

Blagrove, Richard, Howe, Louis, Cushion, Emily, Spence, Adam, Howatson, Glyn, Pedlar, Charles and Hayes, Philip (2018) Effects of strength training on postpubertal adolescent distance runners. *Medicine and Science in Sports and Exercise*, 50 (6). pp. 1224-1232.

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1 **Effects of Strength Training on Post-Pubertal Adolescent Distance Runners**

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Effects of Strength Training on Post-Pubertal Adolescent Distance Runners

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.

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

57

58 **Introduction**

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

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

74 There is also convincing evidence that strength training is safe and effective for adolescent
75 athletes [16]. Current guidelines suggest that adolescents should participate in 2-3 supervised
76 resistance training sessions per week [17]. Studies that have investigated the effects of
77 resistance training in youth populations have tended to focus on the development of strength-
78 related qualities in pre-pubertal and peri-pubertal participants, which underpin a variety of

79 different sports skills. Resistance training can also positively influence sprint performance (5-
80 40 m), beyond that which would be expected with maturation alone [18]. Mikkola and co-
81 authors [19] provide the only study to investigate the impact of a strength training intervention
82 on markers of performance in post-pubertal runners (16-18 years). Replacing 19% of total
83 running volume with explosive strength training exercises for eight weeks improved
84 neuromuscular and anaerobic characteristics, but without any significant impact on aerobic
85 performance markers. The strength training activities (sprints, jumps and low-load resistance
86 training) were performed in low frequency (each on average once per week), and resistance
87 training primarily targeted single-joint actions. It is recommended that distance runners
88 incorporate 2-3 strength training sessions per week [20], and utilize multi-joint closed-chain
89 exercises, which provide a high level of mechanical specificity to the running action [21].
90 Therefore the effect of a strength training programme, involving multi-joint resistance
91 exercises performed more than once per week by adolescent runners, on determinants of
92 distance running performance remains unknown.

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

98

99 **Methods**

100 *Participants*

101 A sample size estimation of $n=20$ was calculated a priori based upon statistical power of 80%,
102 at a 5% probability threshold, and an effect size of 0.67 for the primary outcome variable, RE.
103 Typical error (TE) and minimal detectable change at the 95% confidence level (MDC_{95}) for
104 RE were derived from a previous reliability study in this population [22]. Based upon an
105 anticipated 20% drop-out, 25 participants (13 female, mean \pm SD age: 17.2 ± 1.2 years, range:
106 15.2-18.8 years) initially volunteered to take part. The study received institutional level ethical
107 approval and was conducted in accordance with the Declaration of Helsinki. Participants were
108 required to meet the following inclusion criteria: age 15-18 years, no formal strength training
109 experience, free from injury in the month preceding the study, competed regularly at county,
110 regional, national or international level in middle- (800 m – 3,000m) or long-distance (5 – 10
111 km and cross-country) running. A parent/guardian provided a signature of consent prior to
112 participation, and in the case of those age 18 years, consent was provided by the participant
113 themselves.

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

119 *Testing overview*

120 Testing took place over two days before and after the intervention period, at the same time of
121 day for each participant and under similar laboratory conditions (temperature, 16-20°C; relative
122 humidity, 36-54%; barometric pressure, 746-773 mmHg). The first testing session involved
123 measurements of anthropometrics, a submaximal running assessment and a maximal running
124 test. Following thirty minutes of passive recovery, participants were familiarised with the

125 strength tests. The second testing session took place 48-72 h later, and was used to test
126 participant's maximal speed, and force-producing capabilities under dynamic and isometric
127 conditions. Every effort was made to schedule testing sessions on the same days pre- and post-
128 intervention to maximise the likelihood that participants would adhere to requests to adopt a
129 similar pattern of exercise and diet in the 48 h prior.

