators in an elite population [2].

Economy is the amount of metabolic energy expended at a given velocity or power output [3]. Economical movement is multifactorial and is determined by training history, anthropometrics, biomechanics and physiology [4]. During

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a race, an economical athlete will use less energy at submaximal intensities, and spare vital carbohydrate stores for significant stages in competition (i.e. sprint finish). East Africans have dominated distance running for the past few decades and it is believed that their success is partly due to their superior running economy [3]. Improvements in economy may be difficult to obtain in highly-trained endurance athletes and therefore any novel training modality that results in marginal improvements may be crucial for success.

Endurance-specific muscle power is the ability of the neuromuscular system to rapidly produce force following a sustained period of high-intensity exercise (high glycolytic and/or oxidative energy demand) [5]. This ability may be the differentiating factor for elite endurance performance as successful athletes at world level can produce high velocities and power outputs to win a race following a sustained period of high-intensity exercise (i.e. sprint finish). Therefore, rate of force development (RFD) is essential not only in sprint and power sports, but also in elite endurance competition. Endurance-specific muscle power assessments, such as peak velocity during the maximal anaerobic running test (vMART), have been found to be better predictors of running performance in an elite population because they are both highly influenced by neuromuscular and anaerobic factors [2]. The vMART consists of a series of incremental 20 s runs with 100 s recoveries on a treadmill until volitional exhaustion [6]. Peak velocity/power at $\dot{V}O_{2\,\max}$ ($v\dot{V}O_{2\,\max}/w\dot{V}O_{2\,\max}$), is influenced by $\dot{V}O_{2\,\max}$, economy and LT. However, it is also shown to have a large 'muscle power' component because it is strongly correlated to vMART ($r = 0.85$; $p < 0.001$) [2]. McLaughlin et al. [7] found that in well-trained runners $v\dot{V}O_{2\max}$ was the best predictor of running performance over 16 km. Also, Millet et al. [8] found that peak power output during an incremental cycling test (W_{peak}) was correlated to overall performance in elite triathletes. Consequently, in addition to cardiovascular ability, limitations to elite endurance performance may be dictated by other dynamical system factors, including neuromuscular function.

One training technique for improving muscle force–velocity function in athletes is through strength training [9]. It is proposed that through neuromuscular adaptations (musculotendinous stiffness, motor unit recruitment and synchronization, rate coding, intra- and intermuscular coordination, and neural inhibition) strength training has the potential to improve performance in endurance athletes through increased economy and endurance-specific muscle power factors (i.e. vMART) [2]. Theoretically, a strength-trained endurance athlete will (1) be more economical as submaximal forces developed during each stride or pedal revolution would decrease to a lower percentage of maximal values, and (2) have improved endurance-specific muscle power as they are able to produce higher maximum running or cycling velocities through an improved ability to rapidly absorb and create force against the ground or pedal (Fig. 1).

Elite endurance athletes are renowned for their high volume of (low force) endurance training. Unfortunately, unlike strength training, specific endurance training such as 'interval' or 'tempo' sessions are not effective in improving neuromuscular function in well-trained endurance athletes (Fig. 1). Traditionally, for unknown reasons, endurance athletes have been cautious to strength train. In fact, research investigating the training characteristics of runners competing in the 2008 US Olympic Marathon trials found that they "included little strength training in their training programmes … and nearly half the runners did no strength training at all" [10]. This philosophy may be due to endurance athletes and coaches being uneducated in strength training science and the associated potential performance improvements. The aim of this systematic review was to search the body of scientific literature for original research investigating the effect of strength training on performance, specifically economy and assessments that included an endurance-specific muscle power component (i.e. $v\dot{V}O_{2\,\max}/\dot{V}O_{2\,\max}$, and vMART), in well-trained endurance athletes.

2 Methods

A search was performed using the MEDLINE, PubMed, ScienceDirect, SPORTDiscus and Web of Science search engines to identify studies that assessed the effect of strength training on performance in competitive endurance athletes. The following keywords were used in the search ('strength training' OR 'resistance training' OR 'weight training' OR 'weightlifting' OR 'concurrent training' OR 'plyometrics') AND ('endurance athletes' OR 'cyclists' OR 'runners' OR 'triathletes' OR 'cross-country skiers') AND ('performance'). Strength training was defined as non-cycling/running/cross-country skiing, weight-loaded activity including bodyweight, free-weight and machine-based exercises. The subcategories for strength training included (1) maximal-strength training that targets maximal force development through high-load, low-velocity movements (i.e. squats, deadlifts); (2) explosive-strength training (strength-speed and speed-strength) that improves RFD and maximal power output through medium- to high-load, high-velocity movements (i.e. squat jumps, Olympic lifts); and (iii) reactive-strength training that targets musculotendinous stiffness and stretch-shortening cycle (SSC) function through low-load, high-velocity exercises (i.e. jumps, drop jumps, hops, bounds, sprints).

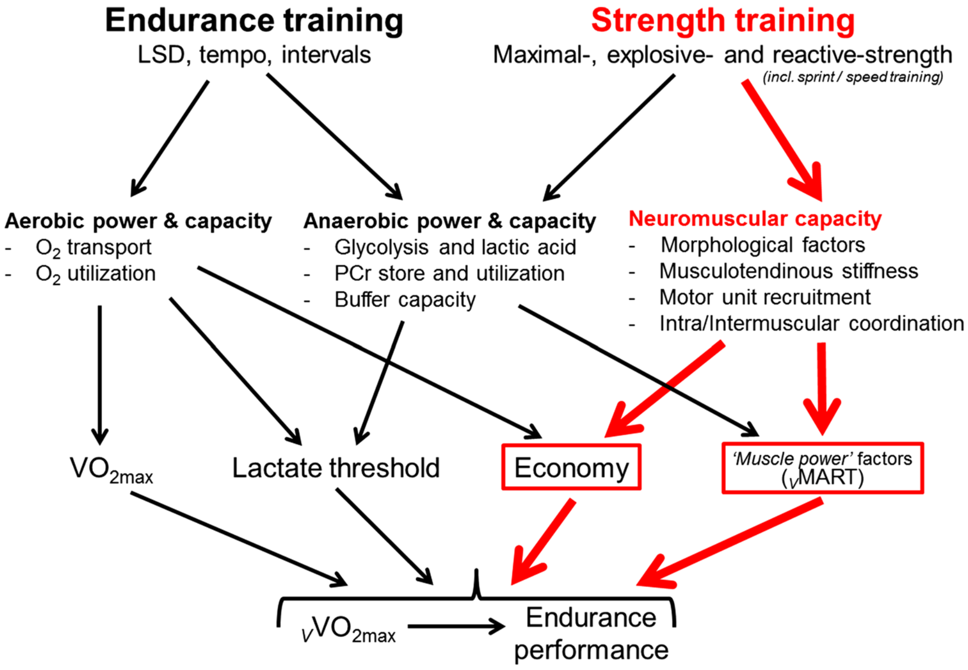

Fig. 1 Hypothetical model of the determinants for elite endurance performance and the potential benefits from strength training. *Red font* and *bold arrows* highlight the potential benefit of strength training on endurance performance (adapted from Paavolainen et al. [5], with permission). *LSD* long slow distance training, *intervals* repeated bouts of exercise lasting ~1 to 8 min and eliciting an oxygen demand equal to ~90 to 100 % of $\dot{V}O_{2\,max}$, *PCr* phosphocreatine, $\dot{V}O_{2\,max}$ maximal O$_2$ uptake, *vMART* peak velocity in maximal anaerobic running test, v$\dot{V}O_{2max}$ peak velocity at $\dot{V}O_{2\,max}$

