HITCHCOCK, HARRY C. Recovery of short-term power after dynamic exercise. J. Appl. Physiol. 67(2): 677–681, 1989.—The intensity of prior cycle ergometer exercise alters the pattern in recovery of maximal short-term power output (STPO). STPO was measured on an isokinetic dynamometer after 0, 1, 2, 3, 4, and 8 min of recovery. Immediately after exercise, STPO fell to 85, 75, 55, and 47% of preexercise values for prior exercise equivalent to 60, 80, 100, and 120% of maximal O2 uptake, respectively. STPO had fully recovered by 1 min of postexercise after submaximal work rates (60 and 80%). Recovery was delayed until after 4 min of postexercise after maximal exercise (100%). STPO remained at ~90% of preexercise values 8 min postexercise after supramaximal exercise (120%). STPO immediately after exercise and during recovery was inversely proportional to prior exercise intensity. The recovery curve for STPO was similar to that previously reported for creatine phosphate resynthesis after dynamic and isometric exercise. The absolute STPO regained in the initial phase was not equivalent to 60, 80, 100, and 120% of each subject's VO2 max. STPO at 90 rpm was employed, which allowed either four or five stages before exhaustion in each subject. Regression analysis was performed to predict experimental work rates equivalent to 60, 80, 100, and 120% of each subject's VO2 max.

Although muscle pH is strongly correlated with the degree of muscle fatigue during exercise, restoration of force is more rapid than the restoration of pH during recovery (28). There is also a clear difference between the time course of PC and pH recovery in skeletal muscle after exercise. The resynthesis of PC occurs very rapidly after dynamic exercise in humans (9, 15, 20); 75–90% of the initial concentration is restored in 2 min (9, 15). Total recovery of muscle pH after dynamic exercise takes ~20 min (14, 30). An immediate reduction in postexercise anaerobic power has been found to be inversely proportional to the intensity of the preceding exercise (7, 21, 31). Recently, Sargeant and Dolan (31) found recovery in power after steady-state exercise to be a two-phase phenomenon, similar to the pattern of recovery in strength (2, 3, 33) and the recovery of PC (15, 20, 29, 35). Thus, studies of recovery from fatiguing exercise may prove valuable in clarifying the relationships between physiological metabolic events associated with the onset of fatigue (6). The principal aim of this investigation was to determine whether the relative intensity [percent of maximal O2 uptake (% VO2 max)] of dynamic exercise alters the recovery of short-term power output (STPO) after termination of exercise.

SUBJECTS AND METHODS

Subjects. Six male and two female competitive triathletes (31 ± 6 yr of age) gave informed consent and volunteered for the study. A week before the first experimental session each subject came to the laboratory for a VO2 max test to participate in a familiarization session on an isokinetic dynamometer. VO2 max scores ranged from 53.6 to 62.2 ml·kg−1·min−1 (58.1 ± 3.0) for the males and were 44.5 and 44.7 ml·kg−1·min−1 for the females.

O2 uptake. VO2 max was measured by the open-circuit method using meteorological balloons and a low resistance breathing valve. Gas fractions were measured using an Applied Electrochemistry S-3A O2 and a CD-A3 CO2 analyzer calibrated via the Scholander method. A Parkinson-Cowan CD-4 gas meter and a Narco Biosystems DMP-4 recorder were used to measure and record inspired minute ventilation.

A staged graded (270 kpm/min per 3-min stage) protocol using a mechanically braked Monark cycle ergometer at 90 rpm was employed, which allowed either four or five stages before exhaustion in each subject. Regression analysis was performed to predict experimental work rates equivalent to 60, 80, 100, and 120% of each subject's VO2 max.

Short-term power output. Torque was measured by a Cybex II isokinetic dynamometer during leg extensions at 60°/s, the velocity of maximum torque (25). Because velocity was the same throughout the experiment and any change in STPO was equal to the change in torque, STPO was calculated as the mean peak torque for three consecutive extensions. At the test velocity and for the 105° range of motion, the duration of each contraction was 1.75 s. Thus, STPO was calculated during 7.0 s (3 exten-
performed a sequence of dynamometer tests to establish experimental work rates were assigned in random order. Subjects refrained from exercise on the test days.

