Eur J Appl Physiol (1997) 75: 499–503

ORIGINAL ARTICLE

O. Buttelli · H. Vandewalle · J.C. Jouanin
D. Seck · H. Monod

Effects of aerobic exercise on the torque-velocity relationship in cycling

Accepted: 25 November 1996

Abstract The kinetics of the torque-velocity (T-ω) relationship after aerobic exercise was studied to assess the effect of fatigue on the contractile properties of muscle. A group of 13 subjects exercised until fatigued on a cycle ergometer, at an intensity which corresponded to 60% of their maximal aerobic power for 50 min (MAP60%); ten subjects exercised until fatigued at 80% of their maximal aerobic power for 15 min (MAP80%). Of the subjects 7 exercised at both intensities with at least a 1-week interval between sessions. Pedalling rate was set at 60 rpm. The T-ω relationship was determined from the velocity data collected during all-out sprints against a 19 N · m braking torque on the same ergometer, according to a method proposed previously. Maximal theoretical velocity (ω_0) and maximal theoretical torque (T_0) were estimated by extrapolation of the linear T-ω relationship. Maximal power ($P_{\max}$) was calculated from the values of T_0 and ω_0 ($P_{\max} = 0.25\,\omega_0 T_0$). The T-ω relationships were determined before, immediately after and 5 and 10 min after the aerobic exercise. The kinetics of ω_0, T_0 and $P_{\max}$ was assumed to express the effects of fatigue on the muscle contractile properties (maximal shortening velocity, maximal muscle strength and maximal power). Immediately after exercise at MAP60% a 7.8% decrease in T_0 and 8.8% decrease in $P_{\max}$ was seen while the decrease in ω_0 was nonsignificant, which suggested that $P_{\max}$ decreased in the main because of a loss in maximal muscle strength. In contrast, MAP80% induced a 8.1% decrease in ω_0 and 12.8% decrease in $P_{\max}$ while the decrease in T_0 was nonsignificant, which suggested that the main cause of the decrease in $P_{\max}$ was probably a slowing of maximal shortening velocity. The short recovery time of the T-ω relationship suggests that the causes of the decrease of torque and velocity are processes which recover rapidly.

Key words Fatigue · Aerobic · Exercise · Cycling

Introduction

It has been shown that the force-velocity relationship can be used to assess the contractile properties of normal (Close 1972) or fatigued skeletal muscle (Fitts and Holloszy 1978; de Haan 1988). According to Seck et al. (1995), it is possible to determine the torque-velocity (T-ω) relationships on a cycle ergometer within a few seconds during a short all-out sprint. The relationship between total torque (T_{tot}) and pedal velocity (ω) has been demonstrated to be linear as in isokinetic cycling (Sargeant et al. 1981; McCartney et al. 1983) and can be expressed by the following equation derived from the equation proposed by Vandewalle et al. (1985, 1987):

$$T_{\text{tot}} = T_0(1 - \omega/\omega_0)$$

where ω_0 and T_0 are maximal velocity and maximal torque, respectively. The study of the effects of fatigue upon contractile properties during a short anaerobic cycling exercise has been investigated by the assessment of the T-ω relationship corresponding to four all-out sprints without recovery (Buttelli et al. 1996). The results of that study have suggested that the observed maximal power decrease (31%) was the consequence of similar decreases in maximal strength and maximal shortening velocity, as T_0 and ω_0 decreased by 17.3% and 16.3%, respectively. The effect of fatigue upon contractile properties should depend on the exercise duration and/or intensity and the type of the fibres which are recruited. Consequently, the effect of fatigue on maximal force and shortening velocity indices (T_0 and ω_0, respectively) could be different during long-lasting aerobic exercise.

