Effects of Strength Training on Post-Pubertal Adolescent Distance Runners

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Abstract

Purpose: Strength training activities have consistently been shown to improve running economy (RE) and neuromuscular characteristics, such as force producing ability and maximal speed, in adult distance runners. However the effects on adolescent (<18 years) runners remains elusive. This randomized control trial aimed to examine the effect of strength training on several important physiological and neuromuscular qualities associated with distance running performance. *Methods:* Participants (*n*=25, 13 female, 17.2 ±1.2 years) were paired according to their sex and RE and randomly assigned to a ten week strength training group (STG), or a control group (CG) who continued their regular training. The STG performed twice weekly sessions of plyometric, sprint and resistance training in addition to their normal running. Outcome measures included body mass, maximal oxygen uptake ($\dot{V}O_{2max}$), speed at $\dot{V}O_{2max}$, running economy (quantified as energy cost), speed at fixed blood lactate concentrations (sFBLC), 20 m sprint, and maximum voluntary contraction (MVC) during an isometric quarter-squat. *Results:* Eighteen participants (STG, *n*=9, 16.1 ±1.1 years; CG, *n*=9, 17.6 ±1.2 years) completed the study. The STG displayed small improvements (3.2-3.7%, ES: 0.31-0.51) in running economy that were inferred as 'possibly beneficial' for an average of three submaximal speeds. Trivial or small changes were observed for body composition variables, $\dot{V}O_{2max}$ and s$\dot{V}O_{2max}$, however the training period provided likely benefits to sFBLC in both groups. Strength training elicited a very likely benefit and a possible benefit to sprint time (ES: 0.32) and MVC (ES: 0.86) respectively. *Conclusion:* Ten weeks of strength training added to the programme of a post-pubertal distance runner was highly likely to improve maximal speed, and enhances running economy by a small extent, without deleterious effects on body composition or other aerobic parameters.

Key words: running economy, resistance training, youth, concurrent training

Introduction

Success in distance running can be attributed to a variety of physiological and biomechanical factors [1]. From a physiological perspective, energy acquired via aerobic means contributes a significant proportion to performance outcomes of middle- and long-distance events [2]. Indeed, several studies have demonstrated that aerobic qualities such as maximal oxygen uptake ($\dot{V}O_{2max}$), the speed associated with $\dot{V}O_{2max}$ (s$\dot{V}O_{2max}$), running economy (RE) and sub-maximal lactate values have a strong relationship with distance running performance [3-5]. These variables have also been shown to be important predictors of performance in adolescent distance runners [6, 7].

In addition to an obvious need to develop aerobic qualities, it is apparent that the neuromuscular system plays an important role in optimizing distance running performance [8, 9]. RE, the metabolic cost of running a given distance, is underpinned by physiological attributes, anthropometrics and biomechanics [10]; however there is also emerging evidence demonstrating that strength training enhances RE in trained distance runners [11-14]. The proposed mechanism for this improvement relates to enhancements in neuromuscular characteristics such as lower limb stiffness and force producing ability [15].

There is also convincing evidence that strength training is safe and effective for adolescent athletes [16]. Current guidelines suggest that adolescents should participate in 2-3 supervised resistance training sessions per week [17]. Studies that have investigated the effects of resistance training in youth populations have tended to focus on the development of strength-related qualities in pre-pubertal and peri-pubertal participants, which underpin a variety of different sports skills. Resistance training can also positively influence sprint performance (5-40 m), beyond that which would be expected with maturation alone [18]. Mikkola and co-authors [19] provide the only study to investigate the impact of a strength training intervention on markers of performance in post-pubertal runners (16-18 years). Replacing 19% of total running volume with explosive strength training exercises for eight weeks improved neuromuscular and anaerobic characteristics, but without any significant impact on aerobic performance markers. The strength training activities (sprints, jumps and low-load resistance training) were performed in low frequency (each on average once per week), and resistance training primarily targeted single-joint actions. It is recommended that distance runners incorporate 2-3 strength training sessions per week [20], and utilize multi-joint closed-chain exercises, which provide a high level of mechanical specificity to the running action [21]. Therefore the effect of a strength training programme, involving multi-joint resistance exercises performed more than once per week by adolescent runners, on determinants of distance running performance remains unknown.

Accordingly, the purpose of this study was to examine the effect of supplementing post-pubertal adolescent distance runners with strength training on the physiological and strength-related indicators of performance. It was hypothesized that the addition of strength training would result in superior improvements in RE, s$\dot{V}O_{2max}$, maximal speed and strength measures compared to the control group (CG).

Methods

Participants

A sample size estimation of *n*=20 was calculated a priori based upon statistical power of 80%, at a 5% probability threshold, and an effect size of 0.67 for the primary outcome variable, RE. Typical error (TE) and minimal detectable change at the 95% confidence level (MDC_{95}) for RE were derived from a previous reliability study in this population [22]. Based upon an anticipated 20% drop-out, 25 participants (13 female, mean ±SD age: 17.2 ±1.2 years, range: 15.2-18.8 years) initially volunteered to take part. The study received institutional level ethical approval and was conducted in accordance with the Declaration of Helsinki. Participants were required to meet the following inclusion criteria: age 15-18 years, no formal strength training experience, free from injury in the month preceding the study, competed regularly at county, regional, national or international level in middle- (800 m – 3,000m) or long-distance (5 – 10 km and cross-country) running. A parent/guardian provided a signature of consent prior to participation, and in the case of those age 18 years, consent was provided by the participant themselves.

