AMERICAN COLLEGE OF SPORTS MEDICINE

Published ahead of Print

Strength Training Improves Running Economy Durability and Fatigued High-Intensity Performance in Well-Trained Male Runners: A Randomized Control Trial

Michele Zanini[1], Jonathan P. Folland[1,2], Han Wu[1], and Richard C. Blagrove[1]

[1]School of Sport, Exercise, and Health Sciences; Loughborough University, Loughborough, UNITED KINGDOM; [2]National Institute for Health and Care Research (NIHR), Leicester Biomedical Research Centre, Leicester, UNITED KINGDOM

Accepted for Publication: 20 February 2025

Medicine & Science in Sports & Exercise® **Published ahead of Print** contains articles in unedited manuscript form that have been peer reviewed and accepted for publication. This manuscript will undergo copyediting, page composition, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered that could affect the content.

Medicine & Science in Sports & Exercise, Publish Ahead of Print
DOI: 10.1249/MSS.0000000000003685

Strength Training Improves Running Economy Durability and Fatigued High-Intensity Performance in Well-Trained Male Runners: A Randomized Control Trial

Michele Zanini[1], Jonathan P. Folland[1,2], Han Wu[1], and Richard C. Blagrove[1]

[1]School of Sport, Exercise, and Health Sciences; Loughborough University, Loughborough, UNITED KINGDOM; [2]National Institute for Health and Care Research (NIHR), Leicester Biomedical Research Centre, Leicester, UNITED KINGDOM

Address for correspondence: Jonathan P. Folland, School of Sport, Exercise & Health Sciences, Loughborough University, LE11 3TU, United Kingdom; Phone: +44 (0)1509 226334; E-mail: j.p.folland@lboro.ac.uk

Conflict of Interest and Funding Source:

This study was funded by the National Strength Conditioning Association via the "Young Investigator Research Grant."

ABSTRACT

Introduction: Strength training improves running economy (RE) in a non-fatigued state and performance after prolonged exercise at moderate intensity. However, it is unknown if strength training improves RE durability at marathon race intensity, or high-intensity performance akin to the final stages of a competitive race. This study quantified the effect of a supplementary 10-week strength training program on RE throughout 90 min of running in the heavy-intensity domain, and subsequent fatigued performance in runners. **Methods:** Twenty-eight well-trained male runners (maximal oxygen uptake ($\dot{V}O_2max$) 58.6 ml·kg^{-1}·min^{-1}; 10 km 39:02 mm:ss) were performance-matched and randomly assigned to a habitual running-only control (E; n=14) or supplementary strength training group (E+S; n=14) that performed maximal strength and plyometric training twice weekly for 10 weeks. Before the training, participants performed a 90 min run at 10% Δ between lactate threshold 1 and 2 (13.1±1.4 km/h, 79.7% $\dot{V}O_2max$). RE, quantified as oxygen cost (ml·kg^{-1}·km^{-1}), was recorded at 15 min intervals during the run, immediately thereafter, participants ran a time to exhaustion (TTE) at 95% pre-test $\dot{V}O_2max$ (16.1±1.6 km/h). The 90 min run and TTE were repeated after the training intervention. **Results:** A large interaction effect of training x group x run time was found for RE ($p=0.003$, $\eta_p^2=0.13$), with E+S improving vs E at 90 min (-2.1% vs +0.6; $p=0.04$). For TTE, a large group x training interaction effect was detected ($p=0.004$, $\eta_p^2=0.28$), changing by +35% in E+S and -8% in E. **Conclusions:** This study demonstrated that adding strength and plyometrics training to a programme of endurance running improved RE durability and substantially increased high-intensity TTE at the end of a 90 min run in the heavy intensity domain in well-trained male runners.

Key Words: MARATHON, PHYSIOLOGICAL RESILIENCE, CONCURRENT TRAINING, ENDURANCE, DISTANCE RUNNING, FATIGUE

INTRODUCTION

Running economy (RE) is an important determinant of endurance running performance, with more economical runners able to run at faster speeds for the same metabolic cost (1). For performance in long-distance events (e.g., half-marathon and marathon) RE, defined as the physiological cost of covering a given distance at a sub-maximal speed, may be particularly important, as small differences in metabolic cost accumulate over a prolonged distance manifesting as a substantial difference in total energy expenditure that may influence race outcomes (2). Furthermore, it is well-established that RE tends to deteriorate during prolonged running (3–5). Importantly, the acute deterioration of endurance performance determinants (RE, maximal oxygen uptake ($\dot{V}O_2max$), and metabolic thresholds) following prolonged exercise has been defined as "durability" or "physiological resilience" (6,7) and is suggested to be an independent factor determining performance.

Although little is currently known about the physiological underpinnings of durability, training strategies to offset the deterioration of physiological determinants during prolonged exercise are of considerable interest to coaches and athletes (7). Recent observational data suggests that accumulated years of endurance training (8,9), along with medium-term strength training (ST), may improve the durability of endurance athletes (10,11). It is well-established that ST improves running performance and RE in endurance runners when measured in an unfatigued state (12,13). Specifically, ST-induced increases in maximal muscle force could reduce relative neuromuscular activation/recruitment and the relative muscle force requirements of running at a given speed (14). In addition, ST causes an increase in tendon stiffness that appears to reduce muscle shortening velocity and increase the efficiency of stretch-shortening cycle contractions, thus improving RE (15). Given the established benefits of ST for RE measured in an unfatigued state, ST could also improve the durability of RE during prolonged exercise. For example, since the rise in energy cost during a prolonged run is concomitant with increased muscle fibre recruitment (5,16) and muscle damage (17), training interventions that delay the recruitment of less efficient muscle fibres (i.e. type II fibres) and reduce the potential for damage may enhance durability. Consequently, ST-induced adaptations could lead to firstly a delayed neuromuscular fatigue and secondly a glycogen-sparing effect, due to a late activation of type II fibres, during prolonged running.

Despite the large number of studies that have investigated the effects of a ST programme on the RE of runners, there has been very little attention to the effects of ST on the durability of RE. We are aware of only one study that surprisingly reported no changes in performance or RE, in a fresh or fatigued state after 11 weeks of ST in a cohort of female duathletes (11). Thus, the effects of ST on the durability of RE remains largely unknown, particularly in male runners. To provide physiological insights relevant to performance, trials assessing "durability" should closely simulate the demands of the race (e.g. the marathon) one aims to inform (18,19). Moreover, changes in RE following prolonged exercise have been recently demonstrated to depend on the runner's performance level (20). Therefore, investigating the influence of ST on the physiological responses of a prolonged run at intensities similar to the marathon, typically occurring in the heavy intensity domain in well-trained runners, has ecological relevance and is of particular interest.

Another important factor that often determines the outcome of running race performance is the ability to produce a high-intensity effort towards the end of the event. Sustained high-intensity efforts and sprint finishes are performed in the severe intensity domain, with performance as a function of the physiological work capacity above maximal metabolic steady state (represented as D' for distance, and W' for work). An athlete's W' is known to be influenced by their muscle size and neuromuscular capabilities (21,22), with improved W' following ST demonstrated in cyclists (23,24). Thus, improving these attributes via ST may also enhance high-intensity time trial performance. Furthermore, studies on cyclists and duathletes have reported ST improved time trial performance following prolonged exercise (10,11,25). However, whether these performance improvements at relatively low intensities (50-60% of $\dot{V}O_2max$) also apply to the heavy intensity domain performance of well-trained endurance runners during the final stages of half-marathon and marathon races remains unknown. It is therefore possible that ST may improve high-intensity performance following prolonged running close to marathon efforts, and could be an effective strategy to increase the likelihood of winning championship races.

The primary aim of this study was to examine the effect of a supplementary 10-week strength training intervention in well-trained male runners, compared to an endurance running only control group, on the durability of RE during a 90 min run in the heavy intensity domain. A secondary aim was to measure the impact of strength training on time trial performance at 95% of $\dot{V}O_2max$ following the prolonged run. It was hypothesised that strength training would improve the durability of RE, and time trial performance.

METHODS

Participants

Thirty-eight male endurance runners initially volunteered and gave written informed consent to participate in this study, which was approved by the Loughborough University Ethics Sub-Committee. To be eligible to take part participants had to meet the following criteria: 18-45 years, run 10 km in <50 min in the previous 6 months, running >20 $km \cdot week^{-1}$, primarily competing in races of ≥5 km, accustomed to running >90 min continuously (at least 3 $times \cdot month^{-1}$), had not engaged in muscle strengthening exercise aiming to improve lower limb strength and power in the previous 6 months, free of musculoskeletal injury, and no known health conditions. Participants were asked to complete a questionnaire to report their training over the previous 4 weeks and identify their fastest 10 km race performance over the previous 6 months, which were subsequently verified online. Participants were also instructed to record all training conducted on a daily basis in a written log throughout the intervention, and that was submitted after 5 and 10 weeks of the intervention period. Although running training was not systematically tracked by the researchers from their GPS devices, at least one 'spot check' per runner was done on the data recorded on their GPS compared to the written log, to validate that their training record was accurate.

Experimental overview

Participants initially visited the laboratory on two occasions, separated by 3 to 10 days. The first visit consisted of a discontinuous incremental treadmill running assessment to characterize the physiological response to increasing exercise intensity, followed by a continuous incremental test to establish $\dot{V}O_2$max. Following ~30-min passive recovery, participants were then familiarized with three strength and power tests: a counter-movement jump, maximal unilateral leg press, and a unilateral seated ankle plantarflexion isometric maximal voluntary force (MVF). Prior to the second visit, participants were asked to consume a high-carbohydrate meal for up to 2 h before arriving in the laboratory and were allowed to drink only water thereafter. Participants recorded their diet and exercise in the 48 hours before the visit and were instructed to replicate these behaviours before the post-intervention test. In the second visit, participants were initially tested for body composition (whole body and leg fat mass (FM) and lean mass (LM)) via a dual x-ray absorptiometry (DXA) scanner (Lunar iDXA, GE HealthCare, WI, US), followed by the three strength tests. After ~15 min recovery, participants ran for 90 min on the treadmill in the heavy intensity domain (10% Δ LT1-LT2). At the 90 min time point, the treadmill speed was increased to 95% of speed at $\dot{V}O_2max$ (from visit 1) and participants ran to exhaustion. Participants were required to wear the same footwear for both trials, and carbon fibre plated trainers were not permitted, due to their ergogenic effect on RE (26). Initial testing was performed 5-10 days before the start of a 10-week training intervention period. Participants were then pair-matched for their 10 km best performance and randomly assigned to either an endurance-only training group (E) or an endurance and supplementary strength training group (E+S). Both groups were instructed to continue their regular running training, with group E+S also completing two additional supervised strength training sessions per week for 10 weeks.