The present research was designed to estimate the effects of fatigue upon mechanical maximal power out-

---

O. Buttelli (✉) · H. Vandewalle · D. Seck · H. Monod
Laboratoire de Physiologie du Travail et du Sport,
91 bd de l'Hôpital, F-75634 Paris Cedex 13, France

J.C. Jouanin
Centre Médico-Sportif, Ecole Interarmées des Sports.
F-77307 Fontainebleau Cedex, France

put (P_{max}) and the T-ω relationship (maximal force and shortening velocity). The kinetics of the effects of fatigue was studied by determining the T-ω relationship on a cycle ergometer before, immediately and 5 and 10 min after long-lasting aerobic exercise, during which the recruitment pattern of muscle fibre types I and II should be different. The exercise was not performed up to exhaustion to avoid fatigue in all the fibre types. The cycle exercise performed at 60% of maximal aerobic power (MAP60%) for 50 min was assumed to correspond to the recruitment of type I fibres as glycogen depletion has been reported to occur in type I fibres after a 60-min exercise at 60% of MAP in a study by Vøllestad and Blom (1985). During 15 min exercise at 80% of maximal aerobic power (MAP80%) the muscle fibre recruitment probably involves type I and IIA fibres as has been suggested by the glycogen depletion occurring in these fibre types during such an exercise (Vøllestad et al. 1984).

Methods

Subjects

A group of 10 healthy male volunteers [mean age 29.4 (SD 7.5) years, mean body mass 70.6 (SD 6.4) kg] gave their informed consent to exercise until fatigued at MAP80%. Similarly, 13 healthy male volunteers [mean age 29.8 (SD 6.2) years, mean body mass 73.9 (SD 10.0) kg] gave their consent to exercise at MAP60%. Of these subjects 7 exercised at both intensities. In this case, the tests were separated at least by 2 days and performed in a random order. All the subjects were well trained and habituated to cycling exercise because of their usual practice (cyclism, triathlon, moutain bike riding) or several previous anaerobic tests on a cycle ergometer.

Materials

A friction-loaded cycle ergometer (Monark 864) was modified to measure the acceleration of the flywheel (Seck et al. 1995; Buttelli et al. 1996). Toe clips and well-fastened straps were used to avoid the feet slipping off the pedals. The subjects had to stay seated on the saddle, the height of which was adjusted for each subject and was the same for all exercise protocols.

Maximal aerobic power assessment

At least 2 days prior to the fatigue tests, the subjects exercised on an ergometer to estimate MAP. This test consisted of incremental cycling exercise until they were exhausted during which heart rate (*HR*) was recorded continuously with a monitor (Polar PE 4000). The initial load was 0.5 kg, corresponding to the mass of the basket. The pedalling frequency required was 60 rpm. Power was increased by 15 W every 2 min by adding a 0.250-kg mass in the basket. The rate for pedalling was indicated by a metronome and the rate achieved was displayed on a computer monitor during the test. The total number of revolutions was also displayed on the monitor. The subjects were considered to be exhausted when they were unable to maintain the required power output. The value of MAP was calculated from the extrapolation of the linear part (Arts and Kuipers 1994) of the relationship between *HR* and power output (*P*):

$$HR = \mathrm{a}P + \mathrm{b}$$

$$MAP = (HR_{max} - \mathrm{b})/\mathrm{a}$$

where HR_{max} was the maximal heart rate during the test. The MAP calculated was around 10 W lower than *P* at the last step.

Fatigue test protocols

The fatigue tests consisted in a pre-exercise assessment of the T-ω relationship, fatiguing exercise performed either at 60% MAP for 50 min (MAP60%) or 80% MAP (MAP80%) for 15 min and finally a set of postexercise assessments of the T-ω relationship.

Assessment of the T-ω relationship

The linear relationship between T and ω was determined during the acceleration phase of a single all-out test according to Seck et al. (1995) and Buttelli et al. (1996). Every 10 ms, the torque corresponding to pedal ω was calculated as being equal to the sum of braking T and the T necessary to accelerate the flywheel. According to this linear relationship P_{max} was equal to $0.25\,T_0\omega_0$.

Pre-exercise tests

Before the fatigue tests, the subjects performed all-out cycling exercise (about 6 s) against the same braking T (19 N · m) in order to determine the T-ω relationship during the acceleration phase. This all-out cycling exercise was repeated three times. The best T-ω relationship (highest P_{max} provided that the coefficient of correlation of the linear T-ω relationship exceeded 0.99) of these trials was considered as the reference ($P_{max\ best}$, $T_{0\ best}$ and $\omega_{0\ best}$) in the non-fatigued state. The subjects were vigorously encouraged to cycle as fast as possible during acceleration phases. They recovered passively during 5 min between these all-out exercise tests.

Fatiguing exercises

The subjects began the fatiguing exercises 5 min after the last pre-exercise all-out test. They cycled at 60 rpm at an intensity corresponding to 60% or 80% of MAP. Pedal rate was monitored by the micro-computer using the same procedure as during the assessment of MAP.