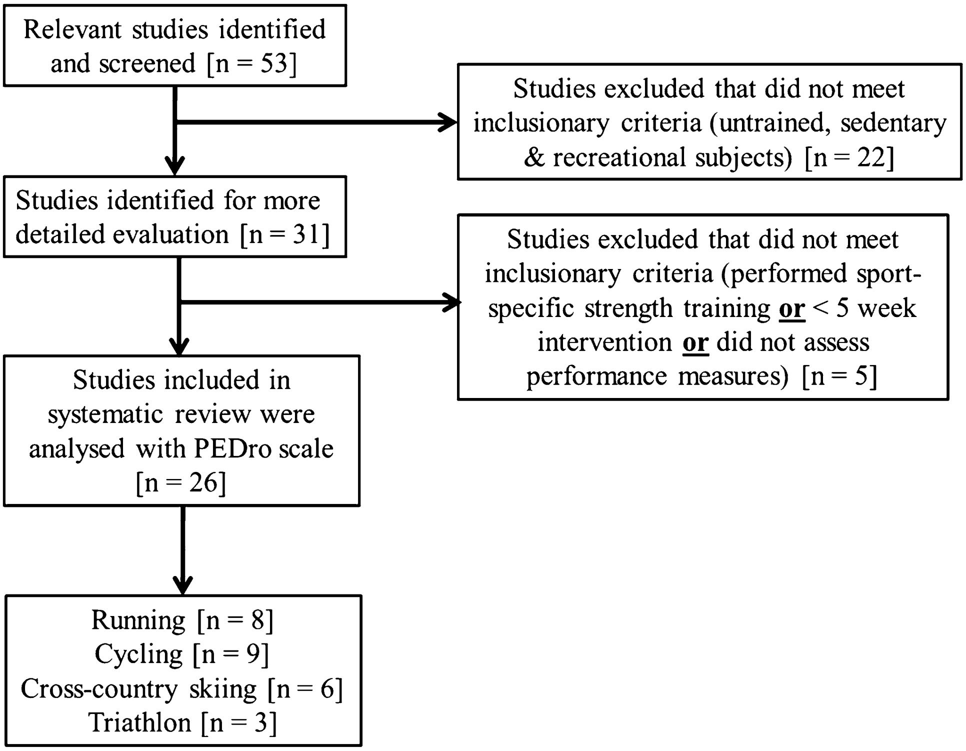

Fig. 2 PRISMA (Preferred Reporting Items for Systematic Reviews) flowchart illustrating the inclusion and exclusion criteria used in the systematic review. *PEDro* physiotherapy evidence database

Inclusion criterion for this analysis were (1) athletes had to be trained endurance athletes (≥6 months endurance training, training ≥6 h per week, $\dot{V}O_{2\,max}$ ≥50 mL/min/kg); (2) the strength interventions had to be ≥5 weeks in duration; and (3) control groups had to be used. All articles were read and the outcomes of each study summarized. Articles were excluded if the study methodology did not meet the specific inclusion criteria. Other relevant articles were obtained through additional bibliographical means (Fig. 2).

The Physiotherapy Evidence Database (PEDro) scale was used to rate the quality of the selected articles. The PEDro scale is an 11-item scale designed for rating the methodological quality of randomized controlled trials [11]. Each satisfied item (except for the first item, which relates to external validity) contributes 1 point to the total PEDro score [11]. The items include random allocation; concealment of allocation; comparability of groups at baseline; blinding of subjects, researchers, and assessors; analysis by intention to treat; and adequacy of follow-up. The PEDro scale ranges from 0 to 10, where 0 points (the worst possible score) are awarded to a study that fails to satisfy any of the included items, and 10 points (the best possible score) are awarded to a study that satisfies all the included items. Studies scoring 9 or 10 on the PEDro scale are considered to have methodologically excellent internal validity, those scoring 6 to 8 are considered good, those scoring 4 or 5 are fair, and those scoring less than 4 are poor. All studies graded using the PEDro scale were included.

3 Results

Twenty-six papers met the inclusion criteria. Of these papers, eight were from running, nine from cycling, six from cross-country skiing and three from triathlon. Tables 1, 2 and 3 compare the results. The tables are subdivided into the four sports (running, cycling, cross-country skiing and triathlon) and are structured to compare (1) subjects (sample size, sex, standard of racing, $\dot{V}O_{2\,\max}$, weekly training volume) and research design (PEDro score, group allocation, control of training) [Table 1]; (2) strength intervention (type of strength training, programme overview, frequency and duration of training (Table 2); and (3) results (Table 3).

3.1 Physiotherapy Evidence Database (PEDro) Score Analysis

Scores on the PEDro scale for the 26 selected articles ranged from 5 to 6 of a maximum 10 points. Only 14 studies randomly allocated their subjects into training groups and scored 6 out of 10 on the PEDro scale [12–25]. The additional 12 studies scored 5 out of 10: four studies did not mention randomized allocation of subjects [26–29] and four studies allowed the subjects to select their own groups [30–33]. Other studies allocated subjects into training groups by $\dot{V}O_{2\,\max}$ [34], $\dot{V}O_{2\,\max}$ and 5 km time-trial performance [5], mean training time [35], or by randomly allocating half of the subjects into groups and then the rest by age and 5 km time-trial performance [36].

3.2 Running (Time-Trial Performance, v$\dot{V}O_{2\,\max}$ and Economy)

In runners, improvements were found in time-trial performance, economy, v$\dot{V}O_{2\,\max}$ and vMART after a strength training intervention. The studies show that 8 weeks of explosive-strength training can improve 3 km time-trial performance [15], and reactive-strength training can significantly improve 5 km [5] ($p < 0.05$) and 3 km [13] ($p < 0.05$; effect size [ES] = 0.13) performance. Mikkola et al. [27] and Berryman et al. [15] both found an increase in v$\dot{V}O_{2\,\max}$ from 8 weeks of both reactive-strength and explosive-strength training. The two studies that assessed vMART both found a significant ($p < 0.01$) improvement following an 8-week [27] and 9-week [5] reactive-strength programme. Five studies found significant improvements in economy from both maximal- [12, 36] and reactive-strength training interventions [5, 13, 15].

3.3 Cycling (Time-Trial Performance, w$\dot{V}O_{2\,\max}$ and Economy)

In cyclists, 12–16 weeks of maximal-strength training was found to significantly improve 5 min [30] ($p < 0.01$) and 45 min time-trial performance [19] ($p < 0.05$; ES = 0.66). Improvements were also found in 40 min [31] and 60 min time-trial ability [35]; however, these improvements were not found to be significantly different to their allocated control groups. From the six cycling studies that analysed power at $\dot{V}O_{2\,\max}$ (w$\dot{V}O_{2\,\max}$), three found improvements [28, 30, 35], but only the work by Rønnestad et al. [28, 30] found a significant effect when compared against the control group ($p < 0.05$; ES = 0.81 [28], ES = 84 [30]). Bastiaans et al. [35] found significant improvements in 'delta efficiency' ($p < 0.05$; ES = 0.49), and Rønnestad et al. [30] showed improvements in economy and 'work efficiency' during the final 60 min of a 185 min cycle test ($p < 0.05$).

3.4 Cross-Country Skiing (Time-Trial Performance and Economy)

In cross-country skiers, Losnegard et al. [33] found a significant increase in a 1.1 km 'upper body double-poling' time trial ($p < 0.05$), as well as a non-significant improvement in a 1.3 km 'full-body roller ski' time trial from their strength training intervention. Mikkola et al. [26] also found a significant improvement in 2 km 'upper-body double-poling'; however, there was no significant difference in change between the control and the experimental group. Rønnestad et al. [32] found no improvement in 7.5 km 'full-body roller ski' time-trial performances. Improvements in economy were seen for both 'whole-body roller skiing' [32] ($p < 0.05$; ES = 0.77) and 'isolated upper-body double-poling' movements [21, 22, 26].

