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Original Article

The effects of strength training on distance running performance and running injury prevention

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Abstract
Introduction: From recreational to elite runners, strength training has become a popular addition to distance running training programs to improve performance and prevent running-related injuries. However, some incompatibilities exist between aerobic endurance training and strength training, including muscle hypertrophy and mitochondrial and capillary densities. Although our knowledge of the independent effects of aerobic endurance training and strength training date back a long time, our knowledge of the effects of strength training on aerobic endurance performance is still young. **Purpose:** To bring greater clarity of the subject of strength training for distance running performance and running injury prevention to runners, coaches, clinical practitioners, and the scientific community, this comprehensive literature review offers a critical narrative summary of the research on strength training and distance running performance and running injury prevention and includes several important directions for future research. **Methods:** All English-language published studies on the effects of strength training on distance running performance and the effects of strength training on distance running injury prevention were found using PubMed and Google Scholar databases. All studies were eligible for selection, as long as the intervention included some type of strength training using various loads and reps/sets combinations and the dependent variable was either running performance, physiological factors related to running performance, or prevalence of distance running-related injury. **Results and Conclusions:** Strength training, either with heavy loads (≥ 90% 1-rep max) or with explosive movements, has been shown to have a small, positive effect on running economy, laboratory measures of performance (e.g., maximal aerobic speed, time to exhaustion), and running time-trial performance over distances from 3 to 10 kilometers. However, strength training has not been found to improve other aerobic physiological factors related to distance running performance, including VO_2max and lactate threshold. Furthermore, no studies have examined the effect of strength training on real-life distance running race performance or on long-distance running performance (e.g., marathon, half-marathon). Regarding running-related injuries, muscle weakness, especially of the hip, seems to be a characteristic of injured runners in both retrospective and prospective studies, however, the evidence is lacking that muscle weakness is a cause of running injuries and is equivocal that strength training prevents running injuries, with studies limited to novice or recreational runners.
Key Words: endurance performance, running economy, distance runners, resistance exercise, plyometrics, running-related injuries

Introduction

The ability to run fast for long distances, even for a race as short as two minutes, primarily depends on the delivery and use of oxygen (Spencer & Gastin, 2001), which are cardiovascular and aerobic in nature, with mitochondrial respiration the dominant metabolic energy pathway. Middle-distance races, including 800, 1,500, and 3,000 meters, also heavily depend on anaerobic metabolism, including glycolysis and the buffering of metabolic acidosis.

While our knowledge of aerobic and anaerobic endurance training dates back a century, with its effects since well documented (e.g., increases in stroke volume, cardiac output, hemoglobin concentration, muscle capillary and mitochondrial densities, and glycolytic, citric acid cycle, and electron transport chain enzyme activity) (Coyle, 1995; Holloszy & Coyle, 1984; MacInnis & Gibala, 2017), our knowledge of strength training on distance running physiology and performance is nascent.

Regardless of the level of runner, all runners want two things: to get faster and to avoid injuries. To achieve these ends, runners utilize a number of means. Over the last couple decades, strength training has become one of those means among recreational and elite runners alike, even to the extent that it is often touted as an elixir, with many runners and coaches espousing its ability to improve performance and prevent injuries. However there remains controversy about the efficacy of strength training to improve performance. For example, Karp (2007) found that, as recently as 2004, athletes who qualified for the 2004 U.S. Olympic Marathon Trials

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averaged less than one strength workout per week (men) or one and a half strength workouts per week (women) during the year leading up to the Olympic Trials, with about half of the athletes not doing any strength training at all.

Theoretically, strength training may improve performance by improving muscle power, anaerobic, and/or neuromuscular factors related to distance running and may prevent injuries by strengthening muscle or tendon weaknesses. Survey- and interview-based research have found that lack of muscle strength is cited as the most common reason (or one of the most common reasons) for running injuries, with strength training cited as the most common way to prevent injuries (Blagrove et al, 2020; Johansen et al, 2017; Saragiotto et al, 2014). Contrary to the old days of only running, most runners these days believe strength training is a necessary part of training.

Perhaps in response to this newer, more holistic style of distance running training that incorporates both aerobic and strength components, there has been considerable research over the last two decades examining the effects of strength training on distance running physiology and performance and on running injuries. However, the collective results have been equivocal, necessitating a critical review of the subject.

To attempt to get closer to answering the complicated question of whether or not strength training makes runners faster and prevents or reduces the risk of running injuries, this review offers a critical narrative summary of the research on strength training and distance running performance and running injury prevention. Repeated and separate searches were made to find all English-language published studies on the effects of strength training on distance running performance and the effects of strength training on distance running injury prevention, using PubMed and Google Scholar databases. All studies, regardless of study design (with or without a control group), level of runner in their population sample (e.g., novice, recreational, elite), and type and duration of intervention were eligible for selection and included in this review, as long as the intervention included some type of strength training (e.g., machines, free weights, bodyweight exercises, core exercises) using various loads and reps/sets combinations and the dependent variable was either running performance, physiological factors related to running performance (e.g., running economy), or prevalence of distance running-related injury.

Distance Running Performance

Several of the physiological adaptations that result from aerobic endurance and strength training are incompatible. Endurance training promotes mitochondrial biogenesis and angiogenesis through its stimulation of molecular pathways (e.g., PGC-1, Ca2+/calmodulin-dependent kinases (CaMK), adenosine monophosphate-activated protein kinase (AMPK), and mitogen-activated protein kinases (ERK1/2, p38 MAPK)) that underlie the cellular processes that improve aerobic endurance capacity (Hawley et al, 2014). On the other hand, strength training promotes muscle hypertrophy as a result of myofibrillar protein synthesis, which may result in a consequent decrease in mitochondrial and capillary densities, characteristics that could impair aerobic endurance performance. An inverse relationship exists between muscle fiber cross-sectional area and mitochondrial oxidative capacity (van der Zwaard et al, 2018; van Wessel et al, 2010).

Recent systematic reviews and meta-analyses on concurrent strength and endurance training have found some interference effects, with compromised lower-body strength gains in males (but not in females) and a blunted improvement in VO2max in untrained (but not in trained) subjects (Huiberts et al, 2024) and a small negative effect on type I muscle fiber hypertrophy with aerobic running (Lundberg et al, 2022). The meta-analysis by Schumann et al. (2022) found no effect of concurrent training on hypertrophy and maximal strength, but did find attenuated explosive strength gains, especially when both types of exercise are performed in the same training session. Since strength training using a high intensity/low volume has been found to be the most effective method to improve maximal strength (Lopez et al, 2021; Schoenfeld et al, 2017), it has since become the main type of strength training research has focused on for distance running performance. Table 1 summarizes the research.