Post-exercise tests

At the end of the fatiguing exercise, within a second, the flywheel velocity was returned to zero by strong pressure on the basket by an investigator and simultaneously the braking torque was adjusted to 19 N · m by withdrawal of a part of the load. The subjects then performed a 6-s all-out test for the determination of the T-ω relationship. The same all-out test was repeated after 5 and 10 min of recovery.

In addition, 1 subject performed a fatigue test at MAP80% but the postexercise test consisted of one all-out cycling exercise after 1-min recovery only.

Calculations

The kinetics of T and ω during the acceleration phase were calculated according to the protocol proposed by Seck et al. (1995) and Buttelli et al. (1996), by computing the T necessary to accelerate the flywheel and adding the braking T (19 N · m).

The values of T_0, ω_0 and P_{max} after the fatiguing exercise were expressed as a fraction of the data corresponding to the best sprint (see above).

Statistics

One-way repeated measures analysis of variance (ANOVA) was used to assess differences in the mean values of T_0, ω_0 and $P_{\max}$. Multiple comparison tests (Student-Newman-Keuls method) was used to assess which group differed from the others. Comparison between MAP60% and MAP80% was studied by mean of two-way repeated measures ANOVA using the results from subjects who had performed both tests. Significance level was set at $P < 0.05$.

Results

The T-ω relationships were linear for the postexercise tests in the fatigued state as well as the pre-exercise all-out tests.

60% of MAP

At 0-min postexercise, T_0 and $P_{\max}$ decreased by 7.8 (SD 7.6)% and 8.8 (SD 5.4)%, respectively. At 5-min postexercise, T_0 and $P_{\max}$ partially recovered (95.5% and 97.5% of the pretest values, respectively) and the differences compared to the best pretest values were nonsignificant. However, at 10-min postexercise, the differences between pre and postexercise increased for T_0 and $P_{\max}$. Indeed T_0 and $P_{\max}$ were 8.2 (SD 11.2)% and 6.5 (SD 8.7)% lower than the best pretest values, respectively (Table 1, Fig. 1). On the other hand, the changes in ω_0 were nonsignificant at 0, 5 and 10 min after exercise.

80% of MAP

At 0-min postexercise, ω_0 and $P_{\max}$ decreased significantly by 8.1 (SD 6.5)% and 12.8 (SD 6.5)%, respectively. The decrease in T_0 [4.6 (SD 0.17)%] was nonsignificant. At 5 and 10-min postexercise, T_0, ω_0 and $P_{\max}$ returned to the best pretest values (Table 2, Fig. 1).

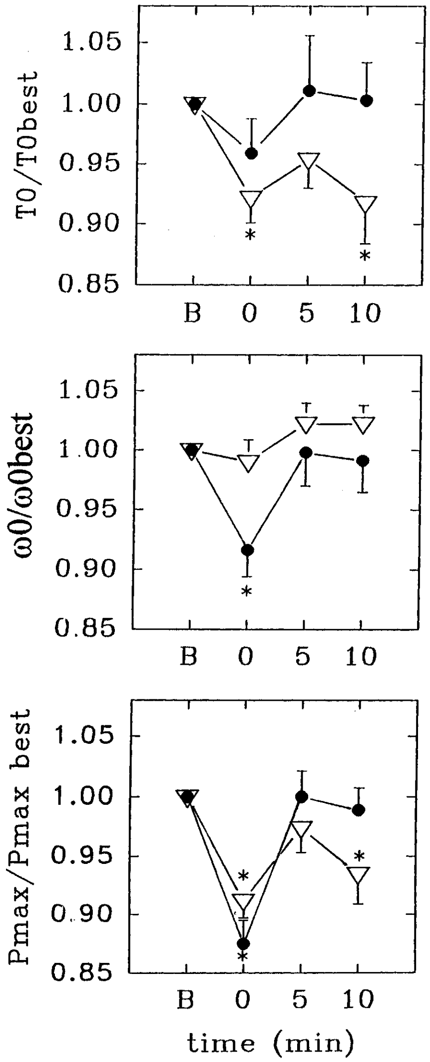

Fig. 1 Relative decreases (mean, standard deviation) in maximal torque (T_0), maximal velocity (ω_0), and maximal power output ($P_{\max}$), immediately after (0), 5-min rest after (5) and 10-min rest after (10) the fatiguing exercise (*unfilled triangles* at 60% maximal aerobic power for 50 min, *filled circles* at 80% maximal aerobic power for 15 min). The decreases are expressed as a fraction of the data corresponding to the best pre-exercise test (*B*) and compared with it. * significant decrease.

