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Pre-Print Version

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Time to exhaustion during severe intensity running: response following a single bout of interval training

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Abstract

The primary aim of this study was to examine the change in performance prior to and following a fatiguing interval training session (TS). A secondary aim of this study was to examine the change in oxygen uptake ($\dot{V}O_2$) during moderate and severe intensity running, and the relationship with the change in performance. Seven male runners (mean ± s.d.: age 24 ± 6 years; height 1.79 ± 0.06 m; body mass 67.9 ± 7.6 kg; $\dot{V}O_2$ max 4.14 ± 0.49 l.min^{-1}) were studied. The $\dot{V}O_2$ during moderate and severe intensity running and running performance were studied immediately prior to, one hour following, and 72 h following the TS. The TS was performed on a treadmill, and consisted of 6 bouts of 800 m at 1 km.h^{-1} below the velocity at $\dot{V}O_2$ max (v-$\dot{V}O_2$ max), with 3 min rest intervals. Performance was also assessed at 1 km.h^{-1} below v-$\dot{V}O_2$ max, in the form of time to exhaustion (t_{lim}). The $\dot{V}O_2$ and heart rate (f_c) were assessed both during the severe intensity performance trial, and the moderate intensity run at 50% v-$\dot{V}O_2$ max. Whilst a significant change was observed in running performance and the $\dot{V}O_2$ during both moderate and severe intensity running prior to and following the TS, no relationship was observed between the magnitude of change in these variables. One hour following the TS, t_{lim} was decreased by 24%, $\dot{V}O_2$ during moderate intensity running was increased by 2%, and the difference in $\dot{V}O_2$ between 2 min 45 s and the end of severe intensity running was increased by 91% compared with values recorded prior to the TS. One hour following the TS, f_c was also increased significantly during moderate intensity running by 5% compared to the value recorded prior to the TS. These findings demonstrate that the TS resulted in a reduction in performance, and that the relationship between running performance and $\dot{V}O_2$ during running may be altered under conditions of prolonged fatigue.

Keywords: Oxygen uptake - endurance - running - fatigue

Introduction

Time to exhaustion (t_{lim}) during severe intensity exercise has been used to assess endurance running performance previously (eg., Billat et al., 1994a; b). According to the critical power concept, t_{lim} during severe intensity exercise, which is defined as being above critical power, is generally less than 30 min (Hill, 1993). During constant load cycle ergometry exercise to exhaustion, it has been found that only exercise at power output above critical power results in the attainment of maximal oxygen uptake ($\dot{V}O_2$ max) (Hill and Smith, 1999). Conversely, Billat et al. (1997) found that during constant velocity running exercise above critical velocity, oxygen uptake ($\dot{V}O_2$) did not reach $\dot{V}O_2$ max in high-level distance runners. It has, however, been suggested that t_{lim} during severe intensity exercise may be related to the magnitude of the change in $\dot{V}O_2$ between 3 minutes and the end of exercise (Poole et al., 1994a). Two recent studies have demonstrated that the $\dot{V}O_2$ during heavy intensity running (James and Doust, 1999) and moderate intensity running (James and Doust, 1998) is increased following an interval training session (TS). It is therefore interesting to examine whether following a similar TS, changes in $\dot{V}O_2$ during moderate and severe intensity running are related to changes in t_{lim}.

Many mechanisms have been proposed to explain the additional $\dot{V}O_2$ during running in a fatigued condition, including reduced neural input to the active muscles resulting in reduced force production, reduced tolerance to stretch loads, reduced recoil characteristics, and depleted muscle glycogen stores (Sherman et al., 1983; Sherman et al., 1984; Buckalew et al., 1985; Nicol et al., 1991a; Nicol et al., 1991b). A greater recruitment of type II muscle fibres, possibly in addition to, or instead of the type I fibres offers a further potential mechanism (Sejersted and Vollestad, 1992). In the case of running exercise, a changed fibre recruitment pattern may be a product of the damage caused by the repeated stretch shortening cycles, glycogen depletion in selected fibres, or other ‘non-metabolic’ fatigue (Hagerman et al., 1984; Vollestad et al,. 1984; Green, 1991).

