

Maximal Strength Training Improves Running Economy in Distance Runners

ØYVIND STØREN^{1,2}, JAN HELGERUD^{1,3}, EVA MARIA STØA², and JAN HOFF^{1,4}

¹Department of Circulation and Medical Imaging, Faculty of Medicine, Norwegian University of Science and Technology, NORWAY; ²Department of Sport and Outdoor Life Studies, Telemark University College, NORWAY; ³Hokksund Rehabilitation Centre, NORWAY; and ⁴Department of Physical Medicine and Rehabilitation, St.Olav University Hospital, NORWAY

ABSTRACT

STØREN, Ø., J. HELGERUD, E. M. STØA, and J. HOFF. Maximal Strength Training Improves Running Economy in Distance Runners. *Med. Sci. Sports Exerc.*, Vol. 40, No. 6, pp. 1087–1092, 2008. **Purpose:** The present study investigated the effect of maximal strength training on running economy (RE) at 70% of maximal oxygen consumption ($\dot{V}O_{2max}$) and time to exhaustion at maximal aerobic speed (MAS). Responses in one repetition maximum (1RM) and rate of force development (RFD) in half-squats, maximal oxygen consumption, RE, and time to exhaustion at MAS were examined. **Methods:** Seventeen well-trained (nine male and eight female) runners were randomly assigned into either an intervention or a control group. The intervention group (four males and four females) performed half-squats, four sets of four repetitions maximum, three times per week for 8 wk, as a supplement to their normal endurance training. The control group continued their normal endurance training during the same period. **Results:** The intervention manifested significant improvements in 1RM (33.2%), RFD (26.0%), RE (5.0%), and time to exhaustion at MAS (21.3%). No changes were found in $\dot{V}O_{2max}$ or body weight. The control group exhibited no changes from pre to post values in any of the parameters. **Conclusion:** Maximal strength training for 8 wk improved RE and increased time to exhaustion at MAS among well-trained, long-distance runners, without change in maximal oxygen uptake or body weight. **Key Words:** OXYGEN COST OF RUNNING, HALF-SQUAT, LONG-DISTANCE RUNNING, MAXIMAL AEROBIC SPEED

Endurance performance in long-distance running, lasting approximately 7–150 min, is 80–99% dependent on aerobic metabolism (1,37). Interindividual variance in aerobic endurance performance in running is dependent on the three factors: maximal oxygen consumption ($\dot{V}O_{2max}$), lactate threshold (LT), and running economy (RE) (2,3,7,11,29). RE is commonly defined as the steady-rate $\dot{V}O_2$ measured as $mL \cdot kg^{-1} \cdot min^{-1}$ at a standard velocity (3,4) or in $mL \cdot kg^{-1} \cdot m^{-1}$ (7). Strength training has been associated with interfering or inhibiting endurance development (10,32). On the other hand, endurance training performed without concurrent strength training has been reported to impair strength and vertical jumping height (8). When combining strength and endurance training, several studies have reported improved RE. Millet et al. (27) found improvements in RE (6.9%), one

repetition maximum (1RM) half-squat, and jump height without concurrent changes in $\dot{V}O_{2max}$ or body weight after 14 wk of strength training using heavy weights among 7 well-trained triathletes. The training in this study by Millet et al. (27) consisted of six different strength exercises for lower limbs, performed as 3–5 repetitions to failure in three sets, twice a week. Paavolainen et al. (28) reported improved 5-km running performance time (2.8%), improved RE (7.8%), and improved sprint and jump performance among 10 orienteering runners after 9 wk of sprint, jump, and strength training. The strength training in this study by Paavolainen et al. (28) consisted of leg press and knee extensor-flexor exercises with low loads but high movement velocities. No differences regarding $\dot{V}O_{2max}$ or body weight were reported. Johnston et al. (20) showed that a 29% increase in 1RM squat improved RE (3.8%) in six female distance runners after a 10-wk strength training program. This was a whole-body strength training program, performed as three sets of 6–20 repetitions, dependent on which type of exercise. Six repetitions per set were used for the parallel squat exercise. No significant changes in body weight or in $\dot{V}O_{2max}$ were reported. Neither Millet et al. (27), Johnston et al. (20), nor Paavolainen et al. (28) have scaled for body weight when reporting the RE results. Also, plyometric training has been reported to influence RE among runners. Turner et al. (33) report 2.3% better RE after 6 wk of plyometric training as a supplement to the regular running training among 18 moderately trained

Address for correspondence: Assistant Professor Øyvind Støren, Department of Circulation and Medical Imaging, Faculty of Medicine, Norwegian University of Science and Technology, NO-7489 Trondheim, Norway, and Telemark University College, Department of Sport and Outdoor Life Studies, NO-3800 Bø, Norway; Email: oyvind.storen@hit.no.