Table 1 Studies included in the meta-analysis: subjects and research design

Study	Subjects					Research design					
	n	Sex	Age (years)	$\dot{V}O_{2max}$ (mL/min/kg)	Level; weekly volume; duration of competitiveness	PEDro score	Assigned to group?	Intervention (*n*)	Control (*n*)	ET controlled?	ST replacement or addition?
Running											
Johnston et al. [12]	12	F	30.3	50.5	32–48 km/week for >1 year	6	RCT	6	6	Yes	Addition
Paavolainen et al. [5]	18	M	23	67.7	Elite cross-country	5	Matched with regard to VO_2 and 5 km TT	10	8	Yes	Replacement
Spurrs et al. [13]	17	M	25	57.6	Trained; 60–80 km/week for 10 years	6	RCT	8	9	Yes—monitored	Addition
Saunders et al. [14]	15	M	23.4	71.1	6 internationals, all national; 107 km/week	6	RCT	7	8	Yes—training duration matched	Addition
Mikkola et al. [27]	25	M and F	17	62.1	Post-pubertal, high-school runners	5	No mention of RCT	13	12	Yes—volume	Replacement
Støren et al. [36]	17	M and F	29.2	59.9	Trained	5	Half RCT, other half matched for 5 km and age	8	9	Yes—volume and intensity	Addition
Berryman et al. [15]	28	M	28	56.9	Provincial standard, 3–5 sessions per week	6	RCT	11 (reactive) 12 (explosive)	5	Yes—volume and intensity	Addition
Fletcher et al. [16]	12	M	24.3	67.5	Highly trained; 70–170 km/week	6	RCT	6	6	–	–
Cycling											
Bastiaans et al. [35]	14	M	25	–	6 ± 6 years competing	5	Matched for mean training time	6	8	Yes—HR and training zones	Replacement
Jackson et al. [17]	23	18 M, 5 F	30	52	≥0.5 years competing	6	RCT	High res 9, High rep 9	5	Yes—HR and training zones	Addition
Levin et al. [18]	14	M	31	62.75	≥1 years competing	6	RCT	7	7	Monitored but not controlled	Addition
Rønnestad et al. [30]	20	18 M, 2 F	28.5	66.35	Well-trained	5	Self-chosen	11	9	Yes—HR and training zones	Addition
Rønnestad et al. [31]	20	18 M, 2 F	28.5	66.35	Norwegian national level	5	Self-chosen	11	9	Yes—HR and training zones	Addition
Sunde et al. [34]	13	10 M, 3 F	32.85	61.05	Well-trained and competitive	5	Matched for $\dot{V}O_{2max}$	8	5	Yes—HR and training zones	Addition
Rønnestad et al. [28]	12	11 M, 1 F	30	66.25	Norwegian national level	5	–	6	6	Yes—HR and training zones	Addition
Aagaard et al. [19]	14	M	19.5	72.5	U23 international	6	RCT	7	7	Yes—HR and training zones	Addition

Table 1 continued

Study	Subjects					Research design					
	n	Sex	Age (years)	$\dot{V}O_{2max}$ (mL/min/kg)	Level; weekly volume; duration of competitiveness	PEDro score	Assigned to group?	Intervention (n)	Control (n)	ET controlled?	ST replacement or addition?
Rønnestad et al. [29]	27	25 M, 2 F	27.6	63.4	20 highly-trained, 7 recreational	5	–	11 (cyclists) 9 (recreational)	7 (cyclists)	Yes—HR and training zones	Replacement
Cross-country skiing											
Hoff et al. [20].	15	F	17.9	55.3	8.8 h/week	6	RCT	8	7	Yes	Replacement of strength-endurance
Hoff et al [21]	19	M	19.8	69.4	‘Well-trained’	6	RCT	9	10	Yes	Replacement of strength-endurance
Østerås et al. [22]	19	M	22.7	61.2	‘Highly trained’ >5 years	6	RCT	10	9	Yes	Replacement of strength-endurance
Mikkola et al. [26]	19	M	23.1	66.5	Finnish national (6–15 years)	5	–	8	11	–	Replacement
Rønnestad et al. [32]	17	M	19.5	66.2	National and international Nordic combined	5	No—self-selected	8	9	Yes	Replacement
Losnegard et al. [33]	19	M and F	21.5	64.7	National	5	No—self-selected	9	10	–	–
Triathlon											
Millet et al. [23]	15	–	22.85	68.7	20.4 h/week; elite/international	6	RCT	7	8	Yes—‘recorded’	Addition
Hausswirth et al. [24]	14	M	31.3	69.2	17.3 h/week; regional and national level	6	RCT	7	7	Yes—‘strictly aerobic, 75 % HR’	Addition
Bonacci et al. [25]	8	M and F	21.6	–	Competed for 4.4 years	6	RCT	3	5	No	Addition

Values are means except where stated otherwise

$\dot{V}O_{2max}$ maximal oxygen uptake, *PEDro score* physiotherapy evidence database score, *ET* endurance training, *ST* strength training, *RCT* randomized controlled trial, *TT* time trial, *high res* high resistance, *high rep* high repetition, *HR* heart rate, *M* male, *F* female

Table 2 Studies included in the meta-analysis: strength interventions

Study	Type	Programme overview/example	Closed-chain leg exercises?	Frequency	Duration (weeks)	Time of year
Running						
Johnston et al. [12]	Maximal-strength	3 × 6 RM (parallel squat, seated press, hammer curl, lung, heel-raise and bench press) 3 × 8 RM (knee flexion/extension, lateral pull-down and seated row) 2 × 20 RM (bent leg heel-raise), 2 × 12 RM (straight leg heel-raise) and 2 × 15 RM weighted sit-up	Yes—squat and lunge	3 × week	10	–
Paavolainen et al. [5]	Reactive-strength	Sprints and jumps Alternative jumps, bilateral countermovement, drop and hurdle jumps, 1-legged, 5 jumps	Yes—all reactive exercises	–	9	Off-season
Spurrs et al. [13]	Reactive-strength	W 1 60 contacts, W2 100, W3 136, W4 150, W5 170, W6 180 Plyo progression: squat jump, split scissor jump, double leg bound, SL hops, depth jump, DL hurdle hop, SL hurdle hop	Yes—all reactive exercises	W 1–3: 2 × week; W 4–6: 3 × week	6	–
Saunders et al. [14]	Reactive-strength	Session 1 (back extension, leg press, CMJs, knee lifts, ankle jumps, hamstring curls) Session 2 (bounds, skips, SL ankles, hurdle jumps, scissors for height)	Yes—all reactive exercises	3 × week	9	–
Mikkola et al. [27]	Reactive-strength	Sprints (5–10 × 30–150 m), pogos, squat jumps, half-squats, knee extensions, calf raises, curls (2–3 × 6–10 reps)	Yes—all reactive exercises	3 × week	8	Pre-competition
Støren et al. [36]	Maximal-strength	4 × 4 half-squats	Yes—squats	3 × week	8	–
Berryman et al. [15]	Reactive- and explosive-strength	Reactive group—drop jumps Explosive group—concentric squat jumps $P_{\max}$ load	Yes—drop jumps and concentric squats	1 × week	8	–
Fletcher et al. [16]	Maximal-/isometric-strength	4 × 20 s at 80 % MVC isometric plantar flexion	No—isolated isometric plantar flexion	3 × week	8	Pre-competition
Cycling						
Bastiaans et al. [35]	Muscular endurance	4 × 30 (squats, leg press, step-up) and 2 × 30 (leg pull and core)	Yes—squats and Smith machine step-ups	3 × week	9	Pre-season
Jackson et al. [17]	Muscular endurance and maximal-strength	Week 1—all 2 × 20, Week 2–10 high res (4 × 4 RM), high rep (2 × 20 RM) All squats, leg press, leg curl, Smith machine step-ups, planks	Yes—squats and Smith machine step-ups	3 × week	10	In-season
Levin et al. [18]	Maximal-strength, explosive-strength and muscular endurance	Strength 4 × 5 (lunges, squats, RDLs, calf raises crunches) Power 3 × 6 (jumps squats, SL jump squats, clean grip deadlift, calf raise back extension) Endurance 3 × 12 (SL leg press, knee extension, knee flexion, calf raise and crunches)	Yes—squats, lunges, RDLs, deadlifts etc	3 × week	6	Pre-season