130 *Anthropometry*

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

138 *Submaximal and maximal running tests*

139 All running testing took place in the same physiology laboratory on a motorised treadmill (HP
140 Cosmos Pulsar 4.0, Cosmos Sports & Medical GmbH, Munich, Germany). Expired air was
141 collected via a low dead-space mask and monitored continuously via an automated open circuit
142 metabolic cart (Oxycon Pro, Enrich Jaeger GmbH, Hoechberg, Germany) to quantify
143 pulmonary ventilation, oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$) and
144 respiratory exchange ratio (RER). Heart rate (HR) was also recorded continuously throughout
145 the test (Polar RS400, Polar Electro Oy, Kempele, Finland). Following a 5 min warm-up,
146 participants completed a discontinuous incremental test at a 1% gradient [24] to determine RE,
147 HR and lactate response. Participant's most recent race performances and their HR response
148 during warm-up were used to determine the start speed and provide at least four speeds before

149 lactate turn-point. The test consisted of five to seven 3 min running stages with speed increases
150 of $1 \text{ km}\cdot\text{h}^{-1}$ each stage, separated by 30 s rest to allow for a $20 \mu\text{l}$ sample of capillary blood to
151 be taken from the earlobe. Each sample was hemolysed and subsequently analysed for blood
152 lactate concentration (Biosen C-Line, EKF Diagnostic, Barleben, Germany). The test was
153 discontinued when the rise in lactate exceeded $1 \text{ mMol}\cdot\text{L}^{-1}$ compared to the previous stage,
154 which defined their speed at lactate turnpoint (sLTP).

155 The data analysis process used to obtain values for RE and $\dot{V}\text{O}_{2\text{max}}$ has been described
156 previously [22]. Breath-by-breath data were initially filtered to remove any errant breath which
157 did not represent the underlying physiological response [25]. The mean values for $\dot{V}\text{O}_2$, $\dot{V}\text{CO}_2$,
158 RER and HR from the final 60 s of the stage corresponding to sLTP and the two speeds prior
159 (sLTP -1 $\text{km}\cdot\text{h}^{-1}$, sLTP -2 $\text{km}\cdot\text{h}^{-1}$) were used in subsequent analysis. The $\dot{V}\text{O}_2$ value was used
160 with the RER value to quantify the energy cost of running using non-protein quotient equations
161 [26], which is likely to provide a more valid [27] and reliable [22] measure of RE compared to
162 oxygen cost. As sLTP varied across participants, RE was expressed as the energy cost of
163 running per km. Speed at fixed concentrations of blood lactate (sFBLC) was estimated from
164 the speed-lactate curve for 2, 3 and $4 \text{ mMol}\cdot\text{L}^{-1}$ using published software [28].

165 Following the submaximal running test, participants rested for 5 min before completing a
166 continuous incremental treadmill test to volitional exhaustion to determine $\dot{V}\text{O}_{2\text{max}}$. The
167 treadmill belt was set to sLTP, and the gradient initially set at 1%. Thereafter, the gradient was
168 increased by 1% every minute until volitional exhaustion, which typically took 6-8 minutes.
169 $\dot{V}\text{O}_{2\text{max}}$ was taken as the highest $\dot{V}\text{O}_2$ achieved in a 30 s period (after filtering). Speed at $\dot{V}\text{O}_{2\text{max}}$.
170 ($s\dot{V}\text{O}_{2\text{max}}$) was predicted for each participant by using the equation for the linear regression line
171 for the relationship between $\dot{V}\text{O}_2$ and speed extrapolated to the $\dot{V}\text{O}_{2\text{max}}$ value. The linearity of
172 regression lines for participants across both trials was $R^2 = 0.981 \pm 0.02$. Prior test-retest

173 reliability work, using a cohort with similar characteristics, demonstrated high inter-session
174 reliability for physiology variables [22].

175 *Speed and strength tests*

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

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

217 Attempts were each separated by 90 s of rest. MVC was defined as the highest force value
218 produced during the contraction. The best score over the three attempts was used in subsequent
219 analysis for each test. The inter-session reliability values (TE; intra-class correlation
220 coefficient, ICC; MDC₉₅) for speed (0.34%, 0.99, 1.0%), peak displacement (4.89%, 0.94,
221 13.5%), vGRF_{jump} (5.71%, 0.50, 15.8%), and MVC (5.10%, 0.65, 14.1%) were considered
222 acceptable in a group of adolescent distance runners (6 females, 6 males, 17.8 ± 1.4 years).