Following baseline testing, participants were assigned to a strength training group (STG) or a CG using a pre-test matched pairs approach. Participants were ranked according to their baseline RE, paired, and randomly allocated to either the STG (*n*=13) or CG (*n*=12). This approach reduces the bias associated with randomization, since it decreases the likelihood of differences between study groups at baseline.

Testing overview

Testing took place over two days before and after the intervention period, at the same time of day for each participant and under similar laboratory conditions (temperature, 16-20^{o}C; relative humidity, 36-54%; barometric pressure, 746-773 mmHg). The first testing session involved measurements of anthropometrics, a submaximal running assessment and a maximal running test. Following thirty minutes of passive recovery, participants were familiarised with the strength tests. The second testing session took place 48-72 h later, and was used to test participant's maximal speed, and force-producing capabilities under dynamic and isometric conditions. Every effort was made to schedule testing sessions on the same days pre- and post-intervention to maximise the likelihood that participants would adhere to requests to adopt a similar pattern of exercise and diet in the 48 h prior.

Anthropometry

Prior to each running trial, participants body mass was measured digitally to the nearest 0.1 kg (MPMS-230, Marsden Weighing Group, Oxfordshire, UK). Stature and sitting height were measured with a stadiometer to the nearest 1 cm (SECA GmbH & Co., Hamburg, Germany). Maturity offset was calculated for each participant from age, stature and sitting height values using published formulae [23]. The sum of skinfolds at four sites (biceps, triceps, subscapula, supra-iliac) was assessed with calipers (Harpenden, Baty International, West Sussex, UK) according to ISAK guidelines.

Submaximal and maximal running tests

All running testing took place in the same physiology laboratory on a motorised treadmill (HP Cosmos Pulsar 4.0, Cosmos Sports & Medical GmbH, Munich, Germany). Expired air was collected via a low dead-space mask and monitored continuously via an automated open circuit metabolic cart (Oxycon Pro, Enrich Jaeger GmbH, Hoechberg, Germany) to quantify pulmonary ventilation, oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$) and respiratory exchange ratio (RER). Heart rate (HR) was also recorded continuously throughout the test (Polar RS400, Polar Electro Oy, Kempele, Finland). Following a 5 min warm-up, participants completed a discontinuous incremental test at a 1% gradient [24] to determine RE, HR and lactate response. Participant's most recent race performances and their HR response during warm-up were used to determine the start speed and provide at least four speeds before lactate turn-point. The test consisted of five to seven 3 min running stages with speed increases of 1 km.h^{-1} each stage, separated by 30 s rest to allow for a 20 µl sample of capillary blood to be taken from the earlobe. Each sample was hemolysed and subsequently analysed for blood lactate concentration (Biosen C-Line, EKF Diagnostic, Barleben, Germany). The test was discontinued when the rise in lactate exceeded 1 mMol.L^{-1} compared to the previous stage, which defined their speed at lactate turnpoint (sLTP).

The data analysis process used to obtain values for RE and $\dot{V}O_{2max}$ has been described previously [22]. Breath-by-breath data were initially filtered to remove any errant breath which did not represent the underlying physiological response [25]. The mean values for $\dot{V}O_2$, $\dot{V}CO_2$, RER and HR from the final 60 s of the stage corresponding to sLTP and the two speeds prior (sLTP -1 km·h^{-1}, sLTP -2 km·h^{-1}) were used in subsequent analysis. The $\dot{V}O_2$ value was used with the RER value to quantify the energy cost of running using non-protein quotient equations [26], which is likely to provide a more valid [27] and reliable [22] measure of RE compared to oxygen cost. As sLTP varied across participants, RE was expressed as the energy cost of running per km. Speed at fixed concentrations of blood lactate (sFBLC) was estimated from the speed-lactate curve for 2, 3 and 4 mMol·L^{-1} using published software [28].

Following the submaximal running test, participants rested for 5 min before completing a continuous incremental treadmill test to volitional exhaustion to determine $\dot{V}O_{2max}$. The treadmill belt was set to sLTP, and the gradient initially set at 1%. Thereafter, the gradient was increased by 1% every minute until volitional exhaustion, which typically took 6-8 minutes. $\dot{V}O_{2max.}$ was taken as the highest $\dot{V}O_2$ achieved in a 30 s period (after filtering). Speed at $\dot{V}O_{2max.}$ (s$\dot{V}O_{2max}$) was predicted for each participant by using the equation for the linear regression line for the relationship between $\dot{V}O_2$ and speed extrapolated to the $\dot{V}O_{2max}$ value. The linearity of regression lines for participants across both trials was R^2 = 0.981 ±0.02. Prior test-retest reliability work, using a cohort with similar characteristics, demonstrated high inter-session reliability for physiology variables [22].

Speed and strength tests

Following a self-paced 3 min warm-up run, participants performed two sub-maximal 20 m sprints from a rolling start, followed by three maximal timed sprints (Brower Timing Systems, Utah, USA) in an indoor sports hall. Each sprint was interspersed by a 2 min walk recovery. Participants were instructed to initiate their sprint with a sufficiently long approach to enable maximal speed to be reached by the first set of timing gates. To assess dynamic strength capabilities, participants performed three squat jumps for maximum height on a fixed force plate sampling at 1000 Hz (Kistler 9287BA, Kistler Instruments Ltd, Hampshire, UK). Each attempt was separated by a 90 s passive recovery. Participants were instructed to place their hands on their hips and squat down to a comfortable position, hold this position for 3 s, and on a signal provided by the tester, jump as high as possible. If there was an indication on the force trace that a counter-movement had been used prior to initiation of the jump, the attempt was repeated. Peak displacement of the centre of mass was estimated using the velocity at take-off method [29]. Peak vertical ground reaction force ($vGRF_{jump}$) was recorded as the highest force produced during the concentric phase of the jump.

