Running Economy is Impaired Following a Single Bout of Resistance Exercise

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The purpose of this study was to determine whether a low-volume high-intensity resistance training session influenced running economy during a subsequent aerobic treadmill run. Nine well trained distance runners (mean±SD; $\dot{V}O_{2max}$, 66.6±10.2 ml•kg^{-1}•min^{-1}; weight, 65.8±10.2 kg; height, 173.4±7.8 cm; age 20±1.1 years) with resistance training experience performed treadmill running at two different speeds (0.56 m•sec^{-1} and 0.20 m•sec^{-1} below speed corresponding to lactate equilibrium) either rested or 1, 8 or 24 hours after a 50-minute whole body resistance training session. Running economy was assessed using open circuit spirometry while heart rate was recorded telemetrically. The contractile properties of the quadriceps femoris were also determined following each resistance training session and prior to each treadmill run using percutaneous electrical stimulation. Submaximal oxygen consumption was significantly increased one hour (2.6±2.3%, p= 0.007), and eight hours (1.6±2.5%, p= 0.032), but not 24 hours after resistance training. No significant differences were found in exercising heart rate, ventilation, respiratory exchange ratio, ratings of perceived exertion, or running mechanics. Peak twitch torque, time to peak torque, and half relaxation time of the quadriceps femoris were significantly reduced immediately following resistance training while peak twitch torque was also lower one hour following resistance training. Running economy following a resistance training session is impaired for up to 8 hours. This change was not paralleled by a concomitant change in exercising heart rate. The mechanism responsible for increased oxygen consumption following resistance training may be related to impairment of the force generating capacity of skeletal muscle, as there was a significant decrement in the contractile properties of the quadriceps femoris following resistance training.

Introduction

Running economy, an individuals steady state oxygen consumption for a given running speed, has been repeatedly shown to be an excellent predictor of endurance performance, particularly in runners with similar maximal aerobic power (Brandon & Boileau, 1987; Conley & Krahenbuhl, 1980; Costill et al, 1973) . The runner with the best running economy will consume less oxygen at a given workload (Brandon, 1995), allowing them to run longer at the same speed or run faster at the same relative oxygen uptake (Johnston et al, 1997).

Little is known about the influence of resistance training on distance running performance and the physiology of distance running. The studies that have investigated the chronic effects of concurrent resistance training and distance running have indicated resistance training doesn't appear to interfere with aerobic development (Hickson et al, 1988), although endurance training may attenuate strength gains (Hickson, 1980) Additionally, supplementing endurance training with resistance training has been shown to enhance performance in female distance

runners by improving running economy (Johnston et al, 1997). The acute effects of a single resistance training session on subsequent endurance exercise have however received limited attention.

The acute responses to resistance training are well documented. Factors investigated include metabolic rate (Melby et all, 1993; Melby et al, 1992), glycogen depletion (Pascoe et al, 1993), free radical production (McBride et al, 1998), protein synthesis (MacDougall et al, 1995), lipoprotein metabolism (Wallace et al, 1991), and immune function (Nieman et al, 1995). It is currently not known whether the changes in these parameters that occur with resistance training influence a subsequent distance running session. Bailey et al. (1996) stated that, "if the physiological sequelae associated with resistance exercise alter normal body homeostasis for a long enough time many assumptions about the acute effects of aerobic exercise, if performed soon after resistance training, may not be completely valid." For example, elevation in variables such as heart rate during subsequent endurance exercise may lead to an inaccurate training prescription. It is known that a resistance training session immediately prior to cycle ergometry doesn't appear to alter aerobic energy demand (Crawford et al, 1991; Wallis, 1995). It is possible however that the detrimental effect of a resistance exercise session on subsequent treadmill running would be greater than that observed during cycle ergometry since biomechanical efficiency is an important determinant of running economy (Williams & Cavanagh, 1987). It is also desirable to know how long any acute residual effects of resistance training impact upon subsequent running economy as this may aid in optimizing recovery between training sessions. Recovery is a critical component of training as it promotes the quality of subsequent training sessions and reduces the risk of over-training (Kuipers & Keizer; 1988). Further, from a methodological perspective when designing experiments one should understand the nature and time-course of any potential physiological perturbations during running that may result from a previous resistance training session. The purpose of this study was therefore to determine whether a single resistance training session influenced running economy during subsequent treadmill running.

