

Power output and fatigue of human muscle in maximal cycling exercise

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MCCARTNEY, NEIL, GEORGE J. F. HEIGENHAUSER, AND NORMAN L. JONES. *Power output and fatigue of human muscle in maximal cycling exercise.* *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol.* 55(1): 218–224, 1983.—We studied maximal torque-velocity relationships and fatigue during short-term maximal exercise on a constant velocity cycle ergometer in 13 healthy male subjects. Maximum torque showed an inverse linear relationship to crank velocity between 60 and 160 rpm, and a direct relationship to thigh muscle volume measured by computerized tomography. Peak torque per liter thigh muscle volume (PT, $N \cdot m \cdot l^{-1}$) was related to crank velocity (CV, rpm) in the following equation: $PT = 61.7 - 0.234 CV$ ($r = 0.99$). Peak power output was a parabolic function of crank velocity in individual subjects, but maximal power output was achieved at varying crank velocities in different subjects. Fiber type distribution was measured in the two subjects showing the greatest differences and demonstrated that a high proportion of type II fibers may be one factor associated with a high crank velocity for maximal power output. The decline in average power during 30 s of maximal effort was least at 60 rpm ($23.7 \pm 4.6\%$ of initial maximal power) and greatest at 140 rpm ($58.7 \pm 6.5\%$). At 60 rpm the decline in power over 30 s was inversely related to maximal oxygen uptake ($ml \cdot min^{-1} \cdot kg^{-1}$) ($r = 0.69$). Total work performed and plasma lactate concentration 3 min after completion of 30-s maximum effort were similar for each crank velocity.

torque-velocity; muscle volume; isokinetic work; fiber type; plasma lactate

THE FORCE DEVELOPED at different velocities of contractile-element shortening describes a fundamental mechanical property of skeletal muscle. The "force-velocity curve" was first investigated by Fenn and Marsh (8) and later described by Hill (13) as a rectangular hyperbola. Hill's characteristic equation was applied to human muscle, by Wilkie (26), who calculated the velocity of shortening of the elbow flexors under conditions in which afterload was the controlled variable. These measurements, however, cannot be made in movements involving large muscle groups or more than one joint. An alternative practical approach is to control the velocity of movement, and measure the external force generated, to characterize the functional force-velocity relationships for the movement. Most previous studies of the maximal short-term power output capacity of human muscle during dynamic exercise have involved activities in which speed of movement was uncontrolled (1, 18).

In the present study we have employed a cycle ergometer which maintains pedal-crank velocity constant at a preset level despite maximal effort of the subject (19). The purposes of the investigation were to establish a torque-velocity relationship for cycling and to examine the effects of crank velocity on power output, fatigue, and total work generated during maximal cycling exercise of 30-s duration, a period of time during which the muscle is theoretically mainly dependent on anaerobic energy sources.

METHODS

Thirteen healthy male university students (19–23 yr) participated in the studies. Height, weight, and maximal oxygen uptake ($\dot{V}O_{2 \max}$) were (mean \pm SD) 178.4 ± 6.5 cm, 80.8 ± 10.2 kg, and 43.1 ± 6.2 $ml \cdot kg^{-1} \cdot min^{-1}$. Procedures involved in the testing, including possible risks, were explained to the subjects, and informed consent was obtained. The studies were approved by the university ethics committee.

The 13 subjects completed the following three tests except for one subject who did not take part in the second test: 1) a progressive multistage exercise test on a cycle ergometer to obtain $\dot{V}O_{2 \max}$ (16); 2) brief (<10 s) maximal bouts of cycling on a constant-velocity ergometer (CVE) at a range of crank velocities between 60 and 160 rpm; and 3) maximum effort for 30 s on the CVE at 60, 100, and 140 rpm. In addition, the volume of muscle between the gluteal fold and knee-joint space (both legs) was determined for each subject from soft tissue X-rays obtained by computed tomography.