Maximal voluntary contraction (MVC) was assessed in a custom built adjustable back-squat rig. Participants gripped a fixed bar, positioned across their upper back, and adopted a quarter-squat position with knees flexed at 140^{o}. This position was determined during the familiarisation session, thus an identical set-up was used in subsequent trials. Participants stood on a force plate (PASPORT PS2141, PASCO, Roseville, CA, USA) measuring at 1000 Hz and were instructed to push against the bar as hard as possible for 3-4 s. Two warm-up repetitions preceded three recorded attempts in which strong verbal encouragement was provided.

Attempts were each separated by 90 s of rest. MVC was defined as the highest force value produced during the contraction. The best score over the three attempts was used in subsequent analysis for each test. The inter-session reliability values (TE; intra-class correlation coefficient, ICC; MDC_{95}) for speed (0.34%, 0.99, 1.0%), peak displacement (4.89%, 0.94, 13.5%), $vGRF_{jump}$ (5.71%, 0.50, 15.8%), and MVC (5.10%, 0.65, 14.1%) were considered acceptable in a group of adolescent distance runners (6 females, 6 males, 17.8 ±1.4 years).

Allometric scaling

To account for differences in body mass between individuals, a ratiometric index has tended to be favoured in similar studies for scaling parameters relating to $\dot{V}O_2$ [12, 13, 19]. This scaling approach is only valid if the relationship between body mass and a physiological variable are directly proportional, which is rarely the case [30]. To calculate appropriate scaling exponents for variables used in the present study, data from a larger cohort of adolescent distance runners (n=42) was log-transformed, and following an analysis of covariance (ANCOVA) comparison for males and females, a common power function was calculated via linear regression. An exponent of two-thirds (95% CI $\dot{V}O_{2max}$: 0.34-0.98, $\dot{V}O_2$: 0.41-0.90) was previously established for $\dot{V}O_2$ parameters [22], and applying the same mathematical process in a similar cohort of participants (n=36), values of 0.76 (95% CI: 0.33-1.20) and 0.61 (95% CI: 0.03-1.22) were established for $vGRF_{jump}$ and MVC respectively.

Training

Both groups were instructed to continue their normal running training throughout the study period. The study took place during early off-season training period (September-December), therefore participants were predominantly performing high volume, low intensity running. Participants maintained training logs, which detailed their daily running volume and the pace associated with each training session.

The STG supplemented their programme with two sessions (60-70 min duration) of strength training per week, each separated by 2-4 days. Following a week of familiarisation with exercise technique and equipment, participants completed a ten week programme of progressive strength training, as shown in Table 1. Recent work has indicated that 6-8 week programmes elicit relatively small changes in RE, whereas programmes of 10 weeks or longer provides moderate-large effects [20]. Each session commenced with a warm-up designed to enhance movement skill and mobility. The second part of the session involved plyometric- and sprinting-based exercises designed to improve explosive- and reactive-strength. The final part of each session was dedicated to resistance training primarily using free weights (barbells and dumbbells). Exercises were selected that possessed similar kinematic characteristics to the running action. Every session was supervised by professionally accredited strength and conditioning coaches. Intensity of each exercise was moderated based upon each participant's technical ability and perceived effort, with load on resistance training exercises typically progressing by 5-10% per week within a mesocycle.

*** Table 1 about here ***

Statistical analysis

An ANCOVA was performed (SPSS v22, IBM, New York, USA) on each dependent variable using baseline scores as the covariate, which adjusts for any chance imbalance between the STG and CG. The assumptions associated with ANCOVA were verified for all variables via Levene's Test for homogeneity of variance, Shapiro-Wilk Test for the assumption of normality, and a customised ANCOVA model to assess homogeneity of regression. A Multivariate

Analysis of Variance with a Bonferroni post-hoc correction was used to compare the data from training logs between groups. Significance was accepted at the $P<0.05$ level with a 95% confidence interval.

To facilitate more widespread use of our findings in applied settings, effect sizes and magnitude based inferences were identified to provide a more qualitative interpretation of the extent to which changes observed were meaningful. Effect sizes were calculated (Microsoft Excel 2013) as a ratio of the difference between the mean change value for each group and the pooled SD at baseline for all participants, and were interpreted as trivial <0.2; small 0.2-0.6; moderate 0.6-1.2; and large >1.2 [31]. For each variable, the MDC_{95}, calculated using the TE of measurement for this group of participants [22], was entered along with the *P*-value and ES into a published spreadsheet [32] to obtain the likelihood that the intervention was beneficial (or indeed harmful) to the population. The MDC_{95} represents the magnitude required for a change in score to be considered clinically meaningful, and therefore provided a robust threshold to judge the efficacy of the intervention. The resulting values were translated into descriptors using the modified thresholds proposed by Batterham and Hopkins [31]: 0-0.5% most unlikely; 0.5-5% very unlikely; 5-25% unlikely; 25-75% possibly; 75-95% likely; 95-99.5% very likely; and >99.5% most likely.

Inter-individual responses to the intervention were considered by calculating the true individual difference in response using the following formula:

$$\sqrt{SD_{STG}^2 - SD_{CG}^2}$$

Where SD_{STG} and SD_{CG} represents the SD of the change score for the STG and CG groups respectively. In this instance, it is more appropriate to use the SD of the CG change value as the comparator variable, rather than the TE derived from a short-term reliability study in this population [22], as within-subject biological variation is likely to increase over time [33]. Descriptive statistics are presented as mean ±SD.