Submitted for publication October 2007.

Accepted for publication January 2008.

0195-9131/08/4006-1087/0

MEDICINE & SCIENCE IN SPORTS & EXERCISE®

Copyright © 2008 by the American College of Sports Medicine

DOI: 10.1249/MSS.0b013e318168da2f

distance runners. Spurrs et al. (32) found approximately 6.5% better RE (measured at three different set velocities) accompanied by a 2.7% improvement in 3-km running time after 6 wk of plyometric training as a supplement to the regular running training among 17 moderately trained distance runners. Neither Turner et al. (33) nor Spurr et al. (32) have scaled for body weight when reporting RE results.

The term *maximal strength training* (MST) has been used to describe strength training using high loads, few repetitions, and emphasis on neural adaptations to strength enhancement rather than muscular hypertrophy (17). In a recent publication, an improvement in maximal strength of 28% improved work efficiency by 32% in a group of Chronic Obstructive Pulmonary Disease patients (17). Similar MST interventions have been used for competitive cross-country skiers in double poling, showing an improvement in work economy of 9% to 27% (15,34). Part of the explanation of improved work economy was reduced load and a shift in the force-velocity and power-load relationship.

The effects of MST on economy when double poling in cross-country skiers do not necessarily transfer to RE in long-distance runners. As legs have a higher training state than upper body in most people, and especially among long-distance runners, the training effects of MST could be different from what is shown in upper-body work among the skiers. However, Hoff and Helgerud (18) reports significant improvements in RE of 4.7% among soccer players after an MST intervention improving 1RM with 33% and rate of force development (RFD) with 52.3%. No changes were observed in body weight, $\dot{V}O_{2\max}$, or LT as % $\dot{V}O_{2\max}$. Hoff and Helgerud (18) suggest that the main training response is from neural adaptations and changes in recruitment patterns.

With increased 1RM, a lower percentage of 1RM in the lower limb extensors would be taxed in each stride, as shown by Hoff et al. (16), lowering the actual demands of number of motor units recruited. Also, if time to peak force in the muscle contractions is shortened as a result of MST, relaxation time in each stride would be increased. As a result of this, a better circulatory flow through the working muscles should improve the access to O_2 and substrates, which might indicate a longer time to exhaustion at a standard submaximal running velocity.

The aim of this study is thus to assess to which extent MST with emphasis on neural adaptations, supposedly not increasing body mass, as a supplement to endurance training will affect RE among well-trained, long-distance runners. The hypothesis is that MST performed as half-squats, and as a supplement to endurance training, will improve 1RM, RFD, RE, and time to exhaustion at maximal aerobic speed (MAS).

METHODS

Subjects. Seventeen well-trained (nine male and eight female) runners were included in this study, after each

having received and signed consent forms approved by the human research committee. Eight of these (four male and four female) runners were randomly assigned to the intervention group whereas the remaining nine runners (five male and four female) acted as time controls. The groups were matched for age and 5-km running performance. Seasonal best 5-km performance was self-reported by each of the runners. None of the subjects had participated in any form of resistance training program for the last 6 months. Subject characteristics are presented in Table 1.