Methods

Participants

After providing written informed consent nine well-trained competitive male and female distance runners, with mean (±SD) best 10 km time 37:03±6:09 min and a minimum of three months high intensity, low volume resistance training experience agreed to participate in this study. The sample comprised five males and four females and their physical and physiological characteristics are reported in Table 1. The

		Height (cm)	Weight (kg)	$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)
Male	Mean±SD	176.0±4.3	68.8±6.6	74.5±4.3
	Range	171.0-180.0	624.-79.1	68.7-79.6
Female	Mean±SD	170.3±10.7	62.0±11.0	56.7±4.0
	Range	156.0-182.0	46.0-70.5	53.4-61.6
Combined	Mean±SD	173.4±7.8	65.8±9.0	66.6±10.2
	Range	156.0-182.0	46.0.-79.1	53.4-79.6

Table 1: Subject characteristics (n=9) (mean±SD).

project was previously approved by the University of Otago Ethics Committee for Experimentation on Human Subjects.

Experimental Design

A repeated measures experimental design was implemented. Participants were initially tested to determine $\dot{V}O_{2max}$ and lactate equilibrium. They then completed in random order four treadmill training sessions. One session consisted only of sub-maximal aerobic exercise and served as a control. The remaining three protocols were identical in nature but the run was preceded by a whole body resistance training session either 1, 8, or 24 hours earlier. During each testing session running economy was measured using open circuit spirometry and the contractile characteristics of the quadriceps were assessed using percutaneous electrical stimulation. To ensure consistent training histories before each trial, one session was tested each week on the same day and participants were instructed to maintain a consistent level of training (volume and intensity) throughout the testing period. Running economy was assessed in each subject at the same time of day to avoid any potential impact of circadian rhythmicity, however this necessitated that the resistance exercise session be performed at a different time of day for each condition.

Familiarisation

Three treadmill and three resistance training familiarisation sessions took place over a two-week period. The purpose of these sessions was to ensure that all participants were comfortable with running on the treadmill and if possible, to reduce delayed muscle soreness induced by the resistance training session. Previous research has indicated that this volume of treadmill accommodation is sufficient (Morgan & Craib; 1992) but there are no guidelines in the literature indicating the number of sessions required to properly familiarise subjects with resistance training. During this time participants were given a demonstration of the correct technique to be used when lifting and in the third session an eight-repetition maximum (the amount of weight that can be lifted eight times but not nine times) was determined for each exercise.

Aerobic Testing

Following familiarisation, participants completed a multi-staged incremental exercise test to determine both $\dot{V}O_{2max}$ and treadmill velocity corresponding to lactate equilibrium, using a similar protocol to that of Tegtbur et al. (1993). That protocol was modified so that the 200-300 m runs used by Tegtbur to elicit lactic acidosis prior to the second incremental running test to determine lactate equilibrium were replaced by an incremental treadmill test to elicit $\dot{V}O_{2max}$. Specifically, the two-stage protocol involved completion of a continuous incremental treadmill test of 10-12 minutes in duration to determine $\dot{V}O_{2max}$ followed by five minutes of active recovery. A discontinuous incremental treadmill protocol was then utilised to determine lactate equilibrium.

$\dot{V}O_{2max}$ Protocol

Participants ran on a level treadmill for two minutes at the speed equivalent to their best ten-kilometre time minus two $km \bullet hr^{-1}$. The speed was subsequently increased by one $km \bullet hr^{-1}$ every two minutes until three two-minute stages had been completed. The treadmill then remained at this speed while the gradient was increased by two percent every minute until volitional exhaustion. During exercise, participants breathed through a Hans Rudolph mouthpiece and one-way valves while respiratory

measures were determined every 20 seconds using open-circuit spirometry (Sensormedics 2900, Yorba Linda, California). Prior to each test, the CO_2 and O_2 analysers were calibrated against Beta certified gases of known concentrations (16.0±0.2 % O_2, 3.95±0.08% CO_2 mixed in N_2 and 26.02±0.2 % O_2 mixed in N_2) and the flow meter was calibrated using a three-litre calibration syringe. Heart rate was monitored using a Polar Sport Tester PE 4000 heart rate monitor (Kemplele, Finland). All treadmill running was carried out on a motorised treadmill (Quinton Q65, Series 90, Seattle). The participants were verbally encouraged to give a maximal effort during the final stages of the incremental test to exhaustion. The primary criteria used to indicate that $\dot{V}O_{2max}$ had been reached was a plateau in the rise of oxygen consumption with a further increase in work. Secondary criteria included attainment of age predicted or known maximal heart rate, a respiratory exchange ratio >1.15 or volitional exhaustion. The reliability of measurement for $\dot{V}O_2$, $\dot{V}e$ and heart rate in our laboratory during treadmill running has previously been reported to be high (intraclass reliability coefficents >0.98) through a range of running velocities (Caird et al 1999).