Results

Group characteristics

Based upon maturity offset values, all participants were considered post-pubertal (≥ 1.0 year), even when the standard error associated with the predictive equation was accounted for [23]. Seven participants withdrew during the course of the study for the following reasons: injury (STG n=3, CG n=1), illness (STG n=1), time commitment (CG n=1), voluntary dropout (CG n=1). The injuries that occurred in the STG were diagnosed as overuse type injuries that could not be directly attributed to the intervention. No other adverse effects were reported during the intervention period. The final sample consisted of nine participants in the STG (5 females, 4 males) and nine in the CG (5 females, 4 males). Group characteristics are shown in Table 2, with $\dot{V}O_{2max}$ shown as a ratio to body mass for comparative purposes.

*** Table 2 about here ***

Training history

Table 3 displays a summary of the training undertaken by participants during the intervention period. Participants typically undertook 2-3 extensive interval training sessions per week at sLTP or faster. These were performed on the same days across the cohort. The remaining volume of running was undertaken at speeds below sLTP, however inter-individual variation was high (135 ±74 min.week^{-1}). No significant differences (P>0.05) between groups were noted in total training time, total running duration, running at low (<sLTP) and high (>sLTP) intensities (ES: 0.17) and aerobic cross-training (ES: 0.01). However moderate effect sizes (0.6-0.7) were observed for the difference in total running duration in favour of the CG. Strength training time differed significantly between groups (F(1,16)=44.96, *P*<0.001, ES: 1.67). Engagement with strength training was high in the STG, with all participants completing ≥ 85% of sessions over the 10 week intervention.

*** Table 3 about here ***

Body composition and running measures

ANCOVA revealed no significant differences between groups post-training for body mass (F(1,16)=0.98, p=0.338), skinfolds (F(1,16)=4.15, p=0.060), $\dot{V}O_{2max}$ (F(1,16)=0.48, p=0.499), s$\dot{V}O_{2max}$ (F(1,16)=1.11, p=0.308), RE at LTP (F(1,16)=0.57, p=0.463), RE at LTP -1 $km{\cdot}h^{-1}$ (F(1,16)=1.39, p=0.256), RE at LTP -2 $km{\cdot}h^{-1}$ (F(1,16)=2.34, p=0.147), s2$mMol{\cdot}L^{-1}$ (F(1,16)=0.54, p=0.474), s3$mMol{\cdot}L^{-1}$ (F(1,16)<0.01, p=0.980), and s4$mMol{\cdot}L^{-1}$ (F(1,16)=0.01, p=0.917). Table 4 shows changes in body composition and physiological parameters for each group and between group comparisons. Body mass displayed a mean increase of (95% CI) 0 to 2.4% in the STG group, which was most likely trivial compared to the CG (ES: 0.08). Skinfold measures also exhibited minimal changes in both groups (ES: 0.24). $\dot{V}O_{2max}$ displayed trivial changes (ES: 0.07) in both groups, and s$\dot{V}O_{2max}$ improved in the STG by only a small margin (95% CI: -2.0 to 8.9%), which compared to the CG was likely trivial (ES: 0.34). RE improved between 3.2-3.7%, and by a magnitude that approximated the MDC_{95} values at all three speeds in the STG group, however increases were relatively small (ES: 0.31-0.51) and only considered 'possibly beneficial' at LTP -1 $km.h^{-1}$ speed. Figure 1A shows the change in average RE for three speeds, which was also considered ‘possibly beneficial’ (ES: 0.44, small) compared to the CG. sFBLC improved to a small extent (3.4-5.8%) in both groups, but between group effects were trivial (ES: 0.09-0.10). Within-group differences were considered ‘likely beneficial’ or ‘very likely beneficial’ for both groups.

Speed and strength measures

As shown in Figure 1B, 20 m sprint time improved by -0.10 s (95% CI: 1.8-5.4%; ES: 0.32, small) in the STG, which generated a significantly faster time compared to the CG post-training (F(1,16)=7.86, P=0.013) and was considered ‘very likely beneficial’. The STG also displayed significantly greater MVC at follow-up (F(1,16)=5.07, P=0.040; ES: 0.86, moderate) compared to the CG; a change which was deemed ‘possibly beneficial’ (95% CI: 6.3-24.5%, Table 5). The magnitude of between group change in peak displacement was ‘most likely trivial’ (ES: 0.10) and the difference non-significant (F(1,16)=0.18, p=0.682). $vGRF_{jump}$ improved to a moderate extent (95% CI: -1.9 to 14.1%) in the STG compared to the CG (ES: 0.93) but this change was considered ‘most likely trivial’ in the context of the MDC_{95} threshold (Table 5).

Inter-individual differences in response could mainly be explained by the within-participant variability in change scores, as for all but one variable (RE at sLTP), the SD for pre-to-post differences was larger in the CG group compared to the STG group (see Table 4 and Table 5). In standardised units the individual responses for RE at sLTP was 0.18, which indicates that individual responses were trivial between groups.

*** Figure 1 (panel A and B) about here ***

*** Table 4 about here ***

*** Table 5 about here ***

Discussion

The primary aim of this study was to investigate the physiological effects of ten-weeks of strength training in a group of competitive post-pubertal distance runners. It was anticipated that the STG would demonstrate superior improvements in RE, s$\dot{V}O_{2\max}$, sprint speed, and neuromuscular parameters compared to a CG. The main finding was that strength training provides a small benefit (3.2-3.7%) to RE across a range of sub-maximal speeds, which can be considered 'possibly beneficial'. Strength training is also likely to provide significant benefits to maximal sprint speed and isometric strength in runners of this age.

