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The Effect of Strength Training on Performance Indicators in Distance Runners

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Abstract

Beattie, K, Carson, BP, Lyons, M, Rossiter, A, and Kenny, IC. The effect of strength training on performance indicators in distance runners. *J Strength Cond Res* 31(1): 9–23, 2017–Running economy (RE) and velocity at maximal oxygen uptake ($_{\text{V}}\dot{\text{V}}\text{O}_2$max) are considered to be the best physiological performance indicators in elite distance runners. In addition to cardiovascular function, RE and $_{\text{V}}\dot{\text{V}}\text{O}_2$max are partly dictated by neuromuscular factors. One technique to improve neuromuscular function in athletes is through strength training. The aim of this study was to investigate the effect of a 40-week strength training intervention on strength (maximal and reactive strength), $_{\text{V}}\dot{\text{V}}\text{O}_2$max, economy, and body composition (body mass, fat, and lean mass) in competitive distance runners. Twenty competitive distance runners were divided into an intervention group ($n = 11$; 29.5 ± 10.0 years; 72.8 ± 6.6 kg; 1.83 ± 0.08 m) and a control group ($n = 9$; 27.4 ± 7.2 years; 70.2 ± 6.4 kg; 1.77 ± 0.04 m). During week 0, 20, and 40, each subject completed 3 assessments: physiology ($_{\text{V}}$2 mmol·L^{-1} BLa, $_{\text{V}}$2 mmol·L^{-1} BLa [blood lactate], $_{\text{V}}$4 mmol·L^{-1} BLa, RE, $_{\text{V}}\dot{\text{V}}\text{O}_2$max, $\dot{\text{V}}\text{O}_2$max), strength (1 repetition maximum back squat; countermovement jump and 0.3 m drop jump), and body composition (body mass, fat mass, overall lean, and leg lean). The intervention group showed significant improvements in maximal and reactive strength qualities, RE, and $_{\text{V}}\dot{\text{V}}\text{O}_2$max, at weeks 20 ($p \leq 0.05$) and 40 ($p \leq 0.05$). The control group showed no significant changes at either time point. There were no significant changes in body composition variables between or within groups. This study demonstrates that 40 weeks of strength training can significantly improve maximal and reactive strength qualities, RE, and $_{\text{V}}\dot{\text{V}}\text{O}_2$max, without concomitant hypertrophy, in competitive distance runners.

Key Words running economy, $_{\text{V}}\dot{\text{V}}\text{O}_2$max, distance running

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Introduction

Performance in distance running is multifaceted; relying on an intricate interaction of physiological, biomechanical, and psychological factors. Even within the physiological domain, there is a complex synergy between the central and peripheral system's role in facilitating adenosine triphosphate (ATP) regeneration for sustained running locomotion (4). Since the original work of Hill and Lupton (15), there has been an abundance of research studies investigating the role of maximal oxygen consumption ($\dot{\text{V}}\text{O}_2$max) in distance running. Research has shown strong relationships between $\dot{\text{V}}\text{O}_2$max and middle- (800 m, $r = 0.75$) and long-distance (marathon, $r = 0.78$) performance in heterogeneous groups (17,37). Because of this, maximal oxygen uptake ($\dot{\text{V}}\text{O}_2$max) protocols have been traditionally used in the laboratory to monitor and predict the performance potential of both middle- and long-distance runners. However, at elite long-distance level (marathon time <2 hours 30 minutes), the relationship between $\dot{\text{V}}\text{O}_2$max and performance is weak ($r = 0.01$), and it is likely that this relationship is negligible at "world-class" standard (marathon time <2 hours 10 minutes) (37). A high $\dot{\text{V}}\text{O}_2$max (>70 ml·kg^{-1}·min^{-1}) may be a prerequisite to be an elite distance runner, but additional physical qualities are needed to succeed at this level. Key performance indicators such as running economy (RE), velocity at maximal oxygen uptake ($_{\text{V}}\dot{\text{V}}\text{O}_2$max), and anaerobic function (velocity during maximum anaerobic running test [$_{\text{V}}$MART] and max velocity sprinting) have been established as superior markers of success in these elite populations (5).

Running economy is defined as the metabolic cost to cover a given distance at a constant velocity (36). Running economy represents the ability of a runner to translate cellular energy production into running locomotion and is normally expressed as the volume of oxygen consumption per unit of body mass required to run a kilometer (ml·kg^{-1}·km^{-1}) (36). Running economy has been shown to be a stronger indicator of performance than $\dot{\text{V}}\text{O}_2$max alone within elite homogenous populations, with interindividual variability ranging between 20 and 30% (27). The east African dominance in distance running has been partly attributed to their superior economy (36). Running economy is determined by the athlete's physiology, anthropometrics, biomechanics, and environment; however, improvements in RE may be difficult to obtain in trained runners, and therefore, any novel training modality that results in marginal improvements may be crucial for success (2,3).

The velocity attained at $\dot{V}O_2max$ ($_V\dot{V}O_2max$) is a "functional" expression of maximal oxygen consumption in velocity units ($km \cdot h^{-1}$). $_V\dot{V}O_2max$ is a composite of both maximal oxygen consumption and economy. Because of this, the variable has shown to be strongly associated with elite middle- ($r = 0.71$) (17) and long-distance ($r = 0.89–0.94$) (27) running performance. Although $\dot{V}O_2max$ may remain stable throughout an elite distance runner's career, research has shown that the velocity at $\dot{V}O_2max$ can improve by approximately 14% (19). This demonstrates that elite distance runners can improve their ability to translate maximal aerobic energy production into faster running velocities. During middle-distance events (800 and 1,500 m), or sprint finishes in long-distance events where velocities exceed $_V\dot{V}O_2max$, the contribution of the anaerobic energy system is increased (27). Endurance-specific "muscle power" is the ability of the neuromuscular system to rapidly produce force after a sustained period of high-intensity exercise (high glycolytic and oxidative energy demand) (28). This ability may be the differentiating factor for succeeding in elite distance running (i.e., sprint finish). Therefore, rate of force development (RFD) is essential not only in short-distance events (i.e., 100, 200, and 400 m) but also in middle- and long-distance running. Consequently, in addition to cardiovascular capacity, limitations to elite distance running performance may be dictated by peripheral neuromuscular force production ability.

One training technique for improving rate of force production in athletes is strength training. Early work from Paavolainen et al. (29,30) demonstrated that the neuromuscular adaptations from strength training (i.e., musculotendinous stiffness, motor unit recruitment and synchronization, rate coding, intramuscular coordination and intermuscular coordination, and neural inhibition) (10,45) have the potential to improve performance in distance runners (44) by improving RE (2), $_V\dot{V}O_2max$, and/or anaerobic function (24). However, strength training is generally still an uncommon physical preparation modality in the distance running community. This is most likely due to the "hypertrophic" connotations associated with lifting weights, with distance runners inadvertently linking strength adaptations to increased musculature and body mass–which would potentially negatively affect relative physiological performance parameters (i.e., $\dot{V}O_2max$, RE). Nonetheless, a recent systematic review by Beattie et al. (5) in competitive distance runners reported that strength training can improve 3 km (2.7%, effect size [ES] = 0.13) (38) and 5 km time-trial performance (3.1%) (30), economy (4.0–8.1%, ES: 0.3–1.03) (6,21,24,29,33,38,40), $_V\dot{V}O_2max$ (1.2%, ES: 0.43–0.49) (6,24), and maximum anaerobic running velocity ($_V$MART) (3%) (24,30). However, Beattie et al.'s (5) review showed that the strength interventions in these studies were relatively short-term (~8 weeks), and used inadequate exercises (i.e., machine-based, isolated exercises) that may have limited optimal strength development of the leg musculature for distance running performance (41). Therefore, this study addressed for the strength and conditioning community, the uncertainty surrounding long-term adaptations to strength training in trained distance runners (1,500–10,000 m).

To our knowledge, the effects of a strength training intervention longer than 10 weeks, on $_V\dot{V}O_2max$ and RE in distance runners, is unknown. Therefore, the aim of this study was to investigate the effect of a 40-week (20-week preseason and 20-week in-season) strength training intervention on strength qualities (maximal and reactive strength), key physiology performance indicators ($_V\dot{V}O_2max$ and RE), and body composition in collegiate and national-level distance runners (1,500–10,000 m). The experimental approach to answer this research question was to conduct a 40-week longitudinal strength intervention study with a parallel control group, measuring physiological, strength, and body composition variables at weeks 0, 20, and 40. We hypothesized that a 40-week strength intervention in distance runners would result in significant changes in strength qualities (maximal and reactive strength), key physiology performance indicators ($_V\dot{V}O_2max$ and RE), and body composition.