Of the three aerobic factors that influence distance-running performance—VO2max, lactate threshold, and running economy (Bassett & Howley, 2000; Joyner & Coyle, 2008)—the latter is the only factor strength training has been shown to improve (Berryman et al, 2010; Blagrove et al, 2018; Festa et al, 2019; Jung, 2003; Li et al, 2021; Llanos-Lagos et al, 2024; Millet et al, 2002; Paavolainen et al, 1999; Yamamoto et al, 2008), although several studies have found no improvement in running economy following strength training (Damasceno et al, 2015; Ferrauti et al, 2010; Mikkola et al, 2007; Vikmoen et al, 2016) or a nonsignificant improvement that was no different from the improvement in an endurance training-only control group (Blagrove et al, 2018). Millet et al. (2002) found a 6.9% improvement in running economy in 7 well-trained triathletes after 14 weeks of strength training (e.g., hamstring curl, leg press, seated press, parallel squat, leg extension, and heel raise) twice per week using 3-5 sets of 3-5 reps to muscular failure. Li et al. (2021) found a 6% improvement in running economy and the velocity at VO2max in recreational runners after 6 weeks of either heavy strength training or complex training (combination of a heavy strength exercise with a plyometric exercise), with no changes in an endurance-strength training group that trained at a much lower intensity. Støren et al. (2008) found a 5% improvement in running economy when running at 70% VO2max and a 21% improvement in time to exhaustion at maximal aerobic speed in 8 well-trained runners (VO2max = 61.4 ml.kg-1.min-1) following 8 weeks of strength training using 4 sets of 4-rep max half-squats three times per week. Studying 23 male and 19 female collegiate cross-country runners during their competition season, Barnes et al. (2013) found a 1.7% (male) and 3.4% (female) improvement in running economy and a significant increase in peak treadmill speed following heavy strength training of 2-4 sets of 6-15 reps twice weekly for 7-10 weeks. In contrast, Ferrauti et al. (2010) found no change in running economy following 8 weeks of strength training twice per week using 4 sets of 3-5 reps for lower body and 3 sets of 20-25 reps for trunk muscles. Damasceno et al. (2015) also found no change in running economy following 8 weeks of strength training with half-squats, leg press, plantar flexion, and knee extension exercises twice per week using a periodized program of 3 sets of 8- to 10-rep max progressing to 3- to 5-rep max. Vikmoen et al. (2016) found no change in running economy in 11 female duathletes following 11 weeks of twice weekly heavy strength training consisting of 3 sets of 4- to 10-rep max of half squats, one-legged leg press, one-legged hip flexion, and ankle plantar flexion. Reasons for contrasting results between studies could be due to several factors, including type and duration of training intervention, intersubject variability in response to the intervention (some studies that reported individual subject data show that not all subjects improved economy, although the mean result was a statistically significant improvement), number of speeds at which economy was tested, too small of a sample size in some studies to detect statistical significance, and timing of testing. For example, Beattie et al. (2017) found a significant improvement in running economy among 11 collegiate and national-level distance runners after 20 weeks of maximal and explosive strength training but a nonsignificant improvement after 40 weeks; thus, if they had tested their subjects only after 40 weeks instead of after 20 weeks, they would have come to a different conclusion.

Also at issue is the combination of several types of training in a single study. For example, using a combination of explosive strength training with low loads and fast movement velocities, plyometric exercises (drop jumps, hurdle jumps, one-legged jumps), and 20- to 100-meter sprints, Paavolainen et al. (1999) found a significant decrease in the oxygen cost of running (improved economy) when running at 4.17 m.min-1 and a significant improvement in 5-km time in an experimental group of 10 distance runners (VO2max = 63.7 ml.kg-1.min-1) who had replaced 32% of their endurance training with the sport-specific explosive training for 9 weeks, while a separate control group of 8 runners (VO2max = 65.1 ml.kg-1.min-1), who replaced only 3% of their normal endurance training with sport-specific explosive training, showed no change in running economy or 5-km time. However, the authors' conclusion that simultaneous explosive-strength and endurance training improved running economy and 5-km time in well-trained endurance athletes is misleading, given that the sprinting and, perhaps secondarily, the plyometric exercises, performed by the subjects were likely the main contributors to the improved economy and 5-km time-trial performance. It is obvious that including sprints in an endurance training program can result in better running performance. Giovanelli et al. (2017) also found a decrease in the energy cost of running in well-trained ultra-endurance runners at four tested speeds following 12 weeks of heavy strength training, explosive strength training, and plyometrics, but did not separate the different types of training. Skovgaard et al. (2014) found a 3.1% significant improvement in running economy after 8 weeks of twice weekly speed endurance training (4-12 x 30-second sprints) and heavy strength training (3 sets of 8 reps of squats, deadlifts, and leg press at 15-rep max, progressing to 4 sets of 4 reps at 4-rep max). They also found 10-km time improved by 3.8% after 4 weeks (but no greater improvement after 8 weeks) and 1,500-meter time improved by 5.5% after 8 weeks (but not after 4 weeks). Vorup et al. (85) found a significant improvement in 400-meter time, maximal aerobic speed, and time to exhaustion during an incremental treadmill test, but a nonsignificant improvement in running economy and no change in 10-kilometer time-trial performance after 8 weeks of twice weekly speed endurance training (4-10 x 30-second sprints at 90-95% max speed) and twice weekly heavy strength training (1 set of 10-rep max, progressing to 2 sets of 8-rep max, 3 sets of 6-rep max, and 4 sets of 4-rep max). In none of these studies was a comparison of results made between the speed endurance training and heavy strength training. A meta-analysis by Balsalobre-Fernández et al. (2016) revealed a significant beneficial effect of strength training interventions on running economy compared to control groups, although four of the five studies included in their analysis (Mikkola et al, 2007; Paavolainen et al, 1999; Saunders et al, 2006; Støren et al, 2008) used a combination of strength training, speed endurance training, and plyometrics. By including different types of training in the same study (or in a review of studies), it is difficult to determine which type of training is responsible for the significant results and makes it difficult for runners and coaches to know which training method(s) work.