Equilibrium Protocol

The lactate equilibrium protocol used to determine lactate threshold was originally outlined by Tegtbur et al. (1993). A modified version of this protocol was designed to enable $\dot{V}O_{2max}$ and lactate equilibrium to be determined during one testing session. At the conclusion of the $\dot{V}O_{2max}$ test and following five minutes of active recovery (walking), participants ran on a level treadmill for three minutes, one km•hr^{-1} below the starting speed for the $\dot{V}O_{2max}$ protocol, followed by one minute of passive recovery. The speed was then increased by one km•hr^{-1} for a further three minutes. This continued until the participant could not maintain the set speed for three minutes. Blood samples were obtained via finger prick during each recovery period and analysed using an automated lactate analyser (YSI, model 27 analyser, Yellow Springs, Ohio) for blood lactate concentration. Blood lactate concentration is elevated at the cessation of the $\dot{V}O_{2max}$ test. In the second stage of this protocol and over the course of the first few workload increments blood lactate drops as it is cleared from the muscle. Eventually blood lactate begins to increase again due to lactate production exceeding clearance. The point at which the lactate concentration bottoms out is defined as the lactate minimum or lactate equilibrium, since lactate production should equal lactate clearance at this point. This point has been shown to be strongly related to maximal lactate steady state and was determined in the present experiment by fitting a 3rd order polynomial to the lactate-running velocity data and interpolating the velocity at the lactate minimum (Tegtbur et al, 1993).

Resistance Training

The resistance-training session consisted of a 50-minute whole body program aimed at exercising the major muscle groups involved in running. The session involved three sets of six exercises at an intensity of 8 RM (except abdominal exercises, which involved three sets of 15-20 repetitions) with two minutes of recovery between sets. The exercises performed were bench press, squat, upright row, dead lift, seated row, and a combination of four abdominal exercises. With the exception of the seated row, all exercises were performed using free weights. The same instructor supervised all sessions to ensure correct technique was maintained (Table 3).

Exercise (order)	Repetitions	Repetitions Maximum	Sets	Load (kg)	Volume (kg) Sets x reps x load
Bench press (1)	8	8	3	(M) 56.5±4.8	1356±23
				(F) 33.1±7.7	795±186
				(C) 46.1±13/6	1106±327
Squat (2)	8	8	3	(M) 65.5±8.7	1572±210
				(F) 41.3±6.3	990±151
				(C) 54.7±14.7	1313±353
Upright Row (3)	8	8	3	(M) 37.0±3.3	888±78
				(F) 24.4±6.3	585±150
				(C) 45.3±11.4	1087±275
Dead Lift (4)	8	8	3	(M) 53.5±4.2	1284±100
				(F) 35.0±8.4	840±201
				(C) 45.3±11.4	1087±274
Seated Row (5)	8	8	3	(M) 57.3±5.2	1374±124
				(F) 37.5±8.4	900±176
				(C) 48.5±11.9	1163±287
				Total Workout	(M) 6474±4445
					(F) 4410±845
					(C) 5423±1385

M=male; F=female; C=combined (male and female)

Table 3: Load lifted during a single bout of resistance exercise (mean±SD).

Treadmill Training

Participants warmed up at a moderate pace (10 km•hr^{-1} females, 12 km•hr^{-1} males) for five minutes. Four ten-minute stages of level treadmill running were then interspersed with one minute of recovery. The first and second stages were run at 0.56 m•s^{-1} below the speed corresponding to lactate equilibrium (easy running) while the third and fourth were run at 0.20 m•s^{-1} below the speed corresponding to lactate equilibrium (hard interval training). The durations, intensities and work/rest ratio were chosen to represent an interval run session that might be performed following a resistance training session and to determine if a resistance training session differentially influenced running economy at different intensities. During exercise, $\dot{V}O_2$ was continually monitored using open circuit spirometry as previously outlined and heart rate was monitored telemetrically (Table 2).