Table 2 continued

Study	Type	Programme overview/example	Closed-chain leg exercises?	Frequency	Duration (weeks)	Time of year
Rønnestad et al. [30]	Maximal-strength	W 1–3: 10 RM session 1, 6 RM session 2 W 4–6: 8 RM and 5 RM W 7–12: 6 RM and 4 RM All half-squat Smith, SL leg press, hip flexion and toe raise	Yes—Smith squat	2 × week	12	Pre-season
Rønnestad et al. [31]	Maximal-strength	W 1–3: 10 RM session 1, 6 RM session 2 W 4–6: 8 RM and 5 RM W 7–12: 6 RM and 4 RM All half-squat Smith, SL leg press, hip flexion and toe raise	Yes—Smith squat	2 × week	12	Pre-season
Sunde et al. [34]	Maximal-strength	4 × 4 RM half-squats (Smith machine)	Yes—Smith squat	3 × week	8	Pre-season
Rønnestad et al. [28]	Maximal-strength	W 1–3: 10 RM session 1, 6 RM session 2 W 4–6: 8 RM and 5 RM W 7–12: 6 RM and 4 RM All half-squat Smith, SL leg press, hip flexion and toe raise W13–25 (season): 2 × 5 (half-squat and leg press) 1 × 6 (hip flexion and ankle plantar flexion)	Yes—Smith squat	2 × week	25	Pre-season prep (12 W) and in-season (12 W)
Aagaard et al. [19]	Maximal-strength	W1: 3 × 12, W2–3: 3 × 10, W4–5: 3 × 8, W6–16: 2–3 × 6 (knee extension, leg press, hamstring curl and calf raises)	No—all machine isolated	2–3 × week	16	–
Rønnestad et al. [29]	Maximal-strength	W 1–3: 10 RM session 1, 6 RM session 2 W 4–6: 8 RM and 5 RM W 7–12: 6 RM and 4 RM All half-squat Smith, SL leg press, hip flexion and toe raise	Yes—Smith squat	2 × week	12	–
Levin et al. [18]	Maximal-strength, explosive-strength and muscular endurance	Strength 4 × 5 (lunges, squats, RDLs, calf raises crunches) Power 3 × 6 (jumps squats, SL jump squats, clean grip deadlift, calf raise back extension) Endurance 3 × 12 (SL leg press, knee extension, knee flexion, calf raise and crunches)	Yes—squats, lunges, RDLs, deadlifts	3 × week	6	Pre-season
Cross-country skiing						
Hoff et al. [20]	Maximal-strength	Pull-downs—3 × 6 Increased by 1 kg every session (control group used their normal ‘strength-endurance’ programme <60 % 1 RM)	No	3 × week	9	Pre-season
Hoff et al. [21]	Maximal-strength	Pull-downs—3 × 6 Increased by 3 kg every session (control group used their normal ‘strength-endurance’ programme <85 % 1 RM)	No	45 min/ week	8	Pre-season

Table 2 continued

Study	Type	Programme overview/example	Closed-chain leg exercises?	Frequency	Duration (weeks)	Time of year
Østerås et al. [22]	Maximal-strength	Pull-downs—3 × 6 Increased by 3 kg every session (control group used their normal 'strength endurance' programme <85 % 1 RM)	No	45 min/week	9	Pre-season
Mikkola et al. [26]	Explosive- and reactive-strength	Day 1: Specific explosive - double poling sprints 10 × 10 s Day 2: General explosive—half-squat, pull over, leg press, lateral pull-down 3 × 6–10 Day 3: Reactive—running sprints, jumps, skating jumps, pogos 3–6 × 20 m	Yes	3 × week	8	–
Rønnestad et al. [32]	Maximal-strength	Deep squat: W1–6 (3–5 × 4–8), W7–12 (4–5 × 3–5) Seated pull-down: W1–6 (3 × 6–10), W7–12 (3 × 5–8) Standing double poling	Yes	2 × week	12	–
Losnegard et al. [33]	Maximal-strength	Half-squat, pull-down, seated pull-down, double poling, triceps press W1–3 (3 × 6–10), W4 (3 × 5–8), W5–8 (4 × 8), W9–12 (3 × 4–6)	Yes	2 × week (W1–8) 1 × week (W9–12)	12	Pre-season
Triathlon						
Millet et al. [23]	Maximal-strength	W1 3 × 5, W2 4 × 5, W3 5 × 5 Hamstring curl, leg press, seated press, parallel squat, leg extension and heel-raise	Yes—parallel squat	2 × week	14	Pre-season
Hausswirth et al. [24]	Maximal-strength	3–5 × 3–5 Leg press, leg extension, hamstring curl, calf raise	No	3 × week	5	Pre-season
Bonacci et al. [25]	Reactive-strength	CMJs, knee lifts, pogos, squats, bounds, skips, scissors etc.	Yes	3 × week	8	–

Values are means except where stated otherwise

CMJ countermovement jump, *DL* double leg, *W* week, *RM* repetition maximum, *RDLs* Romanian deadlifts, *SL* single-leg, *high res* high resistance, *high rep* high repetition, *MVC* maximum voluntary contraction, *reps* repetitions, *prep* preparation, P_{max} maximal power load

Table 3 Studies included in the meta-analysis: results

Study	Tests	Strength	Economy	$v\dot{V}O_{2\max}$[b]	vMART	TT	PP	TTE	Body composition/ other performance
Running									
Johnston et al. [12]	Squat, knee flexion, body composition, RE and $\dot{V}O_{2\max}$	↑ Squat (40 %), knee flexion (27 %) [$p < 0.05$][a]	(mL/kg/min) ↑ at 214 m/min (4 %) [ES = 0.72] and 230 m/min (ES = 0.64) [$p < 0.05$][a]	–	–	–	–	–	Increased body mass and fat-free mass (NS)
Paavolainen et al. [5]	5 km TT, ISO knee extension, $\dot{V}O_{2\max}$, LT, RE, vMART, $_v$20 m, 5BJ	↑ ISO MVC, $_v$20 m, 5BJ ($p < 0.01$)	(mL/kg/min) ↑ at 4.17 m/s (8.1 %) [$p < 0.001$]	– (used gradient)	↑ ($p < 0.01$)[a]	5 km (3.1 %) [$p < 0.05$]	–	–	Increased body mass, calf and thigh girth (NS)
Spurrs et al. [13]	RE, $\dot{V}O_{2\max}$, LT, MTS, ISO MVC, RFD, CMJ, 5BJ, 3 km TT	↑ ISO MVC (12.5 %) MTS @ 75 % MVC (12.9 %) RFD (14.5 %) CMJ (13.2 %) 5BJ (7.8 %) [$p < 0.05$]	(mL/kg/min) ↑ at 12 km/h (7.7 %; ES = 0.45), 14 km/h (6.4 %; ES = 0.45) and 16 km/h (4.1 %; ES = 0.3) [$p < 0.05$][a]	– (used gradient)	–	↑ 3 km (2.7 %; ES = 0.13)[a]	–		Increased body mass (NS)
Saunders et al. [14]	RE, $\dot{V}O_{2\max}$, 5CMJ, RFD	↑ 5CMJ (15 %) RFD (14 %) NS	(L/min) ↑ at 18 km/h (4.1 %) [$p = 0.02$; ES = 0.35][a] but NS at 14, 16 km/h	–	–	–	–		Increased body mass (NS)
Mikkola et al. [27]	ISO MVC, vMART, RE, 30 m, 5J, CMJ, $\dot{V}O_{2\max}$, $v\dot{V}O_{2\max}$	↑ ISO MVC (8 %) 1 RM leg extension (4%) RFD (31 %) [$p < 0.05$][a] No significant changes in CMJ and 5J	(mL/kg/min) ↑ at 12, 13 and 14 km/h NS	↑ 1.2 % NS	↑ 3 % ($p < 0.01$)	–	–		Increased lean body mass, calf and thigh girth (NS) ↑ V30m (1.1 %) [$p < 0.05$]