Berryman et al. (2010) found that plyometric training resulted in an average greater decrease in the energy cost of running than did strength training consisting of loaded squats (7% vs. 4%, respectively, with several of the study's subjects exhibiting an increased energy cost of running following strength training). Other studies have also found an improved running economy or time-trial performance following plyometric training (Pellegrino et al, 2016; Ramírez-Campillo et al, 2014; Saunders et al, 2006; Spurrs et al, 2003; Turner et al, 2003), which may result from enhancement of the muscle stretch-shortening cycle during ground contact (Jung, 2003).

A recent meta-analysis by Eihara et al. (2022), in which they separated the effects of heavy strength training and plyometric training among 22 studies that included a total of 479 subjects revealed that heavy strength training had a greater effect than plyometric training on running economy and time-trial performance. They also found that strength training with loads ≥90% 1-rep max had a larger effect than strength training with loads <90% 1-rep max. Another recent meta-analysis by Llanos-Lagos et al. (2024), in which they separated the effects of different strength training loads on running economy at different speeds, found that heavy strength training (>80% 1-rep max) was most effective for improving economy at higher speeds (8.64 to 17.85 km.h-1), plyometric training was most effective for improving economy at speeds less than 12 km.h-1, and combined training was most effective for improving economy at speeds of 10 to 14.45 km.h-1, while neither submaximal strength training (40-79% 1-rep max) nor isometric training improved running economy. Both meta-analyses noted that although strength training improved running economy, the effect was small.

In addition to the mixing of different types of training in the same study (heavy strength training, explosive strength training, sprinting, and plyometrics) is the issue of how running economy is determined. Although the majority of research has found heavy strength training improves economy in distance runners, nearly all the studies measured changes in oxygen consumption (VO2) at only one submaximal treadmill speed (Table 1), which limits interpretability of the research. Of the studies that measured VO2 at more than one speed, not all found a significant reduction in VO2 (i.e., improved economy) at every speed. Table 1 shows the magnitude of change in submaximal oxygen consumption pre- to post-intervention. It is unclear how the speed(s) used in these studies compare to the subjects' usual training speeds. Based on the scientific literature, the most that can be concluded is that heavy strength training has a small effect on running economy, which agrees with Eihara et al.'s meta-analysis (2022).

All the studies summarized in Table 1 found that subjects increased muscular strength following the strength training intervention and did so without an increase in muscle mass. This would certainly be beneficial for distance runners, since an increase in muscle mass would likely impair running economy and endurance performance. Studies have also found that subjects did not improve other physiological factors related to distance running performance, namely VO2max and lactate threshold, suggesting the improvements in running economy do not result from cardiovascular or metabolic changes, but rather from some other mechanism. Changes to Achilles tendon stiffness and motor unit recruitment are possible candidates responsible for strength training's effect on running economy (Albracht & Arampatzis, 2013; Bohm et al, 2021; Fletcher & MacIntosh, 2017). Albracht and Arampatzis (2013) observed a 4% significant improvement in running economy accompanied by a 7% significant increase in plantar flexor muscle strength and 16% significant increase in triceps surae tendon-aponeurosis stiffness after 14 weeks of isometric ankle plantar flexion exercise. Bohm et al. (2021) found a 4% significant increase in running economy accompanied by a 10% significant increase in plantar flexor muscle strength and 31% significant increase in Achilles tendon stiffness after 14 weeks of isometric ankle plantar flexion exercise. In contrast, Fletcher et al. (2010) found no changes in running economy or tendon stiffness after 8 weeks of plantar flexion exercise.

Alternatively, heavy strength training may train the central nervous system to synchronously and rapidly recruit motor units to enhance muscle force and power production. Athletic performance is ultimately limited by the amount of force and power that can be produced and sustained, which are influenced by several physiological factors, including neuromuscular coordination, skeletal muscle mechanics and energetics, efficiency of converting metabolic power into mechanical power, and muscles' aerobic and anaerobic metabolic capacities. Heavy strength training may enhance neuromuscular coordination and increase muscle rate of force development (i.e., power) by altering firing frequency and motor unit recruitment (Aagaard et al, 2002; Støren et al, 2008). However, these neuromuscular characteristics and muscle rate of force development have been assessed using similar strength exercises to those used in the studies' training interventions (Aagaard et al, 2002; Støren et al, 2008). There is currently no evidence that any muscle strength improvements or altered motor unit recruitment achieved from strength training transfers to running (Trowell et al, 2020), during which force is applied to the ground much more rapidly.

While a slight improvement in running economy may be a benefit of strength training, what runners really want is to get faster. Only a few studies have measured the effect of heavy strength training on running performance. Those studies have yielded mixed results, with most finding an improvement in performance (most often measured as a 3-km to 10-km time trial or other lab-based performance test) (Berryman et al, 2010; Damasceno et al, 2015; Karsten et al, 2016; Skovgaard et al, 2014; Vikmoen et al, 2017), while others have not (Schumann et al, 2015; Schumann et al, 2016; Vikmoen et al, 2016). Of the studies finding a significant improvement, running performance improved by 2 to 4 percent. While improved economy has often been the explanation for why performance improved in these studies, how or why performance was improved remains unclear, since an improvement in performance has been found even with no improvement in economy (Damasceno et al, 2015). It has yet to be determined that strength training results in faster real-life race performance. It's plausible that enhancement of neuromuscular factors and the greater muscle strength and power achieved from strength training can help a runner in middle-distance races (800 to 3,000 meters) that are run at speeds at or faster than VO2max and that include a large anaerobic component, but may not be as important for longer races (e.g., half-marathon, marathon). There is currently no research on the effect of strength training on middle-distance running performance, real-life track or road races, or long-distance races.

In summary, there is ample evidence to conclude that heavy (or explosive) strength training may improve running economy but does not improve other aerobic factors (cardiovascular or metabolic) that influence distance-running performance. Whether or not the improved economy from strength training results in faster race times is a direction for future research, as there is currently no evidence that it does. The scientific literature seems to contradict the popular belief that runners must strength train to run faster races.