Differences in the $\dot{V}O_2$ during running have been shown to have significant implications for performance, especially in subjects with similar values for maximal oxygen uptake ($\dot{V}O_2$ max) (Costill and Winrow, 1970; Daniels, 1974; Morgan et al., 1989a). However, in general, studies with both a cross-sectional and longitudinal design demonstrate equivocal findings with regard to the relationship between $\dot{V}O_2$ during constant velocity running and performance (Morgan and Craib, 1992).

The t_{lim} at the velocity associated with $\dot{V}O_2$ max (v-$\dot{V}O_2$ max) appears to be a suitable measure of running performance, and is probably the best method currently available for the assessment of changes in endurance running performance following an intervention. The t_{lim}

has been demonstrated to be a reliable measure during running at v-$\dot{V}O_2$ max (Billat et al., 1994b). The t_{lim} when measured during running at v-$\dot{V}O_2$ max has been shown to be closely related to velocity maintained during a half marathon competition, and lactate threshold when expressed as %$\dot{V}O_2$ max (Billat et al., 1994a). Based on the usual duration of t_{lim} at v-$\dot{V}O_2$ max (~6 min 30 s), and the proposed physiological factors determining the time limit at this intensity, it is somewhat surprising that t_{lim} is related to half marathon velocity and lactate threshold, but not to $\dot{V}O_2$ max, v-$\dot{V}O_2$ max, running economy or velocity maintained during a 3000 m performance. However, results from previous studies indicate that the measurement of t_{lim} at v-$\dot{V}O_2$ max in a laboratory setting is suitable for studying the effects of an intervention on performance in a group of endurance runners (Billat et al., 1994b).

This study aimed to establish whether t_{lim} was reduced following a bout of severe intensity interval running training, and whether a change in $\dot{V}O_2$ during moderate and severe intensity exercise was related to a change in t_{lim}.

Methods

Seven well-trained male runners gave informed consent to take part in the study which had been approved by the ethics committee of Chelsea School, University of Brighton. The subjects were all thoroughly habituated to laboratory testing procedures.

All subjects rested for 3 days prior to the start of the experiment, and no training was performed throughout the testing period. The subjects were instructed to consume their normal high carbohydrate diet between testing sessions. For 3 hours prior to each testing session subjects refrained from eating, and consuming caffeine and alcohol. Subjects were instructed to arrive at each testing session fully hydrated, and wearing identical footwear and similar clothing. The same individual warm up routine was performed on each occasion. All testing took place between 1 pm and 5 pm.

All running took place on a Woodway treadmill (Cardiosport Ltd., Salford, U.K.). The speed of the treadmill driving motor is monitored by sensors on the motor and is shown on the digital display. Since the treadmill belt is unable to slip due to the rack and pinion arrangement, it always rotates at the same speed as the motor, and therefore the treadmill belt is effectively self-calibrated at the speed displayed on the control console. Routine checks were made, in addition to the self-calibration, by manual counting of belt rotations over a recorded time. The belt length was accurately measured, and when multiplied by the number of revolutions and divided by the time for the known number of revolutions, the belt speed was found. The grade of the treadmill was checked manually using a protractor, and spirit level. The grade was determined as the tangent of the angle of incline (i.e., opposite/adjacent).

On the first occasion subjects visited the laboratory, age, height, mass, $\dot{V}O_2$ max and v-$\dot{V}O_2$ max were determined. $\dot{V}O_2$ max was measured for treadmill exercise using an incremental velocity protocol (Jones and Doust, 1996a). Increment duration was 1 min, with an increase of 1 km.h^{-1} each minute. All running was performed with the treadmill at a 1% grade since this was the gradient found to best represent outdoor running (Jones and Doust, 1996b). The v-$\dot{V}O_2$ max was defined as the velocity corresponding to the highest $\dot{V}O_2$ value recorded during the incremental test. In the event of a plateau, the lowest associated velocity was recorded.