Table 3 continued

Study	Tests	Strength	Economy	v$\dot{V}O_{2\max}$ [b]	vMART	TT	PP	TTE	Body composition/ other performance
Støren et al. [36]	1 RM half-squat, RFD, RE, TTE at MAS	↑ 1 RM (33.2 %), RFD (26 %) of half-squat ($p < 0.01$)	(mL/kg$^{0.75}$/min) ↑ at 70 % $\dot{V}O_{2\max}$ (5 %) [$p < 0.01$; ES = 1.03]^{a}	– (used gradient)	–	–		↑ TTE at MAS (21.3 %) [$p < 0.05$]^{a}	Increased body mass (NS)
Berryman et al. [15]	$\dot{V}O_{2\max}$, $_{v}VO_2$, economy, P_{peak}, 3 km TT, RE	↑ P_{peak} (W) in both reactive and explosive group ($p < 0.01$)	(mL/kg$^{0.75}$/min) ↑ in both reactive (ES = 0.96) and explosive (ES = 0.63) groups ($p < 0.01$)	↑ in both reactive (ES = 0.49) and explosive (ES = 0.43) groups ($p < 0.01$)	–	↑ 3 km TT In reactive (ES = 0.46) and explosive (ES = 0.37) [$p < 0.05$]	–		No changes in body mass
Fletcher et al. [16]	$\dot{V}O_{2\max}$, LT, RE, ISO TST	No improvement ISO TST	(kJ/kg/km) No improvement	– (used gradient)	–	–	–	–	
Cycling									
Bastiaans et al. [35]	60 min TT, incremental $W_{\max}$, DE and 30 s power	–	(Delta efficiency) ↑ 1.41 % ($p < 0.05$; ES = 0.49)	↑ $W_{\max}$ 4.7 % ($p < 0.01$; ES = 0.64)^{b}		(60 min TT) ↑ 7.9 % ($p < 0.01$; ES = 0.86)^{b}	–	–	All groups ↑ (NS)
Jackson et al. [17].	Squats, leg curls, SL press, step-ups, $\dot{V}O_{2\max}$	–	– (only examined peak economy at $\dot{V}O_{2\max}$)	NS		No mean change over 30-km test	–	–	–
Levin et al. [18]	30-km test (with 250 m and 1 km power), 1 RM squat and $\dot{V}O_{2\max}$	↑ 1 RM squat NS	–	↓		No mean change over 30-km test	No significant difference except for last 1 km sprint of 30-km test ($p < 0.05$; ES 0.3)		Increased body mass (NS)
Rønnestad et al. [30]	1 RM half-squat Smith, $\dot{V}O_{2\max}$, 185 min at 44 % $W_{\max}$ + 5 min TT	↑ 1 RM half-squat Smith (26 %) [$p < 0.01$]	(mL/kg/min) ↑ ($p < 0.05$) economy during 185 min at 44 % $W_{\max}$, ↑ during final 60 min ($p < 0.05$)^{a}	↑ $W_{\max}$ (4.2 %) [$p < 0.05$]^{a}		(5 min TT) ↑ power 7 % ($p < 0.01$)	–		Increased body mass (NS) Increased knee flexors/ extensors CSA

Table 3 continued

Study	Tests	Strength	Economy	v$\dot{V}O_{2max}$[b]	vMART	TT	PP	TTE	Body composition/other performance
Rønnestad et al. [31]	Muscle CSA, ISO half-squat, $\dot{V}O_{2max}$, Wingate, 40 min TT	↑ ISO strength (21.2 %) [$p < 0.01$]	–	↑ W_{max} (4.3 %) [$p < 0.05$; ES = 0.44]		(40 min TT) ↑ power (6 %) [$p < 0.01$; ES = 0.57][a]	(30 s Wingate PP) ↑ (9.4 %) PP ($p < 0.01$; ES 0.61)		↑ TTE at maximal aerobic power ($p < 0.05$; ES 0.57)[a] Increased body mass (NS)
Sunde et al. [34]	Smith squat 1 RM, RFD, WE at 70 % $\dot{V}O_{2max}$, TTE, $\dot{V}O_{2max}$, LT	↑ 1 RM Smith squat (14.2%) ↑ RFD Smith squat (16.2 %) [$p < 0.05$]	↑ (WE) [4.7 %] ($p < 0.05$; ES = 0.48)[a] and (mL/kg$^{0.67}$/W) ↑ (3 %) at 70 % $\dot{V}O_{2max}$ ($p < 0.05$; ES = 0.56)	–		–	–		Increased knee extensor/flexor CSA ($p < 0.05$)
Rønnestad et al. [28]	Muscle CSA, half-squat, $\dot{V}O_{2max}$, Wingate, 40 min TT	↑ 1 RM half Smith squat (23 %) 12 weeks and was maintained to 25 weeks ($p < 0.01$)	–	↑ W_{max} (8 %) [$p < 0.05$; ES = 0.81]		–	(Wingate PP) ↑ PP ($p < 0.05$; ES = 0.67)[a]		No change in muscle CSA
Aagaard et al. [19]	ISO knee extensor MVC, RFD, 45 min TT	↑ ISO MVC (12 %) [$p < 0.05$] and RFD (20 %) [$p < 0.01$]	(mL/J) No change in strength group	–		(45 min TT) ↑ 8 % ($p < 0.01$; ES = 0.66)			Reduce freely chosen cadence Increased patellar tendon CSA
Rønnestad et al. [29]	$\dot{V}O_{2max}$, 1 RM Smith half-squat, 5 min at 125 W for VO_2	↑ 1 RM Smith squat (31 %) [$p < 0.01$]	(mL/kg/min) ↑ economy at 125 W but NS	–		–			All groups ↑ (NS)