METHODS

Experimental Approach to the Problem

To investigate the hypothesis of the study, a longitudinal and controlled experimental design was used to investigate the effect of a 40-week (20-week preseason and 20-week in-season) strength training intervention on strength qualities (maximal and reactive strength), key physiology performance indicators ($_V\dot{V}O_2max$ and economy), and body composition in collegiate and national-level distance runners (1,500–10,000 m). A 2-group, repeated measures (pretesting, midtesting, and posttesting) design was used. After an 8-week off-season, subjects were divided into the 2 groups based on their ability to adhere to the study conditions (i.e., time commitments and location relative to training facility). The 2 groups consisted of an intervention group (endurance training AND strength training: $n = 11$; 29.5 ± 10.0 years; 72.8 ± 6.6 kg; 1.83 ± 0.08 m) and a control group (endurance training ONLY: $n = 9$; 27.4 ± 7.2 years; 70.2 ± 6.4 kg; 1.77 ± 0.04 m). There were no significant differences between groups at baseline for all measures. All athletes and coaches were instructed not to deviate from their normal 1,500–10,000 m endurance training. It is known that the control group did not use any strength training as part of their normal training programme. Because of the extensive longitudinal nature of the study, endurance training (volume and intensity) was not controlled.

In addition to their endurance training, the intervention group strength trained twice a week during the preseason period (weeks 1–20, December–March, winter months), and once a week during the in-season "racing" period (weeks

20–40, April–July, summer months) (Figure 1). All strength sessions were coached by an experienced UK Strength & Conditioning Association (UKSCA) accredited coach (the lead author). Each strength session lasted approximately 60 minutes (Table 1).

Subjects

Thirty competitive collegiate and national-level distance runners (1,500–10,000 m) participated in the study; however because of unrelated injury and time commitment, 20 subjects ($n = 20$; 28.2 ± 8.6 years; 71.6 ± 6.6 kg; 1.80 ± 0.07 m) completed the study. The subjects had a mean maximum oxygen uptake ($\dot{V}O_2$max which is close to the British Association of Sport and Exercise Sciences (BASES) "national-level") of 61.3 ± 3.2 $ml \cdot kg^{-1} \cdot min^{-1}$, which is close to the BASES "national-level" physiological standard (65–75 $ml \cdot kg^{-1} \cdot min^{-1}$) for male distance runners (20). It is also important to note that all subjects had no strength training experience. All subjects were recruited through poster and email. After being informed of the benefits and potential risks of the investigation, each subject completed a health-screening questionnaire and signed an informed consent prior to participation in the study. All experimental procedures were ratified by the University of Limerick Research Ethics Committee in accordance with the provisions of the most recent Declaration of Helsinki.

Strength, Physiology, and Body Composition Assessment

During week 0, 20, and 40, each subject completed 3 assessment days: physiology, strength, and a body composition assessment day. All strength, physiology, and body composition assessments were undertaken at the same time of day to avoid diurnal variation in performance. There were 48 hours between each testing day. To control the effect of diet and physical readiness, each subject was asked to consume a habitual diet and avoid alcohol (<48 hours), limit caffeine ingestion (<4 hours), and avoid vigorous exercise (<24 hours) before assessments. For body composition assessment, participants reported to the laboratory after a 3-hour fast, having consumed 500 ml of water, 1 hour before measurement.

Strength Assessment. Before the strength assessment day, each subject performed a familiarization day to ensure habituation with the back squat, countermovement jump (CMJ), and drop jump tests. The familiarization day included the same protocol as the strength assessment day. Also, all subjects were familiarized with the physiological measurement equipment during the warm-up period before physiological measurements ($_{V}2\ mmol \cdot L^{-1}$ BLa, $_{V}4\ mmol \cdot L^{-1}$ BLa, RE, $_{V}\dot{V}O_2$max, $\dot{V}O_2$max) were taken. Before back squat 1 repetition maximum (RM) testing, each subject completed a 5-minute warm-up (self-myofascial release, stretching, and dynamic mobility exercises). After completion of the warm-up, subjects started the back squat 1 RM testing protocol to assess maximal strength (25). This protocol consisted of a warm-up of 10 repetitions at 50% of their (estimated) 1RM load, 5 × 70% 1RM, 3 × 80% 1RM, and 1 × 90% 1RM. Each participant's 1RM was estimated by the researcher based on the athlete's body mass, age, and sex (25). After the warm-up protocol, each subject had 3 attempts to determine their actual 1RM (with 3 minutes in between sets). To ensure safe conditions during testing, a box was set at the lowest depth the athlete could squat while keeping optimal lumbar spinal position. Therefore, squat depth was specific to each subject, and knee angles ranged from 90° to 120° flexion. Only trials in which the subject touched the box were considered successful lifts. The knee flexion angle was recorded to ensure the same squat depth during week 0, 20, and 40 assessments.

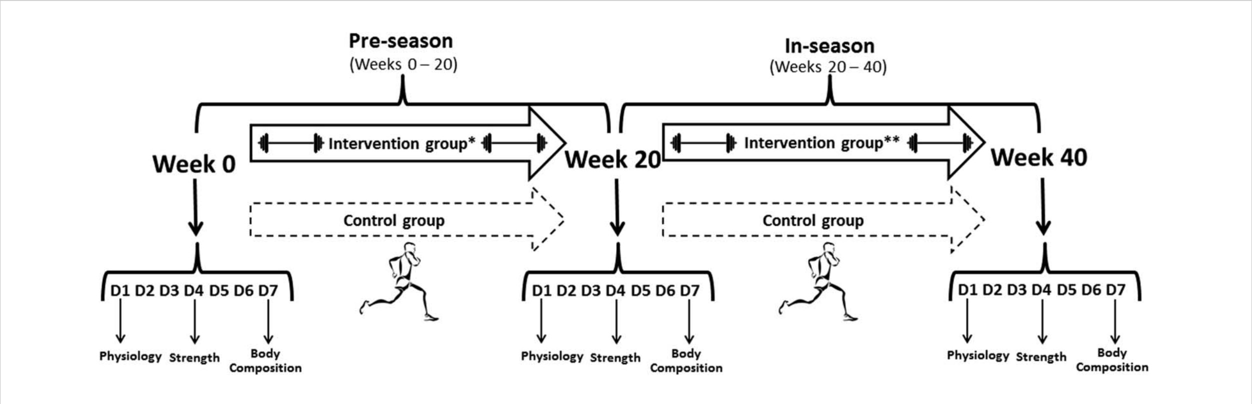

Figure 1. A schematic of the 40-week research design. Physiology: $_{V}2\ mmol \cdot L^{-1}$ BLa, $_{V}4\ mmol \cdot L^{-1}$ BLa, running economy, $_{V}\dot{V}O_2$max; strength: maximal strength (1 repetition maximum back squat), slow stretch-shortening cycle reactive strength (countermovement jump), and fast stretch-shortening cycle reactive strength (0.3 m drop jump reactive strength index); body composition: body mass, fat mass, overall lean, and leg lean. *2 × week strength training during preseason. **1 × week strength training during in-season.