During exercise subjects wore a nose clip and a large, broad flanged rubber mouthpiece (Collins, Mass, USA) fitted to a low-resistance (Inspired < 3 cmH$_2$O and expired < 1 cmH$_2$O at flow rates up to 350 L.min^{-1} ATPS) breathing valve (University of Brighton, England) of negligible volume (90 ml), consisting of lightweight perspex tubing (T-shape) into which is mounted two rubber flap one-way low resistance valves (Mine Safety Appliances Ltd.), connected to a 200 L Douglas bag from the expired side via a 1 m length of light weight Falconia tubing of 36 mm bore (Baxter Woodhouse and Taylor Ltd.). Expired gas was collected for a timed period of whole number of breaths during the final 45 seconds of each minute. The expired gas was analysed for O$_2$ and CO$_2$ content, using a paramagnetic O$_2$ analyser (1100 series, Servomex, Crowborough, U.K.) and an infrared CO$_2$ analyser (1490 series, Servomex, Crowborough, U.K.). Each analyser was calibrated at two points, and checked for linearity using high precision gas mixtures and room air. Gas volume was measured using a dry gas meter (Harvard Apparatus Ltd., Edenbridge, U.K.) previously calibrated against a Tissot spirometer, and regularly checked for linearity throughout the complete collection volume range using a 7 L calibration syringe (Hans Rudolf Inc., Kansas City, Mo., USA).

A standardised relative workload for each subject of 6 x 800 m intervals at 1 km.h^{-1} below v-$\dot{V}O_2$ max, with 3 min rest between each interval, was used as the interval training sessions (TS); this was designed to replicate a severe overload which well-trained runners would regularly perform. The f_c was recorded continuously using a telemetric system (Sport Tester, Polar Electro Oy, Kempele, Finland). The TS was performed on two occasions at a similar time of day (2.00 to 4.00 p.m.) by all subjects.

Prior to and following both TS, a series of moderate intensity constant load runs were perfomed (tests 1m, 2m, 3m, 4m, 5m). Also, a series of severe intensity constant load runs were performed (tests 1s, 2s, 3s). The design of the study, which included the TS to be repeated, was to allow tests to be performed either 1 hour or 72 hours after the training session. Due to the fatiguing nature of the severe intensity runs, it was not considered appropriate to perform tests at 1 hour and 72 hours following the same TS.

The series of moderate intensity runs were at the velocity corresponding to 50% v-$\dot{V}O_2$ max, which was chosen to ensure that all subjects were exercising at an intensity well below that which would elicit a rise in blood lactate above 2 mM (James and Doust 1998). This requirement was necessary to provide steady state gas exchange conditions (Barstow and Mole, 1991). Each subject was weighed and then instructed to begin running on the treadmill ergometer for 15 min. From 10 min to 12 min and 13 min to 15 min f_c and cadence were recorded, along with duplicate collections of expired gas over a timed period of whole number of breaths always in excess of 1 minute duration.

The series of severee intensity runs were designed to allow determination of time to exhaustion (t_{lim}), and were a continuation of certain moderate intensity tests, including test 1m, test 3m, and test 5m respectively. Within 15 s the treadmill was ramped up to 1 km.h^{-1} below v-$\dot{V}O_2$ max, at which point the timing was initiated. Expired gas was collected for 30 second periods, and f_c and cadence were determined from 2 min 30 s until the exercise was terminated. Verbal encouragement was given, but subjects were not told the time elapsed either during or following the test until the whole experiment had been completed, in order to minimise any effects of altered motivation due to a time goal. Timing was stopped as the subjects hands touched the frame of the treadmill. Following the test expired gas was analysed to determine the difference in $\dot{V}O_2$ between the value after 2 min 30 s of severe intensity exercise and the value at the end of the test. The $\dot{V}O_2$ was recorded as representing the mid-point of the collection period (e.g., 2 min 45 s), and all calculations were based upon these time points. Since the difference in $\dot{V}O_2$ was observed over differing durations between subjects, the difference was expressed as a rate of increase in litres per minute per minute (l.min^{-2}).