Variable		control	1 hour	8 hour	24 hour
Velocity (km•hr^{-1})	Slow	13.4 (2.3)	-	-	-
	Fast	14.7 (2.3)	-	-	-
%$\dot{V}O_{2max}$	Slow	67.00 (6.55)	68.84 (6.11)	68.47 (6.71)	68.23 (6.22)
	Fast	72.92 (5.72)	74.35 (5.94)	73.56 (5.74)	73.85 (5.70)
% Max Heart rate	Slow	79.90 (4.05)	81.15 (4.29)	81.39 (3.98)	80.72 (3.75)
	Fast	88.00 (2.32)	89.21 (3.27)	88.98 (3.54)	88.53 (2.92)

Table 2: Exercise intensity during 40-minute submaximal treadmill run at two intensities (20-minutes slow, 20-minutes fast). Values are means (±SD) for control, 1 hour, 8 hour, and 24 hour conditions.

Running economy

Mean relative ($ml \bullet kg^{-1} \bullet min^{-1}$) and absolute ($l \bullet min^{-1}$) $\dot{V}O_2$ was measured over the last five minutes of each ten-minute running interval. The values over 5-minutes for the two low velocity intervals were combined and the two high velocity running intervals were combined and averaged to determine running economy at each velocity. Ventilation ($l \bullet min^{-1}$), respiratory exchange ratio, heart rate (bpm), and ratings of perceived exertion (Borg, 1982) were measured and averaged in the same fashion. Blood lactate concentration was measured at the end of each ten-minute running interval. The lactate concentration determined for both running intervals at each intensity were averaged and reported as the blood lactate concentration at each velocity. A substantial difference in submaximal running speeds and oxygen consumption was evident between genders, therefore any difference in oxygen consumption between protocols was calculated as a percentage change relative to control values.

Running Mechanics

Biomechanical analysis was carried out via two-dimensional videography in the sagittal plane. Mean stride frequency ($strides \bullet min^{-1}$) and length (m) were calculated from the time taken for one hundred and forty sequential strides (Cavanagh & Williams, 1982) measured during the last minute of the second ten-minute stage at each velocity. A stride was defined as that occurring from right toe off to a left foot strike. Stride frequency and stride length were calculated as follows:

Stride Time (sec) = time (sec) / number of strides (1)

Stride Frequency ($strides \bullet min^{-1}$) = 60 / stride time (sec) (2)

Stride Length (m) = Distance covered per minute (m) / stride frequency (3)

Muscle Twitch Characteristics

Muscle twitch characteristics of the left Quadriceps were determined via percutaneous stimulation after each resistance training session and prior to each treadmill run. Immediately following the resistance training session, the participant was prepared as quickly as possible (generally within five minutes) for electrical stimulation. After standard skin preparation, two lead stimulating electrodes (12cm x 18cm) were wrapped in gauze, moistened and covered with electrode gel. One stimulating electrode was placed in the groin over the femoral notch to stimulate the femoral nerve and the second electrode was placed on top of the thigh approximately three centimeters proximal to the patella. Participants were seated into an isokinetic dynamometer (Biodex Corporation, Shirley, New York) via Velcro straps. The dynamometer was calibrated each day using a known mass with the lever arm set 90° to the floor. The dynamometer was connected to a data acquisition interface and computer (Pentium 200MMX) and torque data were sampled at 1 kHz and displayed and analysed using data acquisition software (Windaq version 1.51, Akron, Ohio). The lever arm and seat were adjusted so that the axis of rotation of the participants knee corresponded with that of the lever arm. The lever arm was positioned to achieve 72.5 degrees of knee flexion. This position placed the patello-femoral tendon under stretch to minimize it's compliance and optimize the transference of quadriceps twitch force to the lever arm. Twitches were elicited using a constant current stimulator (Digitimer stimulator model DS7, Hertfordshire, England) with gradually increasing current (square wave pulse; width 1000 ms; voltage 200V) until a supramaximal muscle twitch

had been identified. In no instance was current in excess of 200 mA required. After the stimulating current was set to elicit a supramaximal twitch the participant was instructed to perform a ten-second MVC and verbally encouraged to provide a maximal effort. In order to control for a possible twitch potentiation influencing the twitch characteristics (Always et al, 1987) only twitches elicited following a 10-second maximum voluntary contraction (MVC) were analysed. Ten seconds following the MVC, two sets of three supramaximal twitches were elicited, separated by 30 seconds of recovery. An identical protocol was carried out immediately prior to the submaximal treadmill run. These potentiated muscle twitches were then analysed to determine peak twitch torque, time to peak torque and ½ relaxation time.