Table 3 continued

Study	Tests	Strength	Economy	v$\dot{V}O_{2\max}$ [b]	vMART	TT	PP	TTE	Body composition/ other performance
Cross-country skiing									
Hoff et al. [20]	1 RM DP pull-down, peak force and RFD at 80 and 60 % 1 RM, $\dot{V}O_{2\max}$ (running), $VO_{2\text{ peak}}$ upper body 'poling', TTE upper, economy at max	↑ 1 RM, time to peak force at 80 % 1 RM ($p < 0.05$)	[UB DP (mL/ kg$^{0.67}$/m)] ↑ ($p < 0.001$)[b]	– (UB DP $\dot{V}O_{2\max}$)	–	–	–	↑ TTE ($p < 0.001$)	
Hoff et al. [21]	1 RM DP pull-down, peak force and RFD @ 80 and 60 % 1 RM, $\dot{V}O_{2\max}$ (running), $VO_{2\text{ peak}}$ upper body 'poling', TTE upper, economy at max	↑ 1 RM (9.9 %), peak force at 80 % (34 %) and 60 % (33 %) 1 RM ($p < 0.05$)	[UB DP (mL/ kg$^{0.67}$/m)] ↑1t 1.81 m/min ($p < 0.05$)	– (UB DP $\dot{V}O_{2\max}$)	–	–	–	↑ TTE (56 %) at $VO_{2\text{ peak}}$ velocity ($p < 0.05$)	
Østerås et al. [22]	1 RM 'ski pull-down' F-V, P-V at various loads $VO_{2\text{ peak}}$, TTE	↑ power and velocities at each load (except lowest) [$p < 0.01$]	[UB DP (mL/kg$^{0.67}$/min)] ↑ double poling at pre-test $VO_{2\text{ peak}}$ force ($p < 0.01$; ES = 1.66)	– (UB DP $\dot{V}O_{2\max}$)	–	–		↑ TTE at $\dot{V}O_{2\max}$ velocity ($p < 0.05$; ES = 1.18)	
Mikkola et al. [26]	Leg extensor ISO and concentric force–time, 30 m double poling with roller skis, Velocity and economy 2 km UB double poling, $\dot{V}O_{2\max}$ (walking with poles), MAST	↑ leg extensor ISO and CON NS	[UB DP (mL/kg/min)] ↑ during constant velocity 2 km (7 %) [$p < 0.05$]	– (walking $\dot{V}O_{2\max}$ with poles)	–	No change 2 km UB poling velocity	–		Increased lean body mass, ↑ 30 m (1.4 %) double poling ($p < 0.05$)
Rønnestad et al. [32]	1 RM squat, pull-down, squat jump height, $\dot{V}O_{2\max}$ roller ski, economy, 7.5 km TT	↑ 1 RM squat (12 %), pull-down (23 %), squat jump (8.8 %) [$p < 0.01$]	[Roller ski (mL/kg/min)] ↑ at 5° (3.8 %) [$p < 0.05$; ES = 0.77][a] but no change at 4°	–	–	No change roller ski 7.5 km TT	–		Increased vastus lateralis thickness ($p < 0.05$) No change in body mass

Table 3 continued

Study	Tests	Strength	Economy	v$\dot{V}O_{2max}$ [b]	vMART	TT	PP	TTE	Body composition/ other performance
Losnegard et al. [33]	1 RM half-squat and seated pull-down, CMJ, $\dot{V}O_{2max}$ roller ski	↑ 1 RM half-squat (12 %), pull-down (19 %) [$p < 0.01$] No change in CMJ	[Roller ski (mL/kg/min)] unchanged in both groups	–	–	↑ UB 1.1 km TT (7 %) [$p < 0.05$] but NS roller ski 1.3 km TT (3.7 %)	–		No change in 20, 40, 80 and 100 m velocity, ↑ 5 min W/kg double-poling ($p < 0.05$) No change in quadriceps CSA
Triathlon									
Millet et al. [23]	Concentric half-squat and heel raise, 10 s hopping and limb stiffness Running analysis: $\dot{V}O_{2max}$ and $_{\mathrm{v}}\dot{V}O_{2max}$ on track, economy at 25 and 75 % $_{\mathrm{v}}VO_2$ during ×3 km, VO_2 kinetics	↑ 1 RM half-squat and heel raise ($p < 0.01$) ↑ hopping height and power ($p < 0.05$) Hopping stiffness not different	(mL/kg/min) ↑ at 25 % (ES 1.15) and 75 % (ES = 1.14) $_{\mathrm{v}}VO_2$ during 3 km ($p < 0.05$)	↑ ($p < 0.01$; ES = 0.55)	–	–	–	–	No change in VO_2 kinetics No change in body mass
Hausswirth et al. [24]	1 RM leg press, ISO knee extension Cycling analysis: $\dot{V}O_{2max}$, $_{\mathrm{P}}\dot{V}O_{2max}$, gross efficiency	↑ 1 RM leg press (6.6 %) [$p < 0.01$] ↑ ISO knee but NS	No differences in gross efficiency	Remain unchanged	–	–	–	–	No change in body mass

Table 3 continued

Study	Tests	Strength	Economy	$v\dot{V}O_{2\max}$ [b]	vMART	TT	PP	TTE	Body composition/ other performance
Bonnacci et al. [25]	Running analysis: economy, EMG (for muscle recruitment patterns running after cycling)	No tests for strength	12 km/h NS	–	–	–	–	–	Bike to run testing protocol No change in body mass, thigh or calf girth

Values are means except where stated otherwise

$\dot{V}O_{2\,max}$ maximal oxygen uptake, ↑ improved, *ES* effect size, *NS* no significant difference between strength group pre- and post-test, *TT* time trial, *RE* running economy, *LT* lactate threshold, *vMART* peak velocity in maximal anaerobic running test, $v\dot{V}O_{2\,max}$ peak velocity at $\dot{V}O_{2max}$, $w\dot{V}O_{2max}$ peak power at $\dot{V}O_{2\,max}$, *MVC* maximum voluntary contraction, *RFD* rate of force development, *CMJ* countermovement jump, *5BJ* 5 broad jump test, *ISO* isometric, *MAS* maximum aerobic speed, *MTS* musculotendinous stiffness, *TTE* time to exhaustion, *CON* concentric, *DE* delta economy, *DP* double-poling, *F-V* force-velocity assessment, *SL* single-leg, *CSA* cross-sectional area, *PP* peak power, P_{peak} peak power (strength assessment), *P-V* power-velocity assessment, *MAST* maximal anaerobic ski test, *TST* triceps surae tendon stiffness, *RM* repetition maximum, *UB* upper body, *W* week, *WE* work economy, W_{max} maximum power at $\dot{V}O_{2\max}$, *5CMJ* 5 countermovement jump test, *5J* 5 broad jump test

[a] Significant difference between strength group pre-and post-test only

[b] Except for cycling studies, for which the parameter is $w\dot{V}O_{2\max}$

3.5 Triathlon ($v\dot{V}O_{2max}$, $w\dot{V}O_{2max}$ and Economy)

In triathletes, Millet et al. [23] found a significant increase in peak treadmill velocity at $\dot{V}O_{2max}$ ($p < 0.01$; ES = 0.55) following a maximal-strength training intervention, whereas Hausswirth et al. [24] found no difference in $w\dot{V}O_{2max}$ during a cycling protocol. Out of the three studies that investigated running economy in triathletes, only Millet et al. [23] found significant improvements at 25 % ($p < 0.05$; ES = 1.15) and 75 % $w\dot{V}O_2$ ($p < 0.05$; ES = 0.14).

4 Discussion

Despite the abundance of studies investigating concurrent strength and endurance training, relatively few have examined well-trained endurance athletes. This systematic review is unique due to the focused analysis of strength training on specific performance indicators (economy, $v\dot{V}O_{2\,max}/w\dot{V}O_{2\,max}$, vMART and time trials) in well-trained runners, cyclists, triathletes and cross-country skiers.