A velocity of 1 km.h^{-1} below v-$\dot{V}O_2$ max rather than v-$\dot{V}O_2$ max, which has been widely used to determine t_{lim} previously (Billat and Koralsztein, 1996), was chosen in light of the expected t_{lim}. To determine a difference in $\dot{V}O_2$ between 2 min 30 s and the end of exercise, t_{lim} had to be long enough to make at least two reliable samples of expired gas (i.e., > 210 s) in all three severe intensity tests. The particular concern was the test in the fatigued condition at 1 h following the training session (i.e., test 2s). Accounting for our method of determination of v-$\dot{V}O_2$ max, and our experience of t_{lim} at this velocity under a variety of conditions, 1 km.h^{-1}

below v-$\dot{V}O_2$ max was considered an appropriate velocity to ensure a duration of > 210 s in all subjects.

Test 1m and test 1s were performed following 3 days of rest. Test 2m and 4m were performed immediately prior to the TS. Tests 3m and test 2s were performed 1 hour following the first TS. Test 5m and test 3s were performed 72 h following the second TS. Following the first TS, the subjects were weighed to determine any changes in body mass. The subjects were instructed to consume a volume of water calculated from the change in body mass during the overload to reflect the loss of fluid as sweat. This rehydration strategy has been previously shown to be successful through determination of plasma volume changes (James and Doust, 1998).

Repeated-measures analysis of variance with multiple comparison (Tukey) was used to determine the significance of differences between tests. A p-value of less than 0.05 was chosen prior to the study as the level at which a difference would be regarded as significant.

Results

Subject anthropometric details are given in table 1. All but two subjects completed the TS, with one subject failing to complete the final interval (400 m completed), and the other subject failing to complete the final three intervals in both TS's (630, 660, 520 and 730, 630, 760 m completed respectively). The reason for the failure to complete the TS's was fatigue in both cases, so was not considered a limitation for the overall aim of the experiment.

The f_c response during the first and second TS is shown in figures 1 and 2 respectively. It is clear that the response was not different between the two TS, and the maximal f_c during each interval was approaching the maximal f_c recorded during the incremental test as shown by the line breaking the y-axis in figure 1 and 2. The exercise intensity for both the training session and the run to exhaustion was severe, at a velocity which elicited ~95 % $\dot{V}O_2$ max after 3 minutes of running.

Responses to the severe intensity runs are shown in table 2. A significant difference was observed for t_{lim} between tests 1s and 2s, and tests 2s and 3s ($p < 0.05$). The t_{lim} recorded 1 h following the TS (test 2s) was 24 % less than t_{lim} in the rested condition (test 1s) and 32 % less than t_{lim} 72 h following the TS (test 3s). The decrease in t_{lim} in test 2s was associated with a significantly greater $\dot{V}O_2$ difference between 2 min 45 s and the end of exercise in test 2 compared with test 1 or 3 ($p < 0.05$). No relationship was observed between the change in t_{lim} and the change in $\dot{V}O_2$ between 2 min 45 s and the end of exercise during the severe intensity run (see figure 3).

Responses to the moderate intensity runs are shown in table 3. A significant difference was observed for $\dot{V}O_2$ in test 3m compared with test 2m, and test 5m compared with test 4m ($p < 0.05$). At 1 h following the TS (test 3m), $\dot{V}O_2$ was increased by 2 % above the value prior to the TS (test 2m). At 72 h following the TS (test 5m), $\dot{V}O_2$ was decreased by 3 % below the value prior to the TS (test 4m). A significant difference was observed for f_c in test 3m compared with test 2m, and test 5m compared with test 4m ($p < 0.05$). At 1 h following the TS (test 3m), f_c was increased by 5 % above the value prior to the TS (test 2m). At 72 h following the TS (test 5m), f_c was decreased by 13 % below the value prior to the TS (test 4m). No relationship was observed between the change in t_{lim} and the change in $\dot{V}O_2$ during the moderate intensity run (see figure 4).