Within 3 to 7 days after the intervention period, all participants attended the laboratory to repeat the same procedures as visit 2. The 90 min run and TTE were performed at the same speed as the pre-intervention tests, and subjects presented to the laboratory at the same time as visit 2 (± 1 h). Participants were asked to refrain from any caffeine and alcohol ingestion and intense exercise in the 24 hours preceding each trial. All testing took place in a physiology laboratory on the same motorized treadmill (3DI, Treadmetrix, UT, US). The laboratory conditions were noted prior to each trial using a portable weather station (WS6730, Technoline, Germany) and were similar for all visits (temperature 18–21°C, relative humidity 45–55%).

Sub-maximal and maximal treadmill test

During the first visit, the participant's height and body mass (BM) were measured. Participants then completed a 5 min warm up at a self-selected speed before performing an incremental treadmill test consisting of 6-8 stages of 3 min, with speed increments of 0.5 $km.h^{-1}$ per stage initially, and when BLa on two subsequent stages increased >1 $mMol \cdot L^{-1}$ the speed increments became of 1 $km \cdot h^{-1}$, until volitional exhaustion. The speed for the first stage was determined using the participant's best race times and their physiological response to the warm-up period. The treadmill incline was kept at 1% to account for differences in air resistance compared to overground running (27). Rate of perceived exertion (RPE) using the Borg 6 to 20 scale and capillary blood lactate (BLa) were measured at the end of each stage. After the incremental test, participants passively rested for 5 min, before commencing a continuous maximal test. The speed was set at 2 $km \cdot h^{-1}$ slower than the final speed reached on the discontinuous test, and every minute the incline increased by 1% until volitional exhaustion was reached despite strong verbal encouragement to continue. Throughout both tests, participants wore a low-dead-space mask and breathed through an impeller turbine assembly (Jaeger Triple V, Jaeger GmbH, Hoechberg, Germany) to measure gas composition in inspired and expired air via an open-circuit metabolic cart (Jaeger Vyntus CPX, Carefusion, San Diego, CA). The inspired and expired-gas volume and concentration signals were continuously sampled, the latter using paramagnetic (O_2) and infrared

(CO_2) analysers (Jaeger Vyntus CPX, Carefusion, San Diego, CA) via a capillary line. These analysers were calibrated prior to each test using a known gas mixture (16% O_2 and 5% CO_2) and ambient air. The turbine volume transducer was calibrated using a 3-L syringe (Hans Rudolph, KS). The volume and concentration signals were time aligned, accounting for the transit delay in capillary gas and analyser rise time relative to the volume signal.

Strength and power tests

Following the treadmill test, participants were familiarised with the strength and power assessments. Participants initially performed a warm-up involving 3 dynamic exercises (back lunges, elevated split squats, and calf raises) for 2 sets of 12 repetitions. Counter-movement jumps (CMJ) were performed on a force plate (Kistler, Winterthur, SUI) with a sampling frequency of 2000 Hz, linked to data acquisition software (BioWare, Kistler, Winterthur, SUI). Participants were barefoot, and performed each jump with their hands on hips, and after starting from a quiet upright standing position they performed a countermovement to a self-selected depth. Following a series of warm-up repetitions, participants were instructed to perform 3 maximum jumps (i.e. as high as possible) interspersed with 30 sec recovery.

A custom-built isometric seated plantar flexion (calf raise) dynamometer was used to assess the MVF of the right leg. Participants sat on a rigid chair with their foot placed flat on a portable force plate (Kistler, Winterthur, SUI), so that the ankle, knee, and hip joints were positioned at 90°. A rigid bar was lowered onto the top of the distal thigh, with a wooden brace placed between thigh and bar (Supplemental Figure 1, Supplemental Digital Content, http://links.lww.com/MSS/D193). During each contraction, participants were instructed to push the plantarflex down against the force plate, whilst force was sampled at 2000 Hz, with visual feedback provided via a computer monitor showing the live force-time curve, with a horizontal cursor indicating peak force (Spike2, CED, Cambridge, UK). Participants were instructed to warm up with a series of isometric contractions lasting 3 sec (50% (x3), 75% (x2) and 90% (x1) of maximum perceived effort), with a recovery of 15 sec between each trial. After recovering for 2 min the force plate was zeroed and 3 maximal voluntary isometric contractions lasting ~3 sec each were performed with strong verbal encouragement, separated by a 30 sec rest between each.

Unilateral leg press 1 repetition maximum (1RM) was assessed on the right leg on a 45° incline leg press machine (Watson Gym Equipment, Somerset, UK). Participants performed concentric-only repetitions from a standardised start position set to 90° of knee flexion. For the familiarisation and measurement trials, participants completed a warm-up consisting of 3 sets of increasing loads corresponding to 50, 75 and 85% of the estimated 1RM, executing 8, 4, and 2 repetitions, respectively. In the measurement trials, participants completed a series of single lifts, with the mass increased by 5-10 kg after each successful attempt based upon the participant's perceived effort, with a recovery of 3 min between each repetition. The assessment was terminated when participants could no longer lift the mass through full concentric range, for two successive attempts. The same procedures were repeated before the 90 min run, before and after the training intervention.

Body composition

Upon arrival for visit 2 participants voided their bladder, thereafter their height was measured and body mass, whole-body and leg FM and LM were determined via DXA scan. All scans were performed by the same trained operator in accordance with standardized testing protocols, following the procedures described by Black et al. (28).

Running trial and time-to-exhaustion run

Before the 90 min treadmill run, participants stood quietly on the treadmill for 5 min to record respiratory gases at rest. They subsequently performed two sub-maximal running stages for assessment of RE at standardised speeds; 5 min at 10 $km \cdot h^{-1}$ and 3 min at 12 $km \cdot h^{-1}$. Thereafter the speed was set to 10% Δ between LT1 and LT2 (heavy domain intensity), and participants ran for 90 min.

Participants wore a mask throughout the test and respiratory gases were sampled discontinuously, during the initial 10 and 12 $km \cdot h^{-1}$ run and for 5 min every 15 min during the 90 min run, using the same method and equipment described for Visit 1. Participants stepped off the treadmill for a few seconds before and after each sampling period to attach and detach the mouthpiece. BLa, heart rate (HR), and RPE were sampled at 15 min intervals, and subjects were permitted to drink water *ad libitum* following each measurement. Two motorized industrial fans (0.45 m diameter) were positioned approximately 2 m behind and in front of the participant, to provide a cooling effect throughout the trial and reduce the risk of hyperthermia. Following the 90 min run the treadmill was set to 95% of speed at $\dot{V}O_2max$ assessed in visit 1, and participants were asked to run for as long as possible until voluntary exhaustion. Strong verbal encouragement was provided throughout the run and displays showing elapsed time and distance were obscured. Respiratory gases were recorded throughout, and BLa was collected immediately following the test.

Measurements

Anthropometry and body composition. BM was measured using a digital scale (Seca 700; Seca Hamburg, Germany) to the nearest 0.1 kg, and height was recorded to the nearest 0.01 m using a stadiometer (Harpenden Stadiometer, Holtain Ltd, UK). The DXA scans were conducted using a standardized protocol while participants lay supine on the scanner, and wore minimal clothing, typically running shorts and a vest. A minimum of three daily calibrations were done before any body composition assessment. From the frontal plane DXA image, legs FM and LM were assessed by carefully drawing a customized area around the segment of interest. Briefly, the boundary between trunk and lower limb segments was defined as the outline above the greater trochanter, femoral neck, and below the ischium.

Blood lactate. Capillary blood was collected via a 20-µL capillary tube from the participant's ear lobe. The sample was immediately haemolysed and assessed for BLa concentration (Biosen C-Line, EKF Diagnostics, Cardiff, UK). LT1, defined as the first rise in BLa from baseline, was calculated using a log-log analysis (Beaver et al., 1985), while LT2 was calculated via the modified log-log Dmax method (30).

Respiratory measures. Breath-by-breath $\dot{V}O_2$ data were continuously recorded and initially filtered to exclude errant breaths, defined as values lying more than 4 standard deviations (SDs) from the local mean. Subsequently, the breath-by-breath data were converted to second-by-second data using linear interpolation. $\dot{V}O_2max$ was defined as the highest 30-sec moving average from the $\dot{V}O_2$ data.

Running economy. During visits 2 and 3, the average of $\dot{V}O_2$ and $\dot{V}CO_2$ data collected during the final minute at 10 and 12 km/h, and the final 2 min of each 15 min stage of the 90 min trials, were used to calculate the oxygen cost (OC, $ml \cdot kg^{-1} \cdot km^{-1}$) and energy cost (EC, $Kcal \cdot kg^{-1} \cdot km^{-1}$) of running. Results for EC are included in the Supplemental Digital Content (Supplemental Digital Content, http://links.lww.com/MSS/D193), as it has been recently demonstrated that negligible differences exist between EC and OC when changes are measured over prolonged exercise (20). Briefly, to calculate EC updated nonprotein respiratory quotient equations (31) were used to estimate substrate utilization ($g \cdot min^{-1}$). The energy derived from each substrate was calculated by multiplying fat and carbohydrate utilization by 9.75 and 4.07 kcal, respectively (32). Absolute EC was calculated as the sum of the energy derived from fat and carbohydrate expressed as $kcal \cdot kg^{-1} \cdot km^{-1}$. To account for changes in body mass during the trial, body mass pre- to post-trial was measured and linear regression was used to extrapolate body mass at each measurement time point.

Strength measures. Jump height was measured using the double-integration method as previously described (33). The highest of the 3 jumps was used in subsequent analysis. The plantar flexors MVF was calculated from the highest instantaneous force recorded from the 3 attempts, minus the passive force recorded at baseline before the contractions.

Time to exhaustion. The duration of the time to exhaustion (TTE) run was recorded to the nearest second from the moment the participant released the handrails to the point of exhaustion. The highest 30 sec average $\dot{V}O_2$ recorded in the TTE was considered for analysis if the trial duration was above 120 sec and in the last 30 sec of exercise a plateau in $\dot{V}O_2$ occurred.

Training measures. Participants' self-reported training volume was quantified in hours per week for total training, running training, and strength training. Running training was also expressed as distance per week.