Table 1. Preseason (2 × week) and in-season (1 × week) strength training programme.*†

Preseason (weeks 1–20)

Day 1 (heavy)		Block 1				Block 2				Block 3			
Strength quality	Week	1	2	3	4	5	6	7	8	9	10	11	12
Reactive strength (fSSC)	Pogo jumps	3 × 4	3 × 4	3 × 4	3 × 4	3 × 5	3 × 5	3 × 5	3 × 5	3 × 6	3 × 6	3 × 6	3 × 6
Maximum strength	Back squat	3 × 8	3 × 8	3 × 8	3 × 8	3 × 8	3 × 6	3 × 3	2 × 5‡	3 × 8	3 × 6	3 × 3	2 × 5‡
Assistance 1 (posterior)	RDL	2 × 10	2 × 10	3 × 10	3 × 10	3 × 10	3 × 8	3 × 6	2 × 12‡	3 × 10	3 × 8	3 × 6	2 × 12‡
Assistance 2 (SL)	Split squat	2 × 10	2 × 10	3 × 10	3 × 10	2 × 12	3 × 10	3 × 8	1 × 12	2 × 12	3 × 10	3 × 8	1 × 12

		Block 4				Block 5			
Strength quality	Week	13	14	15	16	17	18	19	20
Reactive strength (fSSC)	DJ 35 cm	3 × 5	3 × 5	3 × 5	3 × 5	3 × 5	3 × 5	3 × 5	3 × 5
Maximum strength	Back squat	3 × 8	3 × 6	3 × 3	2 × 5‡	3 × 5	3 × 3	5,3,2	2 × 5‡
Assistance 1 (posterior)	RDL	3 × 10	3 × 8	3 × 6	2 × 12‡	2 × 5	3 × 5	3 × 5	1 × 5‡
Assistance 2 (SL)	SL squat	1 × 5	2 × 5	3 × 5	1 × 5	2 × 5	3 × 6	3 × 7	1 × 5

Day 2 (light/medium)		Block 1				Block 2				Block 3			
Strength quality	Week	1	2	3	4	5	6	7	8	9	10	11	12
Reactive strength (sSSC)	CMJ	2 × 3	2 × 3	3 × 3	3 × 3	3 × 4	3 × 4	3 × 4	3 × 4	3 × 5	3 × 5	3 × 5	3 × 5
Maximum strength	Back squat	3 × 8	3 × 8	3 × 8	3 × 8	3 × 8	3 × 6	3 × 3	2 × 5‡	3 × 8	3 × 6	3 × 3	2 × 5‡
Assistance 1 (posterior)	RDL	2 × 10	2 × 10	3 × 10	3 × 10	3 × 10	3 × 8	3 × 6	2 × 10‡	3 × 10	3 × 8	3 × 6	2 × 10‡
Assistance 2 (SL)	Rev lunge	2 × 10	2 × 10	3 × 10	3 × 10	2 × 12	3 × 10	3 × 8	1 × 12	2 × 12	3 × 10	3 × 8	1 × 12

		Block 4				Block 5			
Strength quality	Week	13	14	15	16	17	18	19	20
Reactive strength (sSSC)	Cont. CMJ	3 × 5	3 × 5	3 × 5	3 × 5	3 × 6	3 × 6	3 × 6	3 × 6
Maximum strength	Back squat	3 × 8	3 × 6	3 × 3	2 × 5‡	3 × 5	3 × 3	5,3,2	2 × 5‡
Assistance 1 (posterior)	SL RDL	2 × 8	3 × 8	10,8,6	2 × 8‡	2 × 8	3 × 8	10,8,6	2 × 8‡
Assistance 2 (SL)	Skater squat	2 × 8	10,8,8	10,10,8	1 × 8	2 × 8	10,8,8	10,10,8	1 × 8

In-season (weeks 21–40)													
Day 1 (heavy)		Block 6				Block 7				Block 8			
Strength quality	Week	21	22	23	24	25	26	27	28	29	30	31	32
Reactive strength (fSSC)	DJ 45 cm	3 × 4	5 × 4 × 4	3 × 5	1 × 5	3 × 4	5 × 4 × 4	3 × 5	1 × 5	3 × 4	5 × 4 × 4	3 × 5	1 × 5
Explosive strength	Jump squat%	3 × 3	3 × 3	3 × 3	1 × 3	3 × 3	3 × 3	3 × 3	1 × 3	3 × 3	3 × 3	3 × 3	1 × 3
Maximum strength	Back squat	3 × 5	3 × 3	5,3,2	1 × 5‡	3 × 5	3 × 3	5,3,2	1 × 5‡	3 × 5	3 × 3	5,3,2	1 × 5‡
Assistance 1 (posterior)	SL RDL	1 × 8	2 × 6	3 × 5	1 × 5‡	1 × 8	2 × 6	3 × 5	1 × 5‡	1 × 8	2 × 6	3 × 5	1 × 5‡
Assistance 2 (SL)	SL squat	1 × 8	1 × 8	1 × 8		1 × 8	1 × 8	1 × 8		1 × 8	1 × 8	1 × 8	
Notes		Technique emphasis on ALL lifts				Progressively load if competent ‡deload on lifts, 50% of week 5/25 loads				Progressively load if competent ‡deload on lifts, 50% of week 9/29 loads			

In-season (weeks 21–40)									
Day 1 (heavy)		Block 9				Block 10			
Strength quality	Week	33	34	35	36	37	38	39	40
Reactive strength (fSSC)	DJ 45 cm	3 × 4	5,4,4	3 × 5	1 × 5	3 × 4	5,4,4	3 × 5	1 × 5
Explosive strength	Jump squat%	3 × 3	3 × 3	3 × 3	1 × 3	3 × 3	3 × 3	3 × 3	1 × 3
Maximum strength	Back squat	3 × 5	3 × 3	5,3,2	1 × 5‡	3 × 5	3 × 3	5,3,2	1 × 5‡
Assistance 1 (posterior)	SL RDL	1 × 8	2 × 6	3 × 5	1 × 5‡	1 × 8	2 × 6	3 × 5	1 × 5‡
Assistance 2 (SL)	SL squat	1 × 8	1 × 8	1 × 8		1 × 8	1 × 8	1 × 8	
Notes		Progressively load if competent ‡deload on lifts, 50% of week 13/33 loads				Progressively load if competent ‡deload on lifts, 50% of week 17/37 loads			

*fSSC = fast stretch-shortening cycle; DJ 35 cm = drop jump from 35 cm; RDL = Romanian deadlift; SL = single-leg; Cont. CMJs = continuous countermovement jumps; Rev lunge = reverse lunge; jump squat% = jump squat with 20% of 1 repetition maximum back squat; SSC = stretch-shortening cycle; sSSC = slow stretch-shortening cycle.

3 × 4: 3 sets of 4 repetitions. 5,3,2 = 1 × 5, 1 × 3, 1 × 2.

†Preseason (weeks 1–20): maximum strength emphasis and developmental reactive strength (day 1: heavy maximum strength and fast SSC reactive strength focus; day 2: light/medium maximum strength and slow SSC reactive strength focus. There were 48 hours of recovery between day 1 and day 2). In-season (weeks 21–40): reactive strength and explosive strength emphasis, maximum strength maintenance.

Approximately 10 minutes after the 1RM back squat, subjects started the reactive strength assessment. Reactive strength movements are categorized depending on their slow or fast stretch-shortening cycle (SSC) characteristics (34). Slow SSC function was assessed through a CMJ, and fast SSC function was assessed through a 0.3-m drop jump. Both jumps were performed on a force platform (AMTI OR6-5; AMTI, Watertown, MA, USA) operating at a sampling rate of 1,000 Hz. Each subject addressed the CMJ in a standing position while keeping their hands on their hips to restrict arm movement. After instruction, subjects initiated the jump through a downward countermovement. All subjects were instructed to choose a depth that they felt would maximize jump height. For each trial, the subject was told to "jump as high as possible." Two minutes recovery was given between jumps. Three jumps were performed with the highest value used for analysis. After CMJs, subjects performed 3 individual drop jumps from a 0.3 m box onto a force platform. Each jump was separated by 2 minutes of recovery. Before each drop jump, the subject was instructed to step forward off the box, and on contact with the platform to immediately jump as high as possible. They were also instructed to keep their hands on their hips to restrict arm movement. Three drop jumps were performed with the highest reactive strength index (RSI = jump height [m]/contact time [s]) used for analysis.

Physiology Assessment. All physiological variables ($\dot{V}O_2$max, $_V\dot{V}O_2$max, RE, $_V2$ mmol·L^{-1}, and $_V4$ mmol·L^{-1} BLa) were determined during a 2-part treadmill protocol (H/P/Cosmos Pulsar treadmill; H/P/Cosmos Sports & Medical gmbh, Nubdorf, Germany). The treadmill was set at 1% gradient throughout the protocol. Oxygen consumption was determined continuously using a gas analyzer (Moxus, Model DC-3A; AEI Technologies, Naperville, IL, USA). Before each test, the metabolic cart was calibrated for air flow, and the gas analyzer was calibrated against a certified gas mixture. Before the protocol, each subject warmed up on the treadmill for 10 minutes. The first 5 minutes was completed at a velocity that was 7 km·h^{-1} slower than their estimated 4 mmol·L^{-1} blood lactate velocity ($_V4$ mmol·L^{-1} BLa), and the second 5 minutes at a speed that was 6 km·h^{-1} slower than $_V4$ mmol·L^{-1}. After the warm-up, a resting BLa sample was taken using a Lactate Pro Analyser (Lactate Pro, ARKAY Europe, Amstelveen, the Netherlands).