223 *Allometric scaling*

224 To account for differences in body mass between individuals, a ratiometric index has tended to
225 be favoured in similar studies for scaling parameters relating to $\dot{V}O_2$ [12, 13, 19]. This scaling
226 approach is only valid if the relationship between body mass and a physiological variable are
227 directly proportional, which is rarely the case [30]. To calculate appropriate scaling exponents
228 for variables used in the present study, data from a larger cohort of adolescent distance runners
229 ($n=42$) was log-transformed, and following an analysis of covariance (ANCOVA) comparison
230 for males and females, a common power function was calculated via linear regression. An
231 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
232 for $\dot{V}O_2$ parameters [22], and applying the same mathematical process in a similar cohort of
233 participants ($n=36$), values of 0.76 (95% CI: 0.33-1.20) and 0.61 (95% CI: 0.03-1.22) were
234 established for vGRF_{jump} and MVC respectively.

235 *Training*

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

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

235

236 *** Table 1 about here ***

237

238 *Statistical analysis*

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

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

247 To facilitate more widespread use of our findings in applied settings, effect sizes and magnitude
248 based inferences were identified to provide a more qualitative interpretation of the extent to
249 which changes observed were meaningful. Effect sizes were calculated (Microsoft Excel 2013)
250 as a ratio of the difference between the mean change value for each group and the pooled SD
251 at baseline for all participants, and were interpreted as trivial < 0.2 ; small 0.2-0.6; moderate 0.6-
252 1.2; and large > 1.2 [31]. For each variable, the MDC_{95} , calculated using the TE of measurement
253 for this group of participants [22], was entered along with the P -value and ES into a published
254 spreadsheet [32] to obtain the likelihood that the intervention was beneficial (or indeed
255 harmful) to the population. The MDC_{95} represents the magnitude required for a change in score
256 to be considered clinically meaningful, and therefore provided a robust threshold to judge the
257 efficacy of the intervention. The resulting values were translated into descriptors using the
258 modified thresholds proposed by Batterham and Hopkins [31]: 0-0.5% most unlikely; 0.5-5%
259 very unlikely; 5-25% unlikely; 25-75% possibly; 75-95% likely; 95-99.5% very likely; and
260 $> 99.5\%$ most likely.

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

$$263 \sqrt{SD_{STG}^2 - SD_{CG}^2}$$

264 Where SD_{STG} and SD_{CG} represents the SD of the change score for the STG and CG groups
265 respectively. In this instance, it is more appropriate to use the SD of the CG change value as
266 the comparator variable, rather than the TE derived from a short-term reliability study in this

267 population [22], as within-subject biological variation is likely to increase over time [33].
268 Descriptive statistics are presented as mean \pm SD.

269

270 **Results**

271 *Group characteristics*

272 Based upon maturity offset values, all participants were considered post-pubertal (≥ 1.0 year),
273 even when the standard error associated with the predictive equation was accounted for [23].
274 Seven participants withdrew during the course of the study for the following reasons: injury
275 (STG $n=3$, CG $n=1$), illness (STG $n=1$), time commitment (CG $n=1$), voluntary dropout (CG
276 $n=1$). The injuries that occurred in the STG were diagnosed as overuse type injuries that could
277 not be directly attributed to the intervention. No other adverse effects were reported during the
278 intervention period. The final sample consisted of nine participants in the STG (5 females, 4
279 males) and nine in the CG (5 females, 4 males). Group characteristics are shown in Table 2,
280 with $\dot{V}O_{2\max}$ shown as a ratio to body mass for comparative purposes.

