Effect of prior exercise on maximal short-term power output in humans

A. J. SARGEANT AND P. DOLAN
Department of Exercise Physiology and Health Science, Medical Faculty, University of Amsterdam and Faculty of Human Movement Sciences, The Free University, 1105 AZ Amsterdam, The Netherlands; and School of Engineering and Science, Biomechanics Group, Polytechnic of Central London, London W1, United Kingdom

SARGEANT, A. J., AND P. DOLAN. Effect of prior exercise on maximal short-term power output in humans. J. Appl. Physiol. 63(4): 1475-1480, 1987.—The effect of prior exercise (PE) on subsequent maximal short-term power output (STPO) was examined during cycling exercise on an isokinetic ergometer. In the first series of experiments the duration of PE at a power output equivalent to 98% maximum O2 uptake (Vo2,max) was varied between 0.5 and 6 min before measurement of maximal STPO. As PE duration increased subsequent STPO fell to ~70% of control values after 3-6 min. In series ii the effect of varying the intensity of PE of fixed 6-min duration was studied in five subjects. After PE < 60% Vo2,max there was an increase of 12% in STPO, but after > 60% Vo2,max there was a progressive fall in STPO as PE intensity increased, indicating a reduction of ~35% at 100% Vo2,max compared with control values. In series iii we examined the effect on STPO of allowing a recovery period after a fixed intensity (mean = 87% Vo2,max) of 6 min PE before measurement of STPO. This indicated a rapid recovery of dynamic function with a half time of ~32 s, which is similar to the kinetics of PC resynthesis and taken with the other findings suggests the dominant role that PC exerts on the STPO under these conditions.

Significance of high-energy phosphate concentration and resynthesis rate for maximal short-term dynamic exercise. Thus we have measured maximal short-term power output under isokinetic conditions after different durations and intensities of submaximal exercise and after varying recovery intervals.

SUBJECTS AND METHODS

Subjects

Six healthy males who gave informed consent were studied. Their physical characteristics and maximum O2 uptakes are given in Table 1.

Maximum O2 Uptake

Maximum O2 uptake (Vo2,max) was directly determined in accordance with conventional criteria on a separate occasion pedaling a Monark cycle ergometer using an open-circuit system with Douglas bags to measure O2 uptake (4).

Maximal Short-Term Power Output

Short-term power output (STPO) was measured during cycling exercise using an isokinetic cycle ergometer (25). In this technique the cycle cranks were driven by an electric motor at a constant preselected velocity through a variable reduction gear box. Subjects were seated on the ergometer with their feet strapped to the pedals while the motor was switched on and the crank rotation speed adjusted. During this period the subjects allowed their legs to be taken passively around by the motor. They were then instructed to make a maximal effort for 20 s in an attempt to increase crank velocity, but due to the characteristics of the motor-gear system this remained constant. Throughout the 20-s effort the forces exerted and, from the force-time integral, the power generated was independently and continuously monitored by strain gauges bonded to both cranks as previously described (23). All measurements were made at a crank velocity of 112 rpm which was chosen as approximating the optimum velocity for maximal power output as determined by the force-velocity and consequent power-velocity relationships in this form of exer-

IN AN EARLIER STUDY a technique for measuring maximum power output during short-term isokinetic exercise was reported (25). One factor determining the maximum power output may be the availability of high-energy phosphate [ATP + phosphocreatine (PC)], since this represents the major and most immediate source of energy available to the contracting muscle during exercise of a few seconds duration. Previous investigators have shown that the concentration of the high-energy phosphate pool is reduced as the level of steady-state submaximal exercise increases (9, 10). Therefore, it might be expected that after periods of submaximal exercise the maximal short-term power output would be reduced dependent on the level of the prior exercise and hence the availability of high-energy phosphate.

However, there are problems and difficulties in the interpretation of high-energy phosphate measurement in human muscle when chemically determined from needle biopsies (16, 27). We have therefore taken a more direct functional approach in an attempt to examine the likely
TABLE 1. Physical characteristics and maximum \( \text{O}_2 \) uptake of the subjects studied

<table>
<thead>
<tr>
<th>Subj</th>
<th>Age, yr</th>
<th>Ht, cm</th>
<th>Wt, kg</th>
<th>( \text{VO}_2 \text{max} ), l/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>42</td>
<td>170.8</td>
<td>73.8</td>
<td>3.90</td>
</tr>
<tr>
<td>B</td>
<td>22</td>
<td>169.3</td>
<td>66.3</td>
<td>3.76</td>
</tr>
<tr>
<td>C</td>
<td>36</td>
<td>175.8</td>
<td>71.0</td>
<td>3.20</td>
</tr>
<tr>
<td>D</td>
<td>23</td>
<td>184.0</td>
<td>77.5</td>
<td>3.61</td>
</tr>
<tr>
<td>E</td>
<td>22</td>
<td>176.6</td>
<td>84.5</td>
<td>4.81</td>
</tr>
<tr>
<td>F</td>
<td>26</td>
<td>162.8</td>
<td>66.7</td>
<td>3.20</td>
</tr>
</tbody>
</table>

\( \text{VO}_2 \text{max} \), maximum \( \text{O}_2 \) uptake.