Table 1. Studies on Strength Training and Distance Running Performance

Study	Subjects (experimental group)[†]	Intervention	Results	Magnitude of Change in O_2 Cost of Running ml/kg/min (tested speed)
Albracht & Arampatzis, 2013	26 recreational long-distance runners	5 sets of 4 reps of isometric ankle plantar flexion at 90% max 4 times/week for 14 weeks	avg. 4% sig. improvement in RE at 2 tested speeds; 7% sig. increase in maximum plantar flexion muscle strength & 16% sig. increase in triceps surae tendon-aponeurosis stiffness	-1.9 (10.8 km/hr) -1.5 (12.6 km/hr)
Barnes et al, 2013	23 male & 19 female collegiate cross-country runners	heavy strength training of 2-4 sets of 6-15 reps & plyometrics twice weekly for 7-10 weeks	greater improvement in RE with heavy strength training (1.7% male; 3.4% female) compared to plyometrics (0.2% male; 1.0% female); sig. increase in peak treadmill speed after heavy strength training (4.6% male; 4.4% female) compared to plyometric training (1.0% male; 2.2% female)	heavy strength training: -1.2 (14 km/hr) plyometric training: -0.3 (14 km/hr)
Beattie et al, 2017	11 collegiate and national-level distance runners	max strength (3-8 reps), explosive strength (3 reps), & plyometrics; 1-2/week for 40 weeks	4.8% sig. improvement in RE after 20 weeks; 3.5% nonsig. improvement after 40 weeks	-1.8 (16.5 km/hr)
Berryman et al, 2010	35 trained distance runners	3-6 sets of 8 reps of semisquats for 8 weeks	sig. improvements in RE & 3,000-meter time-trial performance	heavy strength training: -1.6 (12 km/hr) plyometric training: -3.0 (12 km/hr)
Bertuzzi et al, 2013	16 recreational runners	3-6 sets of 4-10 reps of half-squats at 70-100% 1-rep max twice weekly for 6 weeks	no change in VO_2max, vVO_2max, time to exhaustion at vVO_2max, & respiratory compensation point	—
Blagrove et al, 2018	9 male & female adolescent runners	2-3 sets of 8-12 reps of back squat, Romanian deadlift, rack pull, single-leg press & calf raise, plyometric jumps, & 30-meter sprints; twice weekly for 10 weeks	nonsig. improvement in RE, with no difference between experimental & control groups; no change in vVO_2max or velocity at various fixed blood lactate concentrations; sig. improvement in 20-meter sprint time & difference from control group	-0.6[(a)] (LTP) -0.7[(a)] (LTP - 1 km/hr) -0.7[(a)] (LTP - 2 km/hr)
Bohm et al, 2021	13 recreational runners	5 sets of 4 reps of isometric ankle plantar flexion at 90% max 3-4 times/week for 14 weeks	sig. 4% increase in RE; sig. increase in plantar flexor muscle strength (10%) & Achilles tendon stiffness (31%)	-0.4[(b)] (9 km/hr)
Damasceno et al, 2015	9 recreational long-distance runners	3 sets of 3-5 rep max to 8-10 rep max of half-squats, leg press, plantar flexion, & knee extension twice weekly for 8 weeks	2.5% improvement in 10-km time trial; no change in peak treadmill speed, respiratory compensation point, & RE	-0.6 (12 km/hr)
Ferrauti et al, 2010	11 recreational runners	4 sets of 3-5 reps lower body; 3 sets of 20-25 reps for trunk muscles	no changes in RE, stride length, stride rate, & blood lactate & heart rate at tested speeds	+1.6 (8.6 km/hr) +0.8 (10.1 km/hr)
Festa et al, 2019	18 recreational runners (9 flywheel strength training, 9 high-intensity run training)	flywheel strength (once weekly for 8 weeks): 4 sets of 7 eccentric reps at max velocity; high-intensity (3 times/week for 8 weeks): 95-140% mean velocity between VT1 & VT2	sig. increase in RE in flywheel strength group; sig. increase in vVT1, vVT2, vVO_2max, & avg. speed of 2- & 10-km time trials in flywheel & high-intensity groups	-13.9[(c)] (75% vVT1)
Fletcher et al, 2010	6 middle- and long-distance regional, national or international-level runners	4 x 20-second isometric plantar flexions at 80% maximum voluntary contraction 3 times/week for 8 weeks	no change in RE at 3 tested speeds & triceps surae tendon stiffness	+0.04[(d)] (12.3 km/hr) -0.01[(d)] (13.9 km/hr) -0.02[(d)] (15.6 km/hr)

Giovanelli et al, 2017	13 well-trained ultra-endurance runners	heavy strength training (single-leg half-squats, step-ups, lunges), explosive strength training (counter-movement jumps, split squats), & plyometrics 3 times/week for 12 weeks	sig. improvement in RE at 4 tested speeds (6.4% at 8 km/h, 3.5% at 10 km/h, 4.0% at 12 km/h, 3.2% at 14 km/h)	-1.7 (8 km/hr) -1.0 (10 km/hr) -1.4 (12 km/hr) -1.4 (14 km/hr)
Guglielmo et al, 2009	16 well-trained runners (9 explosive strength training; 7 heavy strength training)	explosive strength: 3-5 sets of 12-rep max heavy strength: 3-5 sets of 6-rep max; twice weekly for 4 weeks	6.2% sig. improvement in RE only in heavy strength training group; sig. increase in velocity at onset of blood lactate accumulation in both groups	-3.0 (14 km/hr)
Johnston et al, 1997	6 female distance runners	2 sets of 12- to 20-rep max & 3 sets of 6- to 8-rep max of lower & upper-body exercises 3 times/week for 10 weeks	4% sig. improvement in RE at 214 & 230 m/min	-1.7 (12.8 km/hr) -1.7 (13.8 km/hr)
Karsten et al, 2016	8 recreational endurance runners & triathletes	4 sets of 4 reps of Romanian deadlift, parallel squat, calf raises, & lunges at 80% 1-rep max twice weekly for 6 weeks	3.6% sig. improvement in 5-km time trial	—
Li et al, 2021	38 recreational marathon runners (13 complex training, 13 heavy-strength training, 12 endurance-strength training)	complex training: 3 sets of 5 reps at 70-85% 1-rep max for 3 exercise pairs (back squat + drop jump, split squat + single-leg hop, walking lunge + double-leg hurdle hop) heavy-strength: 5 sets of 5 reps at 70-85% 1-rep max (back squat, split squat, walking lunge) endurance-strength: 5 sets of 20-30 reps at 30-40% 1-rep max; twice weekly for 6 weeks	6% sig. improvement in RE at 2 tested speeds in complex & heavy-strength training groups; sig. increase in vVO_2max, squat jump, & counter-movement jump height in complex & heavy-strength training groups; no changes in endurance-strength group	NR (12 km/hr) NR (14 km/hr)
Lum et al, 2023	18 endurance runners (9 isometric strength training, 9 plyometrics training)	strength: 3 sets of 3 reps progressing to 3 sets of 4 reps & 3 sets of 5 reps of isometric mid-thigh pull & isometric ankle plantar flexion plyometrics: depth jumps, single-leg bounding, & split jumps	sig. improvement in RE only in strength training group; sig. improvement in 2.4-km time-trial performance & maximal aerobic speed in both experimental groups, with no differences between groups	strength: -0.02[e] (12 km/hr male/10 km/hr female) strength: -0.04[e] (14 km/hr male/12 km/hr female) plyometrics: -0.01[e] (12 km/hr male/ 10 km/hr female) plyometrics: -0.01[e] (14 km/hr male/12 km/hr female)
Mikkola et al, 2007	13 teenage distance runners	sprinting, jumping, & explosive strength training of 2-3 sets of 6-10 reps for 8 weeks	no difference in RE & maximal aerobic speed	+0.5 (10 km/hr) -0.9 (12 km/hr) -0.7 (13 km/hr) -1.5 (14 km/hr)
Millet et al, 2002	7 well-trained triathletes	3-5 sets to failure of 3-5 reps for 14 weeks	6.9% sig. improvement in RE	-2.6 (17.4-17.6 km/hr)
Paavolainen et al, 1999	10 distance runners	explosive strength training, plyometrics, & 20- to 100-meter sprints for 9 weeks	sig. improvement in RE & 5-km time trial	-4.0 (15 km/hr)
Piacentini et al, 2013	11 masters marathon runners (6 max strength training, 5 resistance training)	max strength training: 4 sets of 3-4 reps at 85-90% 1-rep max resistance training: 3 sets of 10 reps at 70% 1-rep max; twice weekly for 6 weeks	max strength training: 6.2% sig. improvement in RE at 1 of 3 tested speeds resistance training: no change in RE	- ~1.0 (1 km/hr slower than marathon pace) - ~4.0 (marathon pace) + ~1.0 (1 km/hr faster than marathon pace)
Schumann et al, 2015; 2016	13 recreationally endurance-trained runners	maximal & explosive strength training twice weekly for 24 weeks	no difference in 1,000-meter field test time between endurance & endurance + strength groups	—