281

282 *** Table 2 about here ***

283

284 *Training history*

285 Table 3 displays a summary of the training undertaken by participants during the intervention
286 period. Participants typically undertook 2-3 extensive interval training sessions per week at
287 sLTP or faster. These were performed on the same days across the cohort. The remaining
288 volume of running was undertaken at speeds below sLTP, however inter-individual variation
289 was high (135 ± 74 min.week⁻¹). No significant differences ($P > 0.05$) between groups were

290 noted in total training time, total running duration, running at low (<sLTP) and high (>sLTP)
291 intensities (ES: 0.17) and aerobic cross-training (ES: 0.01). However moderate effect sizes
292 (0.6-0.7) were observed for the difference in total running duration in favour of the CG.
293 Strength training time differed significantly between groups ($F(1,16)=44.96$, $P<0.001$, ES:
294 1.67). Engagement with strength training was high in the STG, with all participants completing
295 $\geq 85\%$ of sessions over the 10 week intervention.

296

297 *** Table 3 about here ***

298

299 *Body composition and running measures*

300 ANCOVA revealed no significant differences between groups post-training for body mass
301 ($F(1,16)=0.98$, $p=0.338$), skinfolds ($F(1,16)=4.15$, $p=0.060$), $\dot{V}O_{2\max}$ ($F(1,16)=0.48$, $p=0.499$),
302 $s\dot{V}O_{2\max}$ ($F(1,16)=1.11$, $p=0.308$), RE at LTP ($F(1,16)=0.57$, $p=0.463$), RE at LTP -1 km h⁻¹
303 ($F(1,16)=1.39$, $p=0.256$), RE at LTP -2 km h⁻¹ ($F(1,16)=2.34$, $p=0.147$), s2mMol·L⁻¹
304 ($F(1,16)=0.54$, $p=0.474$), s3mMol·L⁻¹ ($F(1,16)<0.01$, $p=0.980$), and s4mMol·L⁻¹ ($F(1,16)=0.01$,
305 $p=0.917$). Table 4 shows changes in body composition and physiological parameters for each
306 group and between group comparisons. Body mass displayed a mean increase of (95% CI) 0
307 to 2.4% in the STG group, which was most likely trivial compared to the CG (ES: 0.08).
308 Skinfold measures also exhibited minimal changes in both groups (ES: 0.24). $\dot{V}O_{2\max}$ displayed
309 trivial changes (ES: 0.07) in both groups, and $s\dot{V}O_{2\max}$ improved in the STG by only a small
310 margin (95% CI: -2.0 to 8.9%), which compared to the CG was likely trivial (ES: 0.34). RE
311 improved between 3.2-3.7%, and by a magnitude that approximated the MDC₉₅ values at all
312 three speeds in the STG group, however increases were relatively small (ES: 0.31-0.51) and
313 only considered 'possibly beneficial' at LTP -1 km.h⁻¹ speed. Figure 1A shows the change in

314 average RE for three speeds, which was also considered ‘possibly beneficial’ (ES: 0.44, small)
315 compared to the CG. sFBLC improved to a small extent (3.4-5.8%) in both groups, but between
316 group effects were trivial (ES: 0.09-0.10). Within-group differences were considered ‘likely
317 beneficial’ or ‘very likely beneficial’ for both groups.

318 *Speed and strength measures*

319 As shown in Figure 1B, 20 m sprint time improved by -0.10 s (95% CI: 1.8-5.4%; ES: 0.32,
320 small) in the STG, which generated a significantly faster time compared to the CG post-training
321 ($F(1,16)=7.86, P=0.013$) and was considered ‘very likely beneficial’. The STG also displayed
322 significantly greater MVC at follow-up ($F(1,16)=5.07, P=0.040$; ES: 0.86, moderate) compared
323 to the CG; a change which was deemed ‘possibly beneficial’ (95% CI: 6.3-24.5%, Table 5).
324 The magnitude of between group change in peak displacement was ‘most likely trivial’ (ES:
325 0.10) and the difference non-significant ($F(1,16)=0.18, p=0.682$). $vGRF_{jump}$ improved to a
326 moderate extent (95% CI: -1.9 to 14.1%) in the STG compared to the CG (ES: 0.93) but this
327 change was considered ‘most likely trivial’ in the context of the MDC_{95} threshold (Table 5).