Comparison between MAP60% and MAP80%

The results of the fatigue tests at MAP60% and MAP80% could be compared in 7 subjects who performed both tests. The decrease in ω_0 after exercise at MAP80% was different from the decrease in ω_0 after MAP60% ($F = 8.8$, $P = 0.024$), being decreased by 7.4 (SD 4.9)% immediately after MAP80% but unchanged immediately after MAP60%. However, the decreases in T_0 were similar after MAP60% and MAP80% ($F = 0.87, P = 0.39$). Immediately after exercise the decrease in T_0 was equal to 8 (SD 9.2)% and

Table 1 Fatigue at 60% of the subjects' maximal anaerobic power for 50 min. ω_0 maximal velocity, T_0 maximal torque, $P_{\max}$ maximal power for the best pre-exercise, postexercise, 5-min rest and 10-min rest sprint tests

Data	Best pre-exercise		Post-exercise		5-min rest		10-min rest	
	mean	SD	mean	SD	mean	SD	mean	SD
ω_0 (rad · s^{-1})	23.6	2.2	23.3	2.1	24.1	2.8	23.9	2.3
T_0 (N · m)	156	23	142	14	149	27	137	23
$P_{\max}$ (W)	916	146	833	118	893	166	816	112

Table 2 Fatigue at 80% of the subjects' maximal aerobic power for 15 min. ω_0 maximal velocity, T_0 maximal torque, $P_{\max}$ maximal power for the best pre-exercise, postexercise, 5-min rest and 10-min rest sprint tests

Data	Best pre-exercise		Post-exercise		5-min rest		10-min rest	
	mean	SD	mean	SD	mean	SD	mean	SD
ω_0 (rad · s^{-1})	23.2	2.2	21.2	2.2	22.9	2.6	22.8	2.7
T_0 (N · m)	151	25	144	25	153	29	154	23
$P_{\max}$ (W)	876	164	766	153	874	173	876	159

7 (SD 8.9)% for MAP60% and MAP80%, respectively. The decrease in $P_{\max}$ was larger after MAP80% [13.9 (SD 6.8)% versus 7.8 (SD 6.0)%] but this difference was nonsignificant.

Discussion

Both MAP60% and MAP80% induced a decrease of $P_{\max}$ but the magnitude of the $P_{\max}$ decreases were small because the exercise was not continued until the subjects were exhausted to avoid fatigue in all the fibre types. The $P_{\max}$ decrease after MAP80% tended to be larger than after MAP60%. This corroborates the finding of other investigators (Sargeant and Dolan 1987; Hitchcock 1989) who have observed an inverse relationship between $P_{\max}$ immediately after exercise and the intensity of exercise.

The kinetics of the recovery of the T-ω relationship suggested that the causes of the decreases of T and ω were fast recovering processes as T and ω had almost returned to the initial values 5 min after the fatiguing exercise. This was confirmed by the result (Fig. 2) of the T-ω all-out test which was performed 1 min after MAP80% by a subject who was well habituated to this test because of previous anaerobic test sessions. This post-test was the best of all the T-ω tests this subject ever performed. Consequently, the time constant of the recovery of the T-ω relationship can be very short, for example similar to that of phosphocreatine resynthesis the half-life ($t_{1/2}$) of which is approximately 30s (Sahlin and Seger 1995; Takahashi et al. 1995). It was likely that lactate accumulation did not explain the alteration of the T-ω relationship as the turnover of muscle lactate is longer ($t_{1/2}$ about 2.5 min according to Sahlin and Ren 1989).