Before each cycle ergometer exercise bout, each subject performed a sequence of dynamometer tests to establish a preexercise base line of STPO. The subject first executed a series of five maximal knee extensions at 60°/s followed 5 min later by a second series of three extensions. Pilot studies had demonstrated that STPO is higher if preceded by this type of warm-up session. Therefore, to minimize the possibility of a warm-up effect during the recovery measurements, the second series was used to calculate preexercise STPO. The average increase in STPO as the result of warm-up over the four tests was 4.3%.

Each subject exercised for 6 min on a mechanically braked Monark cycle ergometer. The first 4 min were a warm-up at the 60% VO$_2$max work rate, and the final 2 min were at the predetermined experimental work rate (60, 80, 100, or 120% of VO$_2$max). At the 120% intensity, however, six of the eight subjects reached exhaustion before completion of the full 2 min (1.23–2.0 min). Just before completion of each exercise a pneumatic cuff around the upper part of the right thigh was inflated to 260 mmHg to occlude circulation and prevent lactate release from the muscle and to prevent PC resynthesis (29). Inflation of the cuff took 20 s and was timed so that full inflation occurred precisely at the termination of the exercise.

After completion of the ergometer exercise a subject was assisted to the Cybex dynamometer and secured with leg and chest straps. The cuff was then released and the subject performed three maximal knee extensions at 60°/s. Subjects also stabilized themselves during the dynamometer test by gripping small handles on the side of the seat. The elapsed time between completion of cycle ergometer exercise and initiation of the dynamometer test was ~25–30 s. The same verbal command was used as a cue by a technician to release the cuff and by the subject to perform the first extension so that no recovery occurred before the first extension. The subject then repeated the sequence of three knee extensions at 1, 2, 3, 4, and 8 min after exercise (after the restoration of circulation).

At 4 min after exercise a blood sample was taken using the finger prick method, and levels of blood lactate were determined later by conventional enzymatic methods (8).

Statistical methods. A 4 x 6 analysis of variance for repeated measures was used to analyze the pattern of recovery of STPO. Tukey’s range test was used at each recovery point to contrast the four intensity levels. Tukey’s range test was used to test for differences in postexercise blood lactate levels among the four exercise intensities, and Student’s t test was used to test for full recovery of STPO at each intensity-recovery point.

RESULTS

STPO during recovery was normalized as the percent of preexercise values. Immediately after dynamic exercise, maximum STPO was significantly (P ≤ 0.01) decreased at all levels of prior exercise intensity. The decrement was proportional to exercise intensity with decreases to 85, 76, 55, and 47% of initial values for exercise at 60, 80, 100, and 120% of VO$_2$max, respectively.

As expected, recovery followed two-component exponential patterns (Fig. 1) for all intensities of prior exercise. At an intensity of 60%, nearly all (87%) of the decrement in STPO had been regained after 1 min of recovery (Table 1). Similarly, at an intensity of 80%, full recovery had occurred after 1 min, even though the initial decrement in power had been one-third greater than the loss of power after 60% intensity. Full recovery did not occur until after 4 and 8 min postexercise after exercise of 100 and 120% VO$_2$max, respectively. Rapid initial recovery, however, was evident at both intensities with 67 and 55% of the initial decrement in power regained during the 1st min of recovery after exercise of 100 and 120% VO$_2$max, respectively.

The most striking contrast was the difference in recovery from submaximal (60% and 80%) vs. near-maximal (100 and 120%) exercise intensities. There was no difference (P ≤ 0.05) in power decrement between the two submaximal intensities. There was also no difference in power decrement between the two near-maximal intensities. There was, however, a significant (P ≤ 0.05) difference in the immediate 0-min postexercise decrease in STPO between the pairs of exercise intensities (60 and 80% vs. 100 and 120%). This pattern persisted throughout the recovery period.

After submaximal exercise, blood lactate values at 4 min after exercise were 3.0 and 5.4 mM (Fig. 2). Blood lactate values for maximal/supramaximal exercise (100 and 120%) were 8.7 and 11.7 mM, respectively.