Strength and plyometric training intervention

Strength training sessions were separated by 2-4 days and lasted ~45 min per session. Each session was supervised by a qualified strength coach, with participant attendance monitored. Sessions were structured as a standardised warm-up, followed by 2 plyometric exercises and 3 lower limb strength exercises. To adhere to the principle of progressive overload, every 3-4 weeks plyometrics exercises and strength training prescription were progressed. Details of the training program and its progression are provided in Table 1. During vertical plyometric exercises, participants were instructed to spend a short time on the ground (<200 ms) whilst trying to maximise jump height. Visual feedback on these metrics was provided following each repetition via an optical measurement infrared system (Optojump, Microgate, Italy). Horizontal plyometrics were performed on a flat surface outdoors, with participants encouraged to express "as much force to the ground as quickly as possible". During barbell back squats, bar velocity was tracked using an optical camera system (Eliteform, ESP Fitness, UK). Instantaneous feedback was visually displayed on a monitor positioned in front of participants. Participants were encouraged to lift the load as fast as possible with loads adjusted after each set to ensure an average concentric speed between 0.35 and 0.55 m/s was achieved, which is suggested to be associated with an intensity corresponding to 80-90% of 1RM when performed with maximal intent (34). Leg press was executed as described for testing sessions for both legs, and 1RM was re-tested at the beginning of week 6, to adjust training in weeks 6-10 to the participant's strength improvements.

Statistical Analysis

All data are presented as mean ± standard deviation (SD). The Greenhouse–Geisser correction was applied when the assumption of sphericity was violated. An independent t-test was used to determine between-group (E+S vs E) differences in training characteristics and physiological variables assessed in visit 1. Two-way mixed-model ANOVAs (group x training) were used to assess differences in training between the pre-intervention and training period, expressed as total, running only, and strength only training hours. Two-way mixed-model ANOVAs (group x training) were applied to body mass, body composition, and strength measures. The same ANOVA analysis was used to compare changes in unfatigued parameters: OC and EC at 10 and 12 $km \cdot h^{-1}$, and 15 min into the prolonged run for RE (OC and EC), Bla, HR, RER, RPE, and trial intensity ($\dot{V}O_2max$ %).

To assess differences occurring during the 90 min run pre-post training, three-way mixed-model ANOVAs (group x training x run time) were analysed for RE (OC and EC), Bla, HR, RER and RPE for the six time-points collected. If the group x training x run time interaction was significant, to assess between-group differences two-way mixed-model ANOVAs (group x run time) were used for the percentage change pre-post intervention at each time point during the run. To assess within-group changes, two-way repeated-measure ANOVAs (training x run time) were used for the above mentioned measures. Within-group comparisons of EC/OC changes during the 90 min may be somewhat confounded by any change in the initial (15 min) values pre-post intervention and between-participant variability in RE measures. Therefore, for a more robust comparison of changes in RE (OC and EC) during a run, individual percentage change was calculated relative to the first (15 min) measured time point for all subsequent time points, and analysed with a two-way repeated measure ANOVA (training x run time). Finally, two-way mixed-model ANOVAs (group x training) assessed changes in TTE for time, BLa, and percentage of $\dot{V}O_2$max reached.

Post hoc analysis with Bonferroni adjustment was used to identify the origin of any significant difference. Statistical analyses were performed using SPSS version 28 (SPSS Inc, Chicago, IL, USA), effect sizes were calculated as partial-eta squared (η_p^2) and quantified as small (0.01 - 0.06), medium (0.06 - 0.14), and large (>0.14). The threshold for significance was fixed at $p<0.05$.

RESULTS

Participant and training characteristics

Out of 38 participants that initially enrolled, 28 completed the study (E+S n=14; E n=14). Dropout details were as follows illness (n=2), voluntary withdrawal (n=1), no response to communication post-training period (n=3); injury due to the training intervention (n=1); and injury unconnected to the training intervention (n=4). The two groups of participants that completed the study were the same at baseline, with no differences found between E+S and E at the pre-intervention time point in any performance, physiological, training, strength or body composition variables (p>0.05; Table 2, Table 3). Groups did not differ for body mass (71.3 ± 5.9 kg (E+S) vs 69.3 ± 6.9 kg (E)), height (1.75 ± 0.05 m (E+S) vs 1.74 ± 0.07 m (E)), and age (32.6 ± 8.4 y (E+S) vs 37.1 ± 8.7 y (E)). There was no training x group effect for running training volume (F=0.10, p=0.76, η_p^2=0.004) or total training volume (F=3.70, p=0.07, η_p^2=0.13). This was despite E+S increasing training time by 22% (0.8 ± 1.1 h·week^{-1}), due to the addition of strength training, compared to no change in the E group (-0.1 ± 1.5 h·week^{-1}; Table 3). Adherence to the intervention was 99%, with 2 participants missing 1 out of 20 planned training sessions.

Body composition and strength

There was no interaction effect of training x group for BM (F=0.15, p=0.74, η_p^2=0.04) or leg LM (F=1.01, p=0.32, η_p^2=0.03), while an interaction was found for whole body LM (F=4.84, p=0.04, η_p^2=0.14), with an increase in the E+S group by 1 ± 2 % (p=0.03). There was a training x group effect for whole body FM (F=3.07, p=0.02, η_p^2=0.16), with within-group changes showing E+S reduced whole body FM by -11.5 ± 16.0% (p=0.01), with negligible changes in E (p=0.64) (Table 3).

A large training x group effect was found for all the strength and power-related measures, specifically: leg press 1 RM (F=42.43, p<0.001, η_p^2=0.62), PF MVF (F=6.37, p=0.02, η_p^2=0.21), CMJ height (F=12.32, p=0.002, η_p^2=0.32) and CMJ PP (F=20.72, p<0.001, η_p^2=0.44). Within-group changes for E+S displayed significant improvements across all the measures: +22 ± 14% (LP 1RM), +14 ± 14% (PF MVF), +5.9 ± 8.2% (CMJ height), and +7.5 ± 7.3% (CMJ PP) respectively (p<0.02), with no changes in the E group except for a small decrease in CMJ PP (p=0.04) (Table 3, Fig. 1).

Running economy before and during 90 min run

Pre-90 min run, there were no training x group effects for RE at 10 km·h^{-1} (F=0.31, p=0.86, η_p^2=0.01), or 12 km·h^{-1} (F=0.02, p=0.89, η_p^2=0.01). Similarly, no training x group effects were found for RE after 15 min of the 90 min trial (F=1.03, p=0.32, η_p^2=0.04; Table 4; Fig. 2).

During the 90 min run, a training x group x run time effect was found for RE ($F=3.81$, $p=0.003$, $\eta_p^2=0.13$). Subsequent analysis of % change of RE (pre-post) revealed a group x run time interaction effect ($F=3.45$, $p=0.006$, $\eta_p^2=0.12$), with a between-group difference at 90 min (-2.1 ± 3.5% (E+S) vs +0.6 ± 3.8% (E); $p=0.04$; Fig 3A). Within group, a training x run time interaction effect was found for RE in the E+S group ($F=6.14$, $p<0.001$, $\eta_p^2=0.32$), with post-hoc analysis showing a post-training improvement in RE at 90 min compared to pre ($p=0.04$, Table 4). Similarly, when RE changes were calculated relative to the 15 min time point, within S+E post-training there was a reduced deterioration in RE after 75 (3.4 ± 1.0 vs 1.5 ± 1.9%; $p=0.003$) and 90 min of running (4.7 ± 1.7 vs 2.1 ± 1.0%; $p<0.001$; Fig. 2). In the E group, no within-group training x run time interaction was found for RE ($p=0.42$).

Other physiological variables during 90 min run

No group x training interaction effects were found for any physiological variable ($p>0.43$) or RPE ($p=0.09$) after 15 min of the prolonged run trial (table 4). A training x group x run time interaction effect was found for BLa ($F=3.58$, $p=0.02$, $\eta_p^2=0.13$) and RPE ($F=3.62$, $p=0.03$, $\eta_p^2=0.12$), but no effect was noted for HR ($F=0.43$, $p=0.83$, $\eta_p^2=0.02$) and RER ($F=0.65$, $p=0.60$, $\eta_p^2=0.03$, Table 4). A group x run time interaction effect was found for % changes (pre to post) in BLa ($F=2.69$, $p=0.02$, $\eta_p^2=0.11$), with the E group displaying a higher accumulation of BLa at 75 and 90 min compared to the E+S group ($p<0.05$, Fig. 3B). No within-group training x run time interaction was present for BLa in E+S ($F=0.57$, $p=0.60$, $\eta_p^2=0.05$), whilst it was found in the E group ($F=3.95$, $p=0.01$, $\eta_p^2=0.23$; Table 4). Finally, the % changes (pre-post) in RPE showed a group x run time interaction effect ($F=2.54$, $p=0.03$, $\eta_p^2=0.12$), with E+S displaying a larger decrease in RPE at 90 min compared to E ($p=0.03$, Fig. 3C). Within groups RPE changes showed no training x run time effect for E+S ($F=2.10$, $p=0.14$, $\eta_p^2=0.14$) or E ($F=1.83$, $p=0.17$, $\eta_p^2=0.12$), although an overall effect of training was present for E+S ($F=4.79$, $p=0.04$, $\eta_p^2=0.27$), displaying a reduced RPE at 15 ($p=0.01$) and 90 min ($p=0.03$, Table 4).

Time to exhaustion following 90 min run

There was a large training x group interaction effect for TTE ($F=9.92$, $p=0.004$, $\eta_p^2=0.28$), accompanied by within-group improvements after E+S by 35 ± 25% (247 ± 94 vs 324 ± 105 s, $p<0.001$) but no change after E (194 ± 96 vs 169 ± 106 s, $p=0.40$). At the end of TTE, there was no training x group effect for BLa ($F=0.79$, $p=0.38$, $\eta_p^2=0.03$), with E+S reaching a higher concentration pre vs post intervention (5.6 ± 2.0 vs 6.4 ± 2.4 $mMol \cdot L^{-1}$; +22%, $p=0.04$), and no change for E (4.9 ± 1.8 vs 5.3 ± 2.0 $mMol \cdot L^{-1}$; +9%, $p=0.39$). Finally, no training x group effect was found for the $\dot{V}O_2$ reached during TTE ($F=0.03$, $p=0.97$, $\eta_p^2=0.002$), and no within-group differences were found for E+S ($p=0.85$) or E ($p=0.96$, Fig. 4).

DISCUSSION

This study aimed to evaluate the effect of a 10-week strength training program on the changes in RE during 90 min of heavy-intensity running, and subsequent severe-intensity TTE performance. Results showed that strength training improved RE "durability", with reduced deterioration of RE during the final 30 min of the prolonged run after E+S compared to the E training and to the pre-intervention condition. The addition of strength training (E+S group) was also more effective at improving the duration of the TTE run following the 90 min trial, with a 35% improvement compared to no change after endurance-only training.