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

333

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

335 *** Table 4 about here ***

336 *** Table 5 about here ***

337

338 **Discussion**

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

346 The findings of this study are in agreement with those of a recent meta-analysis in mainly adult
347 runners, which showed concurrent strength and endurance training can provide a small
348 beneficial effect ($3.9 \pm 1.2\%$) to RE over a 6-14 week period [20]. Our results are also similar
349 to the only other study that has investigated the efficacy of strength training in adolescent
350 distance runners, which demonstrated small improvements (2.0-2.7%, ES: 0.26-0.40) in RE at
351 12 and 14 km h^{-1} , and trivial changes at 10 and 13 km h^{-1} [19]. The superior effects we observed
352 at all three speeds assessed (3.2-3.7%, ES: 0.31-0.51) may be due to the longer intervention
353 period (10 vs 8 weeks), higher frequency of exposure to each type of strength training activity
354 (2 vs 1 $\text{day}\cdot\text{week}^{-1}$), and the choice of resistance training exercises (multi-joint vs single-joint).
355 It is noteworthy that the intervention group in the Mikkola et al. [19] study performed almost
356 double the volume of training compared to the STG in the present study (273 ± 88 vs 528 ± 126
357 $\text{min}\cdot\text{wk}^{-1}$). Moreover, the CG in the present study spent 41% more time running than the STG
358 (ES: 0.69). This suggests that for the adolescent distance runner, strength training may be more
359 effective than increasing endurance training volume at improving RE, at least in the short-term.
360 It is also possible that the moderate disparity in low intensity running volume between the

361 groups was advantageous to the STG group as less running may have facilitated the recovery
362 process [34]. Despite the apparent trend towards an improvement in RE, it is important to note
363 that the change scores did not exceed the MDC_{95} for any speed or an average of measurements
364 (Figure 1A), indicating that only a possible benefit exists at specific speeds when TE of
365 measurement is taken into account. A longer intervention period may therefore be required to
366 provide higher certainty that strength training provides a practically significant benefit.

367 Neuromuscular factors, such as muscle activation and musculotendinous stiffness, play an
368 important role in distance running [9, 35], therefore strategies to enhance these qualities are
369 likely to lead to an improvement in physiological efficiency. A significant improvement in
370 maximal force producing capability was observed in the STG (95% CI: 6.3-24.5%, ES: 0.86),
371 which is in line with findings from previous studies in adult distance runners over a similar
372 time frame [14, 36]. The strength training programme, which included plyometrics, sprinting
373 and resistance training, was also shown to provide a small but very likely benefit to maximal
374 sprint speed (95% CI: 1.8-5.4%; ES: 0.32); an improvement which was more than three times
375 higher than the MDC_{95} value. Maximal speed is an important anaerobic quality required for
376 middle-distance running [37], and is also related to long-distance running performance [8, 9].
377 Maximal sprinting requires higher ground reaction forces compared to sub-maximal running
378 [38], therefore this finding provides evidence that strength training can improve neuromuscular
379 characteristics during a highly functional assessment of explosive strength in runners. Peak
380 displacement and $vGRF_{jump}$ displayed changes which fell well within MDC_{95} limits, thus the
381 effect of strength training was at best trivial. The specificity of the exercises used in the strength
382 training programme (Table 1) may provide an explanation for this finding, since very little
383 maximal concentric-dominant jumping was included. A relatively higher volume of near-
384 maximal sprinting and loaded exercises that mimic a quarter-squat position were included,
385 which appears to have provided a sufficiently high transfer of training effect to enhance 20 m

386 sprint and MVC. The possibility that the bodyweight movement skill exercises included in the
387 warm-up routine also contributed towards the improvements observed cannot be discounted.
388 Dynamic postural control exercises reduce coactivation of muscles in the lower limb, which
389 may have enhanced efficiency during running via improvements in stabilisation strategy [39].