Test procedures. The runners participated in an 8-wk study. For the intervention group, a pretest preceded 8 wk of MST in addition to the subjects' normal running training. After the intervention period, a posttest, the same as the pretest, was performed. The control group performed the same tests before and after the 8-wk period. However, they only performed their regular endurance training in between the tests. The subjects were tested on two different days, with a minimum of 1 d and a maximum of 6 d of rest or easy training between each. Before the pretest, the runners had to participate in two training sessions, for both weight training and treadmill running during the last 2 wk before pretest. By subjective evaluations from the test leader, all runners were reckoned able to perform half-squats using free weights and to run on the treadmill without technical limitations. The first day of testing consisted of measurements of heart rate (f_c), blood lactate concentration $[La^-]_b$, and oxygen consumption ($\dot{V}O_2$) during 5-min runs (1.5% inclination) at several different set velocities. A Woodway PPS 55 sport (Waukesha, Germany) calibrated for inclination and speed was used for all running tests. $\dot{V}O_2$ was measured using the metabolic test system, Sensor Medics Vmax Spectra (Sensor Medics 229, Yourba Linda, CA, USA). Lactate measurements were performed using an Arcray Lactate Pro LT-1710 analyzer (whole blood) (Arcray Inc. Kyoto, Japan), and f_c was measured using Polar s610 heart rate monitors (Kempele, Finland). The subjects started with a velocity assumed to be about 60% of their $\dot{V}O_{2\max}$ corresponding to 8.0 to 9.5 $km \cdot h^{-1}$. The speed was increased by 1.5 $km \cdot h^{-1}$ every 5 min. The protocol terminated at more than 1.5 $km \cdot h^{-1}$ above the subjects' LT. LT was defined as the warm-up $[La^-]_b$ value (i.e., measured after the lowest velocity) + 2.3 $mmol \cdot L^{-1}$. This is in accordance with the protocol demonstrated by Helgerud et al. (14). After 60 min of rest, a $\dot{V}O_{2\max}$ test was performed, using an incremental protocol at 5.2% treadmill inclination. Maximal aerobic speed was calculated

TABLE 1. Physical and performance characteristics of runners.

Variables	Intervention Group (n = 8), 4 Males and 4 Females	Control Group (n = 9), 4 Males and 4 Females
Age (yr)	28.6 ± 10.1	29.7 ± 7.0
Weight (kg)	60.3 ± 9.3	71.1 ± 12.0
Height (cm)	171 ± 9	179 ± 8
Time, 5 km (s)	1122.4 ± 58.4	1162.6 ± 99.6

Values are mean ± SD.

from these measurements and was defined as the velocity point where the horizontal line representing $\dot{V}O_{2\max}$ meets the extrapolated linear regression representing the submaximal $\dot{V}O_2$ measured in the LT assessment. The linearity from this regression averaged an $R^2 = 0.991 \pm 0.009$. By plotting $\dot{V}O_2$ data against running velocity, individual regression equations for each subject were obtained. The second day of testing consisted of measurements of time, f_c , $[La^-]_b$, and $\dot{V}O_2$ during a run to exhaustion at MAS. To avoid the psychological benefit of knowing the pretest time to exhaustion at the posttest, time to exhaustion during the pretest was not communicated to the subjects. After a rest period of minimum 30 min, the subjects were then tested for 1RM in half-squat, using free weights. From pilot testing before the study, we observed no deterioration in 1RM 30 min after MAS tests as compared to 1RM without the MAS test. Each lift was performed with a controlled slow eccentric phase, a complete stop of movement for approximately 1 s in the lowest position, followed by a maximal mobilization of force in the concentric phase ensuring a follow-up by use of plantar flexors. The measurements of lifting time, distance of work, and thus RFD were performed using the Muscle Lab system (Ergo test Technology, Langesund, Norway). This test started using 10 repetitions at a weight load assumed to be approximately 50% of 1RM. After 3 min of rest, five repetitions at approximately 60% 1RM. After another 3 min rest, three repetitions at approximately 70% 1RM, then 3 min of rest before one repetition at approximately 80% 1RM. From there on, one repetition at a weight load increased by 2.5–5 kg from the subsequent lift, followed by 5 min of resting, until reaching 1RM. The time spent in each lift, as well as the work distance, was measured. As the external force of each lift is represented by the weight of the lifted bars, the RFD can be calculated and expressed as $N \cdot m \cdot s^{-1}$ or watt.