RE durability appears to distinguish high- and low-performing endurance runners (20), however evidence of strategies to improve physiological durability is currently very limited. Strength training resulted in an improvement in RE durability, with the E+S training reducing the drift at 90 min from 4.7% to 2.1% (pre vs post), whilst the deterioration in RE after E training did not change, and consequently E+S showed greater improvements than E only. To our knowledge, there is only one other study that measured RE during a prolonged run before and after a strength training protocol, which involved female duathletes (11). This study reported no changes in RE during the 90 min run, neither before nor after the intervention, possibly due to the low intensity of the trial (60% $\dot{V}O_2$max), which may have limited the RE deterioration usually reported in the literature (3–5). Similar to our results, a study in elite cyclists reported a 2% reduction in $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$) in the last hour of a 3 h ride at 50% $\dot{V}O_2$max following 12 weeks of strength training, which represented a greater improvement compared to an endurance only training group (10). In that investigation, the intensity was lower but the duration was twice as long as the current study, thus depletion of muscle glycogen could be expected, together with a potential shift towards less aerobically efficient type II muscle fibres (35). Indeed, in Ronnestad's study a $\dot{V}O_2$ drift was only reported after 90 min of cycling, which was further delayed following strength training.

The improvements in RE durability following strength training could be linked to several physiological adaptations. Evidence from cyclists and duathletes reported a shift from type IIx to type IIa fibres following strength training in endurance athletes, although no comparisons were made to a control group (36,37). Type II fibres likely make a larger contribution to muscular work during the later stages of prolonged sub-maximal exercise as type I fibres start to fatigue due to glycogen depletion (35). As Type IIa fibres are known to be more metabolically efficient than IIx fibres, an increase in type IIa to type IIx fibre ratio after strength training may induce improved RE only after prolonged running when type I fibres begin to fatigue. Hence, the shift from type IIx to type IIa fibres could be most relevant to RE in a fatigued state (i.e. RE durability), when the type II fibres make a larger contribution than is the case for fresh RE. When considering whole muscle activation, Hausswirth et al. (38) reported a reduction in electromyography (EMG) amplitude of working muscles at the end of 2 hours of cycling following 5 weeks of strength training in a group of highly-trained triathletes, which was not the case at the beginning of exercise or in a group that did only endurance training. This suggests an attenuated rise in neuromuscular activation during prolonged exercise after strength training, perhaps limiting the involvement of metabolically inefficient type II fibres and explaining improved RE durability. It is important to highlight that the above mechanisms suggested to improve RE durability come from previous studies on cycling activities, and were not measured in the current investigation. Future research is therefore warranted to extend these findings to running and could clarify the adaptations underpinning improved RE durability via strength training. It is also possible that other mechanisms may contribute to the improvements in durability, such as increased muscle-tendon stiffness and changes to the force-length-velocity relationship of active muscle fascicles (15).

RPE also displayed a training x run time effect with a reduction in the E+S group at the end of the run, which could be partially explained by the RE improvements and higher energy availability at the end of the run. These results are similar to two studies in cyclists (10,11) and cross-country skiers (39) that showed reduced RPE at the end of a prolonged exercise following strength and endurance training compared to an endurance-only group. Possibly, both a reduced RE drift and RPE contributed to the large improvement in the high-intensity TTE after the 90 min run, as RPE is known to linearly increase over time during exercise and suggested to predict time to exhaustion (40).

Importantly, this is the first study showing a large effect of strength training on improving high-intensity TTE duration following prolonged exercise in the heavy intensity domain, and confirms previous findings testing fatigued high-intensity efforts at a lower exercise intensity (10,11). Our results are in line with running and cycling studies that reported strength training for 8-12 weeks to result in positive changes in all-out time-trial efforts after prolonged low-intensity exercise (50 to 60% $\dot{V}O_2$max, moderate exercise domain) (10,11). In these studies, performance changes were lower than in the current study (+4-7% vs +35%), with the discrepancy explained by the differences between performance assessments, i.e., a TTE vs time trial effort, with TTE typically displaying much larger changes compared to a time trial effort (41). It is worth highlighting that TTE efforts possess lower ecological validity as a surrogate of performance compared to a time trial, although a strong relationship exists between these measures (42). Measures of performance in real world settings (e.g., 1 km outdoor time trial after the 90 min run) are also problematic to standardize before and after an intervention and thus may be relatively insensitive measures of improved performance.

Interestingly, the $\dot{V}O_2$ reached at the end of TTE remained unchanged in both groups following the intervention, suggesting that improvements were not related to a better capacity to use oxygen in a fatigued state. BLa concentration at the end of the TTE run also showed no training x group interaction, suggesting that the intervention did not have an effect on BLa accumulation at the end of the TTE run. Augmented muscle strength could also explain the improved TTE after strength training by reducing motor unit recruitment at a constant absolute running speed, and potentially delaying fatigue (38,43). A further mechanism leading to TTE changes may depend on an increased D' following strength training and could explain the discrepancy between improvements in TTE and smaller changes in RE after the prolonged run. In a fresh state, an improved W', alongside increased lower limb strength, has been demonstrated in cycling following 8 weeks of strength training in untrained subjects, despite no changes in critical power (24). A potential mechanism by which strength training may improve D' could relate to an increased mass of the muscles contributing to the exercise, although this was not found in our results for leg LM. Furthermore, the improved RE durability found in this study could have increased glycogen availability at 90 min and influenced the work capacity above critical speed/power, known to be sensitive to glycogen depletion (44).

The large TTE improvement has important implications for competitive running when the capacity to produce high-intensity efforts in the final minutes often determines winners, medallists, and final race position. In this study, the intensity of the 90 min run and TTE effort were designed to specifically simulate part of a marathon race, with a final high-intensity effort lasting a few minutes at the end. Indeed, the ability to produce high speeds in the last 2 km of the Berlin Marathon has been outlined as a characteristic differentiating better-ranked athletes from an analysis of 11 recent editions of the race (2008-2018) (45). The high ecological validity of the exercise intensity in the current study, substantially higher than previous studies, provides convincing evidence that strength training can enhance fatigued performance towards the end of a long-distance running race. Strength training should therefore be considered as a strategy for athletes preparing for championship competitions, which are often raced at submaximal intensities with a high-intensity effort in the final minutes of a race.

Interestingly, no changes were found in RE in a ‘fresh’ state (i.e. at 10 and 12 $km \cdot h^{-1}$, or after 15 min of the 90 min run), in contrast with most studies investigating the effect of strength training in endurance runners, which tend to show improvements in RE of 3-8% (46–49). Previous studies with participants of a similar age to the current study reported both unchanged (37,49–51) and improved RE (52–54), following a strength training regime with $\dot{V}O_2max$ and training volume similar to this study. Therefore, although the unchanged RE found is surprising, the results are not dissimilar to several previous studies in the same population. It is not surprising that BLa, RER and HR remained unchanged, as $\dot{V}O_2max$ and lactate thresholds have not been reported to improve following a strength training program in endurance runners (12).

The observed changes in strength and power-related measures, increasing between 7 and 22% in the E+S group, are consistent with other literature on endurance runners over similar periods (12). The DXA analysis revealed that the strength intervention had an effect (training x group) on body composition, with the E+S group displaying a whole body FM reduction of 11%, and no changes for leg LM. The much larger increase in strength and power parameters compared to leg LM seem to suggest that these improvements were primarily linked to neural adaptations, with a potential contribution from changes in muscle composition and specific tension (55). Interestingly, previous studies using skinfolds and bioelectrical impedance analysis have not found changes in body composition following strength training in runners (52,53,56), whilst others have reported an increase in leg LM measured via DXA scans (11,57), suggesting differences may depend on the method used to assess body composition. Along these lines, Mikkola and colleagues (2007) did not find changes in whole body FM or FFM via the skinfolds method, but reported an increase in thigh and calf girth, suggesting that specific changes may have occurred in the muscles trained in the strength protocol. It seems plausible that adaptations primarily occurred in the muscles exposed to strength training, and may therefore be of interest analysing changes in muscle morphology via MRI scans to measure adaptation to individual muscles, instead of a gross measure of leg LM.

This study is not without limitations. Strength training was performed supplementary to endurance training, rather than in-place of running sessions. Future studies could match the training volume in the intervention group with added running or low-intensity conditioning sessions in the E group or replace part of running training with strength-based exercises. Interestingly, studies measuring changes in unfatigued RE and performance reported similar results between replacing running with strength training or supplementing the participants' regular running program with strengthening activities (47,59). Participants were not asked to follow a standardised endurance running programme during the training intervention, which could have led to different adaptations in aerobic fitness in the post-intervention visits. However, participants were asked to maintain their usual training regime for the duration of the study, and reported their training during the 10 weeks intervention as well as in the 4 weeks preceding the first visit, with no differences in endurance training volume noted within- or between-groups. Moreover, participants were asked to self-report their endurance training, and stronger control of their running activities would have been beneficial in ensuring training consistency before and during the intervention period.

Finally, only male participants were included in this study, although similar results have previously been found in a cohort of female duathletes (11).

CONCLUSIONS

This study demonstrated that adding strength training to a programme of endurance running improved RE durability and increased high-intensity TTE at the end of a 90 min run in the heavy intensity domain in well-trained male distance runners. These findings are particularly relevant for road races between 10 km and the marathon, which typically occur in the heavy intensity domain. Future studies should focus on the physiological adaptations explaining strength training induced improvements in fatigued TTE and RE durability.

Acknowledgement

This study was funded by the National Strength Conditioning Association via the "Young Investigator Research Grant". We would like to acknowledge all the runners taking part in this study for the time and efforts provided, as well as Hans Wang, Hesham Hafez, and Bongani Mathema, for their support in the delivery of the strength training program. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. Barnes KR, Kilding AE. Running economy: measurement, norms, and determining factors. *Sports Med Open.* 2015;1(1):8.

2. Hoogkamer W, Kram R, Arellano CJ. How Biomechanical improvements in running economy could break the 2-hour marathon barrier. *Sports Med.* 2017;47(9):1739–50.

3. Brueckner JC, Atchou G, Capelli C, et al. The energy cost of running increases with the distance covered. *Eur J Appl Physiol.* 1991;62(6):385–9.

4. Xu F, Montgomery DL. Effect of prolonged exercise at 65 and 80% of $\dot{V}O2max$ on running economy. *Int J Sports Med.* 1995;16(5):309–13.

5. Kyrolainen H, Pullinen T, Candau R, Avela J, Huttunen P, Komi P V. Effects of marathon running on running economy and kinematics. *Eur J Appl Physiol.* 2000;82(4):297–304.

6. Maunder E, Seiler S, Mildenhall MJ, Kilding AE, Plews DJ. The importance of 'durability' in the physiological profiling of endurance athletes. *Sports Med.* 2021;51(8):1619-28.

7. Jones AM. The fourth dimension: physiological resilience as an independent determinant of endurance exercise performance. *J Physiol.* 2024;602(17):4113-28.