Values are reported for the peak power for each revolution (i.e., a mean of right and left leg peak values). For each 20-s determination of STPO, maximal peak power values were determined as the mean of the three consecutive values in which the highest observed peak value occurred (24, 25).

**Prior Exercise**

Prior exercise was performed pedaling the same isokinetic ergometer at the same speed as for the maximal measurements (112 rpm). Subjects were asked to exert a submaximal level of force during each bout of prior exercise. During the prior exercise subjects were shown a meter giving their average force output and asked to maintain a constant target level. Subjects were able to do this with little difficulty after practice. Recordings were made of right and left leg forces and \( \text{O}_2 \) uptake was measured over the last 2 min of each 6-min prior exercise bout.

**Protocol**

Three series of experiments were performed, and the protocol for these is given below and schematically illustrated in Fig. 1.

**Series i: Effect of Duration of Prior Exercise**

Two subjects (E and F) pedaled at an intensity corresponding to 98% \( \text{VO}_2 \text{max} \) during prior exercise lasting for 0.5, 1, 3, and 6 min (Fig. 1, series i). At the end of these periods they were asked to make a maximal effort for 20 s during which force and power output were recorded. These results were compared with the control experiment when the force and power generated in a maximal 20-s effort was measured from rest. When prior exercise lasted for 6 min \( \text{O}_2 \) uptake (\( \text{VO}_2 \)) measurements were made over the last 2 min. In shorter-duration bouts the exercise intensity was monitored by recording the mean peak force exerted during the prior exercise and comparing this with that attained during the 6-min bout.

**Series ii: Effect of Varying the Intensity of Prior Exercise**

Five healthy male subjects were studied (A-E) (Fig. 1, series ii). Control values of STPO were determined from rest. In the experimental bouts the 20-s STPO test was immediately preceded by 6 min of prior exercise on the isokinetic ergometer at exercise intensities ranging from 32 to 100% of the subjects previously determined \( \text{VO}_2 \text{max} \). \( \text{VO}_2 \) was measured over the last 2 min of each 6-min bout of prior exercise.

**Series iii: Effect of Duration of Interposed Recovery Period**

Four subjects (A-D) participated in this series (Fig. 1, series iii). During prior exercise, subjects were asked to maintain a constant power output corresponding to 87% \( \text{VO}_2 \text{max} \). In separate experiments STPO was measured immediately after the prior exercise (no rest) and after rest intervals of 5, 15, 60, 180, and 360 s. \( \text{VO}_2 \) was measured over the last 2 min of each 6-min bout of prior exercise.

**Statistical Methods**

Comparisons between control and experimental determinations were made using Student's t test (paired).

**RESULTS**

**Series i: Effect of Duration of Prior Exercise**

During prior exercise the \( \text{VO}_2 \) achieved during the 6-min bout was 98% of \( \text{VO}_2 \text{max} \) for both subjects. In shorter-duration exercise bouts the intensity was assessed by comparison of the mean peak force with that attained in the 6-min bout. This was rather consistent for the different durations with a coefficient of variation for both subjects of <5%. The level of mean peak force required to sustain this exercise intensity (98% \( \text{VO}_2 \text{max} \)) was 50% of the maximum force available measured at the same velocity of contraction (i.e., 112 rpm).

The effect of different durations of prior exercise on subsequent STPO is shown in Fig. 2. Data points represent peak power for each revolution over the 20 s of the STPO measurement. In all experiments maximal peak power during the 20-s test was attained within a few revolutions from the start after which there was a fall in peak power as the muscles fatigued. An increasing decrement in maximal peak power was observed in both subjects as the duration of prior exercise was increased.

Maximal values of peak power expressed as a percent of the control value after different durations of prior exercise are shown in Fig. 3. After only 30 s of prior exercise at a work intensity equivalent to 98% \( \text{VO}_2 \text{max} \) a mean decrement in maximal power output of ~10% was observed. This decrement increased substantially with the duration of prior exercise up to 3 min when maximal peak power had fallen to 67 and 79% of the control value in the two subjects. When the period of prior exercise was extended to 6 min there was a further 5% reduction in one subject.