The progressive multistage exercise test (16) was performed on a calibrated electrically braked cycle ergometer (Elema, model EM-370). The subject breathed through a low-resistance, low-deadspace valve. Inspired ventilation was measured by a dry gas meter (Parkinson-Cowan CD4). Expired gas was passed through a mixing chamber and analyzed for oxygen and carbon dioxide by calibrated O_2 (Godart Rapox) and CO_2 (Godart Capnograph) analyzers. Analog data displayed on an eight-channel recorder (Mingograf 81, Siemens-Elema) were used to calculate $\dot{V}O_2$.

Twelve subjects participated in the studies of torque-velocity and power-velocity relationships during maximal cycling exercise on the CVE. Crank velocities of 60, 80, 100, 120, 140, and 160 rpm were used; crank velocities

below 60 rpm were not studied because the torque generated at low speeds (below 40 rpm) may permanently deform the pedal cranks, and a margin of safety was allowed. The order of testing was randomized, and the testing protocol was standardized for all subjects. The subject was allowed 2–3 s to catch up to the speed setting of the motor and then instructed to exert maximal force on the pedals. When the force records showed a pattern of decline the test was terminated, usually after 5–10 s. The subject rested for 2 min before repeating the test at another crank velocity. This procedure was followed until the subject had completed tests at each of the chosen crank velocities. The entire testing protocol was repeated on another day to study the variability of measurements within a given subject.

All 13 subjects participated in the study to investigate the effects of pedal-crank velocity on the power output, the decline in power output, and the total work generated during a 30-s maximal effort test. Three crank velocities were selected to provide a range from slow (60 rpm), to intermediate (100 rpm), and fast (140 rpm). The sequence of velocities was randomized. During each test the subject exerted maximal force on the pedals of the CVE for 30 s. Three minutes following completion of the test a venous blood sample was taken from an antecubital vein for subsequent analysis of plasma lactate concentration by a fluorimetric enzymatic technique (14). Tests were separated by at least 1 day.

The machine and protocol used for the testing has been described previously (19). Briefly, it consisted of a modified cycle ergometer fitted with a 3-hp DC electric motor (Boston Gear 18300C) which maintained crank velocity constant (+5%) at any setting between 13 and 166 rpm. The forces exerted on the cranks were recorded continuously using strain gauges. Force data from the ergometer were displayed on a Hewlett-Packard recorder (7700 series). Peak torque (N·m) occurred consistently when the pedal crank was at the forward horizontal position and was calculated for each leg separately during every pedal revolution; a mean value for both legs was recorded. Peak power was calculated from peak torque and crank velocity, and the values obtained on *days 1* and *2* were averaged. The area under the force record was obtained using a Talos digitizer in series with a microprocessor (CompuColor II RS 232) for the measurement of work (J) and average power (W) during each pedal stroke (19). A fatigue index (FI) similar to that devised by Thorstensson and Karlsson (24) was used to quantify the extent of decline in peak power and average power during the 30 s of the test

$$\text{fatigue index} = \frac{\text{initial power} - \text{final power}}{\text{initial power}} \times 100$$

where initial power was the mean of the three pedal strokes which represented the highest observed power output and final power was the mean of the last three pedal strokes in the test. In addition, the absolute rate of decline in power output (initial – final, W·s⁻¹) was calculated.

The volume of muscle between the gluteal fold and knee-joint space (both legs) was determined for each

subject from soft tissue X-rays obtained by computed tomography. The distance between the knee-joint space and gluteal fold was measured, and nine evenly spaced tomographic pictures were taken (Ohio Nuclear 2020 scanner). The cross-sectional areas of the total thigh, muscle, and bone, respectively, were measured in each picture using a graphics analyzer (Numonics model 1239). A program for stepped section volume was used to calculate the total volume of each component. The muscle volumes reported in this study represent an average value for the two legs.

The data from the torque-velocity study were analyzed by an analysis of variance (ANOVA) technique. The relationship between peak torque production and thigh muscle volume was assessed, both across, and within crank velocities, by an analysis of covariance and Pearson correlation analysis, respectively.