8. Almquist NW, Hansen J, Rønnestad BR. Development of cycling performance variables and durability in female and male national team cyclists: from junior to senior. *Med Sci Sports Exerc.* 2023;55(11):2053–63.

9. Gallo G, Mateo-March M, Leo P, et al. Power road-derived physical performance parameters in junior, under-23, and professional road cycling climbers. *Int J Sports Physiol Perform.* 2022;17(7):1094–102.

10. Rønnestad BR, Hansen EA, Raastad T. Strength training improves 5-min all-out performance following 185min of cycling. *Scand J Med Sci Sports.* 2011;21(2):250–9.

11. Vikmoen O, Rønnestad BR, Ellefsen S, Raastad T. Heavy strength training improves running and cycling performance following prolonged submaximal work in well-trained female athletes. *Physiol Rep.* 2017;5(5):e13149.

12. Blagrove RC, Howatson G, Hayes PR. Effects of strength training on the physiological determinants of middle- and long-distance running performance: a systematic review. *Sports Med.* 2018;48(5):1117-49.

13. Balsalobre-Fernández C, Santos-Concejero J, Grivas G V. Effects of strength training on running economy in highly trained runners: a systematic review with meta-analysis of controlled trials. *J Strength Cond Res.* 2016;30(8):2361-8.

14. Fletchern JR, MacIntosh BR. Running economy from a muscle energetics perspective. *Front Physiol.* 2017;8:433.

15. Bohm S, Mersmann F, Santuz A, Arampatzis A. Enthalpy efficiency of the soleus muscle contributes to improvements in running economy. *Proc Biol Sci.* 2021;288(1943):20202784.

16. Vollestad NK, Blom PCS. Effect of varying exercise intensity on glycogen depletion in human muscle fibres. *Acta Physiol Scand.* 1985;125(3):395-405.

17. Black MI, Kranen SH, Kadach S, et al. Highly cushioned shoes improve running performance in both the absence and presence of muscle damage. *Med Sci Sports Exerc.* 2022;54(4):633–45.

18. Black MI, Jones AM, Blackwell JR, et al. Muscle metabolic and neuromuscular determinants of fatigue during cycling in different exercise intensity domains. *J Appl Physiol (1985).* 2017;122(3):446–59.

19. Brownstein CG, Pastor FS, Mira J, Murias JM, Millet GY. Power output manipulation from below to above the gas exchange threshold results in exacerbated performance fatigability. *Med Sci Sports Exerc.* 2022;54(11):1947–60.

20. Zanini M, Folland JP, Blagrove RC. Durability of running economy: differences between quantification methods and performance status in male runners. *Med Sci Sports Exerc.* 2024;56(11):2230-40.

21. Kordi M, Menzies C, Parker Simpson L. Relationship between power–duration parameters and mechanical and anthropometric properties of the thigh in elite cyclists. *Eur J Appl Physiol.* 2018;118(3):637–45.

22. Miura A, Endo M, Sato H, Sato H, Barstow TJ, Fukuba Y. Relationship between the curvature constant parameter of the power-duration curve and muscle cross-sectional area of the thigh for cycle ergometry in humans. *Eur J Appl Physiol.* 2002;87(3):238–44.

23. Denadai BS, Greco CC. Resistance training and exercise tolerance during high-intensity exercise: moving beyond just running economy and muscle strength. *J Appl Physiol (1985).* 2018;124(2):526–8.

24. Sawyer B, Stokes J, Wokman C, Morton R, Weltman A, Gaesser G. Strength training increases endurance time to exhaustion during high-intensity exercise despite no change in critical power. *J Strength Cond Res.* 2014;28(3):601–9.

25. Bláfoss R, Rikardo J, Andersen A, et al. Effects of resistance training cessation on cycling performance in well-trained cyclists: an exploratory study. *J Strength Cond Res.* 2022;36(3):796–804.

26. Hoogkamer W, Kipp S, Spiering BA, Kram R. Altered running economy directly translates to altered distance-running performance. *Med Sci Sports Exerc.* 2016;48(11):2175–80.

27. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *J Sports Sci.* 1996;14(4):321–7.

28. Black MI, Allen SJ, Forrester SE, Folland JP. The anthropometry of economical running. *Med Sci Sports Exerc.* 2020;52(3):762–70.

29. Beaver WL, Wasserman K, Whipp BJ. Improved detection of lactate threshold during exercise using a log-log transformation. *J Appl Physiol (1985).* 1985;59(6):1936–40.

30. Jamnick NA, Botella J, Pyne DB, Bishop DJ. Manipulating graded exercise test variables affects the validity of the lactate threshold and VO2peak. *PLoS One.* 2018;13(7):e0199794.

31. Péronnet F, Massicotte D. Table of nonprotein respiratory quotient: an update. *Can J Appl Sport Sci.* 1991;16(1):23–9.

32. Jeukendrup AE, Wallis GA. Measurement of substrate oxidation during exercise by means of gas exchange measurements. *Int J Sports Med.* 2005;26 Suppl 1:S28-37.

33. Wade L, Lichtwark GA, Farris DJ. Comparisons of laboratory-based methods to calculate jump height and improvements to the field-based flight-time method. *Scand J Med Sci Sports.* 2020;30(1):31–7.

34. Weakley J, Mann B, Banyard H, McLaren S, Scott T, Garcia-Ramos A. Velocity-based training: From theory to application. *Strength Cond J.* 2021;43(2):31–49.

35. Nielsen J, Jensen R, Ørtenblad N. Assessments of individual fiber glycogen and mitochondrial volume percentages reveal a graded reduction in muscle oxidative power during prolonged exhaustive exercise. *Scand J Med Sci Sports*. 2024;34(2):6–11.

36. Aagaard P, Andersen JL, Bennekou M, et al. Effects of resistance training on endurance capacity and muscle fiber composition in young top-level cyclists. *Scand J Med Sci Sports.* 2011;21(6):298–307.

37. Vikmoen O, Raastad T, Seynnes O, Bergstrøm K, Ellefsen S, Rønnestad BR. Effects of heavy strength training on running performance and determinants of running performance in female endurance athletes. *PLoS One.* 2016;11(3):e0150799.

38. Hausswirth C, Argentin S, Bieuzen F, Le Meur Y, Couturier A, Brisswalter J. Endurance and strength training effects on physiological and muscular parameters during prolonged cycling. *J Electromyogr Kinesiol.* 2010;20(2):330–9.

39. Øfsteng S, Sandbakk, van Beekvelt M, et al. Strength training improves double-poling performance after prolonged submaximal exercise in cross-country skiers. *Scand J Med Sci Sports.* 2018;28(3):893–904.

40. Crewe H, Tucker R, Noakes TD. The rate of increase in rating of perceived exertion predicts the duration of exercise to fatigue at a fixed power output in different environmental conditions. *Eur J Appl Physiol.* 2008;103(5):569–77.

41. Amann M, Hopkins WG, Marcora SM. Similar sensitivity of time to exhaustion and time-trial time to changes in endurance. *Med Sci Sports Exerc.* 2008;40(3):574–8.

42. Laursen PB, Francis GT, Abbiss CR, Newton MJ, Nosaka K. Reliability of time-to-exhaustion versus time-trial running tests in runners. *Med Sci Sports Exerc.* 2007;39(8):1374–9.

43. Bonacci J, Chapman A, Blanch P, Vicenzino B. Neuromuscular adaptations to training, injury and passive interventions implications for running economy. *Sports Med.* 2009;39(11):903–21.

44. Miura A, Sato H, Sato H, Whipp BJW, Fukuba Y. The effect of glycogen depletion on the curvature constant parameter of the power-duration curve for cycle ergometry. *Ergonomics*. 2000;43(1):133–41.

45. Muñoz-Pérez I, Lago-Fuentes C, Mecías-Calvo M, Casado A. Pacing and packing behaviour in elite and world record performances at Berlin marathon. *Eur J Sport Sci.* 2023;23(8):1472–9.

46. Berryman N, Maurel D, Bosquet L. Effect of plyometric vs. dynamic weight training on the energy cost of running. *J Strength Cond Res.* 2010;24(7):1818-25.

47. Mikkola J, Rusko H, Nummela A, Pollari T, Häkkinen K. Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in young distance runners. *Int J Sports Med.* 2007;28(7):602–11.

48. Fletcher JR, Esau SP, MacIntosh BR. Changes in tendon stiffness and running economy in highly trained distance runners. *Eur J Appl Physiol.* 2010;110(5):1037–46.

49. Damasceno M V., Lima-Silva AE, Pasqua LA, et al. Effects of resistance training on neuromuscular characteristics and pacing during 10-km running time trial. *Eur J Appl Physiol.* 2015;115(7):1513–22.

50. Pellegrino J, Ruby BC, Dumke CL. Effect of plyometrics on the energy cost of running and MHC and titin isoforms. *Med Sci Sports Exerc.* 2016;48(1):49–56.

51. Ferrauti A, Bergermann M, Fernandez-Fernandez J. Effects of a concurrent strength and endurance training on running performance and running economy in recreational marathon runners. *J Strength Cond Res.* 2010;24(10):2770-8.

52. Giovanelli N, Taboga P, Rejc E, Lazzer S. Effects of strength, explosive and plyometric training on energy cost of running in ultra-endurance athletes. *Eur J Sport Sci.* 2017;17(7):805–13.

53. Johnson R, Quinn T, Kertzer R, Vroman N. Strength training in female distance runners. *J Strength Cond Res.* 1997;11(4):224-9.

54. Skovgaard C, Christensen PM, Larsen S, Andersen TR, Thomassen M, Bangsbo J. Concurrent speed endurance and resistance training improves performance, running economy, and muscle NHE1 in moderately trained runners. *J Appl Physiol (1985).* 2014;117(10):1097–109.

55. Erskine RM, Jones DA, Williams AG, Stewart CE, Degens H. Inter-individual variability in the adaptation of human muscle specific tension to progressive resistance training. *Eur J Appl Physiol.* 2010;110(6):1117–25.

56. Piacentini M, De Ioannon G, Comotto S, Spedicato A, Vernillo G, La Torre A. Concurrent strength and endurance training effects on running economy in master endurance runners. *J Strength Cond Res.* 2013;27(8):2295–303.

57. Schumann M, Pelttari P, Doma K, Karavirta L, Häkkinen K. Neuromuscular adaptations to same-session combined endurance and strength training in recreational endurance runners. *Int* J Sports Med. 2016;37(14):1136–43.

58. Mikkola J, Rusko H, Nummela A, Pollari T, Häkkinen K. Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in young distance runners. *Int J Sports Med.* 2007;28(7):602–11.

59. Paavolainen, Hakkinen K, Hamalainen I, Nummela A, Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol (1985).* 1999;86(5):1527-33.