The first part of the treadmill protocol consisted of a 20-minute submaximal "step" test. The step test consisted of 5, 4-minute stages. Each stage was 4 minutes in length to allow for steady-state oxygen consumption, heart rate, and BLa levels. The first stage was performed at a velocity 5 km·h^{-1} slower than the subject's estimated $_V4$ mmol·L^{-1}. Each stage increased by 1 km·h^{-1} every 4 minutes, so the final stage was at estimated $_V4$ mmol·L^{-1} BLa. Heart rate (Polar s610 HR Monitor, Kempele, Finland) and $\dot{V}O_2$ values used for analysis were the mean values from the last minute of each submaximal stage. Running economy, the oxygen cost of running a kilometer at a specific velocity was calculated using the following formula: $\dot{V}O_2$ (ml·kg^{-1}·min^{-1})/(speed [km·h^{-1}]/60). After every stage, the subject stepped off the treadmill for 15–20 seconds to allow earlobe blood samples to be taken for determination of BLa concentration. The velocity at 2 mmol·L^{-1} and 4 mmol·L^{-1} of blood lactate were calculated using Lactate-E 2.0 Software (26). The subjects rested for 10 minutes after the submaximal treadmill protocol.

The second part of the treadmill protocol consisted of a maximal "ramp" test until exhaustion. The initial velocity of the treadmill was set at 2 km·h^{-1} slower than the subjects' estimated $_V4$ mmol·L^{-1} BLa stage velocity, and increased by 0.5 km·h^{-1} every 30 seconds until exhaustion. To ensure that $\dot{V}O_2$max was reached, each subject had to meet the following criteria: respiratory exchange ratio >1.00; heart rate within 5% of their age-predicted maximum; and/or BLa of 8–10 mM. Maximal oxygen uptake was taken as the highest 60 seconds $\dot{V}O_2$ value. Velocity at $\dot{V}O_2$max was taken as the minimum velocity that elicited $\dot{V}O_2$max. After the maximal ramp test, the subject cooled down for 10 minutes at a velocity that was 7 km·h^{-1} slower than their estimated $_V4$ mmol·L^{-1} velocity.

Body Composition Assessment. A Lunar iDXA (dual-energy X-ray absorptiometry) scanner (GE Healthcare, Chalfont St Giles, Bucks., United Kingdom) with enCORE 2007 v.11 software was used to perform total body scans. Each subject was instructed to refrain from exercise for 12 hours, to refrain from eating for 3 hours, and to consume 500 ml of water 1 hour before testing. Each subject emptied their bladder immediately before the measurement. Participants were positioned on the scanner bed according to the manufacturer's recommendations and instructed to remain as still as possible for the duration of the scan.

Strength Programme

The lead author, an experienced UKSCA accredited S&C coach, designed and coached the strength programme over the 40 weeks. The subcategories for strength training in this programme included (a) maximal strength that targets maximal force development through high-load, low-velocity movements (e.g., back squats); (b) explosive strength (strength speed and speed strength) that improves RFD and maximal power output through medium to high-load, high-velocity movements (e.g., jump squats); and (c) reactive strength that targets musculotendinous stiffness and SSC function through low-load, high-velocity exercises (e.g., pogo jumps, drop jumps) (12).

The programme's aim can simplistically be described as to "*increase the athlete's motor potential and gradually improve their capacity to use (this) motor potential during the performance of specific competition exercises*" (41). Reactive strength is the most important strength quality for short-, middle- and

TABLE 2. Physiological, strength, and body composition values for weeks 0, 20, and 40.

	Mean ± *SD* (95% CI)					
	W0		W20		W40	
	Strength	Control	Strength	Control	Strength	Control
Physiology						
$_{V}$2 mmol·L^{-1} Bla (km·h^{-1})	14.47 ± 1.25 (13.7–15.2)	15.40 ± 1.23 (14.6–16.2)	14.78 ± 1.45 (13.9–15.6)	15.78 ± 1.29 (14.9–16.6)	14.70 ± 1.19 (14.0–15.4)	15.76 ± 1.49 (14.8–16.7)
$_{V}$4 mmol·L^{-1} BLa (km·h^{-1})	16.46 ± 1.20 (15.8–17.2)	17.10 ± 1.04 (16.4–17.8)	16.80 ± 1.43 (16.0–17.6)	17.73 ± 1.09 (17.0–18.4)	16.81 ± 1.30 (16.0–17.6)	17.49 ± 0.93 (16.9–18.1)
$_{V}\dot{V}O_2$max (km·h^{-1})	20.15 ± 0.91 (19.6–20.7)	21.17 ± 1.03 (20.5–21.8)	20.85 ± 1.18* (20.2–21.5)	21.56 ± 1.24 (20.7–22.4)	20.95 ± 0.96† (20.4–21.5)	21.50 ± 1.03 (20.8–22.2)
Economy (ml·kg^{-1}·km^{-1})	208.5 ± 12.0 (201–216)	203.4 ± 11.0 (196–211)	198.0 ± 9.0* (193–203)	199.9 ± 12.0 (192–208)	201.2 ± 11.1 (193–205)	199.0 ± 9.3 (195–208)
$\dot{V}O_2$max (ml·kg^{-1}·min^{-1})	59.6 ± 2.5 (58.1–61.1)	63.2 ± 2.9 (61.3–65.1)	60.0 ± 3.0 (58.2–61.8)	64.0 ± 4.0 (61.4–66.6)	61.6 ± 5.2 (58.5–64.7)	65.0 ± 3.2 (62.9–67.1)
Strength						
1RM Back Squat (kg·kg^{-1} BW)	1.18 ± 0.18 (1.07–1.29)	1.43 ± 0.25 (1.27–1.59)	1.42 ± 0.22†‡ (1.29–1.55)	1.50 ± 0.26 (1.33–1.67)	1.39 ± 0.24‡ (1.25–1.53)	1.47 ± 0.24 (1.31–1.63)
Countermovement jump (m)	0.26 ± 0.06 (0.22–0.30)	0.27 ± 0.03 (0.25–0.29)	0.29 ± 0.06* (0.25–0.33)	0.30 ± 0.03 (0.28–0.32)	0.29 ± 0.06* (0.25–0.33)	0.28 ± 0.02 (0.27–0.29)
Drop jump 30 cm (RSI)	1.10 ± 0.28 (0.93–1.27)	1.28 ± 0.31 (1.08–1.48)	1.18 ± 0.26‡ (1.03–1.33)	1.26 ± 0.18 (1.14–1.38)	1.26 ± 0.33‡ (1.06–1.46)	1.16 ± 0.12 (1.08–1.24)
Body composition						
Body mass (kg)	73.0 ± 6.6 (69.1–76.9)	70.4 ± 6.7 (66.0–74.8)	74.1 ± 4.0 (71.7–76.5)	70.3 ± 6.7 (65.9–74.7)	71.7 ± 7.3 (67.4–76.0)	70.6 ± 6.1 (66.6–74.6)
Body fat (kg)	10.6 ± 2.5 (9.1–12.1)	10.0 ± 3.1 (8.0–12.0)	10.3 ± 2.4 (8.9–11.7)	8.7 ± 2.5 (7.1–10.3)	10.3 ± 2.4 (8.9–11.7)	9.7 ± 2.6 (8.0–11.4)
Overall lean (kg)	60.8 ± 7.1 (56.6–65.0)	57.6 ± 5.4 (54.1–61.1)	60.6 ± 3.5 (58.5–62.7)	58.4 ± 5.6 (54.7–62.1)	58.2 ± 6.8 (54.2–62.2)	57.6 ± 4.7 (54.5–60.7)
Leg lean (kg)	21.9 ± 3.1 (20.1–23.7)	21.6 ± 2.4 (20.0–23.2)	22.0 ± 1.6 (21.1–22.9)	21.4 ± 2.3 (19.9–22.9)	21.0 ± 2.7 (19.4–22.6)	21.2 ± 2.0 (19.9–22.5)

	p and magnitude (*d*)					
	W0–20		W20–40		W0–40	
	Strength	Control	Strength	Control	Strength	Control
Physiology						
$_{V}$2 mmol·L^{-1} Bla (km·h^{-1})	$p > 0.05$ small (0.2)	$p > 0.05$ small (0.3)	$p > 0.05$ trivial (0.0)	$p > 0.05$ trivial (0.0)	$p > 0.05$ small (0.2)	$p > 0.05$ small (0.3)
$_{V}$4 mmol·L^{-1} BLa (km·h^{-1})	$p > 0.05$ small (0.2)	$p > 0.05$ moderate (0.6)	$p > 0.05$ trivial (0.0)	$p > 0.05$ small (0.2)	$p > 0.05$ small (0.3)	$p > 0.05$ small (0.4)