Sedano et al, 2013	12 well-trained male runners (6 explosive-strength training + plyometrics; 6 endurance-strength training)	explosive-strength: 3 sets of 7 reps at 70% 1-rep max & plyometrics endurance-strength: 3 sets of 20 reps at 40% 1-rep max; twice weekly for 12 weeks	sig. difference in peak treadmill speed in both strength training groups; sig. improvement in 3-km time trial for explosive strength group; sig. improvement in RE at 2 of 3 tested speeds for explosive-strength group & 1 of 3 speeds for endurance-strength group	explosive strength: NR (12 km/hr) explosive strength: -2.3 (14 km/hr) explosive strength: NR (16 km/hr) endurance-strength: NR (12 km/hr) endurance-strength: -1.1 (14 km/hr) endurance-strength: NR (16 km/hr)
Skovgaard et al, 2014	12 moderately trained male runners	speed endurance training (4-12 30-sec sprints) & heavy resistance training (3 sets of 8 reps of squats, deadlifts, & leg press at 15-rep max, progressing to 4 sets of 4 reps at 4-rep max) twice weekly for 8 weeks	3.8% sig. improvement in 10-km time trial after 4 weeks & 5.5% sig. improvement in 1,500-meter time trial after 8 weeks; 3.1% sig. improvement in RE	-1.2 (12 km/hr)
Støren et al, 2008	8 well-trained runners	4 sets of 4-rep max half-squats 3 times per week for 8 weeks	5% sig. improvement in RE & 21% improvement in time to exhaustion at maximal aerobic speed	-0.034[f] (70% VO_2max & 1.5% incline)
Taipale et al, 2010	28 male recreational runners (11 maximal strength, 10 explosive strength, 7 circuit training)	maximal strength: 3 sets of 4-6 reps at 80-85% 1-rep max (squats, leg press) & 2 sets of 12-15 reps at 50-60% 1-rep max (calf exercise); explosive strength: 3 sets of 6 reps at 30-40% 1-rep max (squats, leg press) & jumping exercises; circuit training: 3 sets of 40-50 seconds of lower- & upper-body exercises; twice weekly for 8 weeks	sig. improvement in speed at VO_2max in all groups; sig. improvement in RE at both tested speeds in maximal strength group & 1 speed in explosive strength group; no improvement in RE in circuit training group	maximal strength: - ~3.0 (10 km/hr) maximal strength: NR (12 km/hr) explosive strength: - ~1.0 (10 km/hr) explosive strength: NR (12 km/hr)
Vikmoen et al, 2016; 2017	11 female duathletes	3 sets of 4- to 10-rep max of half squats, one-legged leg press, one-legged hip flexion, & ankle plantar flexion twice weekly for 11 weeks	no change in RE; 4.7% sig. increase in running distance covered during all-out 5-min treadmill run following 90 min submax treadmill run; no change in running distance covered during all-out 40-min treadmill run	+ ~0.1 (10 km/hr)
Vorup et al, 2016	8 male endurance runners	strength training (1-4 sets of 4- to 10-rep max of squat, leg press, deadlift) twice weekly & speed endurance training (4-10 x 30 sec at 90-95% max speed) twice weekly for 8 weeks	4.8% sig. improvement in 400-meter time; 0.6 km/hr sig. improvement in maximal aerobic speed; 9.2% sig. improvement in time to exhaustion during incremental treadmill test; 32% sig. higher peak blood lactate during incremental treadmill test; no change in RE & 10-km time trial	-2.1 (60% max aerobic speed, ~11 km/hr) -2.2 (10-km pace, ~15 km/hr)

† Experimental groups performed combined endurance running and strength training. All studies with one experimental group included a control group of equal or similar size that performed only endurance running training.
(a) in kJ/kg-0.67/km
(b) in W/kg
(c) in ml/kg/km
(d) in kJ/kg/km
(e) in J/kg/km
(f) in ml/kg0.75/min
sig. = statistically significant; nonsig. = not statistically significant; NR = not reported; RE = running economy; vVO2max = velocity at VO2max; VT1 & VT2 = velocity at ventilatory thresholds 1 & 2

Running Injury Prevention

Another perceived reason why runners strength train is to prevent injuries. In runners aged 15 to over 60, from local club level to international level, Blagrove *et al.* (2020) found that 62.5% engaged in strength training, with the most common reason for doing so to lower the risk of getting injured (63.1%).