FIGURE LEGENDS

Fig. 1. Percentage change in leg press 1 RM (LP 1 RM; kg), plantar flexors maximal voluntary force (PF MVF; N), countermovement jump height (CMJ H; m) and peak power (CMJ PP; $W \cdot kg^{-1}$), following the 10-week training in which one group did combined endurance and strength training (E+S, dark grey bars, n=14) and the other performed endurance training only (E, light grey bars, n=14). Individual data points are displayed with circles (E+S) and triangles (E). Difference between groups: # $p<0.05$; ## $p<0.001$. Data are mean ± SD.

Fig. 2. Changes before (open circles/triangles) and after (filled circles/triangles) the intervention period during the 90 min run at 10% Δ between LT1 and LT2 (~80% $\dot{V}O_2max$). Panels represent running economy (RE) for the E+S (A, n=14) and E groups (B; n=14) measured during the run, and the percentage change from the initial 15 min time point for each group (C and D). Red circles indicate the E+S group, and blue triangles the E group. Data are mean ± SD. Different between measures at that time point: * $p<0.05$; ** $p<0.001$.

Fig 3. Percentage changes in running economy, blood lactate, and RPE post the 10-week intervention period at each time-point during the 90 min run at 10% Δ between LT1 and LT2, for the endurance and strength group (red circles, n=14) and endurance only group (blue triangles, n=14). Difference between groups: # $p<0.05$; ## $p<0.01$. Data are mean ± SD.

Fig. 4. Changes in time to exhaustion, $\dot{V}O_2$ reached, and blood lactate accumulated, at the end of the TTE (95% of $\dot{V}O_2max$) following 90 min of continuous running before (light grey) and after

(dark grey) the 10 weeks intervention period. One group combined endurance and strength training (E+S, n=14) and the other performed endurance training only (E, n=14). Circles correspond to individual data points. Within group pre vs post difference: * $p<0.05$; ** $p<0.001$. Group x training interaction effect: ## $p<0.001$.

SUPPLEMENTAL DIGITAL CONTENT

SDC 1: Supplemental Digital Content 1.docx

Figure 1

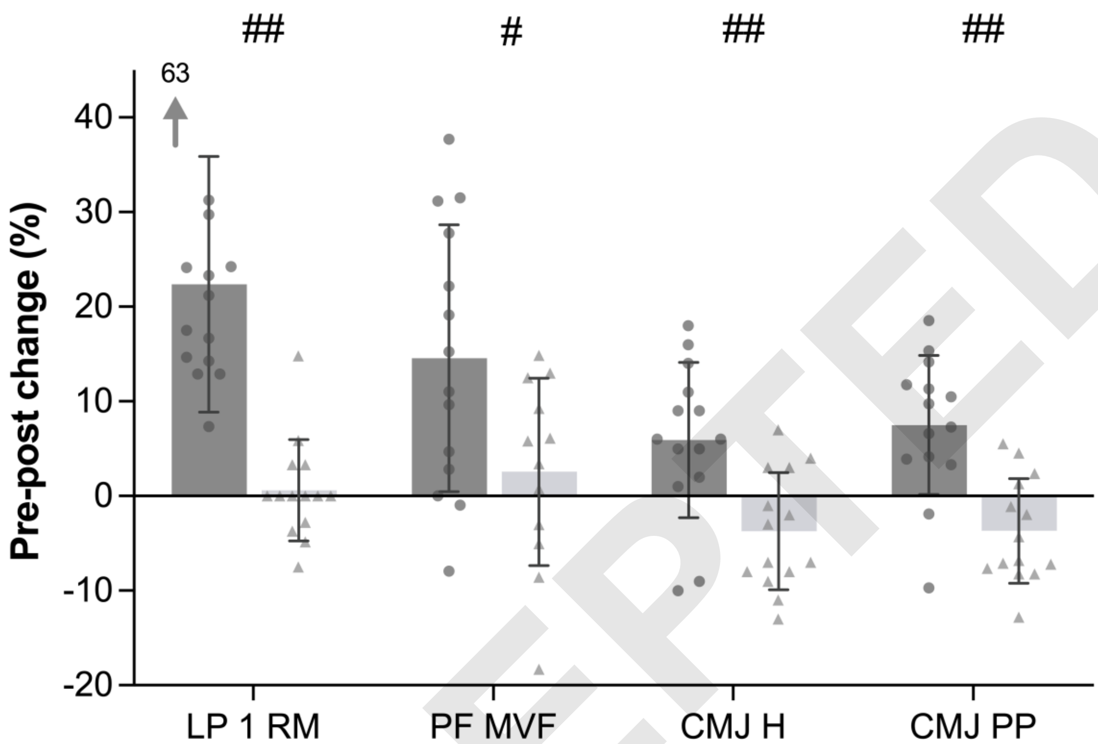
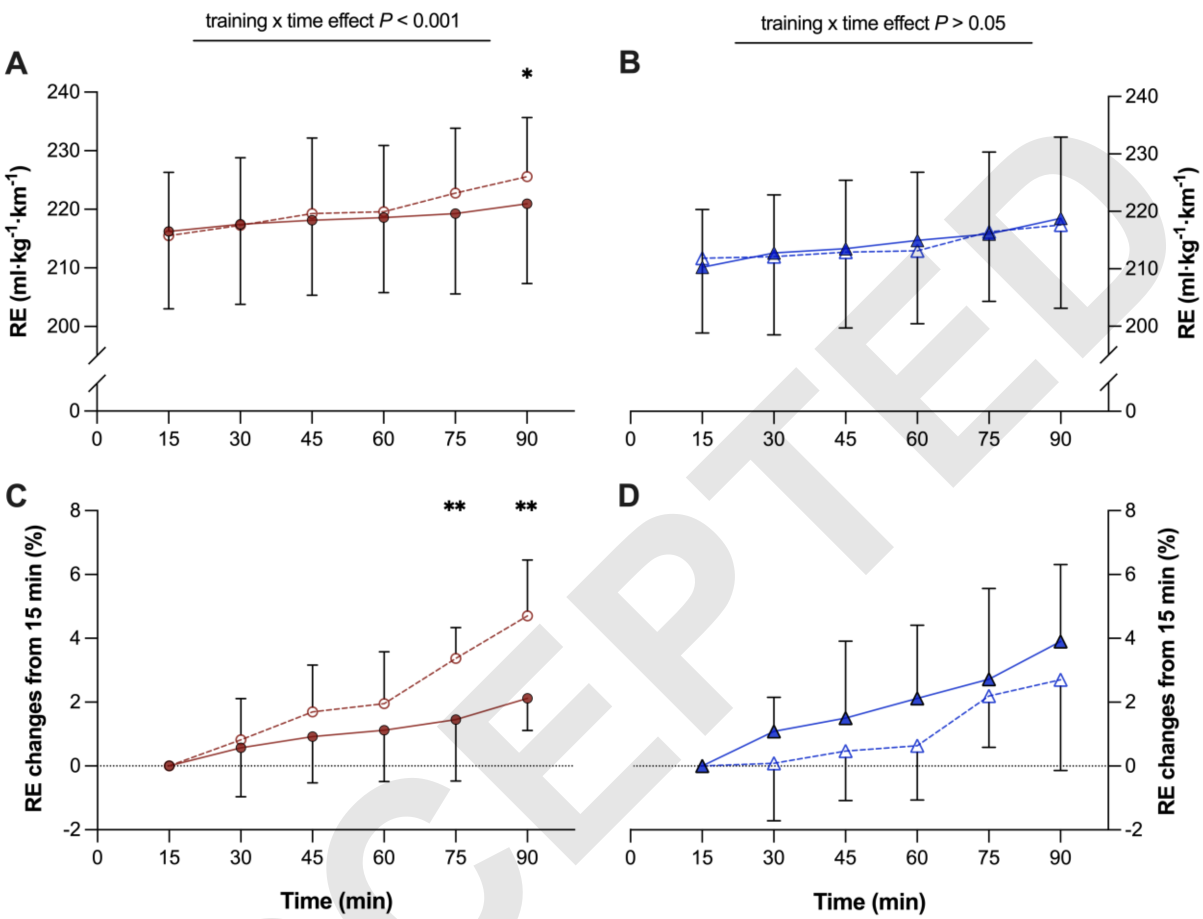
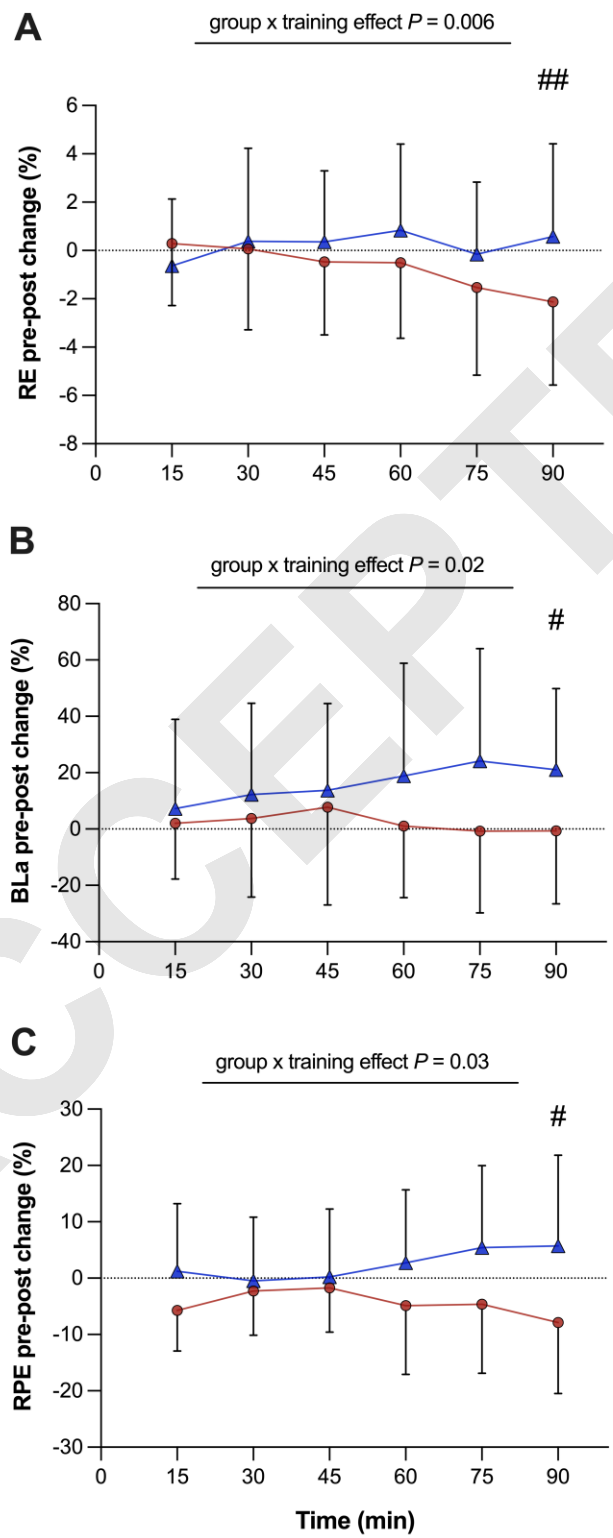