The findings of this study are in agreement with those of a recent meta-analysis in mainly adult runners, which showed concurrent strength and endurance training can provide a small beneficial effect (3.9 ±1.2%) to RE over a 6-14 week period [20]. Our results are also similar to the only other study that has investigated the efficacy of strength training in adolescent distance runners, which demonstrated small improvements (2.0-2.7%, ES: 0.26-0.40) in RE at 12 and 14 $km \cdot h^{-1}$, and trivial changes at 10 and 13 $km \cdot h^{-1}$ [19]. The superior effects we observed at all three speeds assessed (3.2-3.7%, ES: 0.31-0.51) may be due to the longer intervention period (10 vs 8 weeks), higher frequency of exposure to each type of strength training activity (2 vs 1 $day.week^{-1}$), and the choice of resistance training exercises (multi-joint vs single-joint). It is noteworthy that the intervention group in the Mikkola et al. [19] study performed almost double the volume of training compared to the STG in the present study (273 ±88 vs 528 ±126 $min \cdot wk^{-1}$). Moreover, the CG in the present study spent 41% more time running than the STG (ES: 0.69). This suggests that for the adolescent distance runner, strength training may be more effective than increasing endurance training volume at improving RE, at least in the short-term. It is also possible that the moderate disparity in low intensity running volume between the groups was advantageous to the STG group as less running may have facilitated the recovery process [34]. Despite the apparent trend towards an improvement in RE, it is important to note that the change scores did not exceed the MDC_{95} for any speed or an average of measurements (Figure 1A), indicating that only a possible benefit exists at specific speeds when TE of measurement is taken into account. A longer intervention period may therefore be required to provide higher certainty that strength training provides a practically significant benefit.

Neuromuscular factors, such as muscle activation and musculotendinous stiffness, play an important role in distance running [9, 35], therefore strategies to enhance these qualities are likely to lead to an improvement in physiological efficiency. A significant improvement in maximal force producing capability was observed in the STG (95% CI: 6.3-24.5%, ES: 0.86), which is in line with findings from previous studies in adult distance runners over a similar time frame [14, 36]. The strength training programme, which included plyometrics, sprinting and resistance training, was also shown to provide a small but very likely benefit to maximal sprint speed (95% CI: 1.8-5.4%; ES: 0.32); an improvement which was more than three times higher than the MDC_{95} value. Maximal speed is an important anaerobic quality required for middle-distance running [37], and is also related to long-distance running performance [8, 9]. Maximal sprinting requires higher ground reaction forces compared to sub-maximal running [38], therefore this finding provides evidence that strength training can improve neuromuscular characteristics during a highly functional assessment of explosive strength in runners. Peak displacement and $vGRF_{jump}$ displayed changes which fell well within MDC_{95} limits, thus the effect of strength training was at best trivial. The specificity of the exercises used in the strength training programme (Table 1) may provide an explanation for this finding, since very little maximal concentric-dominant jumping was included. A relatively higher volume of near-maximal sprinting and loaded exercises that mimic a quarter-squat position were included, which appears to have provided a sufficiently high transfer of training effect to enhance 20 m sprint and MVC. The possibility that the bodyweight movement skill exercises included in the warm-up routine also contributed towards the improvements observed cannot be discounted. Dynamic postural control exercises reduce coactivation of muscles in the lower limb, which may have enhanced efficiency during running via improvements in stabilisation strategy [39].

Despite our prediction that s$\dot{V}O_{2max}$ would improve to a greater extent in the STG, this was not the case (95% CI:-2.0 to 8.9%, ES: 0.34, likely trivial benefit). s$\dot{V}O_{2max}$ provides a composite measure of physiological performance that appears to differentiate adolescent runners with greater accuracy than traditional determinants [6]. Our findings are in agreement with other works that utilised a similar intervention duration [12, 19], but differ from studies which lasted ≥ 14 weeks [11, 13], suggesting longer time frames may be required to realise a positive effect. It is also likely that large improvements in constituent qualities ($\dot{V}O_{2max}$, RE) are required to elicit a meaningful change in s$\dot{V}O_{2max}$. Although RE displayed small improvements, $\dot{V}O_{2max}$ showed little alteration, implying that a greater stimulus may be required to influence these variables.

Following an eleven week period of running training, it was expected that aerobic variables would exhibit improvements in a group of adolescent athletes. The intervention period provided a small (3.4-5.8%) but very likely or likely benefit to sFBLC in both groups, suggesting the running training caused metabolic adaptations [40], which were not augmented by strength training (ES: 0.09-0.10, trivial). The lack of change in $\dot{V}O_{2max}$ in both groups corroborates findings from previous investigations [11-14, 36]. Improvements in aerobic capacity are influenced by a variety of factors including initial training status, and the duration and nature of training conducted [41]. Both groups spent 25-28% of their running training above sLTP, an intensity which is likely to have provided a strong stimulus for improving $\dot{V}O_{2max}$ [42]. Therefore it appears the study duration and the initial fitness level of participants provide the most likely explanation for the unaltered values observed. Despite the absence of change in several parameters, it is notable that strength training caused no deleterious effects in physiological predictors of performance despite the STG spending ~40% less time running compared to the CG.