The prevalence of running injuries is well documented and widespread, with estimates ranging from 19% to 79% (van Gent et al, 2007), with the majority being joint/tendon or bone injuries, such as patellofemoral pain syndrome, Achilles tendinosis/tendonitis, and bone stress fractures. Running injuries are caused by a confluence of complex training and biomechanical factors. Most running injuries occur as a result of repeated microtrauma (from training volume and/or intensity) that causes the load experienced by the tissue to exceed its capacity.

Strength training recommendations to prevent running injuries are all over the Internet and social media—covering everything from resistance band clamshells and Russian twists to planks and pistol squats. The prevalence of these recommendations assumes that muscle weakness is a cause of running injuries. However, despite how much strength training is touted as a solution to the problem and despite the sizable percentage of runners who include strength training in their training programs, runners still get injured (Loudon & Parkerson-Mitchell, 2022). Indeed, injury rates among runners have not decreased over the last several decades.

The etiology of running injuries is complex, multifactorial, and outside the scope of this review (for reviews, see Correia et al, 2024; Saragiotto et al, 2014; van der Worp et al, 2015). Research has shown that muscle weakness (commonly measured by knee extension, knee flexion, hip abduction, hip adduction, and ankle plantar flexion) may be associated with certain injuries, such as patellofemoral pain syndrome, anterior knee pain, iliotibial band friction syndrome, and Achilles tendinopathy (Duffey et al, 2000; Mahieu et al, 2006; Messier et al, 1991; Messier et al, 1995; Ramskov et al, 2015). For example, Niemuth *et al.* (2005) found that hip abductor strength of the injured leg of 32 recreational runners was significantly less than and hip adductor strength was significantly greater than the uninjured leg, while no differences in hip muscle strength between legs were found in a control group of 30 non-injured runners. In another descriptive study, Fredericson *et al.* (2000) found weaker hip abductors (isometrically) in the injured leg compared to the healthy leg of 24 male and female college and club long-distance runners with iliotibial band syndrome and compared to uninjured runners. In a mixed-methods retrospective study, Vannatta *et al.* (2021) found that isometric hip abduction strength asymmetry in male runners and combined isometric hip abduction weakness and isometric hip external rotation weakness in female runners were significant predictors of a previous running injury. Whether the strength deficits observed in these studies is a cause of, consequence of, or unrelated to the injuries is unknown and needs to be elucidated by future research.

In a two-year prospective study of 98 high school runners, Finnoff *et al.* (2011) found that baseline hip external-to-internal strength ratio was lower in runners who developed patellofemoral pain than in uninjured runners. Among injured runners, hip abduction and external rotation strengths decreased from pre-injury to post-injury. Runners with greater baseline hip abduction strength and abduction-to-adduction strength ratio had an increased risk of injury, while runners with greater pre-injury hip external-to-internal rotation strength ratio had a decreased risk of injury. In a 1-year prospective study of 629 novice male and female runners who started a self-structured running program, Ramskov *et al.* (2015) found that runners with higher-than-normal eccentric hip abductor strength were less likely to experience patellofemoral pain within the first 25 and 50 km of their running program. However, greater eccentric hip abductor strength was only protective against patellofemoral pain up to the first 50 km of running, since there were no significant differences between the high-strength group and the normal-strength group after 100, 250, or 500 km of running.

Many studies have found that strength is not associated with the development of running injuries. For example, in a two-year prospective observational study of 300 uninjured runners, Messier *et al.* (2018) found that hip abductor, knee extensor and flexor, and ankle plantar flexor strengths were similar between runners who became injured and those who did not and were not predictive of injury. In a one-year prospective study, Dillon *et al.* (2023) found that maximal isometric strength (ankle dorsiflexion, hip extension, and hip internal and external rotation) was not associated with the development of running injuries among 225 recreational runners, nor were measures of loading (impact acceleration) or factors affecting the dissipation of load (muscle strength, knee flexion angle at initial contact, foot strike pattern). Examining 36 male and female collegiate distance runners, Moffit *et al.* (2020) found no associations between back squat strength or isometric knee and hip extension strength and 14 kinematic and kinetic characteristics of running biomechanics that have previously been associated with overuse injuries in competitive distance runners. A systematic review by Mucha *et al.* (2017) found no meaningful association between hip abductor strength and injury status among runners across all levels of distance running. Reviewing the research on iliotibial band syndrome, patellofemoral pain syndrome, medial tibial stress syndrome, tibial stress fracture, and Achilles tendinopathy, only for iliotibial band syndrome did they find strong support for a relationship between muscle weakness and injury. In a meta-analysis of prospective studies, Peterson *et al.* (2022) found that runners who developed an injury had significantly less knee extension strength and significantly lower hip adduction velocity than uninjured runners, however, the effect sizes were trivial to small and 23 of 25 pooled analyses detected no relationship between baseline biomechanical and musculoskeletal measures and the development of running injury, leading them to conclude that the currently available literature does not support biomechanical or musculoskeletal measures as risk factors for running injury in non-elite runners. Taken together, although muscle weakness in specific areas seems to be a characteristic of injured runners, most notably for iliotibial band syndrome, the effect is small and it cannot be said that muscle weakness is a *cause* of running injuries.

Only a handful of prospective running injury prevention studies have focused on strength training, and all of them have been conducted on novice or recreational runners. Table 2 summarizes the prospective and retrospective studies on strength training and running injuries. Of the 9 prospective studies, 4 of them found a significant difference in running injury prevalence between the strength training group and control group and 5 found no difference. Of the 4 studies that found a significant difference, one was conducted on youth female track and field athletes. Studying 433 recreational runners (21-55 years old), Desai *et al.* (2023) found no difference in overall running injury risk between a control group and a strength training group following 18 weeks of twice weekly strength training and foam-rolling exercises. However, the runners who were highly compliant with the intervention had a significantly lower risk of running injuries compared to the control group. Taddei *et al.* (2020) found an experimental group of 57 male and female runners performing foot and ankle muscle training 4 times per week for 12 months was 2.4 times less likely to experience a running injury than a control group. Comparing hip and core muscle strengthening and foot and ankle muscle strengthening for 24 weeks, Leppänen *et al.* (2024) found a significantly lower incidence of running injuries in the hip and core group compared to a stretching-only control group, but no significant difference in the ankle and foot group. Toresdahl *et al.* (2020) found no difference in the prevalence of running injuries among 352 first-time marathon runners training for the New York City Marathon between those who strength trained 3 times per week for 12 weeks and those who did not (7.1% vs. 7.3%, respectively).