Nutrition

No nutritional or dietary control was employed other than instruction given to the subjects to maintain regular eating habits throughout the testing period. Except for the one-hour recovery protocol participants were encouraged to consume a meal as soon as possible following completion of the resistance training session. To control for possible hydration effects, participants were provided with 1000 ml of a carbohydrate and electrolyte solution of known concentration (carbohydrate 6.3g/100 ml; sodium, 1.8 mM/100 ml; potassium, 0.3 mM/100 ml) to consume during and after each resistance training session.

Statistical Analysis and Presentation

The results were analyzed using Statistics Package for Social Sciences (version 7.5). For each dependent variable a two-way repeated measures analysis of variance (recovery time and intensity) was used to determine the effect of recovery duration between resistance training and submaximal running on running physiology at two velocities. Degrees of freedom were adjusted using the Huynh-Feldt episilon procedure to account for any violations in the sphericity assumption. If a significant difference was detected for any of the dependent variables between protocols, Neumann-Keuls post-hoc comparisons were used to determine where these specific differences occurred. The relationship between muscle twitch characteristics was calculated using Pearson's correlation coefficient. For all statistics, significance was set at $P< 0.05$.

Results

Running economy

A single bout of resistance training increased $\dot{V}O_{2submax}$ during subsequent treadmill running (F [3, 24] = 4.51, P= 0.01) (Figure 1). When compared to the control trial (46.4±7.4 ml•kg^{-1}•min^{-1}), $\dot{V}O_{2submax}$ was higher at both running intensities one hour (47.5±7.4 ml•kg^{-1}•min^{-1}, 2.6±2.3%, P= 0.007) and eight hours (47.1±7.4 ml.kg^{-1}•min^{-1}, 1.6±2.5%, P = 0.032), but not 24 hours after resistance training, due to slightly higher variability. (47.2±7.7 ml•kg^{-1}•min^{-1}, 1.6±2.5%, P= 0.071).

Heart rate and ventilation

Resistance training had no effect on exercising heart rate or ventilation. Similarly, resistance training also had no effect upon respiratory exchange ratio, blood lactate concentration, ratings of perceived exertion, stride frequency, and stride length during subsequent submaximal treadmill running (Table 4).

Muscle twitch characteristics

Resistance training had a significant effect on peak twitch torque (F [3.06, 24.48] = 4.155, P= 0.02), time to peak torque (F [3.47, 27.74] = 2.97, P= 0.05), and half

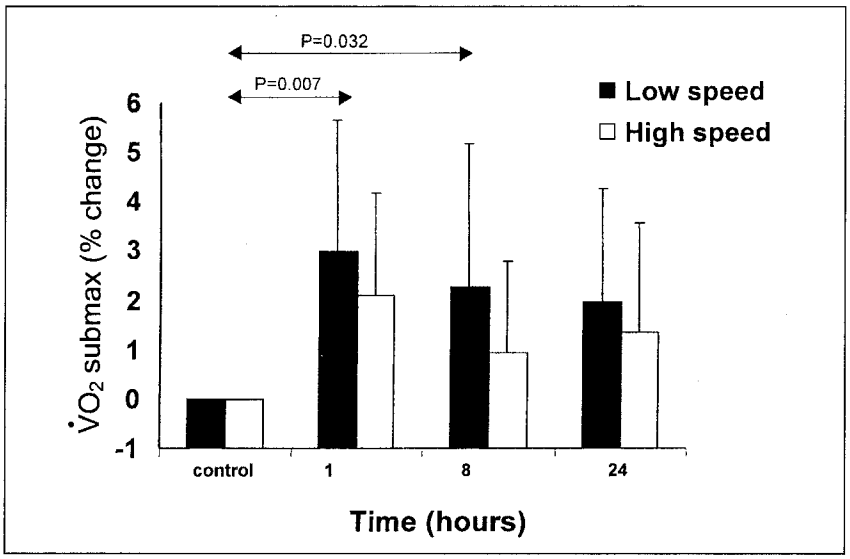

Figure 1: Submaximal oxygen consumption (Mean±SD) expressed as percent change relative to control values at two speeds (low speed= 0.56m•s^{-1} below the speed corresponding to lactate equilibrium; high speed= 0.20m•s^{-1} below the speed corresponding to lactate equilibrium) during a 40-minute submaximal treadmill run, rested (control), one, eight, and twenty four hours following resistance training.