390 Despite our prediction that $s\dot{V}O_{2\max}$ would improve to a greater extent in the STG, this was not
391 the case (95% CI:-2.0 to 8.9%, ES: 0.34, likely trivial benefit). $s\dot{V}O_{2\max}$ provides a composite
392 measure of physiological performance that appears to differentiate adolescent runners with
393 greater accuracy than traditional determinants [6]. Our findings are in agreement with other
394 works that utilised a similar intervention duration [12, 19], but differ from studies which lasted
395 ≥ 14 weeks [11, 13], suggesting longer time frames may be required to realise a positive effect.
396 It is also likely that large improvements in constituent qualities ($\dot{V}O_{2\max}$, RE) are required to
397 elicit a meaningful change in $s\dot{V}O_{2\max}$. Although RE displayed small improvements, $\dot{V}O_{2\max}$
398 showed little alteration, implying that a greater stimulus may be required to influence these
399 variables.

400 Following an eleven week period of running training, it was expected that aerobic variables
401 would exhibit improvements in a group of adolescent athletes. The intervention period
402 provided a small (3.4-5.8%) but very likely or likely benefit to sFBLC in both groups,
403 suggesting the running training caused metabolic adaptations [40], which were not augmented
404 by strength training (ES: 0.09-0.10, trivial). The lack of change in $\dot{V}O_{2\max}$ in both groups
405 corroborates findings from previous investigations [11-14, 36]. Improvements in aerobic
406 capacity are influenced by a variety of factors including initial training status, and the duration
407 and nature of training conducted [41]. Both groups spent 25-28% of their running training
408 above sLTP, an intensity which is likely to have provided a strong stimulus for improving
409 $\dot{V}O_{2\max}$ [42]. Therefore it appears the study duration and the initial fitness level of participants

410 provide the most likely explanation for the unaltered values observed. Despite the absence of
411 change in several parameters, it is notable that strength training caused no deleterious effects
412 in physiological predictors of performance despite the STG spending ~40% less time running
413 compared to the CG.

414 Increases in body mass are potentially disadvantageous to distance runners, therefore gains in
415 muscle mass, which is often an inevitable consequence of strength training, are unfavourable.
416 Although the confidence interval for the change in body mass in the STG did not overlap zero
417 (95% CI: 0-2.4%), the differences between groups were most likely trivial (ES: 0.08).
418 Furthermore, any slight increase in body mass in the STG did not adversely affect the
419 physiological variables that were allometrically scaled for body mass. Despite the association
420 between resistance training and a hypertrophy response [43], there is consensus that strength
421 training has little impact upon body mass in distance runners, at least in the short- to medium-
422 term [20]. The interference phenomenon, which is often observed when endurance and strength
423 training are performed concurrently within the same programme, has been offered as one
424 explanation [44]. The impairment of muscle fibre hypertrophy is likely to occur under
425 conditions of energy depletion [45], or when strength training is performed alongside a high
426 frequency and intensity endurance exercise [46]. Given, the relatively low volume of endurance
427 training undertaken by the STG (Table 2), the interference effect was perhaps less likely.
428 Therefore practitioners should be cognisant that gains in muscle mass may occur over longer
429 periods if a low volume of running is performed.

430 This study is subject to a number of limitations. Firstly with the exception of sprint time, the
431 measures taken in this study were laboratory-based, thus it is not known what impact the
432 training intervention had on middle- or long-distance performance. Secondly, the cohort of
433 participants were of both sexes and mixed event specialisms and abilities, therefore had a more
434 homogenous group been targeted, firmer conclusions may have been possible. Thirdly, the

435 scaling exponents utilized for normalization of body mass were derived from relatively small
436 samples ($n \leq 42$), which may have generated small errors during the calculation of values.
437 Although we do not believe that these errors are sufficiently large to alter the findings of this
438 study, the changes observed in RE were equal to or slightly less than the MDC_{95} at each speed
439 (Table 4), therefore a more accurate scaling factor may have provided greater confidence that
440 the changes observed were meaningful. Finally, the study was conducted during the early off-
441 season, which was characterized by training of a more extensive nature, known to cause
442 interference with strength adaptation [44]. It is not known what effect a strength training
443 programme would have on physiological parameters during a different training phase,
444 particularly one that had a larger emphasis on intensive training.