(continued on next page)

$_{\text{V}}\dot{V}O_2$max (km·h^{-1})	$p > 0.05$ moderate (0.7)	$p > 0.05$ small (0.3)	$p > 0.05$ trivial (0.1)	$p > 0.05$ trivial (0.0)	$p > 0.05$ moderate (0.9)	$p > 0.05$ small (0.3)
Economy (ml·kg^{-1}·km^{-1})	$p = 0.01$ moderate (1.0)	$p > 0.05$ small (0.3)	$p > 0.05$ small (0.3)	$p > 0.05$ trivial (0.1)	$p = 0.183$ moderate (0.6)	$p > 0.05$ small (0.5)
$\dot{V}O_2$max (ml·kg^{-1}·min^{-1})	$p = 0.013$ trivial (0.1)	$p > 0.05$ small (0.3)	$p > 0.05$ small (0.4)	$p > 0.05$ small (0.3)	$p = 0.003$ small (0.5)	$p > 0.05$ moderate (0.6)
Strength						
1RM back squat (kg·kg^{-1} BW)	$p = 0.001$ large (1.2)	$p > 0.05$ small (0.3)	$p > 0.05$ trivial (0.1)	$p > 0.05$ trivial (0.1)	$p = 0.052$ moderate (0.7)	$p > 0.05$ small (0.2)
Countermovement jump (m)	$p > 0.05$ small (0.5)	$p > 0.05$ moderate (0.9)	$p > 0.05$ trivial (0.6)	$p > 0.05$ moderate (0.6)	$p > 0.05$ moderate (0.6)	$p > 0.05$ small (0.5)
Drop jump 30 cm (RSI)	$p > 0.05$ small (0.3)	$p > 0.05$ trivial (0.1)	$p > 0.05$ small (0.3)	$p > 0.05$ moderate (0.7)	$p > 0.05$ small (0.5)	$p > 0.05$ small (0.5)
Body composition						
Body mass (kg)	$p > 0.05$ small (0.2)	$p > 0.05$ trivial (0.0)	$p > 0.05$ small (0.4)	$p > 0.05$ trivial (0.1)	$p > 0.05$ small (0.2)	$p > 0.05$ trivial (0.0)
Body fat (kg)	$p > 0.05$ trivial (0.1)	$p > 0.05$ small (0.5)	$p > 0.05$ trivial (0.0)	$p > 0.05$ small (0.4)	$p > 0.05$ trivial (0.0)	$p > 0.05$ small (0.4)
Overall lean (kg)	$p > 0.05$ trivial (0.0)	$p > 0.05$ small (0.2)	$p > 0.05$ small (0.4)	$p > 0.05$ trivial (0.0)	$p > 0.05$ small (0.4)	$p > 0.05$ trivial (0.0)
Leg lean (kg)	$p > 0.05$ trivial (0.0)	$p > 0.05$ trivial (0.1)	$p > 0.05$ small (0.4)	$p > 0.05$ trivial (0.1)	$p > 0.05$ small (0.3)	$p > 0.05$ small (0.2)

*Significantly different from week 0 value, $p \leq 0.05$.
†Significantly different from week 0 value, $p < 0.01$.
‡Significantly different from control group, $p \leq 0.05$.

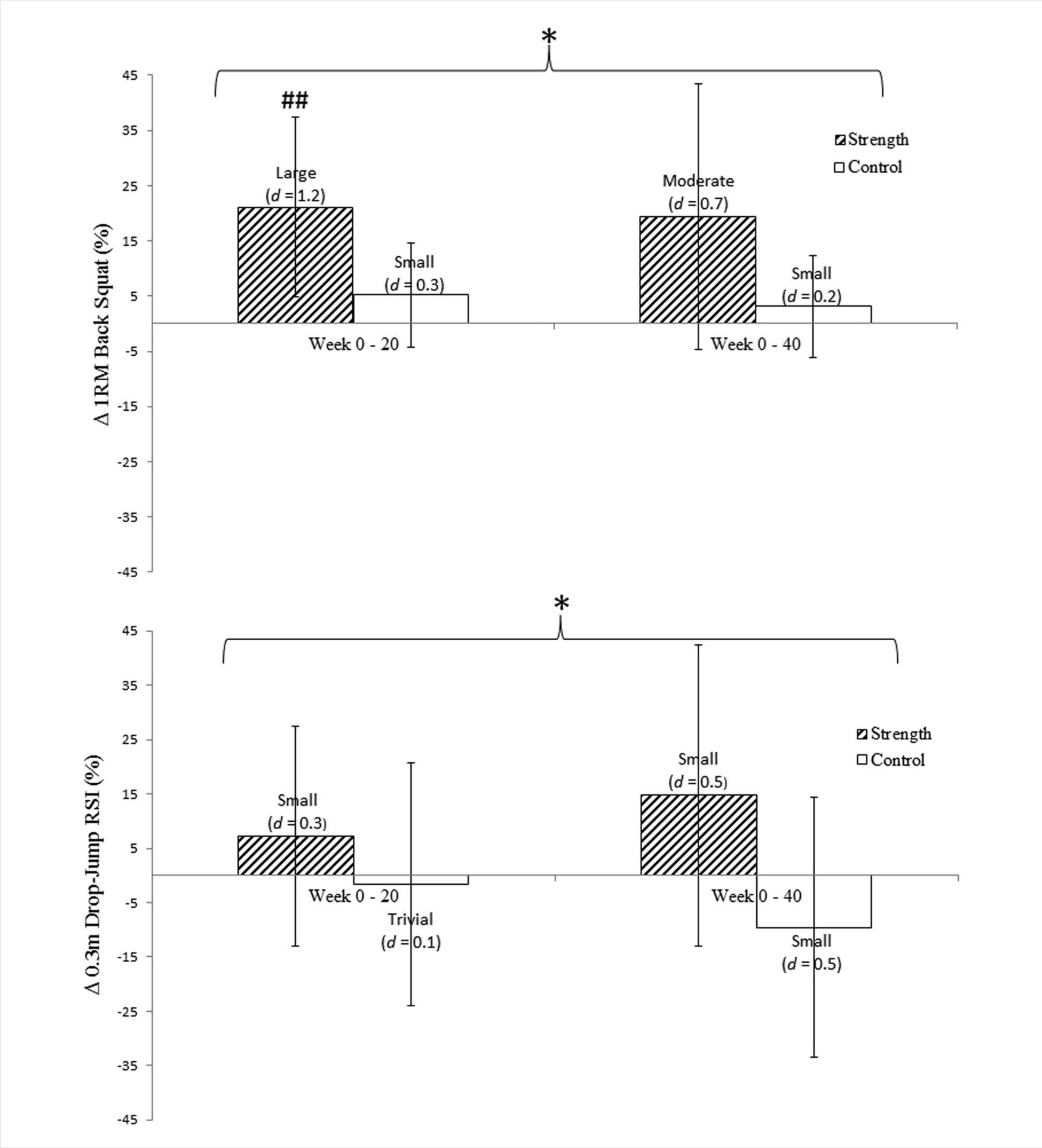

Figure 2. Maximum strength (1RM back squat) and fast stretch-shortening cycle reactive strength (RSI) percentage change. RM = repetition maximum; RSI = reactive strength index. * Significantly different from control group, $p < 0.05$; # significantly different from week 0 value, $p < 0.05$, ## significantly different from week 0 value, $p < 0.01$.

long-distance running events (42). The kinematic and kinetic characteristics of "fast" SSC reactive strength exercises (i.e., knee and hip joint displacement, elastic musculotendinous force production) are similar to those of running. However, during the first 20 weeks (preseason, December–March), the primary focus of the programme was maximal strength development, with a secondary focus on developmental reactive strength training (Table 1). There were 2 strength sessions per week with at least 48 hours of recovery between sessions during the preseason period. The rationale for a "general" maximal strength emphasis is that (a) there is a positive correlation between relative maximum strength