**Series ii: Effect of Prior Exercise Intensity**

The effect of varying the intensity of prior exercise on subsequent STPO is illustrated by Fig. 4 which shows data for one subject. After prior exercise at 39 and 56% \( \text{VO}_2 \text{max} \) maximal peak power was increased by 15.0 and 10.5%, respectively, during the subsequent STPO test compared with the control value. After higher intensities equivalent to 74 and 80% \( \text{VO}_2 \text{max} \) a substantial and increasing decrement in power output was observed.

Figure 5 summarizes the changes in maximal peak power for all five subjects expressed as a percent of the control value and plotted against the prior exercise intensity (% \( \text{VO}_2 \text{max} \)).

After the lower levels of prior exercise (<60% \( \text{VO}_2 \text{max} \))
all five subjects showed an increase in maximal peak power compared with control values, although in one of the subjects this improvement was slight (1%). The greatest increases were observed where the prior exercise intensity was between 33 and 48% \( \dot{V}O_2 \text{max} \); this was when improvements of 8-15% were achieved in four of the five subjects.

After higher intensities (>60% \( \dot{V}O_2 \text{max} \)) an inverse relationship was observed between prior exercise intensity and subsequent STPO, resulting in decreases of 20-40% in maximal peak power after the highest prior exercise levels.

**Series iii. Effect of Duration of Interposed Recovery Period**

The mean intensity during the prior exercise (based on results from the four studied subjects over the com-
EFFECT OF PRIOR EXERCISE ON SHORT-TERM POWER

FIG. 3. Maximal peak power (% control) after different durations of prior exercise at 98% maximum O$_2$ uptake. Filled circles, subject F; Open circles, subject E.

FIG. 4. Peak power for each revolution during 20-s test when performed from rest (filled circles) and after 6 min of prior exercise at 39 (open triangles), 56 (squares), 74 (filled triangles) and 80% (open circles) O$_2$ uptake. Data are for subject D.

FIG. 5. Maximal peak power (% control) after different intensities of prior submaximal exercise lasting for 6 min. VO$_2$ max, maximum O$_2$ uptake. Subjects: A, filled circles; B, open triangles; C, open circles; D, filled triangles; E, squares.

FIG. 6. Time course of recovery in maximal peak power after 6 min prior exercise at 87% maximum O$_2$ uptake (VO$_2$ max). Mean (± SD) data for 4 subjects studied.

However, in the other experiments maximum values of peak power in the STPO test increased very rapidly as the duration of the interposed recovery period was increased.

Mean (±SD) values of maximal peak power based on all four subjects are shown in Fig. 6. This indicates that STPO recovered with a half time of ~32 s. Initially recovery was very rapid, so that control values of maxi-
mal peak power were reattained within ~1 min of terminating prior exercise. Beyond this there was a further increase in maximal peak power to levels exceeding the control values. Thus at 6 min there was a mean increase in power output of 9.6 ± 3.8% over control values (P < 0.01).

DISCUSSION

In the first part of the study an increasing decrement in maximal STPO was observed as the duration of prior exercise was increased from 30 s to 3 min. The additional loss of power incurred by extending the time of prior exercise from 3 to 6 min was only small. This response is suggestive of and follows a similar time course to the kinetics of \( V_{\text{O}2} \) at the commencement of exercise. It may directly or indirectly reflect the necessary utilization and depletion of anaerobic energy stores at the start of the exercise at an intensity that may be subsequently sustained by the supply of aerobic energy once the \( O_2 \) transporting system has adjusted to the new demands.

In the second series of experiments an inverse relationship between prior exercise intensity and subsequent STPO was observed when the former exceeded 60% \( V_{\text{O}2\text{max}} \). This finding, but not the observed increase in STPO after low levels of prior exercise, is in agreement with the findings of Margaria et al. (14) who measured maximal anaerobic power using a stair-run technique and reported an increasing decrement in power output with increasing level of prior submaximal exercise.

Analogous findings have also been reported from biochemical studies in which the concentration of high-energy phosphate in human muscle during exercise was determined in needle biopsies (9, 10, 12). In these studies a direct relationship was found between the degree of high-energy phosphate depletion and the intensity of the previous exercise. In general most of the depletion could be accounted for by a reduction in the PC concentration; since appreciable decreases in ATP were usually only observed when PC had become depleted to a critically low level. In a more recent study using \( ^{31} \text{P} \) nuclear magnetic resonance Dawson et al. (5) also found that the decrease in force during repeated fatiguing contractions of frog gastrocnemius muscle was closely correlated with a fall in the PC concentration, although the ATP concentration showed little change until fatigue was very advanced.