Training interventions. The intervention group completed an 8-wk intervention, whereas the controls completed an 8-wk normal training period. During these weeks, both the intervention group and the control group were thus performing their running training as normal. To control the training, each subject had to report weekly the exact amount of time spent in the different training intensity zones 60–85%, 85–90%, and 90–95% heart rate maximum ($f_{c\max}$). In addition to their normal endurance training, the intervention group completed an MST session consisting of four sets of 4RM half-squats, divided by 3 min of rest between each, 3 d a week. Every time a subject managed to do five repetitions during a set, 2.5 kg were added for the next set. The subjects used free weights. Guidance and instructions were given all participants during the training period. Training logs for the MST were made by all participants in the intervention group. If any of these runners completed less than 70% of the planned 24 strength training sessions, or if they suffered from illness or injuries lasting more than 1 wk during the intervention period, they

were to be taken out from the statistical material. The 70% threshold was selected from minimum training response expected. Seventy percent of three times per week average two times per week, which is considered sufficient by Kraemer and Ratamess (24) for not strength-trained subjects to significantly increase strength. None of the subjects met the exclusion criteria.

Allometric scaling. Energy cost for movement does not increase in the same rate as body weight. According to Bergh et al. (1) and Helgerud (11), comparisons of $\dot{V}O_2$ should be expressed relative to body mass raised to the power of 0.75 when running. Allometric scaling has been reported to decrease the SDs in RE between subjects (11–13,18,19). Main $\dot{V}O_2$ considerations are thus related to the expression in $mL \cdot kg^{-0.75} \cdot min^{-1}$ in the present study.

Statistical analysis. Statistical analyses were performed using the software program SPSS, version 13.0 (Statistical Package for Social Science, Chicago, IL, USA). In all cases, $P < 0.05$ was taken as the level of significance in two-tailed tests. Descriptive statistical analysis was made to display means and SD. To compare means, paired t -tests and independent samples t -tests were used. The data were tested for normal distribution using quantile–quantile plots. Correlations were calculated using the Pearson correlation test.

RESULTS

The intervention and the control group were matched for age and 5-km performance time (Table 1).

After the 8-wk MST intervention, significant improvements in 1RM half-squat (33.2%), RFD half-squat (26.0%), RE at 70% $\dot{V}O_{2\max}$ (5.0%), time to exhaustion at MAS (21.3%), f_c at LT (2.8%), and f_c at 70% $\dot{V}O_{2\max}$ (1.9%) in the intervention group was shown. None of these improvements were found in the control group (Table 2). No changes in body weight, $\dot{V}O_{2\max}$, LT velocity, or LT as percentage of $\dot{V}O_{2\max}$ in neither the intervention group nor the control group were apparent (Table 2).

During the 8 wk, three times a week intervention, the runners in the intervention group completed 20 ± 2.3 (83.3%), ranging from 17 (71%) to 23 (96%) of the scheduled MST sessions. The endurance training completed by the runners during this period was similar to the training before the intervention in both the intervention group (total mean of 414 min before vs 391 min after) and in the control group (total mean of 325 min before vs 274 min after). The endurance training before and during the intervention period is presented in Table 3.

Significant correlations were found between 5-km running time (s) and LT velocity ($km \cdot h^{-1}$) ($R^2 = 0.79$, $P < 0.01$), between 5-km running time (s) and MAS ($km \cdot h^{-1}$) ($R^2 = 0.67$, $P < 0.01$), and between 5-km running time (s) and $\dot{V}O_{2\max}$ ($mL \cdot kg^{-0.75} \cdot min^{-1}$) ($R^2 = 0.64$, $P < 0.01$). However, no correlation was found between 5-km running time (s) and LT (% $\dot{V}O_{2\max}$). Although the intervention

TABLE 2. Physiological results in the intervention and control groups.