Increases in body mass are potentially disadvantageous to distance runners, therefore gains in muscle mass, which is often an inevitable consequence of strength training, are unfavourable. Although the confidence interval for the change in body mass in the STG did not overlap zero (95% CI: 0-2.4%), the differences between groups were most likely trivial (ES: 0.08). Furthermore, any slight increase in body mass in the STG did not adversely affect the physiological variables that were allometrically scaled for body mass. Despite the association between resistance training and a hypertrophy response [43], there is consensus that strength training has little impact upon body mass in distance runners, at least in the short- to medium-term [20]. The interference phenomenon, which is often observed when endurance and strength training are performed concurrently within the same programme, has been offered as one explanation [44]. The impairment of muscle fibre hypertrophy is likely to occur under conditions of energy depletion [45], or when strength training is performed alongside a high frequency and intensity endurance exercise [46]. Given, the relatively low volume of endurance training undertaken by the STG (Table 2), the interference effect was perhaps less likely. Therefore practitioners should be cognisant that gains in muscle mass may occur over longer periods if a low volume of running is performed.

This study is subject to a number of limitations. Firstly with the exception of sprint time, the measures taken in this study were laboratory-based, thus it is not known what impact the training intervention had on middle- or long-distance performance. Secondly, the cohort of participants were of both sexes and mixed event specialisms and abilities, therefore had a more homogenous group been targeted, firmer conclusions may have been possible. Thirdly, the scaling exponents utilized for normalization of body mass were derived from relatively small samples ($n \leq 42$), which may have generated small errors during the calculation of values. Although we do not believe that these errors are sufficiently large to alter the findings of this study, the changes observed in RE were equal to or slightly less than the MDC_{95} at each speed (Table 4), therefore a more accurate scaling factor may have provided greater confidence that the changes observed were meaningful. Finally, the study was conducted during the early off-season, which was characterized by training of a more extensive nature, known to cause interference with strength adaptation [44]. It is not known what effect a strength training programme would have on physiological parameters during a different training phase, particularly one that had a larger emphasis on intensive training.

In conclusion, the addition of low frequency (2 days$\cdot$week^{-1}) strength training to the programme of an adolescent distance runner is possibly beneficial for RE at specific speeds, and very likely to benefit maximal sprint speed, which are both important factors for middle- and long-distance running performance. It was speculated that changes in neuromuscular characteristics, such as maximal force producing capability, underpin the small improvements in RE observed. A ten-week period of strength training was insufficient to alter $s\dot{V}O_{2max,}$ therefore further studies are required to investigate the time course of change in this and other determinants. There appears to be little risk that strength training increases body mass; any change over a period of 2-3 months is likely to be trivial.

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Conflict of Interest

The authors report no conflict of interests. The results of the present study do not constitute endorsement by ACSM. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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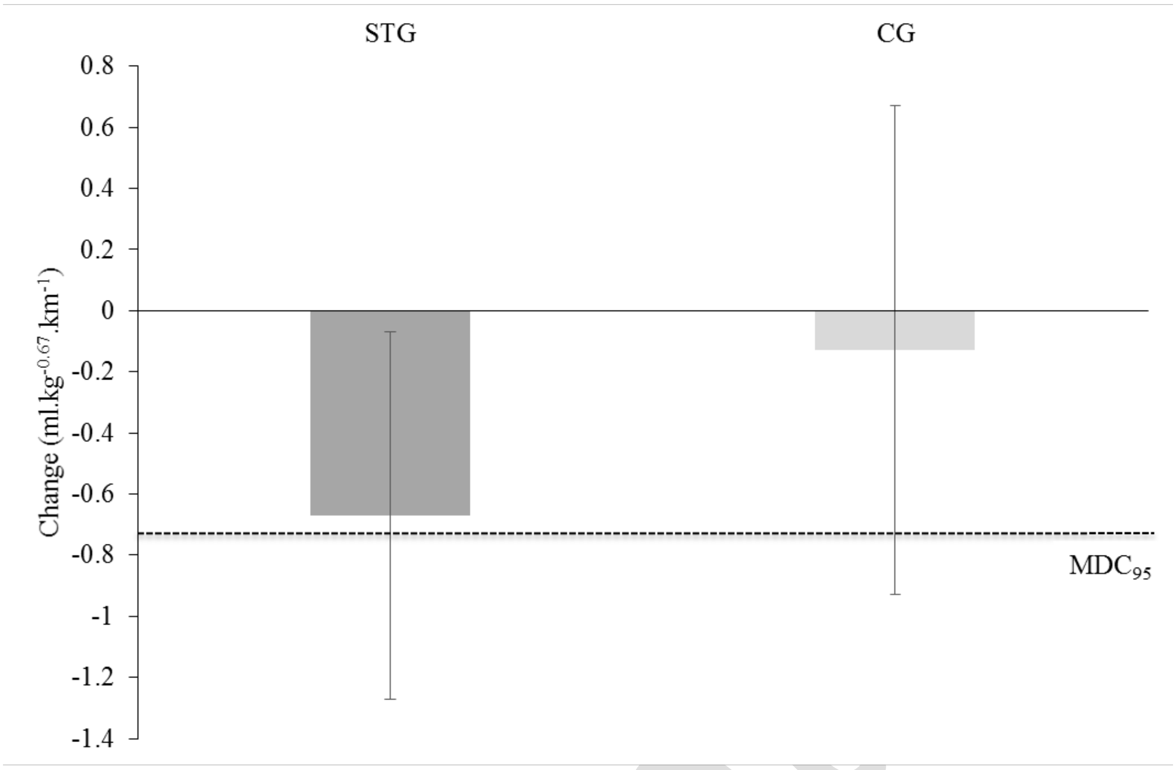
Figure. **A,** Change in average running economy in the strength training group (STG) and control group (CG). The change score for running economy is normalized for body mass using a scaling exponent derived from a previous study in this group (22). **B,** Change in 20 m sprint time in the strength training group (STG) and control group (CG). Error bars represent the 95% confidence interval for the mean change. Minimal detectable change at 95% confidence (MDC_{95}) is shown as the dashed line. A value which exceeds this line provides 95% confidence that the change is meaningful and not the result of typical error in measurement.