Although a significantly greater $\dot{V}O_2$ difference between 2 min 45 s and the end of severe intensity running, and a significantly greater $\dot{V}O_2$ during moderate intensity running was observed in test 2 compared with test 1, no relationship was found between these two measures (see figure 5). No significant differences were observed for cadence between any of the conditions in either the moderate intensity, or the severee intensity run ($p < 0.05$).

Discussion

Although a decrease in t_{lim} and an increase in the $\dot{V}O_2$ response were observed during the severe intensity trial following the TS in the present study, no relationship existed between the change in these two variables. Likewise, although $\dot{V}O_2$ during moderate intensity exercise was increased following the TS, no relationship existed between this change and the decrease in t_{lim}.

Whilst the primary aim of the study was to examine the change in t_{lim}, in order to establish possible mechanisms, it was interesting to examine whether t_{lim} was changed in association with the $\dot{V}O_2$ response during severe intensity running. Although gas exchange has been shown not to reach a steady state during severe intensity exercise (e.g., Barstow and Mole, 1991), examination of the $\dot{V}O_2$ response at the same intensity as that used for the assessment of t_{lim} and the TS may provide useful information. Poole et al., 1994a suggest that t_{lim} during severe intensity exercise may be related to the magnitude of the change in $\dot{V}O_2$ between 3 minutes and the end of exercise. This suggestion is based on the notion that the quicker $\dot{V}O_2$ reaches $\dot{V}O_2$ max, the quicker fatigue will develop, since exercise at $\dot{V}O_2$ max can only be sustained for a finite time. In the present study, the change in the $\dot{V}O_2$ between 2 min 45 s and the end of exercise was expressed as an acceleration and then examined in this regard, but no relationship was found between the change in t_{lim} and the change in the $\dot{V}O_2$ response following the TS. Due to the off-line technique used to determine gas exchange in the present study, if subjects reached $\dot{V}O_2$ max prior to t_{lim}, it was not possible to account for this when calculating the acceleration in $\dot{V}O_2$. It is also possible that an increase in $\dot{V}O_2$ may be constrained as $\dot{V}O_2$ approaches $\dot{V}O_2$ max, thereby slowing the attainment of $\dot{V}O_2$ max. Since the slow component of $\dot{V}O_2$ kinetics is yet to be characterised, the extent of the limitation imposed by our gas analysis technique is unknown. Withstanding this limitation, the finding suggests that other factors, such as anaerobic capacity may be important in determining time to exhaustion at a severe intensity. It has been previously demonstrated that anaerobic capabilities may contribute significantly to distance running performance (Bulbulain et al., 1986).