A randomized block ANOVA was selected to examine the relationship between crank velocity, fatigue, and total work performed during the four 30-s tests. Analysis of covariance was used to examine the associations between fatigue, total work, and the following variables: $\dot{V}O_{2\max}$, thigh muscle volume, and venous plasma lactate concentration. The relationship between the variables within each velocity was examined by a Pearson correlation analysis.

RESULTS

Torque-velocity relationships. In all subjects peak torque was inversely and linearly related to crank velocity ($P < 0.0005$). Mean (\pm SD) peak torque ranged from 212.4 ± 30.8 to 109 ± 18.6 N·m, at 60 and 160 rpm, respectively. Individual results were grouped and calculated as mean values at each velocity, the relationship being expressed by the following equation: $y = 266.59 - 1.016x$ ($r = 0.99$, Fig. 1), where y is peak torque in N·m, and x is crank velocity in rpm.

Although peak torque values were most strongly influenced by variations in crank velocity, the volume of thigh muscle exerted a significant effect on force output ($P < 0.023$). Peak torque values were corrected for thigh muscle volume (muscle volumes varied between 3.73 and 5.34 litres); the range was 49.1 ± 7.3 to 25.5 ± 4.4 N·m·l⁻¹ of thigh muscle volume, at 60 and 160 rpm, respectively. The relationship was described by $y = 61.7 - 0.234x$ ($r = 0.99$), where y is peak torque per liter thigh muscle volume, and x is crank velocity in revolutions per minute.

The relationship between peak torque and crank velocity was linear in all subjects, but there were distinct differences between subjects in the values for the slope and intercept. Figure 2 illustrates the largest variation in slope in the group of subjects studied.

Power-velocity relationships. Peak power output was a parabolic function of crank velocity (Fig. 3). Mean (\pm SD) values for maximal peak power ranged between $1,826 \pm 287$ and $1,323 \pm 198$ W at 140 and 60 rpm, respectively, corresponding to 425 ± 66 and 303 ± 49 W·l⁻¹ thigh muscle volume. There was no consistent crank velocity for maximal peak power output, the plateau in Fig. 3 indicating a range of crank velocities for optimal per-

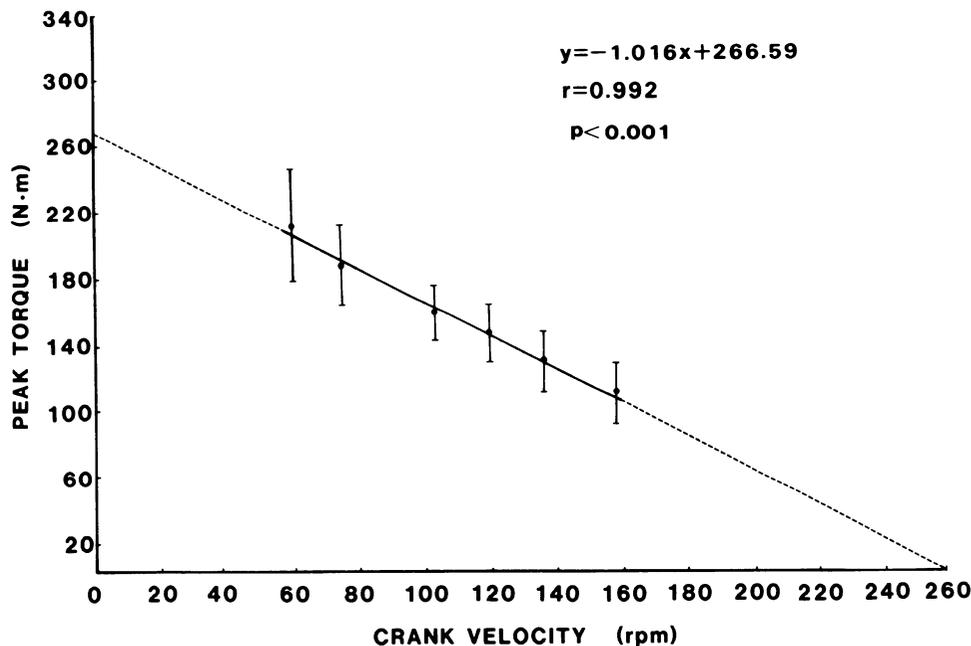


FIG. 1. Measurements of peak torque (mean \pm SD) obtained in 13 subjects at 6 pedal-crank velocities.