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

454

455 **Acknowledgments**

456 This paper is dedicated to the memory of Lucy Pygott, a participant in this study who sadly
457 passed away shortly after its completion. We thank the British Milers Club for providing
458 funding for this research. The technical support provided by Jack Lineham and Ian Grant during

459 this project is also greatly appreciated. The authors would also like to thank the participants
460 and their parents/guardians for the time they committed to this study.

461 **Conflict of Interest**

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

465

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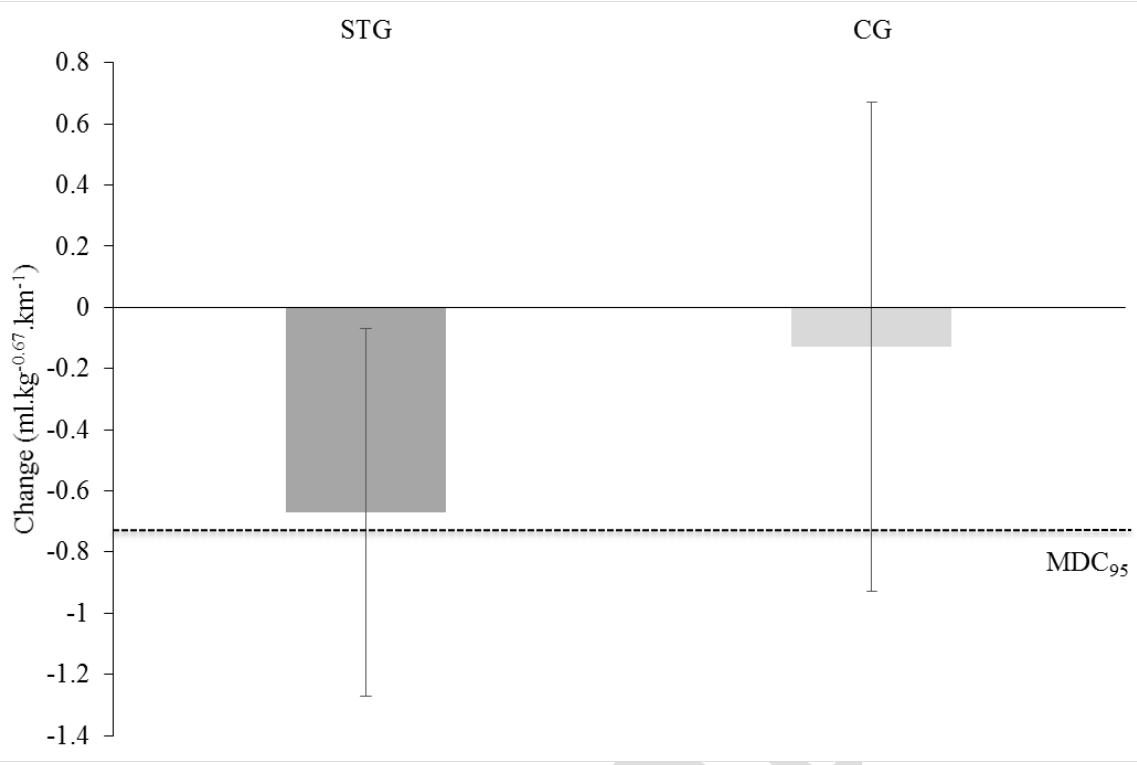
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623 Figure. **A**, Change in average running economy in the strength training group (STG) and
624 control group (CG). The change score for running economy is normalized for body mass
625 using a scaling exponent derived from a previous study in this group (22). **B**, Change in 20 m
626 sprint time in the strength training group (STG) and control group (CG). Error bars represent
627 the 95% confidence interval for the mean change. Minimal detectable change at 95%
628 confidence (MDC_{95}) is shown as the dashed line. A value which exceeds this line provides
629 95% confidence that the change is meaningful and not the result of typical error in
630 measurement.