Variables	Intervention Group (I) n = 8		Control Group (C) n = 9		Difference (I - C)
	Pretraining	Posttraining	Pretraining	Posttraining	
Weight (kg)	60.3 ± 9.3	60.9 ± 9.2	71.1 ± 12.0	71.6 ± 12.3	0.1
VO _{2max}					
mL·kg ⁻¹ ·min ⁻¹	61.4 ± 5.1	61.0 ± 5.8	56.5 ± 8.2	56.0 ± 7.0	0.1
mL·kg ^{-0.75} ·min ⁻¹	170.6 ± 15.3	170.1 ± 19.4	164.0 ± 26.8	163.0 ± 23.9	0.5
LT					
% VO _{2max}	83 ± 4	83 ± 6	85 ± 4	87 ± 5	3
f _c (beats·min ⁻¹)	180 ± 10	175 ± 10**	168 ± 10	169 ± 9	6#
MAS					
Time (s)	337 ± 124	409 ± 164*	412 ± 163	371 ± 134	113##
C _{R70}					
mL·kg ^{-0.75} ·min ⁻¹	0.679 ± 0.036	0.645 ± 0.030*	0.675 ± 0.051	0.687 ± 0.047	0.045##
f _c (beats·min ⁻¹)	159 ± 11	156 ± 11**	145 ± 7	148 ± 6	6#
Strength					
1RM squat 90° (kg)	73.4 ± 20.5	97.8 ± 21.3**	92.5 ± 24.5	94.4 ± 22.2	22.4##
RFD squat 90° (W)	466.7 ± 163.2	588.0 ± 147.9**	717.3 ± 259.6	742.6 ± 251.9	96
Training					
Total time (min·wk ⁻¹)	414 ± 214	391 ± 169	324 ± 155	274 ± 151	27

Values are mean ± SD. C_{R70}, C_R measured on treadmill at 70% of VO_{2max} with 1.5% inclination.

* *P* < 0.05, significantly different from preintervention value.
 ** *P* < 0.01, significantly different from preintervention value.
 # *P* < 0.05, significantly different from Δ control value.
 ## *P* < 0.01, significantly different from Δ control value.

group improved significantly in 1RM and in RE from pre- to postintervention, there was no correlation between improvements in 1RM and in RE among the runners in the intervention group. When both the control group and the intervention group were put together, there was a significant ($R^2 = 0.38$, $P < 0.01$) correlation between improvements in 1RM and in RE. A significant correlation ($R^2 = 0.26$, $P < 0.05$) between pre RFD and RE was found.

DISCUSSION

The major finding in this study is that MST significantly improved RE and time to exhaustion at MAS.

Cost of running. The 5% improvement in RE at 70% VO_{2max} in the present study, accompanied by a 1.9% improvement in f_c at this intensity, supports the finding of improved work economy in cross-country skiing reported by Hoff et al. (15) and Østerås et al. (34). The results from

the present study are also in close agreement with the results reported by Hoff and Helgerud (18) who found that RE among soccer players at pretest LT improved with 4.7%. However, although in the present study the long-distance runners were running on a treadmill with only 1.5% inclinations, soccer players in the study of Hoff and Helgerud (18) were running at 3° (5.25%) inclinations. The present results thus demonstrates that the improvements in RE previously reported for upper-body work among cross-country skiers and for uphill running among soccer players are representative also for running at 1.5% inclinations. The design of the present study differs from some of the previous studies as there are six different exercises in the study of Millet et al. (27); eight different exercises in the study of Johnston et al. (20); and two different sprint exercises, five different jump exercises as well as two different strength exercises in the study of Paavolainen et al. (28). This variety of exercises makes it difficult to assess which type of strength training may have lead to an improvement in RE. The study by Paavolainen et al. (28) used both plyometric and strength exercises. Because

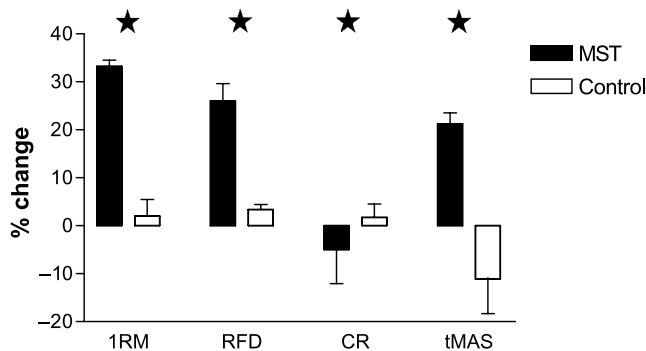


FIGURE 1—Percent changes from pre- to postintervention in the training group and the control group. **P* < 0.05, between-group differences. 1RM, one repetition maximum half-squat; RFD, RFD half-squat; CR, cost of running; tMAS, time to exhaustion at MAS.