Figure 2



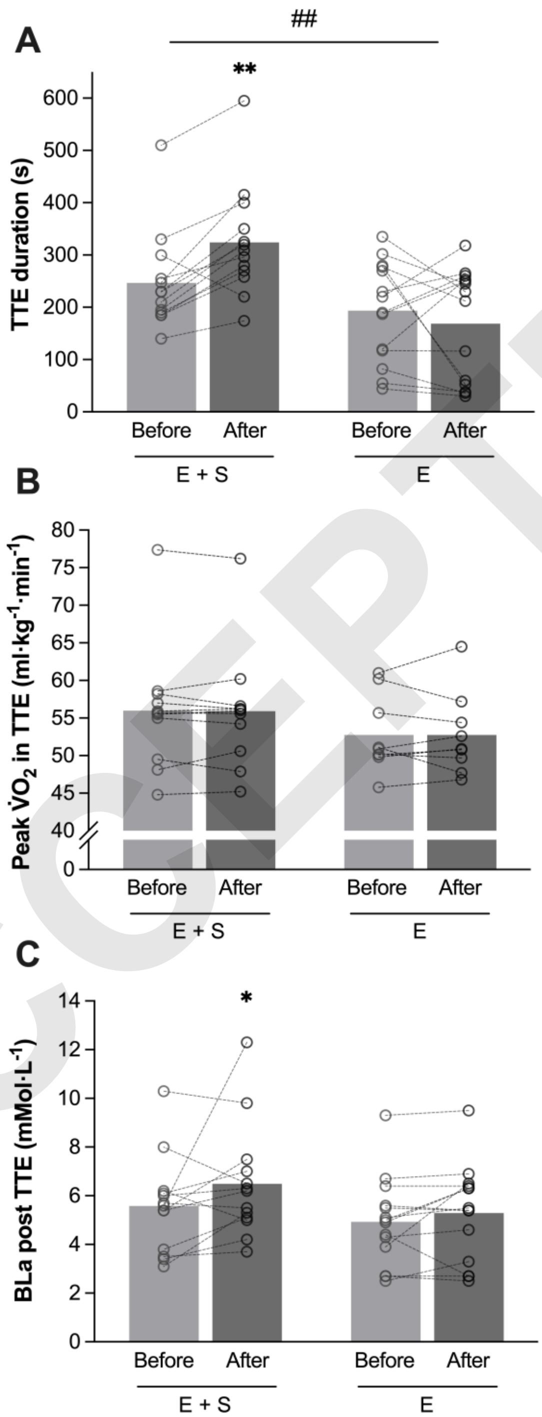
training x time effect P < 0.001
training x time effect P > 0.05
A
B
C
D
RE (ml·kg-1·km-1)
RE changes from 15 min (%)
Time (min)
*
**
**

Figure 3



A
group x training effect *P* = 0.006
##
RE pre-post change (%)
6
4
2
0
-2
-4
-6
-8
0
15
30
45
60
75
90
B
group x training effect *P* = 0.02
#
BLa pre-post change (%)
80
60
40
20
0
-20
-40
0
15
30
45
60
75
90
C
group x training effect *P* = 0.03
#
RPE pre-post change (%)
30
20
10
0
-10
-20
-30
0
15
30
45
60
75
90
Time (min)

Figure 4



A
##
**
TTE duration (s)
600
500
400
300
200
100
0
Before
After
Before
After
E + S
E
B
Peak VO2 in TTE (ml·kg-1·min-1)
80
75
70
65
60
55
50
45
40
0
Before
After
Before
After
E + S
E
C
*
BLa post TTE (mMol·L-1)
14
12
10
8
6
4
2
0
Before
After
Before
After
E + S
E

Table 1. Details of the 10 weeks strength training intervention.

		Week 1-3	Week 4-7	Week 8-10
Vertical plyometrics	Exercise	Pogo jumps	Drop jumps	Drop jumps
	Set x reps / rest	3 x 10-12 / 90 s	3 x 6 / 120 s	3 x 6 / 120 s
Horizontal plyometrics	Exercise	Hop and stick	Stiff leg bounds	Bounds for length
	Set x reps / rest	3 x 6 / 90 s	3 x 10 / 90 s	3 x 8-12 / 90 s
Back squat	Set x reps / rest	3 x 6-8 / 120 s	3 x 5-6 / 120-150 s	3 x 4-5 / 150 s
	Load (%1RM)	65-80 %	80-85 %	85-90 %
Single-leg press	Set x reps / rest	3 x 6-8 / 120 s	3 x 5-6 / 120-150 s	3 x 4-5 / 150 s
	Load (%1RM)	65-80 %	80-85 %	85-90 %
Seated isometric calf raises	Set x reps / rest	4 x 6-8 / 60 s	5 x 4-6 / 90 s	5 x 4-6 / 90 s
	MVF %	80-100 %	100 %	100 %

1RM %: Percentage of 1 maximal repetition; MVF %: Percentage of maximal voluntary isometric force. Sets are described as “number of sets” x “number of repetitions” / “recovery time”. Plyometrics exercises are described in the supplementary materials.

Table 2. Baseline performance and physiological characteristics of the combined endurance and strength training group (E+S, n=14) and endurance training only (E, n=14).

	E+S	**E**	**Matching (p value)**
10 km speed ($km \cdot h^{-1}$)	15.3 ± 1.7	15.4 ± 1.6	0.88
$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	58.9 ± 7.5	56.8 ± 5.7	0.41
RE ($ml \cdot kg^{-1} \cdot km^{-1}$)	215 ± 11	212 ± 13	0.45
90 min run speed ($km \cdot h^{-1}$)	13.1 ± 1.3	13.0 ± 1.6	0.86
90 min run ($\dot{V}O_2max$ %)	79.5 ± 3.9	79.9 ± 3.9	0.65
TTE speed ($km \cdot h^{-1}$)	16.1 ± 1.8	16.0 ± 1.5	0.80

Values are mean ± SD. $\dot{V}O_2max$: maximal oxygen uptake; RE: running economy; TTE: time to exhaustion post 90 min run.

Table 3. Training characteristics, strength, power, and DXA tests before (pre), during, and after (post) 10 weeks of combined endurance and strength training (E+S, n=14) and endurance training only (E, n=14).

	E+S			E			η_p^2
	Pre	**During**	**Post**	**Pre**	**During**	**Post**	
Training volume:							
Total ($h \cdot w^{-1}$)	3.9 ± 1.4	4.8 ± 0.9	-	3.9 ± 2.4	3.8 ± 1.8	-	0.13
Strength ($h \cdot w^{-1}$)	0.4 ± 0.6	1.6 ± 0.2	-	0.2 ± 0.5	0.3 ± 0.5	-	0.54$^{\#\#}$
Running ($h \cdot w^{-1}$)	3.5 ± 1.5	3.2 ± 1.0	-	3.7 ± 2.2	3.5 ± 1.7	-	0.00
Running ($km \cdot w^{-1}$)	47 ± 22	43 ± 20	-	51 ± 26	48 ± 27	-	0.00
Strength & Power:							
Leg press 1RM (kg)	164 ± 22	-	200 ± 25**	158 ± 19	-	159 ± 16	0.62$^{\#\#}$
PF MVF (N)	1177 ± 235	-	1327± 184**	1087 ± 243	-	1110 ± 252	0.21$^{\#}$
CMJ height (m)	0.33 ± 0.05	-	0.35 ± 0.05*	0.32 ± 0.04	-	0.31 ± 0.04	0.32$^{\#}$
CMJ PP ($W \cdot kg^{-1}$)	45.0 ± 5.3	-	48.4 ± 6.6**	44.7 ± 5.3	-	43.0 ± 5.1*	0.44$^{\#\#}$
Body composition:							
Body mass (kg)	71.1 ± 1.7	-	70.6 ± 1.9	69.3 ± 1.7	-	69.1 ± 1.9	0.04
Whole body FM (kg)	11.9 ± 4.6	-	10.8 ± 4.8*	11.8 ± 3.9	-	12.0 ± 3.7	0.16$^{\#}$
Whole body LM (kg)	56.3 ± 4.3	-	57.0 ± 3.9	54.4 ± 5.2	-	54.1 ± 4.9	0.14$^{\#}$
Leg LM (kg)	19.4 ± 2.0	-	19.5 ± 1.7	18.3 ± 1.9	-	18.2 ± 1.9	0.03

Values are mean ± SD. 1RM: 1 maximal repetition; PF MVF: plantar flexors maximal voluntary force; CMJ: counter movement jump; PP: peak power; FM/LM: fat/lean mass. η_p^2= training x group interaction effect size. Different from Pre: * p<0.05 ** p<0.001. Interaction effect: # p<0.05 ## p<0.001

Table 4. Physiological changes over the 90 min run before (pre) and after (post) 10 weeks of combined endurance and strength training (E+S, n=14) and endurance training only (E, n=14).