Bernard et al (1998) has recently demonstrated the importance of determining $\dot{V}O_2$ during running at velocities representative of performance velocities. This importance is greatest for athletes competing in events performed above the lactate threshold. Exercise above the lactate threshold (heavy intensity) has been shown to elicit an excess $\dot{V}O_2$ above that predicted from the velocity-$\dot{V}O_2$ relationship derived from exercise below the lactate threshold, which has both an intensity and time component (Whipp and Wassermann, 1972). Bernard et al (1998) refer to $\dot{V}O_2$ during exercise above the lactate threshold as the ‘aerobic energy cost’, and suggest that an increase in the aerobic energy cost occurs at heavy intensities. However, due to the time dependent nature of the development of the excess $\dot{V}O_2$, Bernard et al (1998) demonstrate that it is not satisfactory to determine the aerobic energy cost after 3 minutes of exercise. The difference between the true aerobic energy cost when a steady state is reached, and aerobic energy cost through inadequate determination (i.e., prior to attainment of steady state or velocity too low), may be termed the aerobic energy deficit, or more simply the ‘oxygen cost deficit’. The oxygen cost is defined as the $\dot{V}O_2$ per body mass (kg) per unit distance (km) expressed in millilitres (ml), and is calculated as the quotient of exercising minus resting $\dot{V}O_2$ (ml.kg^{-1}.min^{-1}), and velocity (km.min^{-1}) (Lacour et al., 1990, adapted from di Prampero, 1986). In the case of the present study, we analysed our data to determine the oxygen cost deficit, which we defined as the difference between $\dot{V}O_2$ (ml.kg^{-1}.km^{-1}), after 10 minutes of moderate intensity running (50% v$\dot{V}O_2$ max) and the $\dot{V}O_2$ (ml.kg^{-1}.km^{-1}) at exhaustion during severe intensity running (~95% $\dot{V}O_2$ max), in the fatigued and non-fatigued conditions. However, we found no relationship between oxygen cost deficit changes and performance changes between pre and post TS (see figure 6). This finding would suggest that the fatigue 1 h following the TS, as evidenced by reduced t_{lim}, is not simply related to altered oxygen cost deficit.

Although t_{lim} is itself a performance measure, t_{lim} at v-$\dot{V}O_2$ max has also been shown to correlate with other endurance running performances such as the velocity maintained during a half marathon competition (Billat et al., 1994a). The results of studies examining the relationship between t_{lim} at v-$\dot{V}O_2$ max and other physiological measures which are often related to endurance running performance have been equivocal (see table 4). Interestingly, in one study anaerobic capacity has also been shown to partially account for differences in t_{lim} at v-$\dot{V}O_2$ max (Hill and Rowell, 1996). These different findings may reflect variations between the fitness level of the subjects, and methodological variations. The protocol for determination of $\dot{V}O_2$ max, and particularly v-$\dot{V}O_2$ max, may be particularly important. For example, the duration of each increment of a graded exercise test may influence the $\dot{V}O_2$ - velocity relationship, since it is now widely acknowledged that with long increments an excess $\dot{V}O_2$ will develop for each increment above the anaerobic threshold (Hansen et al., 1988). The effect of the developing excess $\dot{V}O_2$ during slow incremental protocols will result in lower velocities for a given $\dot{V}O_2$, and hence a relatively reduced v-$\dot{V}O_2$ max. Although we exercised subjects a 1 km.h^{-1} below v-$\dot{V}O_2$ max in the present study, the graded test to maximum consisted of rapid increments (i.e., 1 km.h^{-1}.min^{-1}).

Whilst Billat et al. (1994b) found that t_{lim} was repeatable in a group of sub-elite runners as a whole, the intra-subject variation was in the region of 10%. Intra-subject variation of this magnitude may have confounded our findings that no relationship exists between either the change in t_{lim} and $\dot{V}O_2$ during moderate intensity running, or the change in t_{lim} and $\dot{V}O_2$ response to severe intensity running.

Reduced performance at one hour following the TS compared with performance after rest or 72 hours following the TS may be due to a variety of factors. It is unlikely, however, that factors such as dehydration or increased core body temperature were responsible due to our findings following an identical TS in previous studies (James and Doust, 1998; James and Doust, 1999). In these studies, by one hour following the TS, plasma volume and rectal temperature had both returned to values recorded prior to the TS. Furthermore, it was demonstrated in the present study that cadence was unchanged one hour following the TS. Although this finding has been demonstrated previously, the initial measurement was not made until one day following the training session (Morgan et al., 1990; 1996). In contrast, Xu and Montgomery (1995) found that immediately following prolonged moderate intensity exercise, cadence is slightly, but significantly altered. However, it should be noted that this change was observed immediately following the training session.