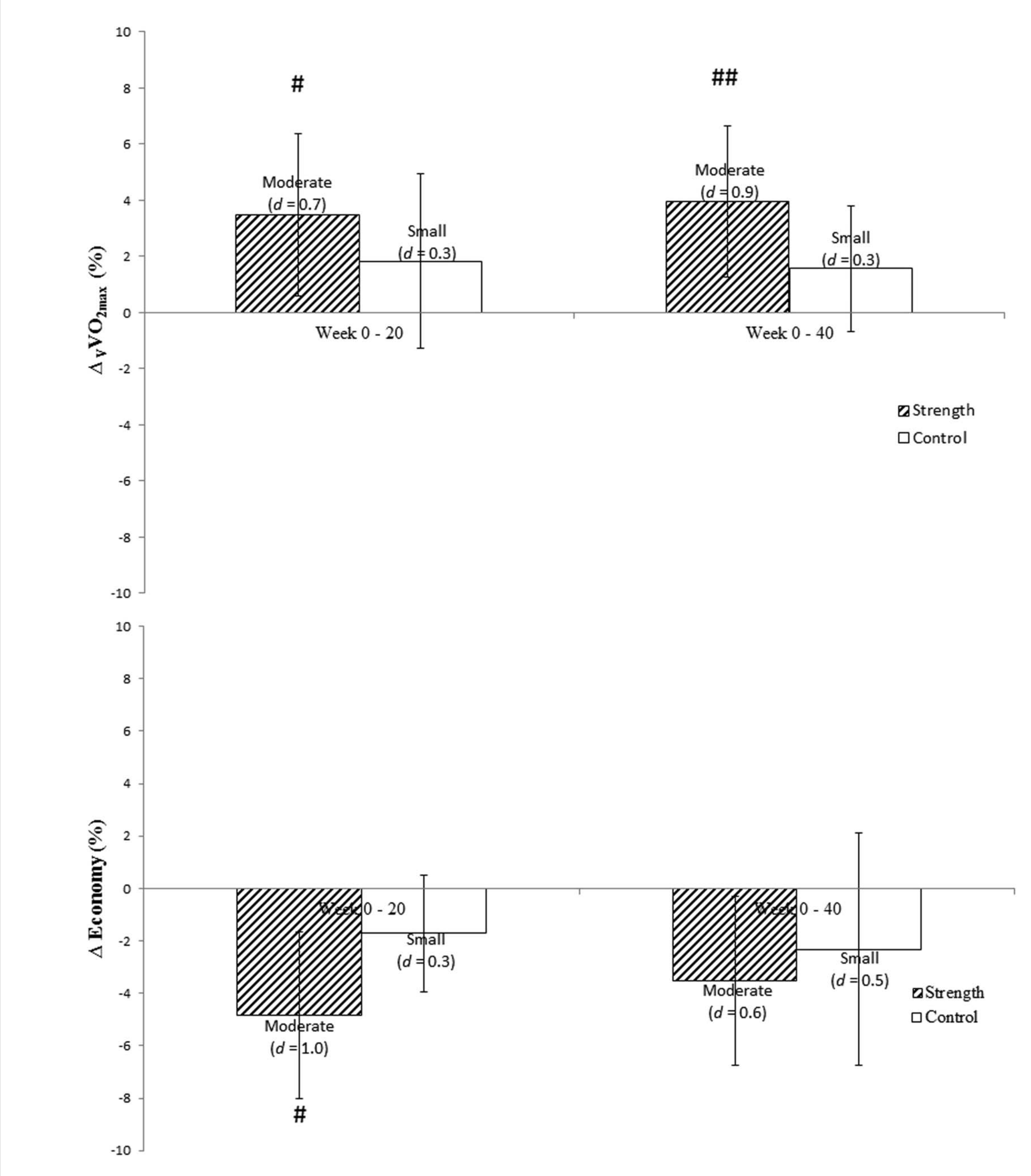

Figure 3. Velocity at $\dot{V}O_2$max and economy percentage change. * Significantly different from control group, $p < 0.05$; # significantly different from week 0 value, $p < 0.05$, ## significantly different from week 0 value, $p < 0.01$.

and reactive strength levels in athletes ($r = 0.63$) (11), (b) a maximum strength programme can concurrently improve maximal strength, explosive, and sSSC reactive strength qualities in relatively "weak" athletes (7), (c) maximum strength training improves stiffness (K_{leg}) in relatively weak athletes (8), and (d) relatively "strong" athletes adapt quicker to power training when compared with the "weaker" athletes (9).

During the in-season racing period (weeks 20–40, April–July), after an increased level of maximum strength had been attained, the primary emphasis of the programme changed to reactive and explosive strength development, with the secondary focus on maintenance of maximal strength adaptations. The frequency of strength sessions decreased to 1 per week during the in-season racing period.

Assistance work throughout the 40 weeks consisted of either single-leg squat (e.g., split squat, reverse lunge, and single-leg squat) or single-leg deadlift variations (e.g., single-leg Romanian deadlift) in the 5–12 repetition range to target (a) additional strength development through the "submaximal effort" method (45) and (b) gluteal strength and femoral control for knee stability (43). Supplementary gluteal and abdominal strength work was performed during the warm-up and "core circuit" at the end of each session. The strength programme was designed and developed from the works of Haff and Nimphius (12), Rippetoe and Baker (31), Verkhoshanky and Verkhoshanky (41), and Zatsiorsky and Kraemer (45).

Statistical Analyses

Independent variables were defined in terms of the different interventions (strength vs. control) and the 3 measurement points (pretest vs. midtest vs. posttest). The dependent variables were strength (maximum strength: 1RM back squat; slow SSC reactive strength: CMJ; fast SSC reactive strength: 0.3 m drop jump), physiology (2 and 4 mmol·L^{-1} BLa LT, $\dot{V}O_2$max, $_V\dot{V}O_2$max, and economy), and body composition (body mass, body fat, overall lean, and leg lean). All data sets are presented as mean ± *SD* or percentage change. To test for differences between groups at week 0, an independent *t*-test was used. For each group, variables (physiology, strength, and body composition) at week 0, week 20, and week 40 were compared using a 1-way repeated-measures analysis of variance (ANOVA). To test for differences between groups, 2-way repeated-measures ANOVA was used. Homogeneity of variance was evaluated using Mauchly's test of sphericity, and when violated, the Greenhouse-Geisser adjustment was used. To determine the magnitude of within-group change in variables, a Cohen's *d* ES was performed. The criteria to interpret the magnitude of the ES were 0.0–0.2 trivial, 0.2–0.6 small, 0.6–1.2 moderate, 1.2–2.0 large, and >2.0 very large (16). The level of significance was set at $p \leq 0.05$. IBM SPSS Statistics 22 software (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY, USA) was used for all statistical calculations. Reliability (coefficient of variation %; intraclass correlation coefficient) values for back squat 1RM (<4.3%; 0.91–0.99) (23), CMJ (<6.5%; 0.83–0.99) (23), 0.3 m drop jump RSI (<5%; >0.90) (22), submaximal and maximal $\dot{V}O_2$ (<2.4%), $_V$4 mmol·L^{-1} BLa (<6%), and $_V\dot{V}O_2$max (<2.4%) (32) are all within acceptable ranges.

RESULTS

There were no significant differences between the strength and control group at baseline (week 0) with respect to strength, physiological, and body composition variables (Table 2).