4.1 Strength Diagnostics

As expected, the majority of the reviewed studies demonstrated an improvement in muscle force–velocity characteristics following a strength intervention [5, 12, 13, 15, 17, 19–22, 27, 28, 31–34, 36]. However, it is important to highlight that there were a wide variety of exercises administered throughout the literature to measure maximal-, explosive- and reactive-strength adaptations. Running, cycling, triathlon and cross-country skiing all require the hip, knee and ankle musculature to work in unison to produce force against the ground or pedal. A valid strength test for these sports would measure the force capabilities of the leg extensors in the same way—through closed-chain, multi-joint exercises such as squats, jump squats or drop jumps [37]. However, some studies in this review [5, 19, 24, 27] assessed strength ability through open-chain, isolated exercises (i.e. knee extension, leg press). Testing force production in an isolated manner may have reduced the validity of the overall force capabilities of the endurance athlete's leg musculature. Another criticism is that most studies only measured force output in one or two velocity ranges, either through low-velocity (one repetition maximum) or high-velocity (unloaded jumps and hops) exercises. It is important to measure force output through a range of velocities to determine maximal-, explosive- (strength-speed and speed-strength) and reactive-strength ability [38]. Assessing force capabilities with valid exercises through a range of velocities would highlight sensitive changes in strength qualities following an intervention period, and allow for a more accurate relationship between strength adaptation and endurance performance.

4.1.1 *Reactive-Strength Diagnostics in Runners and Triathletes*

Runners and triathletes need to have proficient eccentric muscular capabilities to rapidly absorb and utilize the elastic energy produced during each ground contact. The short ground contact phase in running is the only phase in which a runner or triathlete can produce force and influence running velocity. Paavolainen et al. [5] demonstrated the importance of reactive-strength by finding a strong relationship between ground contact time and running economy ($r = 0.64$; $p < 0.001$). Reactive-strength is affected by musculotendinous stiffness and SSC function [39]. Schmidtbleicher [40] demonstrated that the SSC can be classified as either slow or fast. Fast SSC is characterized by short contact times (<0.25 s) and small angular displacement of the hip, knee and ankle joint; whereas slow SSC involves longer contact times (>0.25 s) and larger angular joint displacements. Unfortunately, the running and triathlon studies in the current review did not take into consideration fast or slow SSC function and only assessed reactive-strength through 'general' reactive-strength measurements such as countermovement jumps [13, 27], broad jumps and hopping tests [5, 13, 14, 23]. The 'reactive-strength index' (RSI) is a popular assessment used by strength and conditioning coaches to examine the relationship between force production and ground contact time through a series of drop jumps at differing heights [41]. The RSI test may have been a more appropriate and sensitive assessment to track reactive-strength adaptations and transferability to running and triathlon performance.

4.2 Time-Trial Performance

In well-trained endurance athletes, the current literature indicates that strength training can significantly improve 3 km [13] ($p < 0.05$; ES = 0.13) and 5 km [5] ($p < 0.05$) time-trial performance in runners, 5 min [30] ($p < 0.01$) and 45 min time-trial performance [19] ($p < 0.05$; ES = 0.66) in cyclists, and 1.1 km 'upper body double-poling' time-trial performance in cross-country skiers ($p < 0.05$). However, it is important to note that elite endurance racing success is not dictated by average velocity or power output over a set distance and therefore time-trial ability is not a 'true' reflection of racing performance [42]. Further analysis of economy and assessments that include an endurance-specific muscle power component (i.e. $v\dot{V}O_{2\,max}/\dot{V}O_{2\,max}$, and vMART) may add to the potential beneficial effect of strength training on performance in well-trained endurance athletes.

4.3 Economy

Economy is represented by energy expenditure and is normally expressed as submaximal $\dot{V}O_2$ at a given velocity or power output. It is now established that economy is a critical factor for success in elite endurance sport [43]. The present research shows that there were significant improvements in economy from both maximal- [12, 36] and reactive-strength training interventions [5, 13, 15] in well-trained runners. This supports Noakes' [44] philosophy that runners with poor economy may lack musculotendinous stiffness and therefore strength training may improve the ability of the leg musculature to rapidly absorb and utilize the elastic energy produced during each ground contact. Also in cyclists, the literature shows that strength training significantly improved 'delta efficiency' [35] ($p < 0.05$; ES = 0.49), economy during the final 60 min of a 185 min cycle test [30] ($p < 0.05$) and 'work efficiency' [34]. In cross-country skiers, improvements in economy were found in both 'whole-body roller skiing' [32] ($p < 0.05$; ES = 0.77) and 'isolated upper-body double-poling' movements [21, 22, 26]. Out of the three studies that investigated running economy in triathletes, only Millet et al. [23] found significant increases at 25 % ($p < 0.05$; ES = 1.15) and 75 % $v\dot{V}O_2$ ($p < 0.05$; ES = 0.14).

Interestingly, improvements in economy were found to be velocity-specific in runners. Spurrs et al. [13] found a 6.7 % and 6.4 % significant increase at both 12 km/h (ES = 0.45) and 14 km/h (ES = 0.45), but only a 4.1 % increase at 16 km/h ($p < 0.05$; E = 0.3). Furthermore, Saunders et al. [14] only found a significant improvement at 18 km/h in elite international runners ($p = 0.02$; ES = 0.35), with no change at 14 and 16 km/h. This supports Berg's [45] view on adaptation specificity that marathoners may be more economical at marathon pace than 800 and 1,500 m specialists, whereas middle distance runners may be more efficient at higher velocities. Consequently, the most valid measurement of economy may be at specific race velocities and power outputs, rather than an arbitrary submaximal intensity which is commonly used. Future researchers should take this into consideration when assigning velocities for economy assessment.

4.4 Endurance Muscle Power

Endurance-specific muscle power is the ability of the neuromuscular system to rapidly produce force following a sustained period of high-intensity exercise (high glycolytic and/or oxidative energy demand) [5]. This combined neuromuscular and anaerobic ability may be the differentiating factor for elite endurance performance as successful athletes at world-level can produce high velocities and power outputs to win a race following a sustained period of high-intensity exercise [46] (i.e. sprint finish). As illustrated in Fig. 1, $v\dot{V}O_{2\,max}$ is not only dictated by $\dot{V}O_{2\,max}$, LT and economy, but also by muscle power factors (neuromuscular and anaerobic ability). Noakes [47] originally suggested that velocity at $\dot{V}O_{2\,max}$ ($v\dot{V}O_{2\,max}$) could be used as a potential measure of muscle power in runners. From this review, only Mikkola et al. [27] and Berryman et al. [15] assessed $v\dot{V}O_{2\,max}$. Both researchers found an increase in $v\dot{V}O_{2\,max}$ after an 8-week reactive-strength programme, with only the latter study showing a significant effect from both reactive-strength ($p < 0.01$; ES = 0.49) and explosive-strength ($p < 0.01$; ES = 0.43) programmes. From the six cycling studies that analysed power at $\dot{V}O_{2max}$ ($w\dot{V}O_{2max}$), three found improvements [28, 30, 35], but only the work by Rønnestad et al. [28, 30] found a significant effect when compared against the control group ($p < 0.05$; ES = 0.81 [28], ES = 84 [30]). In triathletes, Millet et al. [23] established a significant increase in peak treadmill velocity at $\dot{V}O_{2max}$ ($p < 0.01$; ES = 0.55), whereas Hausswirth et al. [24] found no difference in $w\dot{V}O_{2max}$ during a cycling protocol.

Conversely, Paavolainen et al. [2] argue that the aerobic system is still strongly involved during a $\dot{V}O_{2max}$ test, and $v\dot{V}O_{2max}/_{w}\dot{V}O_{2max}$ should not be used as a pure measure of endurance-specific muscle power performance. The vMART (peak velocity attained during a maximal anaerobic running test), which consists of a series of incremental 20 s sprints on a treadmill until exhaustion, is believed to place more emphasis on assessing neuromuscular and anaerobic performance. The two running studies that assessed vMART in this review both found a significant ($p < 0.01$) improvement following an 8-week [27] and 9-week [5] reactive-strength programme.