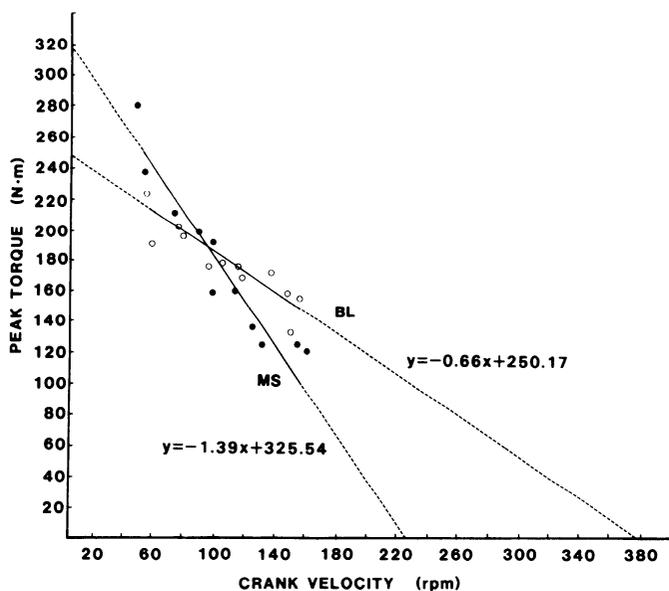


FIG. 2. Relationship between peak torque and pedal-crank velocity in 2 subjects representing widest range of force generation.

formance between about 120 and 160 rpm. Figure 4 displays results from the same two subjects (*BL* and *MS*) who exhibited the widest difference in crank velocities for maximal peak power; *subject MS* achieved maximal peak power output at a crank velocity of approximately 120 rpm, whereas the maximal peak power output in *subject BL* was not attained with the crank velocities studied and may be calculated to occur at about 170 rpm.

Power output and fatigue during a maximal effort test of 30-s duration, at 60, 100, and 140 rpm. The mean (\pm SD) time taken to attain maximal peak power output was 5.3 ± 2.1 , 2.2 ± 1.7 , and 1.4 ± 0.7 s at 60, 100, and 140 rpm, respectively. This relationship applied equally to the peak average power output data obtained by integrating the area under the force records.

The maximal peak power output and peak average power output showed a descending sequence from 140 to 100 and 60 rpm ($P < 0.0005$). The greatest power output that could be generated during one complete revolution of the pedals was (mean \pm SD) 758 ± 100 , 964 ± 121 , and $1,050 \pm 175$ W, at 60, 100, and 140 rpm, respectively, corresponding to 1.02 ± 0.13 , 1.29 ± 0.16 , and 1.41 ± 0.23 hp. The average power output that could be maintained throughout the entire 30-s test was 679 ± 85 , 728 ± 90 , and 702 ± 128 W, at 60, 100, and 140 rpm, respectively, corresponding to 0.91 ± 0.11 , 0.98 ± 0.12 , and 0.94 ± 0.17 hp. The differences between the three velocities were not significant.

Fatigue index. The FI for both peak and average power was significantly different between the three crank velocities and showed a descending sequence from 140 to 100 and 60 rpm ($P < 0.0005$). The relative decline in peak power was highly correlated with the relative decline in average power ($r = 0.94$, $P < 0.0005$), and the values for the FI at each velocity were almost identical. The FI for both peak power, and average power, respectively was (mean \pm SD) 23.6 ± 5.7 and $23.7 \pm 4.6\%$ at 60 rpm, 45.7 ± 8.0 and $47.7 \pm 5.7\%$ at 100 rpm, 59.3 ± 6.2 and $58.7 \pm 6.5\%$ at 140 rpm.