TABLE 3. Endurance training before and during intervention, in minutes per week

% f _{cmax}	Intervention Group (n = 8), 4 Males and 4 Females		Control Group (n = 9), 5 Males and 5 Females	
	Preintervention	During Intervention	Preintervention	During Intervention
Running (min)				
60–85	195 ± 160	172 ± 165	124 ± 78	116 ± 165
85–90	67 ± 54	54 ± 31	53 ± 94	27 ± 28
90–95	34 ± 30	27 ± 26	22 ± 23	11 ± 14*
Other endurance training (min)				
60–85	68 ± 112	68 ± 73	104 ± 105	105 ± 109
85–90	42 ± 44	57 ± 54	19 ± 40	14 ± 32
90–95	9 ± 14	14 ± 18	2 ± 7	1 ± 4

Values are mean ± SD. Other endurance training consisted mainly of roller skiing and bike cycling.

* *P* < 0.05, significantly different from preintervention value.

plyometric exercises are reported by Turner et al. (33) and Spurr et al. (32), to improve RE, it is difficult to assess which exercises in the study by Paavolainen et al. (28) actually improved RE, and to what extent. A high number of exercises also lead to a relatively high percentage of strength or ballistic training in total training time. Neither of the three studies (20,27,28) have scaled for body weight when reporting the RE results. The way the $\dot{V}O_2$ results are presented in the study of Millet et al. (27) and in that of Paavolainen et al. (28) makes them difficult to scale for body weight. When scaling the mean RE results from Johnston et al. (20) to $\dot{V}O_2 \text{ mL}\cdot\text{kg}^{-0.75}\cdot\text{min}^{-1}$, the improvement in RE decreases from 3.8% (unscaled) to 3.2% (scaled). However, they all find improvements in RE by 2–7%, which are well in line with the RE results from the present study.

One repetition maximum and RFD. The runners who completed the present MST intervention increased 1RM half-squat by 24.4 kg or 33.2%. RFD was elevated by 121.3 W or 26.0%. The improvement in 1RM is well above the 9.9% improvement in a cable pulley apparatus among cross-country skiers reported by Hoff et al. (15) but in close agreement with the 33.7% improvement in half-squat among soccer players reported by Hoff and Helgerud (18). The 26% improvement in RFD in the present study is however somewhat below the 52.3% improvement reported by Hoff and Helgerud (18). Hoff and Helgerud (18) suggest that the main training response in their intervention is from neural adaptations and changes in recruitment patterns because the improvement in RFD exceeds the improvement in 1RM. An increased muscular strength due to MST can be explained by both neural adaptations and muscle hypertrophy (24). In the present study, the runners exhibited no changes in body weight after the intervention period. Because they are all well-trained athletes with low body weight, a possible hypertrophic response to the MST should be detectable with regard to their body weight. It is thus reasonable to expect mainly neural adaptations and changes in recruitment patterns as the main training response from the present training intervention. As a result of the improvement in 1RM, an increase in muscle–tendon stiffness may also have occurred, but this was not tested in the present study. Strength training has been reported to increase muscle–tendon stiffness (25). Also, exposure to intermittent high load has been reported to increase tendon cross-sectional area (23). One of the most important roles of the muscle is to modulate tendon stiffness to enhance exploitation of elastic energy. A tight musculo-tendinous system and consequently a higher degree of stiffness may thus also be advantageous for RE, as shown in kangaroos from the study by Dawson and Taylor (6). This is supported by the findings of Jones (21) and Craib et al. (5), that runners who were the least flexible in the lower limbs also had the best RE. Lichtwark and Wilson (26) have demonstrated a model predicting an optimal degree of muscle–tendon stiffness, suggesting that optimal muscle–tendon stiffness may be gait- or task-dependent and that the

highest degree of stiffness thus does not necessarily lead to better muscle efficiency. Also, Kerdok et al. (22) have shown changes in both muscle–tendon stiffness and RE when manipulating the stiffness of running surface. Kerdok et al. (22) are thus indicating that human runners adjust the level of muscle tendon stiffness toward the most optimal degree, to maintain consistent support mechanics on different surfaces.