4.5 Intervention Analysis

4.5.1 Programme Duration

Aside from Rønnestad et al.'s [28] strength intervention lasting 25 weeks, the average intervention period in this review was approximately 10 weeks. Much of what we know about neurological and structural adaptations in strength training derives from similar short-term (8–12 week) interventions involving relatively untrained or inexperienced subjects [48]. There are only a few studies investigating the long-term strength adaptations in well-trained athletes; however, these are from strength and power sports [49]. Future research in well-trained endurance athletes should focus on long-term strength interventions (12–18 months) and subsequent endurance performance.

4.5.2 Exercise Prescription

There were a variety of strength programmes administered in all of the 26 investigations. The two main distinctions in the interventions are in the prescription of exercises and loads and velocities of exercises (see Sect. 4.5.3). ‘Transfer of training’ is a term used to describe the effectiveness of adaptations from a strength exercise transferring to sporting performance [50]. The ability to generate force is dependent on the limb and joint positioning of the leg extensors [51]. Therefore, the exercises selected in a programme can influence the magnitude of neuromuscular adaptations, strength gains and potential improvements in endurance performance. A large portion of the strength exercises used in both the cycling [17, 19, 28–31] and running literature [12, 16] were open-chain, isolated and machine-based exercises (i.e. leg extension, seated hamstring curl, leg press, isometric plantar flexion). Stone and Stone [50] state that strength programmes dominated by open-chain exercises may not provide adequate movement pattern specificity for optimal performance improvements in closed-chain sporting movements (i.e. running). As previously discussed, endurance sports require the hip, knee and ankle joint musculature to work in unison to produce force against the ground or pedal and provide locomotion. As a result of decreased mechanical specificity, the transferability of these strength exercises to performance may have been reduced. Although running can contain a combination of both open- and closed-chain movements, it is the closed-chain phase where force is produced against the ground to provide locomotion. Also, Stensdotter et al. [52] demonstrated that there can be varying muscle activation patterns when an isolated, open-chain quadriceps exercise is compared with a multi-joint, closed-chain quadriceps exercise. These intra- and inter-muscular differences in exercises may complicate the learning and neural effects in the transfer of training process. Traditional multi-joint strength exercises, whether they are maximal-strength (i.e. squats, deadlifts and single-leg equivalents), explosive-strength (i.e. jump squats, Olympic lift variations) or reactive-strength exercises (i.e. drop jumps, sprints), are believed to be superior for eliciting optimal neuromuscular adaptations and increasing the force capabilities of the leg musculature [50]. Future studies investigating the effect of strength training in endurance sports should programme these functionally superior exercises.

4.5.3 Load and Velocity Prescription

There are three main types of strength training: maximal-strength, explosive-strength (strength-speed and speed-strength) and reactive-strength training. Each can be categorized by velocity of the movement [38]. All types of strength training were used in this review: reactive-, [5, 13–15, 27] explosive- [15] and maximal-strength-orientated programmes [12, 16, 17, 19, 28–31, 34, 36]. Others used a mixed approach with no emphasis on a specific strength quality [17, 18, 35]. A strength programme should be tailored to the current strength level of the athlete and should evolve as they increase their force capabilities. Programming for a weak, or neuromuscular inefficient, athlete can be completely different (exercise, load, velocity, volume and frequency) to a strong athlete. Continual improvements in strong athletes require the development of programmes that target a specific strength quality (maximal-strength, strength-speed, speed-strength, and reactive-strength) in the force–velocity relationship [51]. In contrast, athletes with low levels of strength, even though they may be a well-trained endurance athlete, can display improvements in neuromuscular function and force production from relatively non-specific and general strength programmes [53]. This could be an explanation for why there were significant improvements in running economy from all three types of strength training: reactive-, [5, 13, 15] explosive- [15] and maximal-strength interventions [12, 36]. However, future studies that investigate longitudinal strength adaptations in endurance athletes should consider specifically prescribed programming for long-term gains.

Research in untrained subjects has shown that the neuromuscular adaptations from general strength training can result in a shift of the force–velocity curve in which force production is greater at any given velocity [54]. Recent work from Cormie et al. [53] found that in weak subjects, maximal-strength training not only improved the maximal force capabilities of the leg extensors, but the programme was also as effective as an explosive-strength programme in improving maximal power output. Further research from Dymond et al. [55] found that subjects with higher levels of relative maximal-strength demonstrated superior reactive-strength ability. The work of Dymond et al. [55] supports anecdotal evidence that reactive-strength, specifically the slow SSC (i.e. a countermovement jump), can be improved in non-strength-trained individuals following a period of maximal-strength training. In weak endurance athletes, especially where long-term improvements are the goal, a maximal-strength-emphasized programme may initially be an efficient and effective training modality for improving several strength qualities together. Thus, weak endurance athletes may not necessarily need to place focus on explosive- or reactive-strength training until a solid foundation of relative maximal-strength and neuromuscular efficiency is obtained. Nonetheless, reactive-strength can still be trained in low volume and supplemented alongside a maximal-strength orientated programme (i.e. basic plyometric progressions, stiff-leg pogos), and emphasis towards strength specificity can shift as the athlete enhances their neuromuscular ability.

4.5.4 The Interference Effect

As illustrated in Fig. 1, appropriate strength training improves neuromuscular capacity, whereas endurance training targets both aerobic and anaerobic energy systems. However, recent molecular physiology research is starting to explain the intracellular signalling networks mediating exercise-induced skeletal muscle adaptations to both strength and endurance training stimuli. Simultaneously training for both strength and endurance may result in an acute compromised adaptation when compared with single-mode training [56]. Strength training can activate the phosphatidylinositol 3-kinase (PI3-k)-Akt-mammalian target of rapamycin (mTOR) signalling pathway that regulates the rate of protein synthesis and, over a prolonged period of time, muscle hypertrophy. Whereas endurance training activates another signalling cascade, the adenosine-monophosphate-activated protein kinase (AMPK)-p38 mitogen-activated protein kinase (MAPK)-peroxisome proliferator-activated receptor-gamma coactivator (PGC)-1 axis pathway. However, the activation of AMPK from the endurance training stimulus may interfere with, and inhibit, the mTOR signal for strength training-induced muscle protein synthesis [56]. In short, an endurance-specific training session (i.e. long slow distance training, tempo, interval) may inhibit the signalling pathway for optimal neuromuscular adaptation from the strength training stimulus. Nonetheless, molecular research in the area is in its infancy and there is much work to be undertaken before the information can be directly applied to the physical preparation of endurance athletes. Still, it is important that coaches are aware of the potential compromised adaptations when periodizing strength sessions in an endurance athlete's programme.

5 Conclusion and Future Directions

The present research available suggests the inclusion of strength training in an endurance athlete's programme for improved economy, muscle power and performance. It is important that future researchers and coaches are aware that muscular force–velocity adaptations are dependent upon the duration of the strength programme, the current strength-level of the athlete and the exercises administered (including the velocity and loads of the exercises). For long-term improvements in weak (neuromuscular inefficient) or non-strength trained endurance athletes, the present literature demonstrates that a general maximal-strength orientated programme may initially be the most appropriate and efficient method for improving maximal force, power and reactive-strength capabilities. Endurance athletes with high-force capabilities may need to place a greater emphasis on specific explosive- and reactive-strength training to gain further improvements in performance. However, it is evident that further research is needed in this area. Future investigations should include valid strength assessments (i.e. squats, jump squats, drop jumps) through a range of velocities (maximal-strength ↔ strength-speed ↔ speed-strength ↔ reactive-strength), and administer appropriate programming (exercise, load and velocity prescription) over a long-term intervention period (>6 months) for optimal transfer to performance.

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