Relationships between variables were also examined separately within each velocity. At a crank velocity of 60 rpm there was a significant negative correlation between the FI for peak power and $\dot{V}O_{2\max}$ ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) ($r = -0.63$, $P < 0.006$). Such a relationship was not significant at the faster crank velocities.

Rate of decline in power. The rate of decline in power ($\text{W} \cdot \text{s}^{-1}$) at each velocity reflected the results for the FI; as velocity increased, the rate of decline in both peak and average power increased similarly ($P < 0.0005$) (Fig. 5). The rate of decline in peak power and average power ($\text{W} \cdot \text{s}^{-1}$), respectively, was (mean \pm SD) 11.6 ± 4.1 and 7.5 ± 1.9 at 60 rpm; 24.5 ± 5.4 and 17.3 ± 3.4 at 100 rpm; and 32.4 ± 7.5 and 21.6 ± 5.1 at 140 rpm.

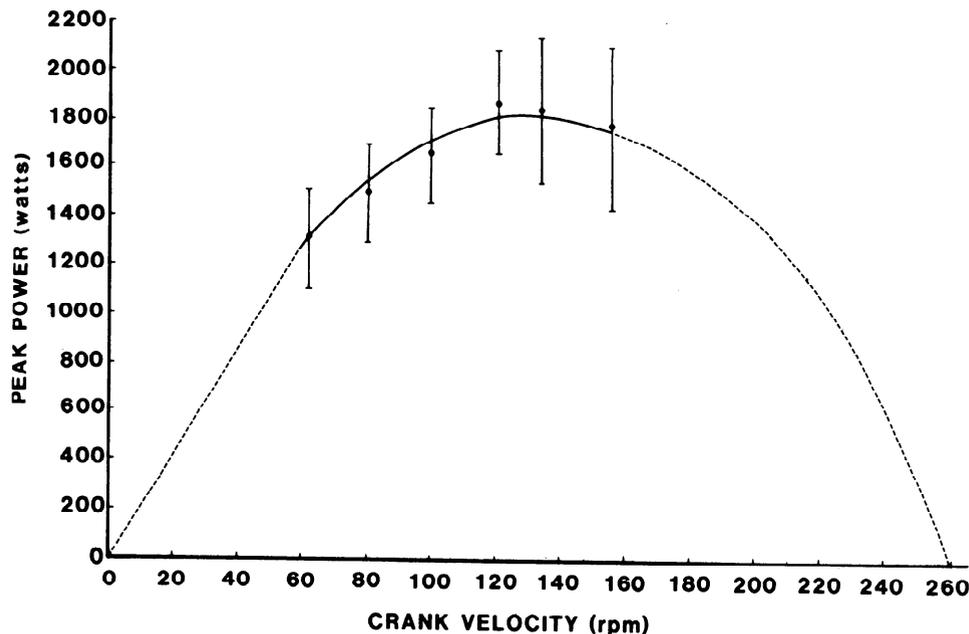


FIG. 3. Measurements of peak power (mean \pm SD) obtained in 13 subjects at 6 pedal-crank velocities.

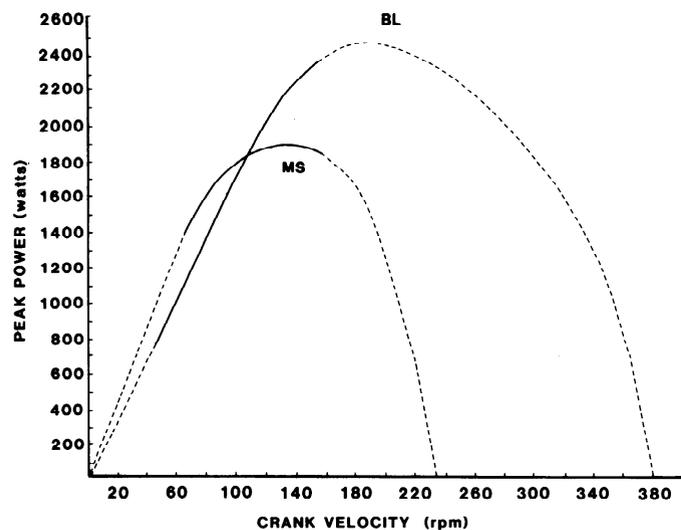


FIG. 4. Relationship between peak power and pedal-crank velocity in 2 subjects representing widest range of values.