While weaker evidence than prospective studies, retrospective studies on the prevalence of running injuries have shown no apparent protective effect of strength training. All 3 known retrospective studies reported no difference in incidence of running injuries between runners who strength trained and those who did not (Table 2). Reasons for contrasting results between studies may be due to methodological differences (e.g., type and duration of strength training intervention), the degree of compliance with the intervention (in prospective studies), accuracy of reporting of past strength training (in retrospective studies), and the multifactorial nature of running injuries. For example, if an injury is due to suboptimal biomechanics or training errors rather than a muscle weakness or imbalance, it cannot be expected that strength training would prevent the injury. Without knowing the precise cause of a running injury, it becomes difficult to determine whether or not strength training may prevent it. It's likely that the injured runners of these studies have multiple reasons for why they became injured. Studies and reviews on other non-strength training injury prevention interventions (e.g., stretching, pre-conditioning, warm-up, plyometrics) have also found no difference in injury rates between intervention and control groups (Bredeweg et al, 2012; Edouard et al, 2021; Fields et al, 2010; Lundstrom et al, 2019). Specific neuromuscular training comprised of a variety of jumps, landings, plyometrics, body-weight exercises, and running drills that include strength, endurance, agility, and balance exercises has been shown to be protective of injury in youth female track-and-field athletes when performed in addition to their normal training (Mendez-Rebolledo et al, 2021). However, a recent meta-analysis by Wu *et al.* (2024) and narrative review by Šuc *et al.* (2022) concluded there is little evidence to support inclusion of strength and conditioning exercises for the purpose of reducing running injuries. However, a *post hoc* analysis by Wu *et al.* (2024) revealed that when study interventions were supervised, there was greater compliance with the exercise programs and injury risk was significantly lower in the intervention groups compared to the control groups. However, there is evidence that greater quadriceps muscle strength is associated with *more* stress to the knee when running due to larger knee-joint loading, which may lead to injury (Messier et al, 2008).

In summary, there is ample evidence, at least from retrospective studies, that muscle weakness, especially of the hip, is a characteristic of injured runners, but there is little evidence that strength training prevents runners from getting injured, especially when the training is unsupervised. There is currently no evidence that runners who don't strength train are more likely to experience a running injury. The scientific literature on this subject seems to contradict the popular belief that runners must strength train to prevent injuries.

Table 2. Retrospective and Prospective Studies on Strength Training and Running Injury Prevention

Study	Subjects (experimental group)†	Intervention	Results
Baltich, 2016; Baltich et al, 2017	24 novice runners (resistance strength training group) 23 novice runners (functional strength training group)	resistance strength training: elastic band exercises, 4 sets of 10 reps functional strength training: lunges, squats, hops, single-leg stand; 3-5 times/week for 8 weeks, then twice weekly for 4 months	no difference in running injury rates between experimental groups and control group

Brushøj et al, 2008	487 soldiers undergoing military training	strength, flexibility, & coordination training 3 times/week for 12 weeks	no difference in incidence of lower-extremity injury between experimental & control groups
Desai et al, 2023	433 recreational runners (21-55 years)	strength exercises (1-leg squats, forward lunges, side-plank, diagonal lifts, & side-steps, supine abduction, & foot supination with elastic training band) & foam-rolling exercises twice weekly for 18 weeks	no difference in overall running injury risk between experimental group & control group; experimental high-compliance group had significantly lower risk of running injuries compared to control group
Leppänen et al, 2024	hip & core: 108 male & female novice recreational runners ankle & foot: 111 male & female novice recreational runners	8 strengthening & neuromuscular control exercises for hip & core muscles or ankle & foot muscles for 24 weeks	sig. lower incidence of running injuries in hip & core group compared to control; no sig. difference in ankle & foot group compared to control
Letafatkar et al, 2020	neuromuscular training (NMT): 20 male novice runners neuromuscular training + knee valgus control instructions (NMT+VCI): 20 male novice runners	neuromuscular training: 2-3 sets of 10-20 reps of squats, deadlifts, lateral walks with resistance band, hip abduction & rotation, forward lunge, & balance exercises 3 times/week for 6 weeks; verbal & visual instructions to control pelvis & knee movement	sig. improvements in kinetics & kinematics in both groups after 6 weeks; sig. greater differences in kinetics between NMT+VCI compared to NMT; sig. 31.6% & 65.5% reduction of running injuries in NMT group & NMT+VCI group after 1 year
Loudon & Parkerson-Mitchell, 2022	68 masters female runners (>45 years)	—	97% of surveyed runners cross-trained & 78% strength trained; 71% had sustained more than one injury over their running history & 45% reported recurring injury; cross-training/strength training not associated with self-reported injury rates
Luedke et al, 2015	68 high school cross-country runners (47 females, 21 males)	—	runners with stronger isometric hip abductor, knee extensor, & knee flexor muscle strength had sig. lower incidence of knee injury but not shin injury
Lundstrom et al, 2019	core training group: 12 college students (18-23 years) training for marathon plyometric training group: 11 college students (18-23 years) training for marathon	core training: low-to-moderate velocity muscular strengthening exercises for abdominal, hip, back, & gluteal muscles plyometric training: maximal velocity jumping & sprinting exercises; once/week for 12 weeks	no differences between core & plyometric training groups during marathon training in days missed, days missed due to injury, readiness to run, soreness, or RPE
Mendez-Rebolledo et al, 2021	11 youth female track & field athletes (15 years)	neuromuscular training, including jumps, landings, plyometrics, body-weight exercises, & running mixed with strength, endurance, agility, & balance exercises, 3 times/week for 6 weeks	sig. lower injury rate in experimental group compared to control group
Stenerson et al, 2023	473 female & 143 male recreational runners	—	no difference in running injury prevalence between runners who strength trained and those who did not
Taddei et al, 2020	57 runners (28 male, 29 female; mean age = 40.5 years)	foot & ankle muscle training consisting of 12 exercises 4 times/week for 12 months	experimental group was 2.42 times less likely to experience a running injury than control group
Toresdahl et al, 2020	352 first-time marathon runners training for New York City Marathon	strength training for core, hip abductors, & quadriceps, 3 times/week for 12 weeks prior to New York City Marathon	no difference in overuse injury resulting in marathon non-completion between strength training group & control group (7.1% vs. 7.3%), nor any difference in average marathon finishing time
Vannatta et al, 2021	82 NCAA Div III college cross-country runners (38 males, 44 females)	—	males with hip abduction strength asymmetry & females with combined hip abduction weakness & hip external rotation weakness had increased likelihood of history of running injury
Voight et al, 2011	50 runners in Twin Cities Marathon	—	44% of surveyed runners strength trained; 54% did some type of cross-training (weight lifting, biking, swimming, yoga, aerobics, in-line skating, roller skiing, power walking, Nordic walking or skiing, rowing); no difference in injury rates between runners who cross-trained while training for a marathon & runners who didn't (14% cross-training vs. 8% no cross-training)