It may be speculated that changes in other kinematic and kinetic variables may have occurred following the training session, which are not evident when examining cadence. For example, recently Candau et al. (1998) have demonstrated increased variability in step frequency with fatigue during running. The relationship demonstrated by Candau et al. (1998) between step variability and $\dot{V}O_2$ during running is of particular interest.

Several physiological changes have been associated with an increased $\dot{V}O_2$ during moderate intensity running, and changed $\dot{V}O_2$ response to severe intensity running, which may act to reduce performance. Importantly, studies by Poole et al. (1991; 1992) suggests that pulmonary $\dot{V}O_2$ closely reflects $\dot{V}O_2$ measured over the working limb both during moderate and severe intensity exercise. Therefore, factors that may contribute to a changed $\dot{V}O_2$ in the exercising limbs should be considered as possible candidates for altered t_{lim}. With regard to moderate intensity running, due to the steady state response, it is possible to derive a caloric equivalent. Following exactly the same overload as that used in this study, we have observed that 31% of the change in $\dot{V}O_2$ was due to increased metabolism of fat (James and Doust, 1998). In the present study, 10% of the change in $\dot{V}O_2$ was due to increased metabolism of fat, as calculated from pulmonary gas exchange variables. It is possible that time to exhaustion is influenced by substrate availability, and an increased metabolism of fat in the moderate intensity run one hour following the TS indicates a depletion of muscle glycogen stores. A previous study has demonstrated the importance of muscle glycogen stores prior to exercise for short duration performance (Maughan and Poole, 1981).

With regard to severe intensity exercise, whilst a close relationship between blood lactate concentration and the $\dot{V}O_2$ response to severe intensity running has been observed, it has been suggested that blood lactate concentration is simply correlated with, but not causal to the $\dot{V}O_2$ response. A dissociation between the two has been demonstrated via training and infusion of epinephrine during exercise in humans which increases blood lactate concentration and decreases pH (Gaesser, 1994) and infusion of lactate into working dog muscle (Poole et al., 1994b). Factors which are associated with lactate production in the working limb have also been investigated. Although evidence is not direct, changes in muscle fiber recruitment is thought to be a likely explanation for a significant part of the $\dot{V}O_2$ response to severe exercise (Poole et al., 1994a). The suggestion that a progressively greater recruitment of type II fibres may contribute to the $\dot{V}O_2$ response to severe intensity exercise may also partly explain the reduced performance following an interval training session.

In conclusion, the significant reduction in performance during severe intensity running following the training session was associated with an increase in $\dot{V}O_2$ during moderate intensity running, and a changed $\dot{V}O_2$ response to severe intensity running. However, no relationship existed between the magnitude of the change in performance and the $\dot{V}O_2$ response during either moderate or severe intensity running.

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These experiments comply with the current laws of the United Kingdom

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Table 1: Anthropometric data: Values are expressed as mean (SD). n = 7. ($\dot{V}O_2$ max maximal oxygen consumption, v-$\dot{V}O_2$ max velocity at maximal oxygen consumption)

Age (years)	Height (m)	Mass (kg)	$\dot{V}O_2$ max ($l.min^{-1}$)	v-$\dot{V}O_2$ max ($km.h^{-1}$)
24 (6)	1.79 (0.10)	67.9 (7.6)	4.14 (0.49)	19.4 (1.3)

Table 2: Responses to the severe intensity run to exhaustion following rest (test 1s), 1 h following (test 2s) and 72 h following (test 3s) the training session (TS): Values are expressed as mean (SD). (t_{lim} time limit to exhaustion, 2 min 45 s $\dot{V}O_2$ oxygen consumption at 2 min 45 s, End $\dot{V}O_2$ oxygen consumption at exhaustion, $\dot{V}O_2$ diff difference between oxygen consumption at 2 min 45 s and exhaustion, Max f_c heart rate at exhaustion, Caden. cadence)