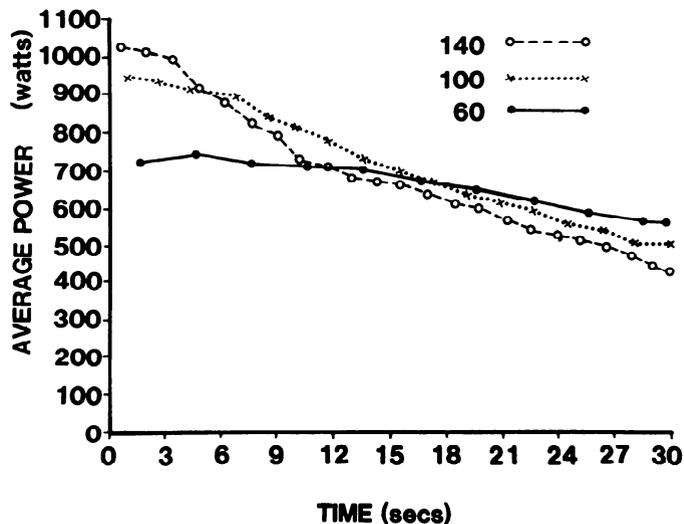


FIG. 5. Decline in average power during 30 s of maximal effort at crank velocities of 60, 100, and 140 rpm.

There was a high correlation between the rate of decline in peak power at the three velocities, and the rate of decline in average power ($r = 0.93, P < 0.0005$). There was also a strong correlation among the initial peak power output, the rate of decline in peak power ($r = 0.86, P < 0.0005$) average power ($r = 0.81, P < 0.0005$), and the total amount of work performed ($r = 0.69, P < 0.002$).

Work and total work. The maximum amount of work that could be generated in one complete revolution of the pedal cranks was (mean \pm SD) 801 ± 98 , 588 ± 70 , and 476 ± 75 J, at 60, 100, and 140 rpm, respectively. Total work output during the 30-s test, however, was not significantly different between the three crank velocities, the respective values being $21,828 \pm 2,712$, $21,068 \pm 3,849$, and $20,363 \pm 2,542$ J at 100, 140, and 60 rpm. The results obtained during each consecutive 5-s period, however, did not consistently follow this pattern (Fig. 6). During the initial 10 s of the test the amount of work

performed increased with crank velocity, whereas in the last 10 s of the test the pattern was reversed and the greatest amount of work was generated at 60 rpm followed by 100 and 140 rpm.

Lactate. Values for venous plasma lactate taken three min postexercise (mean \pm SD) were 9.68 ± 2.83 , 10.57 ± 2.55 , and 9.15 ± 2.68 mmol^{-1} , at 60, 100, and 140 rpm respectively, and not significantly different.

DISCUSSION

Torque-velocity relationships. The purpose of the present study was to characterize the relationship between pedal-crank velocity and peak torque generation during conditions in which crank velocity could not be increased by maximal muscular efforts.

Previous work by Sjogaard (22) using a dynamically braked cycle ergometer demonstrated a leveling off of