DISCUSSION

The results of this study corroborate the findings of other investigators (7, 21, 31) that show an inverse relationship between before exercise intensity and maximal anaerobic power immediately after exercise. Margaria et al. (21) found that maximal anaerobic

![FIG. 1. Recovery of short-term power measured by isokinetic knee extension at 60°/s after dynamic exercise at 4 intensities of maximal O$_2$ uptake.](image)
TABLE 1. Tukey's range (honestly significant difference) test for recovery of short-term power output

<table>
<thead>
<tr>
<th>Intensity, %</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>8</th>
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<tr>
<td>60</td>
<td>85±7.6*</td>
<td>98±4.4*</td>
<td>99±4.2*</td>
<td>101±6.0*</td>
<td>103±4.8*</td>
<td>103±5.6*</td>
</tr>
<tr>
<td>80</td>
<td>76±9.8**</td>
<td>97±5.8**</td>
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<td>101±6.4**</td>
<td>106±5.3**</td>
</tr>
<tr>
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<tr>
<td>120</td>
<td>47±9.5*</td>
<td>76±7.2*</td>
<td>84±2.8*</td>
<td>86±3.6*</td>
<td>88±4.0*</td>
<td>92±4.2*</td>
</tr>
</tbody>
</table>

Values are normalized means ± SE of short-term power output. Means with the same superscript letters within a recovery time are not significantly different at P ≤ 0.05. Significantly different from preexercise value: * P ≤ 0.01; † P ≤ 0.05.

FIG. 2. Blood lactate values 4-min after exercise at 4 different intensities of maximal O2 uptake.

Power is reduced to ~80% of initial values after maximal exercise. This is considerably less than the reduction to 55% found in the current study; however, Margaria's stair-run test involved a 2-s lag time during which considerable recovery may have occurred.

The work of Sargeant and Dolan (31) provides more comparable data, because their postexercise testing protocol allowed no recovery to occur. After prior exercise at an intensity equivalent to 87% \( \dot{V}O_2_{max} \), maximal STPO was reduced to 68% of control values. The current study resulted in comparable decrements in STPO to 76 and 55% of preexercise values for before exercise of 80 and 100% intensity, respectively.

Ferretti et al. (7) used a vertical jump after cycle ergometry to measure postexercise anaerobic power. They reasoned that the short time basis (0.004 s) of the test would reflect mechanical energy derived solely from the splitting of ATP with no resynthesis from PC. Their data indicated a reduction in instantaneous power to 91, 85, and 78% of preexercise values after exercise at 70, 100, and 120% of \( \dot{V}O_2_{max} \), respectively. The decrement in power was considerably less than that found in the current study; however, their protocol allowed for a 3-s rest before the jump test during which time some recovery may have occurred.

Initial recovery. Few studies have been conducted investigating the recovery in anaerobic power after dynamic exercise. Sargeant and Dolan (31) found a two-component recovery curve after steady-state exercise with maximal STPO being reattained within 1 min after exercise. After isotonic hand-gripping exercise, Stull and Clarke (33) found that an initial loss in strength to 55% of initial values was totally (96%) recovered within 70 s after exercise.

Data from the present study support the notion that there is an inverse relationship between the intensity of prior exercise and maximal anaerobic power during recovery. A similar relationship has been shown to exist between exercise intensity and high-energy phosphagen concentration (15). A parallel between the intensity-anaerobic power and the intensity-phosphagen dynamics during the exercise/recovery cycle has led some investigators to suggest a functional relationship between the unsplit phosphagen level and maximal anaerobic power (15, 21, 31).

Hultman et al. (15) observed that after the onset of steady-state exercise the phosphagen level decreased during the first 2 min and remained constant thereafter. Similarly, Sargeant and Dolan (31) found that STPO decreased during the first 3 min after the onset of maximal exercise. Continuation of the exercise, however, had no further effect. After dynamic exercise, phosphagen concentration has been observed to recover rapidly in a one- or two-component exponential pattern with 75–90% of the initial PC concentration restored in 2 min (9, 15). Sahlin et al. (29) have proposed that the slow phase of PC resynthesis is coupled with pH recovery, whereas the initial phase is limited by oxygen availability. Data from this study and that of other investigators (31, 33) suggest a similar two-phase pattern in recovery of power after dynamic exercise with 50–85% of recovery occurring in the 1st min after exercise.

Although there appears to be a strong relationship among prior exercise intensity, phosphagen concentration, and anaerobic power, a cause-effect relationship

FIG. 3. Recovery of short-term power output during the first 2 min after dynamic exercise at 4 different intensities of maximal O2 uptake.
cannot be concluded because of the lack of properly designed experiments, and, as Wilkie (36) has noted, there is no obvious biochemical basis for postulating that PC depletion is singularly responsible for fatigue. Furthermore, ATP levels are maintained even when PC concentration is at an extremely low level (15). Thus it may be that the observed drop in phosphagen concentration is a correlate rather than a mediator of fatigue and that the effect of other factors should be considered.