	Group		Trial time (min)						
			15	**30**	**45**	**60**	**75**	**90**	**η_p^2**
RE ($ml \cdot kg^{-1} \cdot km^{-1}$)	E+S	Pre	215 ± 11	217 ± 11	219 ± 13	220 ± 11	223 ± 11	226 ± 10	0.13 $$
		Post	216 ± 13	217 ± 13	218 ± 13	219 ± 13	219 ± 14	221 ± 14 *#	
	E	Pre	212 ± 13	212 ± 14	213 ± 13	213 ± 13	217 ± 12	218 ± 15	
		Post	210 ± 10	213 ± 10	214 ± 12	215 ± 12	216 ± 14	219 ± 14	
BLa ($mMol \cdot L^{-1}$)	E+S	Pre	1.9 ± 0.3	1.8 ± 0.3	1.9 ± 0.4	2.0 ± 0.4	2.2 ± 0.4	2.3 ± 0.4	0.13 $
		Post	1.9 ± 0.1	1.8 ± 0.3	1.9 ± 0.3	1.9 ± 0.3	2.1 ± 0.3 #	2.2 ± 0.5 #	
	E	Pre	1.9 ± 0.5	1.9 ± 0.5	2.0 ± 0.5	2.1 ± 0.5	2.1 ± 0.4	2.4 ± 0.5	
		Post	2.0 ± 0.6	2.1 ± 0.6	2.2 ± 0.6	2.4 ± 0.7	2.6 ± 0.7 *	2.9 ± 0.8 *	
HR ($beats \cdot min^{-1}$)	E+S	Pre	160 ± 8	163 ± 8	166 ± 8	167 ± 8	169 ± 7	171 ± 8	0.02
		Post	162 ± 9	165 ± 10	167 ± 10	168 ± 11	169 ± 11	171 ± 11	
	E	Pre	158 ± 9	162 ± 8	163 ± 8	165 ± 8	168 ± 8	171 ± 8	
		Post	160 ± 7	164 ± 6	165 ± 7	167 ± 7	169 ± 7	172 ± 7	
RER	E+S	Pre	0.95 ± 0.03	0.93 ± 0.03	0.92 ± 0.04	0.92 ± 0.04	0.91 ± 0.03	0.90 ± 0.03	0.03
		Post	0.94 ± 0.04	0.93 ± 0.04	0.92 ± 0.04	0.92 ± 0.03	0.92 ± 0.03	0.91 ± 0.04	
	E	Pre	0.94 ± 0.04	0.93 ± 0.04	0.92 ± 0.04	0.91 ± 0.03	0.90 ± 0.03	0.90 ± 0.03	
		Post	0.95 ± 0.03	0.94 ± 0.04	0.93 ± 0.03	0.93 ± 0.03	0.93 ± 0.04	0.92 ± 0.04	
RPE (6-20)	E+S	Pre	12.1 ± 1.3	12.7 ± 1.4	13.2 ± 1.7	14.2 ± 1.7	14.9 ± 1.7	15.7 ± 2.0	0.12 $
		Post	11.3 ± 1.4 *	12.4 ± 1.5	13.0 ± 1.6	13.5 ± 2.0	14.2 ± 2.1	14.4 ± 2.1 *#	
	E	Pre	11.6 ± 1.3	12.7 ± 1.2	13.7 ± 1.2	14.8 ± 1.2	15.6 ± 1.4	16.5 ± 1.5	
		Post	11.7 ± 1.5	12.5 ± 1.2	13.6 ± 1.2	15.1 ± 1.5	16.2 ± 1.5	17.3 ± 1.6	

Values are mean ± SD. RE: running economy; BLa: blood lactate; HR: heart rate; RER: respiratory exchange ratio; RPE: rate of perceived exhaustion; η_p^2: training x group x run time interaction effect size. Different from Pre within group: * p<0.05. Difference in pre-post change between groups: # p<0.05. Training x group x run time interaction effect $ p<0.05; $$ p<0.01

Supplementary Materials

Methods

Fig. S1. Example picture of in-situ position during the plantar flexors maximal voluntary force test. The same position was replicated during the 10-week training intervention.

Results

Energy Cost (EC) of running

Pre-90 min run, there were no training x group effects for EC at 10 $km \cdot h^{-1}$ ($F=0.01$, $p=0.94$, $\eta_p^2=0.00$), or 12 $km \cdot h^{-1}$ ($F=0.06$, $p=0.81$, $\eta_p^2=0.00$). Similarly, no training x group effects were found for EC after 15 min of the 90 min trial ($F=0.78$, $p=0.39$, $\eta_p^2=0.03$; Table S1).

A training x group x run time effect was found for EC ($F=2.64$, $p=0.03$, $\eta_p^2=0.09$) during the 90 min run. Subsequent analysis of % change of EC (pre-post) revealed a group x run time interaction effect ($F=2.64$, $p=0.03$, $\eta_p^2=0.09$), and post-hoc analysis a between-group difference at 90 min (-1.8 ± 3.5% (E+S) vs +0.8 ± 3.9% (E); $p=0.03$; Fig S2). Within group, a training x run time interaction effect was found for EC in the E+S group ($F=3.18$, $p=0.01$, $\eta_p^2=0.20$; Table S1). Similarly, when EC changes were calculated relative to the 15 minute time point, within S+E post-training there was a reduced deterioration in EC 90 min of running (+3.8 ± 2.2 vs +1.7 ± 1.0%; $p<0.01$; Fig. S3). In the E group, no within-group training x run time interaction was found for EC ($p=0.37$).

Fig S2. Percentage changes in energy cost post the 10-week intervention period at each time-point during the 90 min run at 10% Δ between LT1 and LT2, for the E+S (red circles, n=14) and E group (blue triangles, n=14). Difference between groups: # p<0.05. Data are mean ± SD.

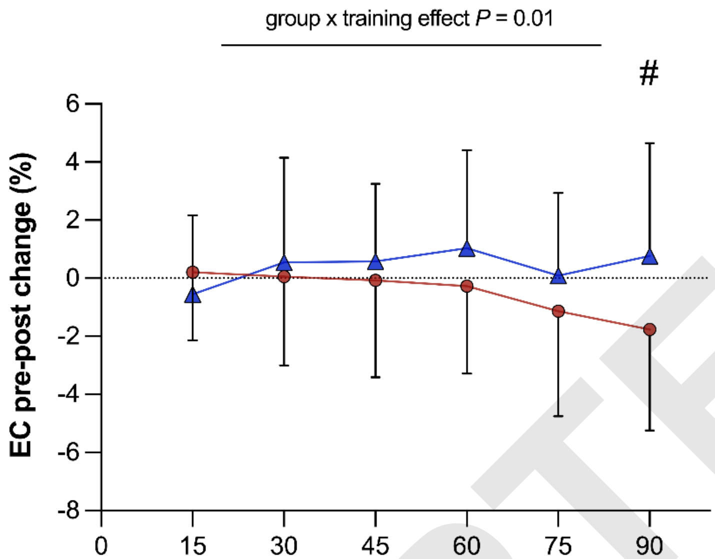


Fig. S3. Changes before (open circles/triangles) and after (filled circles/triangles) the intervention period during the 90 min run at 10% delta between lactate threshold 1 and 2 (~80% $\dot{V}O_2$max). Panels represent energy cost (EC) for the E+S (A; n=14) and E groups (B; n=14) measured during the run, and the percentage change from the initial 15 min time point for each group (C and D). Red circles indicate the E+S group, and blue triangles the E group. Data are mean ± SD. Different between measures at that time point: ** p<0.01.

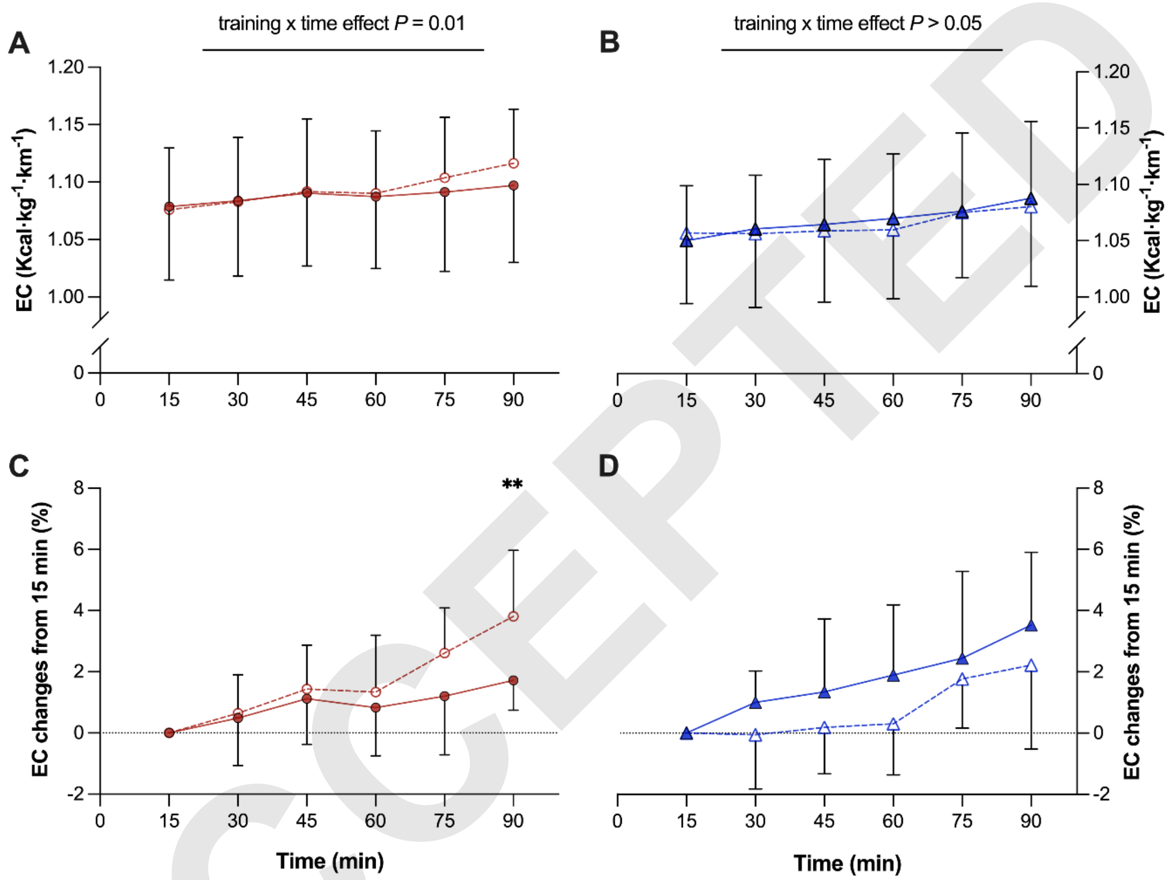


Table S1. Energy cost changes over the 90 min run before (pre) and after (post) 10 weeks of combined endurance and strength training (E+S, n=14) and endurance training only (E, n=14).

	Group		Trial time (min)						
			15	30	45	60	75	90	η_p^2
EC	E+S	Pre	1.08 ± 0.05	1.08 ± 0.06	1.09 ± 0.06	1.09 ± 0.05	1.10 ± 0.05	1.12 ± 0.05	
($Kcal \cdot kg^{-1} \cdot km^{-1}$)		Post	1.08 ± 0.06	1.08 ± 0.07	1.09 ± 0.06	1.09 ± 0.06	1.09 ± 0.07	1.10 ± 0.07 *#	0.09$
	E	Pre	1.06 ± 0.06	1.06 ± 0.07	1.06 ± 0.06	1.06 ± 0.06	1.08 ± 0.06	1.08 ± 0.07	
		Post	1.05 ± 0.05	1.06 ± 0.05	1.06 ± 0.06	1.07 ± 0.06	1.08 ± 0.07	1.09 ± 0.07	

Values are mean ± SD. EC: Energy cost; η_p^2: training x group x run time interaction effect size. Different from Pre within group: * $p<0.05$. Difference in pre-post change between groups: # $p<0.05$. Training x group x run time interaction effect $ $p<0.05$