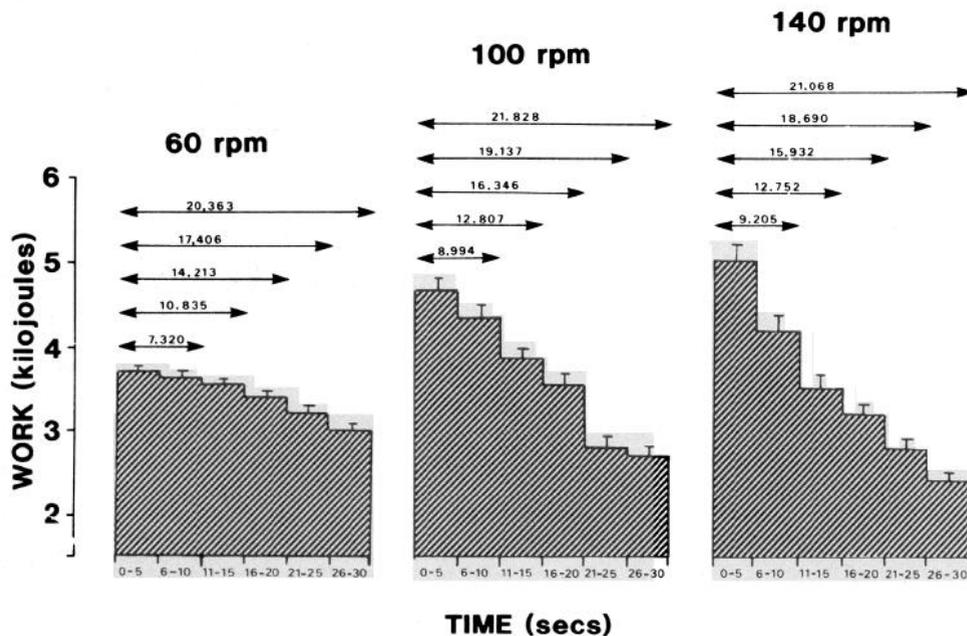


FIG. 6. Total work generated in each 5-s period of a maximal effort 30-s test at crank velocities of 60, 100, and 140 rpm; \leftrightarrow denotes cumulative work.

peak torque at high crank velocities. In contrast, Sargeant et al. (21) reported a linear relationship between peak force and pedal-crank velocity, with maximal power output occurring consistently at about 110 rpm. We also observed a linear relationship between peak torque and crank velocity over the range of 60–160 rpm (Fig. 1), but in our subjects maximal power output was achieved at various crank velocities between 120 and 160 rpm (Fig. 3), possibly because we studied a less homogeneous group of subjects than that of Sargeant et al. (21). Moreover, the cranks of the ergometer used by them are driven at constant speed by the motor, not the subject, and the subject attempts to exert force on the moving pedals. Such a system may lead to contractions becoming more eccentric at faster speeds and may also result in considerable reflex and antagonistic activity. In the ergometer used in the present study the subject drives the cranks and the motor sets an upper limit to angular velocity which cannot be overcome. Thus our data may be more representative of true maximal voluntary effort. The data reported by Sjogaard (22) could be described by a linear equation if the value for maximal isometric tension were ignored. The latter is also true of results obtained during maximal knee extensions on the isokinetic Cybex apparatus (23). Experimental data from these studies cannot be fitted by the equation for a rectangular hyperbola as defined by Hill (13). Classical force-velocity testing was performed on isolated frog muscle, whereas the forces exerted on the cranks during cycling result from the cooperative action of several muscles operating across at least two joints. The torque-velocity relationship described in this study must be considered functional, and it seems unrealistic to attempt a mathematical comparison with the elegant work performed on isolated muscle.

We observed considerable intersubject differences in the ability to generate high levels of torque and hence power at fast crank velocities. This may be related to many factors including the proportion of fast-twitch

(type II) fibers in the exercising muscle (23, 9). Type II fibers are known to have faster contraction times and rates of tension development than slow-twitch (type I) fibers (3), and are more dependent on glycolysis to maintain ATP rather than the slower process of oxidative phosphorylation (6). It was not a major purpose of this study to examine the relationship between power output at fast crank velocities and muscle fiber type. However, in the two subjects who exhibited the greatest differences in power output at fast crank velocities (Fig. 4), three needle biopsy samples were taken from two sites in the right (dominant) vastus lateralis muscle of each subject to determine fiber type distribution. Approximately 3,000 fibers were counted for each subject. In *subject BL*, who achieved a maximal peak power output of 2,539 W at a crank velocity of 162 rpm, 72% of the fibers were type II, whereas in *subject MS*, who attained a maximum value of 1,708 W at 119 rpm, 53% were type II. These limited results concur with the findings of Thorstensson et al. (23) and the empirical observations on fiber type distribution in athletes (9), which have confirmed a greater proportion of type II fibers in athletes engaged in activities requiring short-lived or "sprint" power output.