Previous investigators have found a direct relationship between lactate accumulation and a decrease in PC concentration after exercise (10, 16). These findings are consistent with the theory that increasing phosphorus levels associated with PC hydrolysis stimulate glycolysis, which leads to increased acidosis (1, 23). The effect of increased H+ on fatigue may be mediated by a direct effect on the force-generating apparatus (5, 11) or indirectly via increased H2PO4 (24, 37).

In the current study increasing blood lactate levels 4 min after exercise were associated with increasing exercise intensity. Although blood lactate concentration is appreciably less than that of muscle after exercise (17), they are highly correlated (17, 34) and muscle lactate may be used as a relative indicator of muscle pH (11). Because resynthesis of PC is a net proton-producing reaction (22, 27) there is a slight decrease or no change in muscle pH during the 1st min after exercise (35). Therefore the rapid recovery in power observed during the 1st min after exercise cannot be totally explained by recovery in muscle pH alone.

Secondary recovery. There are no known studies comparing recovery of anaerobic power after dynamic exercise of various intensities. Data obtained in the present investigation indicate similarities in recovery after two levels of submaximal work and also similarities between maximal and supramaximal work. A clear difference exists, however, between submaximal and near-maximal normalized recovery patterns; the former show full recovery in 1 min, whereas the latter require a prolonged recovery.

Interestingly, although the initial restoration in power during the 1st min of recovery after submaximal exercise was a greater percentage of the initial decrement than that after maximal/supramaximal exercise, the absolute reclamation of power was greater after maximal/supramaximal exercise. This phenomenon was the result of a substantially greater loss, ~50% (maximal/supramaximal) vs. 20% (submaximal) immediately after exercise (Fig. 3). The absolute recovery in power during the first 2 min after exercise was identical after both maximal and supramaximal work. These data suggest that factors other than change in pH alone mediate initial power recovery.

Elevated recovery. Sargeant and Dolan (31) found that STPO after moderate (87% max) dynamic exercise not only recovered rapidly but subsequently reached values at 3 and 6 min after exercise that exceeded those measured before exercise. They suggested that additional factors such as temperature elevation or increased oxidative metabolism may be contributing factors that increase power output after low-intensity exercise.

Stull and Clarke (33) observed a similar phenomenon after isotonic hand-gripping exercise but not after isometric exercise. They attribute elevated postexercise strength to a warm-up effect resulting from increased blood flow.

In the current study a warm-up sequence of movements was employed before exercise. The initial torque used to normalize power was increased 4.3% above that obtained during the warm-up exercise. Thus normalized values measured during recovery were less than they would otherwise have been without a warm-up. Even with the warm-up technique employed, STPO was elevated at 8 min (P ≤ 0.05) postexercise after 80% intensity prior exercise, although no elevation occurred after 60% intensity exercise. These data suggest that in studies not employing a warm-up, apparent recovery may be the result of the warm-up effects of prior exercise (i.e., the testing procedure) as well as to actual recovery.

Summary. Exercise-induced fatigue, as measured by changes in maximal STPO, may be mediated by reduced PC stores or increased metabolite concentration. Data from this study confirm that a reduction in maximal anaerobic power occurs after dynamic exercise, which is inversely proportional to the intensity of the prior exercise.

The pattern of recovery in maximal anaerobic power after dynamic exercise follows a two-component exponential pattern demonstrating a rapid initial recovery and a slower more prolonged secondary phase. The major recovery occurs within the 1st min after exercise. The decrement in power and the initial pattern of recovery are similar to that previously reported for PC depletion/recovery during dynamic and isometric exercise. The absolute power regained in the initial phase is not inversely proportional to exercise intensity or blood lactate levels 4 min after exercise, which suggests that factors other than changes in pH alone may mediate initial power recovery.

Address for reprint requests: H. C. Hitchcock, Dept. of Health Education, Physical Education, University of Alabama at Birmingham, Birmingham, AL 35294.

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REFERENCES

7. FERRETTI, G. M., M. GUSSONI, P. E. DI PRAMPERO, AND P. CER-
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