Strength

No significant differences were observed for any strength measures between the intervention and control groups at baseline. The change in absolute maximal strength in the intervention group (85.7 ± 14.7 kg → 99.3 ± 19.0 kg) was

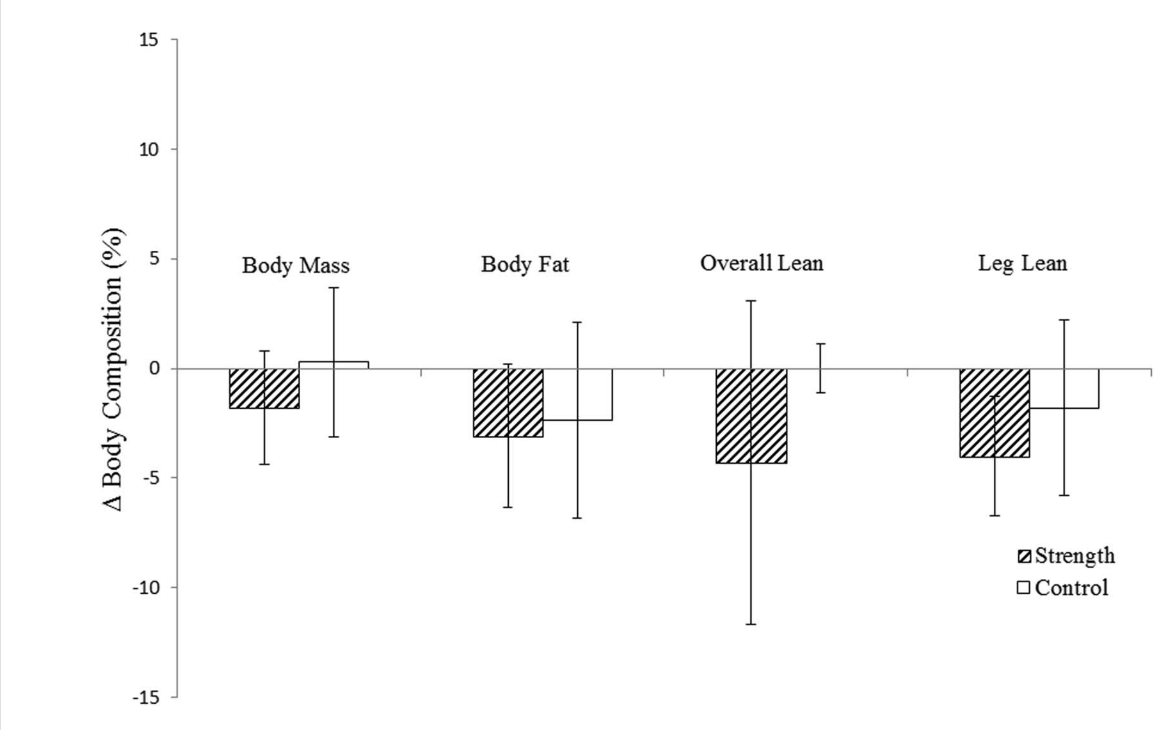

Figure 4. Body composition (body mass, body fat, overall lean, and leg lean) percentage change.

not significantly different to the change in the control group (100.0 ± 18.4 kg → 101.6 ± 17.1 kg) throughout the 40 weeks ($p = 0.116$) (Figure 2). However, the change in relative maximum strength (1RM back squat) in the intervention group was significantly different to that in the control group throughout the 40 weeks ($p = 0.039$). Specifically, there was a 19.3 ± 24.1% increase in the intervention group maximum strength from week 0 to week 40 ($d = 0.7$, $p = 0.052$), largely accounted for by week 0–20 increases ($d = 1.2$, $p = 0.001$). The control group had a 3.1 ± 9.2% increase in maximum strength from week 0–40 ($d = 0.2$, $p > 0.05$); however, these changes were not significantly different. There was a significant 12.7 ± 13.2% increase in sSSC reactive strength from week 0 to week 40 ($d = 0.6$, $p = 0.007$), largely accounted for by week 0 to week 20 increases (11.2 ± 15.2%; $d = 0.5$, $p = 0.009$). The change in sSSC reactive strength in the intervention group was not significantly different to that in the control group. The change in fast stretch-shortening cycle (fSSC) reactive strength (drop jump RSI) in the intervention group was significantly different to that in the control group ($p = 0.035$). Specifically, there was a 7.2 ± 20.1% increase in fSSC reactive strength in the intervention group from week 0 to week 20 ($d = 0.3$, $p = 0.596$), and a 14.7 ± 27.8% increase from week 0 to week 40 ($d = 0.5$, $p = 0.155$). However, in the control group, fSSC reactive strength deteriorated by 1.6 ± 22.4% from week 0 to week 20 ($d = 0.9$, $p > 0.05$), and by 9.5 ± 24.0% from week 0 to week 40 ($d = 0.5$, $p = 0.793$).

Physiology

No significant differences were observed for any physiological measures between the intervention and control groups at week 0. Throughout the 40-week intervention period, the increases in $_{v}2\ \text{mmol}\cdot\text{L}^{-1}$ BLa, $_{v}4\ \text{mmol}\cdot\text{L}^{-1}$ BLa, and $\dot{V}O_2max$ for both intervention and control groups were not significant (all $p > 0.05$) (Figure 3). There was a 3.5 ± 2.9% increase in $_{v}\dot{V}O_2max$ in the intervention group from week 0 to week 20 ($d = 0.7$, $p = 0.013$), and a 4.0 ± 3.1% increase from week 0 to week 40 ($d = 0.9$, $p = 0.003$). The control group demonstrated no significant increase from week 0 to week 20 ($d = 0.3$, $p = 0.579$) or week 0 to week 40 ($d = 0.3$, $p = 0.507$). There was a 3.5 ± 3.2% increase in RE in the intervention group from week 0 to week 40 ($d = 0.6$, $p = 0.183$), largely accounted for by week 0–20 increases ($d = 1.0$, $p = .01$). The control group had a 1.7 ± 2.2% increase from week 0 to week 20 ($d = 0.3$, $p = 0.648$), and a 2.3 ± 4.4% increase from week 0 to week 40 ($d = 0.5$, $p = 0.353$). These changes were not significantly different from week 0 values.

Body Composition

No significant differences were observed for any body composition measures (body mass, fat, overall lean, and leg lean) between intervention and control groups at week 0. Over the 40-week intervention period, there were no significant changes in body composition variables between or within groups (Figure 4).

DISCUSSION

The aim of this study was to investigate the effect of a 40-week strength training intervention on key physiological performance indicators, strength, and body composition in competitive distance runners. The main finding of this study was that strength training can significantly improve strength (maximal and reactive strength) and key physiological performance indicators, specifically RE and $_{v}\dot{V}O_2max$, in competitive distance runners. Interestingly, the improvements in strength, RE, and $_{v}\dot{V}O_2max$ were attained without significant changes in body composition (body mass, fat, and lean tissue mass). These results strongly support the application of strength training within the distance running community; demonstrating that to optimize endurance performance, strength training should be a vital component in the physical preparation of distance runners.

Economy and $_{v}\dot{V}O_2max$

Running economy and $_{v}\dot{V}O_2max$ are accepted as the 2 most important performance indicators in elite distance running (5). Running economy represents the ability of a runner to translate energy production at a cellular level into running locomotion (36). An economical runner will use less energy for any given workload and spare vital reserves for maximal and supramaximal stages of competition (i.e., a sprint finish). Running economy is dictated by a complexity of factors such as volume and intensity of endurance training, nutrition, and environment (2). In this study, the strength training group displayed a significant 3.5 ± 3.2% improvement in economy from week 0 to week 40, largely accounted for by week 0 to week 20 increases (4.8 ± 3.2%). These improvements in RE occurred without significant changes in $_{v}2\ \text{mmol}\cdot\text{L}^{-1}$ BLa, $_{v}4\ \text{mmol}\cdot\text{L}^{-1}$ BLa, and $\dot{V}O_2max$. The control group showed no change in RE throughout the 40 weeks (Figure 3). The results support previous research that noted similar improvements (4.0–8.1%) in RE after strength training in competitive distance runners albeit in shorter time frames (6,21,24,29,33,38,40).

Velocity at $\dot{V}O_2max$ ($_{v}\dot{V}O_2max$) has strong associations with both middle- ($r = 0.71$) (17) and long-distance ($r = 0.89$–0.94) (27) performance in elite running populations. These relationships are most likely due to $_{v}\dot{V}O_2max$ being a composite variable of both economy and maximal oxygen consumption. Interestingly, the maximal anaerobic running test ($_{v}$MART) was found to be strongly associated with $_{v}\dot{V}O_2max$ ($r = 0.85$) and maximal velocity sprinting ($r = 0.96$) (30); emphasizing the anaerobic system's contribution in providing energy production for race velocities at, and above, $\dot{V}O_2max$ (28). In this study, the strength training group showed a significant improvement in $_{v}\dot{V}O_2max$ (3.5 ± 2.9%) during the first 20 weeks of strength training (week 0→20), and a significant (4.0 ± 3.1%) improvement throughout the 40 weeks (Figure 3). The control group however showed no significant changes in $_{v}\dot{V}O_2max$ throughout the 40 weeks. The change in $_{v}\dot{V}O_2max$ in the strength group most likely resulted from an accumulation of improvements in economy (3.5%), $\dot{V}O_2max$ (3.4%), and potentially other anaerobic factors that were not assessed in this study (i.e., $_{V}$MART and maximum velocity sprinting). The results support the work of Mikkola et al. (24) and Berryman et al. (6) who found similar improvements (1.2–4.2%) in $_{V}\dot{V}O_2max$ in competitive distance runners after an 8-week strength intervention.