The present study shows a significant correlation between pre-RFD and pre-RE values, suggesting that there may be a relationship between RFD in the muscles active in running movements and RE. Arterial inflow to exercising muscle occurs almost exclusively between muscle contractions (31). Mean transit time is found to positively correlate with A-V difference (30). A shorter contraction time in working muscles should thus prolong transit time and consequently the access to O_2 . Human muscle fatigue is not only dependent on peripheral changes at the muscle level but also on the central nervous system's ability to adequately drive the motor neurons, as discussed in Gandevia (9). Central changes affecting muscle activation may occur both at a supraspinal as well as at a spinal level (9). We speculate that an increase in maximal strength and in RFD, as shown in the present study, may be representing a more optimal activation of motoneurons and muscle fibers. If fewer motor units are recruited at the same time at a given running velocity as shown by Hoff et al. (16), lowering the actual demands of number of motor units recruited, a longer time to exhaustion at this velocity may be expected.

Time to exhaustion at MAS. Time to exhaustion at pretest MAS increased by 72 s or 21.3%. Because no changes were found in the present study regarding body weight, $\dot{V}O_{2\text{max}}$, LT velocity, or LT as percentage of $\dot{V}O_{2\text{max}}$, the improvement in running time to exhaustion at MAS should logically be due to the 5% improvement in RE. No changes in any of the measured parameters were found in the control group, and time to exhaustion at pretest MAS in this group did not change. As the endurance training in none of the groups changed during the intervention period, the only logical explanation for the improvement in RE and thus in time to exhaustion at pretest MAS is the MST performed during the intervention.

CONCLUSION

Heavy resistance training for 8 wk increased RE and time to exhaustion at MAS among well-trained, long-distance runners, without concurrent increase in maximal oxygen uptake or body weight. The matched control group exhibited no changes in any of the measured parameters.

The results from the present study do not constitute endorsement by ACSM.