The depletion of PC during exercise may be the major factor responsible for the decrements in power output observed in the present study. The loss of power observed in the first part of the study may reflect a progressively greater depletion of PC in the active muscle fibers as exercise continues. On this basis an equilibrium between the rate of PC breakdown and resynthesis appears to be reached after ~3 min since the effect of extending the duration of prior exercise beyond this time is rather small.

Indeed, Hultman et al. (9), who measured ATP and PC in human muscle during various stages of dynamic exercise, observed a rapid decrease in high-energy phosphate during the first 2 min after which they reported very little change. The present data may be demonstrating the functional consequence of such observations. Nevertheless, although this would appear to be a very plausible explanation for the loss of power observed in the present study, the effect of other factors should not be ruled out. A number of workers have found a direct relationship between lactate accumulation and the decrease in PC in human muscle after both isometric and dynamic exercise (8), and it is possible that the decreases in STPO reported above may be partly due to elevated concentrations of lactic acid as a result of the previous exercise. At physiological pH, increases in lactate are accompanied by an equivalent (equimolar) production of \( H^+ \) and the resultant fall in pH has long been proposed to limit performance during maximal exercise of brief duration. This may be due to a reduced rate of lactate efflux from the muscle (13) and a decreased rate of muscle glycolysis due to inhibition of phosphofructokinase (29), a direct effect on excitation-contraction coupling (6, 17), or a direct effect on the creatine kinase equilibrium in muscle that is shifted toward lower concentrations of PC as the intracellular pH decreases (19).

Some insight into the relative importance of changes in muscle pH may be gained from series iii since the resynthesis of PC after exercise has been shown to be a very rapid process (7, 9, 11), whereas the recovery in pH and muscle lactate follows a much slower time course (20).

The recovery in STPO during dynamic exercise after previous steady-state exercise has not to our knowledge been previously reported in humans. In the present study recovery in maximal STPO was shown to be a very rapid process with three of the four subjects achieving complete recovery within 1 min of terminating the previous exercise. By 6 min of recovery all four subjects had significantly improved their power output beyond the control values. The mean improvement was 9.6 ± 3.8% (P < 0.01).

The pattern of recovery in maximal peak power followed a time course with a half time of ~32 s. These results may be compared with the findings of Stull and Clarke (28) who investigated the recovery in handgrip strength after repeated maximal contractions and found that the strength score of their subjects had returned to 98% of the initial control value after only 70 s of rest.

The rapid recovery in both isometric and dynamic strength suggests that it may be dependent on replenishment of substrate or clearance of metabolite from the muscle. The removal of lactate and the recovery in muscle pH after dynamic exercise have been shown to occur rather more slowly than the recovery in STPO observed in the present investigation, complete recovery only occurring after 20 min or longer (20). However, the half time of 32 s obtained in the present investigation agrees rather well with the half time of 25 s that Margaria, Edwards, and Dill (15) obtained many years ago for the first, rapidly repaid, component of the \( O_2 \) debt which has been assumed to reflect the resynthesis of high-energy phosphate stores. More recently Harris and his associates (7) measured the resynthesis of PC in human muscle after exhaustive cycle ergometer exercise and found this to be a very rapid process. Hence after 1
min of recovery PC was restored to ~76% of its initial value. In the present investigation STPO had recovered to the control value by this time, and if the chemical determinations are correct this may imply that complete resynthesis of the PC store may not be necessary to attain maximal levels of power output or that there may be some additional factor acting to elevate power output. Certainly the subsequent elevation of power output above control values at 3 and 6 min postexercise would suggest such a factor, as would the increase in power output seen after low intensities of prior exercise in series ii. Factors that could contribute to these effects consequent on prior exercise might include changes in muscle temperature and thixotropic effects on the legs (1, 2, 3, 21, 22, 26) or increased contributions from oxidative phosphorylation or glycolysis (18).

Elucidation of the mechanism for the facilitatory effect of prior exercise may be of practical as well as theoretical interest, since many laboratories and most athletes use exercise-based warm-up procedures before the testing of muscle function or before competition. Clearly there are both benefits and disadvantages to such procedures dependent on the intensity, duration, and recovery interval allowed, but the identification of the optimum and standardization of protocols would be more satisfactorily accomplished given a better understanding of the interacting factors.

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REFERENCES