	Test 1s			Test 2s			Test 3s	
t_{lim} (s)	318	(59)	[a]	243	(52)	[b]	359	(130)
2 min 45 s $\dot{V}O_2$ ($l.min^{-1}$)	3.99	(0.62)		3.94	(0.65)		3.96	(0.62)
End $\dot{V}O_2$ ($l.min^{-1}$)	4.21	(0.61)		4.19	(0.62)		4.17	(0.59)
$\dot{V}O_2$ diff ($l.min^{-2}$)	0.11	(0.06)	[a]	0.21	(0.08)	[b]	0.11	(0.11)
Max f_c ($b.min^{-1}$)	193	(12)		191	(11)		192	(13)
Caden. ($Stride.min^{-1}$)	91	(6)		91	(5)		91	(6)

[a] Difference between test 1 and test 2 ($P < 0.05$)

[b] Difference between test 2 and test 3 ($P < 0.05$)

Table 3: Responses to the moderate intensity run following rest (test 1m), prior to (test 2m and test 4m), 1 h following (test 3m) and 72 h following (test 5m) both training sessions (TS). Results are expressed as mean (SD). ($\dot{V}O_2$ oxygen consumption, f_c heart rate)

	Test 1m	Test 2m	Test 3m	Test 4m	Test 5m
$\dot{V}O_2$ (l.min^{-1})	2.21 (0.23)	2.19 (0.26) [a]	2.23 (0.26)	2.23 (0.27) [b]	2.16 (0.23)
f_c (b.min^{-1})	141 (17)	136 (13) [a]	143 (14)	137 (15) [b]	119 (48)
Cadence (strides.min^{-1})	81 (5)	80 (4)	81 (4)	80 (4)	80 (4)

[a] Difference between test 2m and test 3m ($P < 0.05$)

[b] Difference between test 4m and test 5m ($P < 0.05$)

Table 4: Comparison of time to exhaustion and relationship with other physiological characteristics in endurance runners (time to exhaustion t_{lim}, maximal oxygen uptake $\dot{V}O_2$ max, velocity at $\dot{V}O_2$ max v-$\dot{V}O_2$ max, anaerobic threshold, T_{an}).

Study	t_{lim}	Correlation Coefficient		
		$\dot{V}O_2$ max	v-$\dot{V}O_2$ max	T_{an}
This study a	318	-0.793*	-0.621	-0.343
Billat et al. (1994b) b	404	0.138	0.241	0.671*
Billat et al. (1994d)c	360	-0.347*	-0.362*	0.378*
Billat et al. (1995)c	321	-0.200	-0.538*	-0.050
Billat et al. (1994e)b	404	0.170	0.320	0.580*
Billat et al. (1994c) c	325	-0.502*	-0.691*	....
Billat et al. (1994a)b	371	....	....	0.629*
Hill et al. (1996) d	290	....	....	0.660*

* denotes significant correlation ($p < 0.05$)

a: well - trained; b: subelite; c: elite; d: well - trained female

note: all studies used v-$\dot{V}O_2$ max except the present study.

Figure 1: Heart rate at the end of each exercise bout during the first training session (line breaking axis denotes mean maximum during the incremental test) (values are mean and standard deviation)

Figure 2: Heart rate at the end of each exercise bout during the second training session (line breaking axis denotes mean maximum during the incremental test) (values are mean and standard deviation)

Figure 3: Change in time to exhaustion and change in oxygen uptake kinetics during severe exercise performed prior to and 1 h following the training session.

Figure 4: Change in time to exhaustion and change in oxygen uptake during moderate exercise performed prior to and 1 h following the training session.

Figure 5: Change in oxygen uptake kinetics during severe exercise and change in oxygen uptake during moderate exercise performed prior to and following the training session.

Figure 6: Change in time to exhaustion and change in oxygen deficit during severe exercise performed prior to and 1 h following the training session. Oxygen cost deficit is calculated as the difference between the oxygen cost of the moderate and severe exercise.