Variable		control	1 hour	8 hour	24 hour
Ventilation (l•min^{-1})	Slow	76.57 (16.14)	78.48 (18.73)	78.00 (19.03)	77.13 (17.75)
	Fast	88.80 (19.07)	91.72 (23.12)	90.05 (22.16)	89.63 (21.26)
Heart rate (bpm)	Slow	156.18 (9.65)	158.68 (10.61)	159.16 (10.81)	157.83 (9.98)
	Fast	172.08 (8.94)	174.44 (9.85)	174.04 (11.64)	173.10 (9.37)
Respiratory exchange rate	Slow	0.903 (.025)	0.886 (.031)	0.894 (.027)	0.892 (.018)
	Fast	0.938 (.020)	0.938 (.025)	0.937 (.023)	0.903 (.017)
Blood lactate (mmol•l^{-1})	Resting	1.28 (0.51)	1.42 (0.37)	1.06 (0.17)	1.04 (0.41)
	Slow	1.58 ((0.71)	1.48 (0.45)	1.39 (0.66)	1.44 (0.88)
	Fast	2.18 (0.95)	2.50 (1.33)	2.11 (1.07)	2.92 (1.82)
Rates of perceived exertion	Slow	3.78 (0.97)	3.72 (1.44)	4.28 (0.97)	3.56 (1.01)
	Fast	5.78 (1.56)	5.89 (1.67)	6.11 (1.27)	5.78 (1.39)
Stride Frequency (strides•min^{-1})	Slow	171.87 (8.38)	170.92 (7.84)	169.00 (7.49)	170.86 (8.77)
	Fast	173.95 (8.91)	173.78 (8.35)	172.50 (8.33)	174.02 (9.26)
Stride length (m)	Slow	1.29 (0.18)	1.30 (0.18)	1.31 (0.19)	1.30 (0.19)
	Fast	1.40 (0.18)	1.40 (0.18)	1.41 (0.18)	1.40 (0.18)

Table 4: Ventilation, heart rate, respiratory exchange ratio, blood lactate, ratings of perceived exertion, stride frequency, and stride length data during 40-minute submaximal treadmill run at two intensities (20-minutes slow, 20-minutes fast). Values are means (SD).

relaxation time (F [3.07, 24.54] = 3.35, P= 0.04). Paired t-tests indicated that peak twitch torque was significantly lower immediately (t [8] = -3.765, P= 0.01) and one hour following (t [8] = -2.42, P= 0.04) resistance training (Figure 2a). Time to peak torque (t [8] = -2.33, P= 0.05) and half relaxation time (t [8] = -2.59, P= 0.03) were also significantly shorter immediately following resistance training (Figures 2b & c). There was no significant correlation between peak torque and half relaxation time (r= 0.243, P> 0.05) although there was a correlation between peak torque and time to peak torque (r= 0.38, P< 0.05). Additionally, there was no significant difference in twitch characteristics immediately post resistance training between the three sessions.