A:


STG
CG
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Change (ml.kg$^{-0.67}$.km^{-1})
MDC$_{95}$

B:

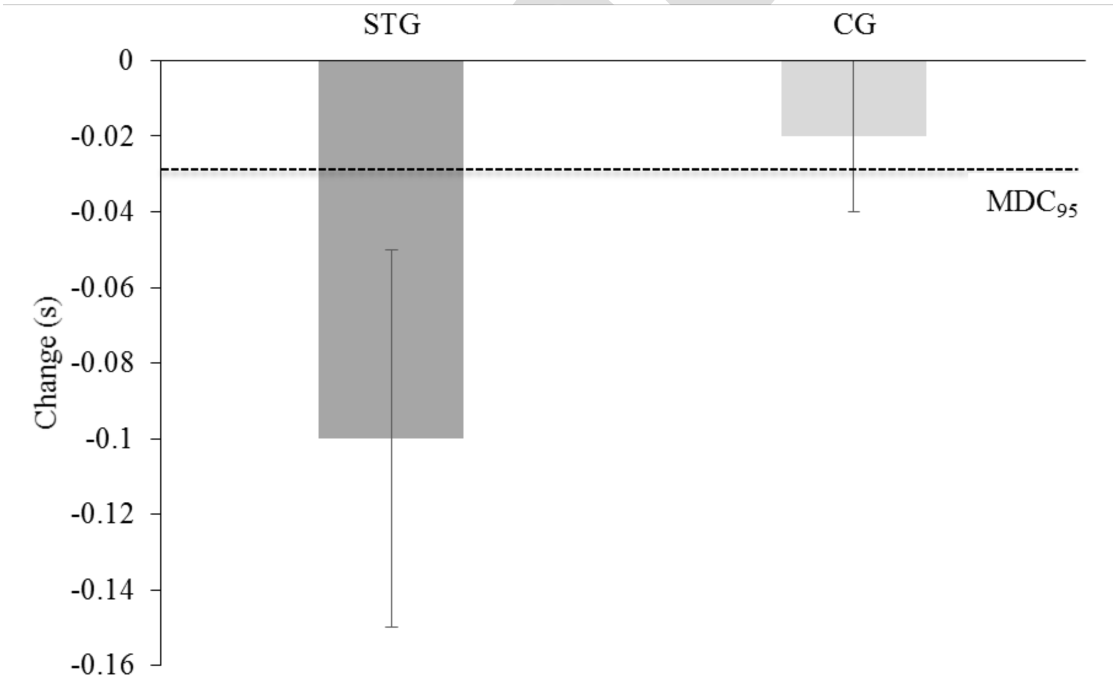

STG
CG
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
-0.16
Change (s)
MDC$_{95}$

Table 1. Ten week programme followed by the strength training group (2 days·week^{-1}). All exercises were prescribed as sets x repetitions (unless stated). Inter-set recovery duration was 90 sec and 180 sec for plyometrics and resistance training respectively.

Mesocycle	Weeks 1-3	Weeks 4-6	Weeks 7-10
Plyometrics	Box jump 3x6 A-skip 3x15 m Hurdle jump and land 3x6	Single leg box jump 3x6 High-knees 3x15 m Hurdle jumps 4x6	Depth jumps 3x6 Sprints 3x30 m Hurdle jumps 4x8
Resistance training	Back squat 3x8 Romanian deadlift 3x8 Single leg press 2x8 Calf raise 2x12	Back squat 3x8 Rack pull 3x8 Single leg press 3x8 Calf raise 3x12	Back squat 3x6 Deadlift 3x6 Step-ups 3x8 Calf raise 3x12

Table 2. Participants characteristics for strength training group (STG) and control group (CG).

	STG (*n*=9)	CG (*n*=9)
Age (years)	16.5 ±1.1	17.6 ±1.2
Body mass (kg)	57.8 ±6.1	58.5 ±9.5
Stature (cm)	170.2 ±6.8	171.6 ±6.5
Maturity offset (years)	3.1 ±1.3	3.9 ±1.1
1500 m time (s)	274.9 ±21.4	264.1 ±15.4
$\dot{V}O_{2max.}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	59.2 ±9.3	61.7 ±5.9
sLTP ($km \cdot h^{-1}$)	14.0 ±2.4	14.9 ±1.1
Running duration ($min \cdot wk^{-1}$)	180.6 ±84.9	195.6 ±86.9

$\dot{V}O_{2max.}$ = maximal oxygen uptake, sLTP = speed at lactate turn point

Table 3. Mean ±SD time spent (min·week^{-1}) performing various training activities during the intervention period.

	Running			Strength training	Aerobic cross-training	Combined total
	< sLTP	> sLTP	Total			
STG	109 ±69	42 ±7	151 ±85	112 ±7*	10 ±16	273 ±88
CG	160 ±73	53 ±18	213 ±88	33 ±35	10 ±18	257 ±106
ES (interpretation)	0.69 (moderate)	0.60 (moderate)	0.69 (moderate)	1.67 (very large)	0.01 (trivial)	0.17 (trivial)

sLTP = speed at lactate turn point, STG = strength training group, CG = control group, ES = effect size between STG and CG. * indicates significantly different (*P*<0.05) from CG group.