† Prospective intervention studies included a control group of equal or similar size not subject to intervention

Conclusions

A total of 45 studies (30 on strength training and distance running performance and 15 on strength training and running injury prevention) were included in this narrative review. While repeated attempts have been made to find all published studies on the subject, the possibility exists that not every study was found. Secondly, a narrative review has inherent limitations compared to a systematic review or meta-analysis, including the assignment and ranking of evidence level. Consequently, all studies are weighted equally. Thirdly, the studies in this review, which are summarized in Tables 1 and 2, exhibit a large variation in interventions that can be described but not statistically accounted for. Acknowledging these limitations, the following conclusions may be drawn based on the available scientific evidence:

1. Heavy and, to a lesser extent, explosive, strength training seem to have a small, positive effect on running economy, although not all studies have found this to be the case.
2. Strength training does not improve other aerobic physiological factors related to distance running performance, including VO_2max and lactate threshold.
3. Strength training improves muscular strength (measured as 1-rep max) in distance runners. Whether or not increased muscular strength *per se* results in faster races has yet to be determined.
4. There is no evidence strength training improves long-distance running performance (e.g., half-marathon, marathon, ultra-marathon). Studies measuring running performance have most often used 3-km to 10-km time trials or other lab-based performance tests to control for the many confounding variables that may affect "real-life" race performance on a given day. Given the impracticability of repeating a half-marathon or marathon time trial pre- to post-intervention and the recovery time needed after racing those distances, it is unknown whether or not strength training may improve long-distance running performance.
5. While retrospective studies have found that muscle weakness, especially of the hip, is associated with several types of running injuries, prospective studies have found that it is not.
6. There is equivocal evidence that strength training prevents or reduces the risk of running injuries. Prospective studies have often used lower loads and more isolated exercises (e.g., bodyweight, hip/core, and foot/ankle exercises) than those used in studies on running performance. Furthermore, there are no studies on runners of a higher than novice/recreational level.

Directions for Future Research

To ascertain whether or not strength training results in faster races and prevents running-related injuries, it would take a lot of systematic trial-and-error by runners and coaches and many carefully controlled, long-term studies. Several directions for future research may help to determine whether or not runners would benefit from including strength training in their training programs. Given the popularity of strength training for running performance improvement and injury prevention, an interesting question to explore in future research is *why* runners and coaches believe what they do about strength training.

The small improvement in running economy has been hypothesized to be due to enhanced neuromuscular characteristics, such as a more efficient use of stored elastic energy and improved muscle power. However, there is no direct evidence to suggest these characteristics translate into more efficient or optimal muscle recruitment patterns when running, as that would violate the law of specificity. Improved neuromuscular coordination would likely benefit only the specific exercises performed by the studies' subjects. Therefore, future studies should investigate the mechanism(s) of improved running economy, directly measuring motor unit recruitment patterns while running before and after strength training interventions.

The research to date that has shown positive effects of strength training on time-trial performance has not included a separate group that significantly increased its running training. Thus, the practical question that research has not yet answered is whether or not simply increasing the volume and/or intensity of one's running training would result in an equivalent (or greater) performance benefit compared to adding strength training to an existing endurance training program. For example, if the goal is to become a faster runner, is it better to increase one's weekly volume from 30 km per week to 50 to 70 km (or more) per week, or to remain at 30 km per week and add strength training two to three times per week? Likewise, is it better to increase the training intensity by introducing high intensity interval workouts or instead introduce heavy strength training? The studies including sprints in their strength training intervention have found that running performance improved (Paavolainen et al, 1999; Skovgaard et al, 2014). It's likely that simply increasing running volume and/or intensity, instead of adding strength training, would also improve performance. Furthermore, if a runner is running high mileage (e.g., $>100\ km \cdot week^{-1}$)—which is typical of runners training for distance-running races—is it better to *reduce* the running volume to accommodate strength training? Nearly all the studies in Table 1 used recreational runners who were running a low enough weekly volume that they could physically handle the addition of strength training. Future studies should investigate the effects of strength training as an adjunct to different volumes and intensities of running training on running physiology and performance, as well as determining the most optimal (periodized) way of combining the two modes of training.

In line with this, it may be beneficial to compare strength training to more running-specific training methods, such as hill training. Although a different research question than the one presented in this review, a comparison of interventions may elucidate whether hill training may achieve the same goal for the runner as does strength training. It is possible, and even likely, that more sport-specific "power" training, such as hill sprints, as well as performing bounding and plyometric exercises up a steep hill, would be just as or more effective than traditional strength training with gym-based exercises for improving neuromuscular coordination, running economy, and distance running performance.

To date, little research has been conducted on the acute effects of strength training on distance running training. Athletes who perform both activities typically run first and then strength train, either immediately afterward or later the same day. Future research should determine which mode of training should be performed first, how strength training is best structured to fit within the context of run training, and whether or not any fatigue induced from strength training negatively affects the next day's run training. Studies on the acute effects of strength training on running physiology have yielded mixed results, with most showing a reduction in economy but no change in VO_2max following strength training (Doma & Deakin, 2014; Doma & Deakin, 2015; Gao & Yu, 2023).

Regarding running injuries, future research should examine the effects of strength training on more experienced runners and those of a higher performance level, as well as using heavier loads, similar to those used in the studies on running performance. In addition, all research to date linking muscle weakness to injury has measured maximal strength. However, maximal strength may not relate to and/or may not be as important to running injury prevention as how strength is applied while running. A strong, stable movement pattern, with optimal activation of muscles during the gait cycle, may be more likely to prevent injury rather than maximal strength itself.

Conflicts of Interest

No conflicts of interest to declare.

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