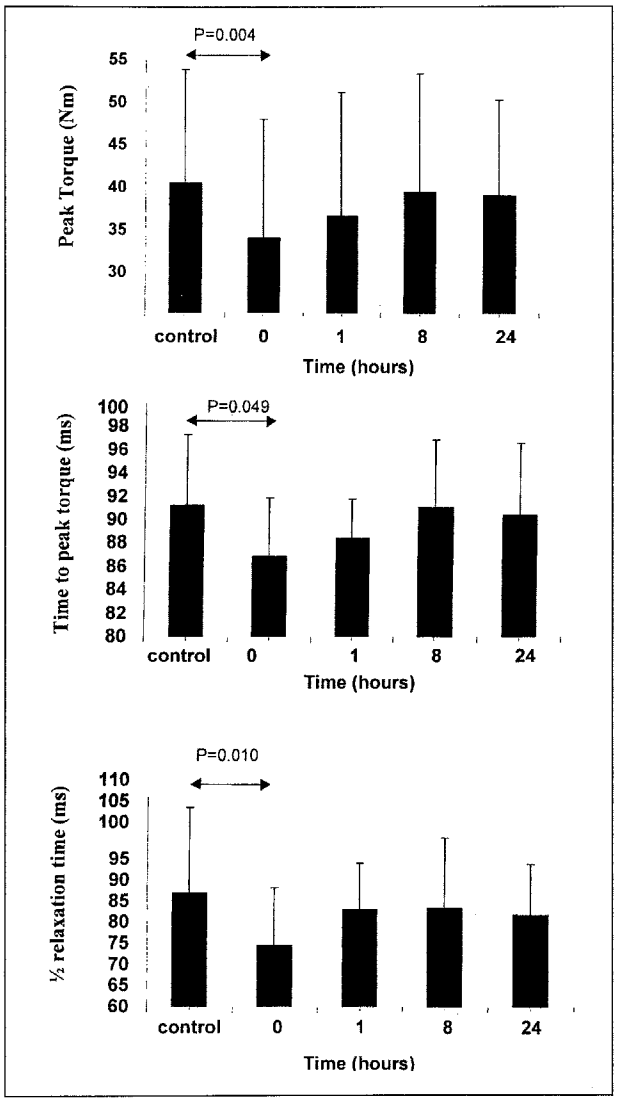

Figure 2: Mean (±SD) muscle contractile characteristics for control, immediately post resistance training (0 Hr),1 hour, 8 hour, and 24 hours post resistance training. a) potentiated peak torque. b) potentiated time to peak torque development. c) potentiated half relaxation time.

Discussion

The purpose of this study was to examine the acute effects of a single resistance training bout on running economy. The primary finding of this study is that running economy can be impaired for up to eight hours after a single session of resistance exercise. Furthermore, the transient negative effects of resistance training on running economy can be incurred at slower or faster submaximal running velocities. It is possible that the subjects could have started with a higher pre-exercise $\dot{V}O_2$ as a result of the previous resistance training, and this elevation may have been responsible for the impairment of running economy shortly after resistance training. Unfortunately, resting $\dot{V}O_2$ was not measured, but previous research examining the energy cost of cycling after a single bout of resistance training does not support this mechanism as being important in raising submaximal VO_2 since the energy cost of cycling is unaffected by previous resistance exercise (Crawford et al, 1991 & Wallis, 1995)

Wallis (1995) found no change in aerobic demand during 30-minutes of cycle ergometry (65% $\dot{V}O_{2max}$) immediately following three sets of leg exercises at an intensity of 8RM. Crawford et al. (1991) also found no change in $\dot{V}O_{2submax}$ following three sets of ten lower limb isokinetic strength exercises during 20-minutes of cycle ergometry at 65% and 75% $\dot{V}O_{2max}$. These resistance training protocols were restricted to the lower body, which may not have been sufficient to induce an increase in aerobic demand during subsequent cycle ergometry. A whole body resistance training programme would elicit a larger post-exercise elevation in oxygen consumption than lower limb only exercise and therefore would have a potentially greater influence on oxygen consumption during subsequent exercise. Additionally, body temperature may have been elevated to a greater extent in the present study which used whole body resistance training, and the well known Q10 effect is one mechanism that could partially explain an increased metabolic rate and the small elevation in submaximal oxygen consumption observed. Morgan et al. (1990) has however reported that a 30-minute prolonged maximal run did not impair running economy measured 24 hours later. This protocol involved whole body exercise but no data was reported inside 24-hours of recovery so adequate time would have passed for excess post-exercise oxygen consumption and elevated body temperature to return to baseline, and any shifts in substrate utilisation to return to pre-exercise values.

In support of the present findings, Guezennec et al. (1996) reported increased aerobic demand during distance running at the end of a triathlon compared to a control run with no prior exercise. James and Doust (1998) also found $\dot{V}O_{2submax}$ to be significantly elevated during 15-minutes of treadmill running at 50% $\dot{V}O_{2max}$ one hour after subjects performed six 800m intervals at one $km \bullet hr^{-1}$ below velocity at $\dot{V}O_{2max}$. Combined with the present findings, these studies indicate that previous exercise may induce residual fatigue or perhaps some other perturbation that can impair running economy for up to eight hours. The results of the present study must be interpreted with caution however, as Morgan and Craib (1992) found the mean coefficient of variation in running economy using data from four studies to range from 1-4%. However, when treadmill running experience, time of day, footwear, and training and performance activity are controlled, as in the present study, the between day coefficient of variation for measuring running economy in trained non-elite runners is reduced to 1.32% in 68% of all trials and 2.64% in 95% of all trials (Morgan et al, 1990) Our laboratory has also previously demonstrated that we can reliably measure running economy using test-retest data over 4 control sessions and intraclass reliability coefficients (ICC). ICC values indicated that these measures were highly