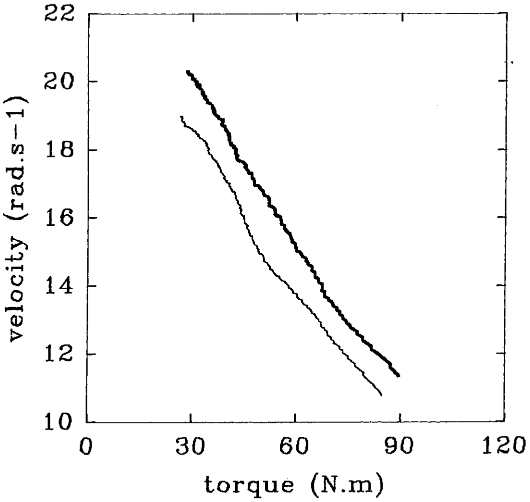

Fig. 2 Relationships between torque and velocity during fatiguing exercise at 80% of maximal aerobic power for 15 min in one subject. The *thin line* corresponds to the best pre-exercise test, the *thick line* to the 1 min postexercise test

The present study suggested that the causes of the decrease in $P_{\max}$ are different for short supramaximal exercise and long-lasting submaximal exercise. Indeed, the decrease in $P_{\max}$ for a short supramaximal exercise (Buttelli et al. 1996) has been suggested to be the consequence of decreases in maximal force and shortening velocity as suggested by the similar decreases in T_0 and ω_0. In contrast, the main cause of the decrease in $P_{\max}$ was probably a loss in maximal muscle strength after long-lasting but not exhausting exercise performed at low intensity (60% of MAP) exercise. Indeed after MAP60%, the nonsignificant decrease in ω_0 was small compared to the decreases in T_0 and $P_{\max}$. On the other hand, the results of the study at MAP80% suggested that $P_{\max}$ decreased in the main because of a slowing down of maximal shortening velocity as the significant decrease in ω_0 (8.1%) was larger than the nonsignificant decrease in T_0 (4.6%).

It has been suggested that the effects of exercise upon T-ω in cycling should depend not only on the effects of fatigue on the different fibre types but also on the effects of muscle temperature upon force, shortening velocity, and power output (Binkhorst et al. 1977; Bennett 1984; Ferretti et al. 1992). Maximal shortening velocity does depends on muscle temperature but it is likely that maximal force is relatively independent of temperature. Consequently, the effect of an increase in muscle temperature, after exercise, could counterbalance in part the effect of fatigue on shortening velocity and ω. This thermal dependance of maximal velocity could partly explain the high value of ω_0 after exercise (Table 1, Figs. 1, 2). The same pattern has been observed in the study by Sargeant and Dolan (1987) where $P_{\max}$ after submaximal dynamic cycling exercise (87% maximal oxygen consumption, $\dot{V}O_{2\,\max}$) was higher at 3 and 6 min after exercise than before exercise. These authors have suggested that additional factors such as temperature or increased oxidative metabolism may have been contributing factors that increased P after ⟨⟨ low-intensity exercise ⟩⟩. Hitchcock (1989) has also observed that $P_{\max}$ on an isokinetic knee ergometer was higher 8 min after a cycling at 80% $\dot{V}O_{2\,max}$.

Examination of the kinetics of the T-ω relationship after fatiguing exercise could be an indirect and noninvasive method which enables the determination of motor unit recruitement patterns, as types I and II fibres have been shown to differ in their contractile properties (Burke et al. 1971; Close 1972; Pette and Staron 1990). According to the model proposed by McIntosh et al. (1993), the value of ω_0 depends on the maximal shortening velocity of the faster fibres, i.e fibre type II; in contrast, maximal muscle force depends on the activity of both fibre types. If we assume that the effects of fatigue concern the active fibres only, 20-min cycling at 75% $\dot{V}O_{2\,max}$ should recruit fast muscle fibres as suggested by the glycogen depletion study of Vøllestad et al. (1984) and should induce a large decrease in ω_0 and a lesser decrease in T_0, which was observed after MAP80% in the present study. In contrast, a 60-min cycling at 60% $\dot{V}O_{2\,max}$ should recruit exclusively slow muscle fibres as suggested by the glycogen depletion studies of Vøllestad and Blom (1985) and Ball-Burnett et al. (1991) and should induce a decrease in T_0 only, which was observed after MAP60% in the present study.

In conclusion, nonexhausting aerobic exercise at 60% and 80% of MAP induced a short-lasting decrease in P_{max}. The decrease of the force index (T_0), with ω_0 being unchanged, indicated that the decrease in P_{max} could be explained in the main by a decrease in the muscle force after MAP60%. In contrast, the decrease in the velocity index (ω_0) after MAP80% implied that the decrease in P_{max} was in the main the result of an alteration in the muscle shortening velocity. The kinetics of the recovery of the contractile properties suggested that the causes of these decreases were fast recovery processes.