Table 4. Changes in body composition and physiological parameters in the strength training group (STG) and control group (CG).

	Group	**Pre**	**Post**	**% change (95% CI)**	**Effect size (interpretation)**	**MDC$_{95}$**	**Magnitude based inference**
Anthropometrics							
Body mass (kg)	STG	57.8 ±6.1	58.5 ±5.9	0 - 2.4	0.08 (trivial)	0.7	Most likely trivial
	CG	58.5 ±9.5	58.6 ±8.9	-1.7 - 2.1			
Skinfold (mm)	STG	36.6 ±13.2	37.9 ±14	-2.2 – 9.3	0.24 (small)	2.6	Most likely trivial
	CG	29.8 ±8.6	28.3 ±6.5	-13.4 – 3.7			
Maximal running							
$\dot{V}O_{2max}$ (ml·kg$^{-0.67}$·min^{-1})	STG	229.2 ±41.3	227.5 ±36.2	-4.8 – 3.3	0.07 (trivial)	7.5	Most likely trivial
	CG	241.2 ±24.2	242.0 ±21.5	-7.5 – 8.3			
s$\dot{V}O_{2max}$ (km·h^{-1})	STG	16.8 ±2.4	17.3 ±2.6	-2.0 – 8.9	0.34 (small)	0.9	Likely trivial
	CG	17.8 ±0.8	17.8 ±1.7	-6.2 – 5.3			
Sub-maximal running							
RE at LTP (kJ·kg$^{-0.67}$·km^{-1})	STG	18.7 ±1.3	18.1 ±1.4	-7.5 – 1.1	0.31 (small)	0.6	Possibly trivial
	CG	18.5 ±1.3	18.3 ±0.9	-5.4 – 3.1			
RE at LTP -1 km·h^{-1}	STG	18.8 ±1.2	18.1 ±1.5	-6.9 – 0.3	0.47 (small)	0.7	Possibly beneficial

($\mathrm{kJ \cdot kg^{-0.67} \cdot km^{-1}}$)	CG	18.6 ±1.4	18.5 ±1.1	-4.5 – 3.9			
RE at LTP -2 $\mathrm{km \cdot h^{-1}}$	STG	19.2 ±1.4	18.5 ±1.6	-7.3 – 1.1	0.51 (small)	0.8	Likely trivial
($\mathrm{kJ \cdot kg^{-0.67} \cdot km^{-1}}$)	CG	18.8 ±1.3	18.7 ±1.2	-4.4 – 3.1			
s2mMol·L^{-1} ($\mathrm{km \cdot h^{-1}}$)	STG	13.0 ±2.6	13.6 ±2.6	1.5 – 7.7	0.09 (trivial)	0.4	Very likely trivial
	CG	13.9 ±1.5	14.7 ±1.4	2.9 – 8.6			
s3mMol·L^{-1} ($\mathrm{km \cdot h^{-1}}$)	STG	14.1 ±2.5	14.7 ±2.6	1.4 – 7.1	0.09 (trivial)	0.3	Unclear
	CG	15.1 ±1.2	15.7 ±1.4	2.0 – 6.6			
s4mMol·L^{-1} ($\mathrm{km \cdot h^{-1}}$)	STG	14.9 ±2.4	15.4 ±2.5	1.3 – 6.7	0.10 (trivial)	0.3	Unclear
	CG	15.8 ±1.0	16.4 ±1.4	1.3 – 6.3			

CI = confidence interval, MDC$_{95}$ = minimal detectable change (95% confidence interval), RE = running economy, LTP = lactate turn point, s2mMol·L^{-1}, s3mMol·L^{-1}, s4mMol·L^{-1} = speed at fixed concentrations of blood lactate.

Variables normalized for body mass have been scaled using an exponent derived from previous a previous study in this group (22).

Table 5. Changes in speed and strength measures in the strength training group (STG) and control group (CG).

	Group	Pre	Post	% change (95% CI)	Effect size (interpretation)	MDC_{95}	Magnitude based inference
20 m sprint (s)	STG	2.79 ±0.22	2.69 ±0.19*	-5.4 to -1.8	0.32 (small)	0.03	Very likely beneficial
	CG	2.64 ±0.24	2.62 ±0.23	-1.5 - 0			
Peak displacement (m)	STG	0.26 ±0.03	0.27 ±0.04	0 – 7.7	0.10 (trivial)	0.03	Unclear
	CG	0.26 ±0.05	0.27 ±0.05	-3.8 – 11.5			
$vGRF_{jump}$ ($N \cdot kg^{-0.76}$)	STG	58.7 ±2.3	62.3 ±6.9	-1.9 – 14.1	0.93 (moderate)	10.1	Most likely trivial
	CG	60.7 ±5.9	60.2 ±9.3	-11.2 – 9.2			
MVC ($N \cdot kg^{-0.61}$)	STG	159.3 ±28.0	183.9 ±26.5*	6.3 – 24.5	0.86 (moderate)	23.7	Possibly beneficial
	CG	159.4 ±25.7	161.5 ±37.1	-9.4 – 12.5			

* significantly different to CG ($P<0.05$). CI = confidence interval, MDC_{95} = minimal detectable change (95% confidence interval), $vGRF_{jump}$ = vertical ground reaction force during squat jump, MVC = maximal voluntary contraction during quarter squat

Variables normalized for body mass have been scaled using an exponent derived from a larger cohort of participants (n=36) with similar characteristics.