reliable (ICC, 95% lower confidence interval, 95% upper confidence interval for VO2 =0.98, 0.91-1.00 with a between day coefficient of variation of 1.3-2.2 % (Caird et al, 1999). The current study detected 2.6 % impairment in running economy one hour following resistance training. This is on the outer edge of day-to-day variability so the results may not be solely attributable to experimental manipulation. The magnitude of this change should not be considered of little practical significance however since it has been shown that small changes in economy can translate to substantial changes in running performance (Paavolainen et al, 1999)

Peak twitch torque decreased by 12% immediately following resistance training and was still depressed by 8% one hour into recovery. These results are consistent with Klein et al. (1988) who found peak torque to decrease 15% and 8%, 15 and 60-minutes following fatiguing exercise respectively. Behm and St-Pierre (1997) also measured a decrease of 14% in twitch torque of the quadriceps muscle group in the 10-minutes following 20-minutes of fatiguing exercise. The reduction in twitch torque observed in the present study and in the literature after previous exercise could be a result of increased muscle-tendon compliance, but since this was not directly measured this is speculation. Alternatively, decreased twitch torque may indicate that the residual fatigue from resistance training is at least partially occurring within the muscle and may be present for up to one hour following fatiguing exercise.

Besides the decrease in twitch torque observed following resistance training, time to peak torque and half relaxation time were 5 and 14 % shorter than control values immediately following resistance training respectively. This suggests that muscle-tendon compliance was probably not a dominant factor in the alteration of twitch characteristics since a more compliant muscle would have longer times to peak torque and half-relaxation. An elevated muscle temperature could have accounted for the quickening of the twitch characteristics however since this is a well known temperature effect. By one hour into recovery, time to peak torque and half relaxation time had returned to control levels. The decrease in time to peak torque and half relaxation time demonstrated in the present study may be partially explained by the decrease in peak torque since a lower peak torque will require less time to attain and consequently less time to return to pre-contraction level. There was however, only a weak correlation between peak torque and time to peak torque ($r= 0.38$, $p< 0.05$) whereas no significant correlation was found between peak torque and half relaxation time. Results of related studies are equivocal and difficult to interpret due to variation in muscle groups trained, fiber type, fitness level of the subjects, fatigue protocols, and time frame of measurements post exercise.

Mechanical efficiency has been reported as an important determinant of running economy, suggesting that any perturbation to this efficiency will subsequently increase aerobic demand. Nevertheless, we observed no changes in stride length or frequency after resistance training, so it would appear that variations in running technique did not account for the impairment of running economy. Cavanagh and Williams (1982) have previously measured aerobic demand in response to systematic variations in stride length and found only small increases in $\dot{V}O_2$ (0.2 $ml \bullet kg^{-1} \bullet min^{-1}$) despite relatively large variations from optimal stride length (0.04 m) so even if we observed more marked changes in these indices of running efficiency there may have been little effect on running economy. It remains possible that the whole body resistance training may have altered additional biomechanical parameters such as trunk rotation or arm drive, which could increase the aerobic demand of running, but this was not measured.

Prior resistance training had no effect on heart rate during the subsequent treadmill

run. These results are in contrast to those of Wallis (1995) where heart rate was elevated by nine beats per minute during 30 minutes of cycle ergometry following resistance training. However, in accordance with the finding of Wallis (1995), there was no significant change in minute ventilation following resistance training in the current study despite an increase in submaximal $\dot{V}O_2$. Other studies investigating the effects of resistance training on subsequent submaximal exercise have neglected to report ventilation measures. It is possible that the minor but non-significant increases in both ventilation and heart rate were sufficient to increase oxygen demand during submaximal exercise leading to a significant increase in $\dot{V}O_{2submax}$.

The results of this study indicate that high intensity, low volume resistance training acutely effects variables associated with distance running performance. The mechanism responsible for increased oxygen consumption following resistance training may be related to impairment of the force generating capacity of skeletal muscle, as there was a significant decrement in the contractile properties of the quadriceps femoris following resistance training. Further research is required to isolate the mechanisms responsible for an increase in the aerobic cost of running following a single resistance training session.

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