REFERENCES

1. Bergh U, Sjödin B, Forsberg A, Svedenhag J. The relationship between body mass and oxygen uptake during running in humans. *Med Sci Sports Exerc.* 1991;23(2):205–11.
2. Bunc V, Heller J. Energy cost of running in similarly trained men and women. *Eur J Appl Physiol Occup Physiol.* 1989;59(3):178–83.
3. Conley DL, Krahenbuhl GS. Running economy and distance running performance of highly trained athletes. *Med Sci Sports Exerc.* 12(5):357–60.
4. Costill DL, Thomas H, Roberts E. Fractional utilization of the aerobic capacity during distance running. *Med Sci Sports Exerc.* 1973;5:248–52.
5. Craib MW, Mitchell VA, Fields KB, Cooper TR, Hopewell R, Morgan DW. The association between flexibility and running economy in sub-elite male distance runners. *Med Sci Sports Exerc.* 1996;28(6):737–43.
6. Dawson TJ, Taylor CR. Energetic cost of locomotion in kangaroos. *Nature.* 1973;246:313–4.
7. Di Pampero PE, Atchou G, Brückner JC, Moia C. The energetics of endurance running. *Eur J Appl Physiol.* 1986;55:259–66.
8. Dudley GA, Fleck ST. Strength and endurance training: are they mutually exclusive? *Sports Medicine.* 1987;4:79–85.
9. Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev.* 2001;1726–89.
10. Gettmann LR, Pollock ML. Circuit weight training: a critical review of its physiological benefits. *The Physician Sports Med.* 1981;9:44–60.
11. Helgerud J. Maximal oxygen uptake, anaerobic threshold and running economy in women and men with similar performance level in marathons. *Eur J Appl Physiol.* 1994;68:155–61.
12. Helgerud J, Engen LC, Wisløff U, Hoff J. Aerobic endurance training improves soccer performance. *Med Sci Sports Exerc.* 2001;33(11):1925–31.
13. Helgerud J, Kemi OJ, Hoff J. Pre-season concurrent strength and endurance development in elite soccer players. In: *Football (Soccer). New Developments in Physical Training Research*, Hoff J and Helgerud J. Trondheim: NTNU, 2003, pp. 60–72.
14. Helgerud J, Ingjer F, Strømme SB. Sex differences in performance-matched marathon runners. *Eur J Appl Physiol.* 1990;61:433–9.
15. Hoff J, Gran A, Helgerud J. Maximal strength training improve aerobic performance. *Scand J Med Sci Sports.* 2002;12(5):288–95.
16. Hoff J, Helgerud J, Wisløff U. Endurance training into the next millennium; muscular strength training effects on aerobic endurance performance: a review. *Am J Med Sports.* 2002;4:58–67.
17. Hoff J, Tjønnå AE, Steinshamn S, Høydal M, Richardson RS, Helgerud J. Maximal strength training of the legs in COPD: a therapy for mechanical inefficiency. *Med Sci Sports Exerc.* 2007;39(2):220–6.
18. Hoff J, Helgerud J. Maximal strength training enhances running economy and aerobic endurance performance. In: *Football (Soccer). New Developments in Physical Training Research*, Hoff J, Helgerud J. Trondheim, Norway: Norwegian University of Science and Technology, 2003, pp. 37–53.
19. Hoff J, McMillan K, Helgerud J. Football (soccer). Specific, simple, low cost, test of endurance performance and maximal oxygen uptake. In: *Football (Soccer). New Developments in Physical Training Research*, Hoff J, Helgrund J. Trondheim, Norway: Norwegian University of Science and Technology, 2003, pp. 217–21.
20. Johnston RE, Quinn TJ, Kertzer R, Vroman NB. Strength training in female distance runners: impact on running economy. *J Strength Cond Res.* 1997;11(4):224–9.
21. Jones AM. Running economy is negatively related to sit-and-reach test performance in international-standard distance runners. *Int J Sports Med.* 2002;23:40–3.
22. Kerdok AE, Biewener AA, McMahon T, Weyand PG, Herr HM. Energetics and mechanics of human running on surfaces of different stiffnesses. *J Appl Physiol.* 2002;92(2):469–78.
23. Kongsgaard M, Aagaard P, Kjaer M, and Magnusson SP. Structural Achilles tendon properties in athletes subjected to different exercise modes and in Achilles tendon rupture patients. *J Appl Physiol.* 2005;99:1965–71.
24. Kraemer WJ, Ratamess NA. Fundamentals of resistance training: progression and exercise prescription. *Med Sci Sports Exerc.* 2004;36(4):674–88.
25. Kubo K, Kanehisa H, Fukunaga T. Effects of isometric training on the elasticity of human tendon structures in vivo. *J Appl Physiol.* 2001;91(1):26–32.
26. Lichtwark GA, Wilson AM. Is Achilles tendon compliance optimized for maximum efficiency during locomotion? *J Biomech.* 2007;40:1768–75.
27. Millet GP, Jaouen B, Borrani F, Candau R. Effects of concurrent endurance and strength training on running economy and VO₂ kinetics. *Med Sci Sports Exerc.* 2002;34(8):1351–9.
28. Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, and Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol.* 1999;86(5):127–1533.
29. Pate RR, Kriska A. Physiological basis of the sex difference in cardiorespiratory endurance. *Sports Med.* 1984;1:87–98.
30. Saltin B. Malleability of the system in overcoming limitations: functional elements. *J Exp Biol.* 1985;115:345–54.
31. Shoemaker JK, Hodge L, Hughson RL. Cardiorespiratory kinetics and femoral artery blood velocity during dynamic knee extension exercise. *J Appl Physiol.* 1994;77:2625–32.
32. Spurrs RW, Murphy AJ, Watsford ML. The effect of plyometric training on distance running performance. *Eur J Appl Physiol.* 2003;89:1–7.
33. Turner AM, Owings M, Schwane JA. Improvement in running economy after 6 weeks of plyometric training. *J Strength Cond Res.* 2003;17:60–7.
34. Østerås H, Helgerud J, Hoff J. Maximal strength-training effects on force-velocity and force-power relationships explain increases in aerobic performance in humans. *Eur J Appl Physiol.* 2002;88(3):255–63.
35. Åstrand, PO, Rodahl K. In: *Textbook of Work Physiology*, New York: McGraw-Hill, 1986, pp. 299–311, 325–332.