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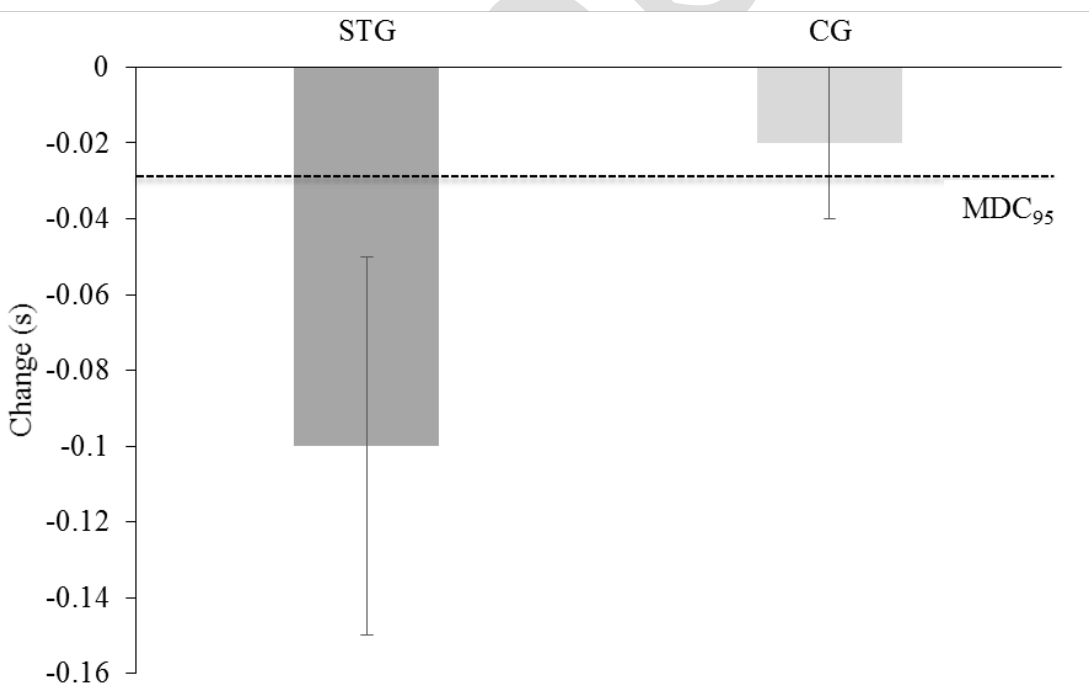
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632 **A:**



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634 **B:**



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638 Table 1. Ten week programme followed by the strength training group (2 days week⁻¹). All
 639 exercises were prescribed as sets x repetitions (unless stated). Inter-set recovery duration was
 640 90 sec and 180 sec for plyometrics and resistance training respectively.

641

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

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

	STG (<i>n</i> =9)	CG (<i>n</i> =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 kg ⁻¹ min ⁻¹)	59.2 ±9.3	61.7 ±5.9
sLTP (km h ⁻¹)	14.0 ±2.4	14.9 ±1.1
Running duration (min wk ⁻¹)	180.6 ±84.9	195.6 ±86.9

646 $\dot{V}O_{2max}$ = maximal oxygen uptake, sLTP = speed at lactate turn point

647

648 Table 3. Mean \pm SD time spent ($\text{min}\cdot\text{week}^{-1}$) performing various training activities during the
 649 intervention period.

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

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

652

653

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
<i>Anthropometrics</i>							
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			
<i>Maximal running</i>							
$\dot{V}O_{2\max}$ (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 $\dot{V}O_{2\max}$ (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			
<i>Sub-maximal running</i>							
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

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

CI = confidence interval, MDC₉₅ = 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·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·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, MDC₉₅ = 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.