References

Arts FJP, Kuipers H (1994) The relation between power output, oxygen uptake and heart rate in male athletes. Int J Sports Med 15:228–231

Ball-Burnett M, Green HJ, Houston ME (1991) Energy metabolism in human slow and fast twitch fibres during prolonged cycle exercise. J Physiol (Lond) 437:257–267

Bennett AF (1984) Thermal dependence of muscle function. Am J Physiol 247:R217–R229

Binkhorst RA, Hoofd L, Vissers ACA (1977) Temperature and force-velocity relationship of human muscles. J Appl Physiol 42:471–475

Burke RE, Levine DN, Zajac FE, Tsairis P, Engel WK (1971) Mammalian motor units: physiological-histochemical correlation in three types in cat gastrocnemius. Science 174:709–712

Buttelli O, Seck D, Vandewalle H, Jouanin JC, Monod H (1996) Effect of fatigue on maximal velocity and maximal torque during short exhausting cycling Eur J Appl Physiol 73: 175–179

Close RI (1972) Dynamic properties of mammalian skeletal muscles. Physiol Rev 52:129–197

De Haan A (1988) Comparison of force-velocity characteristic obtained using twitches and tetani from in situ rat skeletal muscles. Q J Exp Physiol 73:131–133

Ferretti G, Ishii M, Moia C, Cerretelli P (1992) Effects of temperature on the maximal instantaneous muscle power of humans. Eur J Appl Physiol 64:112–116

Fitts RH, Holloszy JO (1978) Effect of fatigue and recovery on contractile properties of frog muscle. J Appl Physiol 45:899–902

Hitchcock HC (1989) Recovery of short-term power after dynamic exercise. J Appl Physiol 67:677–681

McCartney N, Heigenhauser GJF, Sargeant AJ, Jones NL (1983) A constant velocity ergometer for the study of dynamic muscle function. J Appl Physiol 55:212–217

McIntosh BR, Herzog W, Suter E, Wiley JP, Sokolosky J (1993) Human Skeletal muscle fibre types and force-velocity properties. Eur J Appl Physiol 67:499–506

Pette D, Staron RS (1990) Cellular and molecular diversities of mammalian skeletal muscle fibers. Rev Physiol Bioch Pharmacol 116:1–76

Sahlin K, Ren JM (1989) Relationship of contraction capacity to metabolic changes during recovery from a fatiguing contraction. J Appl Physiol 67:648–654

Sahlin K, Serger JY (1995) Effects of prolonged exercise on the contractile properties of human quadriceps muscle. Eur J Appl Physiol 71:180–186

Sargeant AJ, Dolan P (1987) Effect of prior exercise on maximal short-term power output in humans. J Appl Physiol 63:1475–1480

Sargeant AJ, Hoinville E, Young A (1981) Maximum leg force and power output during short-term dynamic exercise. J Appl Physiol 51:1175–1182

Seck D, Vandewalle H, Decrops N, Monod H (1995) Maximal power and torque-velocity relationship on a cycle ergometer during the acceleration phase of a single all-out exercise. Eur J Appl Physiol 70:161–168

Takahashi H, Inaki M, Fujimoto K, Katsuta S, Anno I, Niitsu M, Itai Y (1995) Control of the rate of phosphocreatine resynthesis after exercise in trained and untrained human quadriceps muscles. Eur J Appl Physiol 71:396–404

Vandewalle H, Pérès G, Heller J, Monod H (1985) All-out anaerobic capacity tests on cycle ergometers: a comparative study on men and women. Eur J Appl Physiol 54:222–229

Vandewalle H, Pérès G, Heller J, Panel J, Monod H (1987) Force-velocity relationship and maximal power on a cycle ergometer; correlation with the height of a vertical jump. Eur J Appl Physiol 56:650–656

Vøllestad NK, Blom PCS (1985) Effect of varying exercise intensity on glycogen depletion in human muscle fibres. Acta Physiol Scand 125:395–405

Vøllestad NK, Vaage O, Hermansen L (1984) Muscle glycogen depletion patterns in type I and subgroups of type II fibers during prolonged severe exercise in man. Acta Physiol Scand 122:433–441