Strength Qualities

Elite endurance running performance is not only influenced by cardiopulmonary factors that dictate oxygen transport and utilization, but also peripheral aspects relating to neuromuscular force production. Reactive strength is the most important strength quality in middle- and long-distance running events, as athletes need to have proficient leg musculotendinous stiffness and SSC function to rapidly absorb and use the elastic energy during each stance-phase ground contact (42). Because of this, the primary aim of the strength programme in this study was to increase the subject's reactive strength ability over the 40-week intervention period. However, during the preseason period (week 0→20), the author designed the programme to focus on maximal strength development (see "Strength Programme" in Methods for rationale), with a secondary focus on reactive strength (Table 1). This study showed that a maximal strength–emphasized programme in competitive distance runners resulted in a significant increase in sSSC reactive strength (11.2 ± 15.2%), an increase in fSSC reactive strength (7.2 ± 20.1%), and a significant increase in maximal strength (21.1 ± 16.3%) throughout the preseason period (Figure 2).

During the in-season period (week 20→40), the primary emphasis of the programme shifted toward reactive strength development (especially fSSC), with the secondary focus on maintenance of maximal strength. Because the intervention group increased their level of maximal strength at the end of the preseason training ($1.18 \pm 0.18 \rightarrow 1.42 \pm 0.22$ $kg \cdot kg^{-1}$ BW), this change in programming focus was deemed appropriate. This focus on plyometric development was reflected in the results as the intervention group increased their fSSC reactive strength by a further 6.8% throughout the racing season, while their maximal strength levels were maintained (Figure 2). Interestingly, the control group's fSSC reactive strength decreased by 9.4% throughout the 40-week period ($1.28 \pm 0.31 \rightarrow 1.16 \pm 0.12$ RSI). This highlights the importance of strength training to "maintain" reactive strength ability and musculotendinous elastic properties throughout the season.

Mechanisms

There are various potential mechanisms on how strength training can improve both economy and $_{V}\dot{V}O_2max$. Strength training increases maximal peak force and RFD (45), and therefore, the force required during each stride to produce a desired running velocity may decrease to a lower percentage. Theoretically, this would lower the relative exercise intensity and overall metabolic strain. However, the adaptations that result in increased maximal peak force and RFD are complex. Strength training, whether maximal, explosive, or reactive, can result in morphological (muscle fiber type, architecture, and tendon properties) and neural (motor unit recruitment and synchronization, firing frequency, intermuscular coordination) changes to the musculotendinous system (10). However, the physiological adaptations that aid economy and $_{V}\dot{V}O_2max$ (and maximal velocity sprinting) most likely come from a mixture of both neural and morphological adaptations. From a neural perspective, a more efficient recruitment pattern of leg musculature may decrease running cost. Aligning with size principle of motor units of Henneman et al. (14), strength training may increase the neural recruitment of type I fibers, thereby decreasing their time to exhaustion and delay the activation of the aerobically "inefficient" type II fibers. This would reduce submaximal oxygen consumption (economy) and increase the capacity for high-intensity ($_{V}\dot{V}O_2max$) and anaerobic-dominant sections of a race (i.e., sprint finish). However, the most important morphological adaptation from strength training may be from improved stiffness and elasticity of tendon structures. Theoretically, improved utilization of elastic energy from the tendon would reduce the demand of ATP from the musculature, thus improving RE, $_{V}\dot{V}O_2max$, and maximum-velocity sprinting.

Body Composition and "Concurrent" Training

Despite increasing evidence supporting the positive effect of strength training on endurance performance, it is still an uncommon or less emphasized physical preparation modality in the distance running community (5). One possible reason may be due to the hypertrophic connotations associated with lifting weights, with distance runners inadvertently linking strength training to increased musculature and body mass. Increased body mass can negatively affect relative physiological parameters (i.e., $\dot{V}O_2max$, economy) that would inevitably affect running performance. However, this study demonstrates that when a strength programme is designed and implemented appropriately (Table 1), 40 weeks of strength training can result in significant improvements in maximum (19.3 ± 24.1%) and reactive strength qualities (14.7 ± 27.8%), RE (3.5 ± 4.4%) and $_{V}\dot{V}O_2max$ (4.0 ± 4.0%), without significant changes in body composition variables (body mass, fat mass, overall lean, and leg lean) (Figure 4). Recently, there has been a growth in the literature investigating the compatibility of concurrent training methodologies and their underpinning mechanisms for protein synthesis (e.g., Baar 2014) (1). Molecular physiologists have found that there is an "interference" effect, where signalling pathways activated by endurance training inhibit skeletal muscle hypertrophy from strength training. However, the concurrent training literature only discusses myofibrillar hypertrophy as the sole adaptation from strength training. They do not acknowledge other neural adaptations that contribute to increased rate of force production (i.e., musculotendinous stiffness, motor unit recruitment, intermuscular and intramuscular coordination) (10).

Some applied sport scientists argue that low-intensity aerobic endurance training (i.e., zone 1–3/<LT2/<80%

$\dot{V}O_2$max) is compatible with maximal strength and speed development (18). Both of these modes of training are physiologically harmonious as they mutually target central mechanisms; low-intensity aerobic training increasing blood/oxygen transport (cardiac dimension enlargement and capillarization), whereas maximal strength and maximal speed sprinting improve the rate of neuromuscular force production and absorption qualities (39). Research has found that successful elite endurance athletes spend approximately 80% of their training in these low-intensity, aerobic-dominant training zones (zone 1–3, <lactate threshold 2/<80% $\dot{V}O_2$max) (35)–which gives opportunity to appropriately program strength training sessions without hampering the preparation or recovery of more specific and intense "threshold," "race pace," and/or maximum-aerobic sessions (zone 4 and 5/>lactate threshold 2/>80% $\dot{V}O_2$max). In fact, elite sprint coaches over the last few decades have placed a large emphasis on programming low-intensity aerobic running, termed "extensive tempo," to complement maximal speed development by increasing work capacity and enhancing recovery from intense sessions, thereby demonstrating the compatibility of both low-intensity aerobic and strength/power training in an elite setting (13).

This study demonstrated that 40 weeks of strength training can significantly improve maximal and reactive strength qualities, as well as physiological markers of economy and $_V\dot{V}O_2$max in competitive distance runners. Therefore, the research hypothesis of significant changes in maximal strength, reactive strength, $_V\dot{V}O_2$max, and economy is accepted; the research hypothesis for a significant change in body composition is rejected. Interestingly, the improvements in strength were attained without significant changes in body composition (body mass, fat, and lean). A large proportion of the maximal strength improvements were gained through the preseason period, and then maintained throughout the racing season as programming shifted toward reactive strength development. However, within the control group, fSSC reactive strength ability, arguably the most important strength quality in running, deteriorated throughout the 40-week period. It is important to note that the main limitation to this study was that we did not control for each participant's endurance training (volume or intensity), nutrition, or randomization of groups (as per methods section).

Practical Applications

A general maximal strength–orientated programme (2 × week, with low-volume plyometrics) during the preseason is an appropriate and efficient method for improving both maximal and reactive strength capabilities in distance runners. This study demonstrated that this structure of strength programming can significantly improve economy and $_V\dot{V}O_2$max over a 20-week preseason period. It is advised that during the racing season, strength sessions are performed once per week to maintain strength qualities, especially reactive strength. In fact, the intervention group in this study were able to improve reactive strength by a further 6.8% with only 1 session per week, while maintaining maximal strength. This study showed that in distance runners who do not perform strength training, reactive strength can deteriorate by 7.9% throughout the racing season period. Distance runners who are already strong and have high force capabilities may need to place a greater emphasis on specific reactive strength training (9) and maximal velocity sprinting (13) to gain further improvements in economy and $_V\dot{V}O_2$max. It is important to note that for optimal adaptation and development of endurance and strength qualities, strength sessions should be carefully programmed around "intense" aerobic (i.e., race pace/>lactate threshold 2/>80% $\dot{V}O_2$max) and anaerobic endurance training.

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