In addition to fiber composition, the absolute mass of active muscle may make a significant contribution to force generation, particularly at slow speeds of contraction and during the development of isometric tension (15). Our results indicated a positive relationship between thigh muscle volume, as determined from computed tomography, and peak power output ($P 0.023$). The relationship was not improved at the slowest crank velocity, possibly because testing did not take place below 60 rpm. Adjusting the torque-velocity data for thigh muscle volume did not reduce the overall variability, but it did alter the position of individuals in relation to the mean. The large differences in torque generation were not accounted for solely by the volume of active muscle.

Crank velocity, power output, and fatigue. We investigated the effects of crank velocity on maximum power output, the decrement in power output (fatigue), and the total work generated during maximal cycling exercise of 30-s duration. The mean power output that could be sustained throughout the 30-s test ranged from 679 to 728 W, in close agreement with values calculated in running upstairs (25) and cycling (28).

A major finding of this study was that increases in crank velocity were associated with a higher initial power output, but a greater rate and extent of decline in power (Fig. 5). After approximately 17 s the sustained power output at 60 rpm became greater than at 100 and 140 rpm. Thus at faster crank velocities more external work was produced early in the test, but in the later stages more external work was generated at the lowest velocity (Fig. 6). This changing pattern of power output resulted in minimal differences in the total amount of work produced at the three crank velocities during the total 30 s.

The significantly greater rate and extent of decline in power output at higher crank velocities is suggestive of a decreased mechanical efficiency. In the case of muscular contraction, thermodynamic efficiency is defined as the external work divided by the free energy (27). An estimate of the free energy may be obtained in humans during steady-state exercise by measuring $\dot{V}O_2$ and relating it to biochemical processes in the muscle, but this was not attempted in the present study. Nevertheless, in classical experiments describing the effects of contraction time on the work and efficiency of the elbow flexors (12) and quadriceps group during cycling (4), it was demonstrated that brief maximal and submaximal contractions were associated with an increased waste of potential energy. In both studies the optimal efficiency was 22–25% occurring when the duration of a single contraction (equivalent to half a pedal revolution) was 0.9 s, which corresponds to an angular velocity of 33 rpm; the mechanical efficiency during contractions equivalent to 60, 100, and 140 rpm was 18.7–21.5, 7.5–11.5, and 1–3%, respectively. Moreover, the efficiency was remarkably independent of load as long as speed was maintained approximately constant.

In a system performing mechanical work and in which heat is liberated and free energy is wasted, relatively more free energy must be supplied to maintain performance (27). During maximal exercise of short duration, energy is supplied almost exclusively from the degradation of phosphorylcreatine (PC) and from glycolysis. In frog muscle the breakdown of PC and glycogen over a cycle of contraction and relaxation is directly proportional to the sum of the heat and the work produced (29). Moreover, during isotonic contraction of frog muscle, heat production is at a maximum under conditions in which the work is maximal (7). In our study, during the initial stages of cycling at the fast crank velocities, the work (and by inference, the heat production) was greatest. This may have resulted in an increased rate of degradation of PC and glycogen and greater changes in metabolic substrates and products (such as hydrogen ions and adenine nucleotides), which in turn could have ex-

erted inhibiting effects on the biochemical processes associated with muscle contraction and may have contributed to the greater observed fatigue. Furthermore, at high rates of contraction there would be less time for “washout” of metabolites from muscle, and the intramuscular accumulation of waste products may have proceeded at an accelerated rate.

In the present study the high venous plasma lactate concentrations in samples taken 3 min postexercise were not significantly different at different crank velocities. Although this finding suggests that a similar rate of glycolysis was present during the three exercise bouts, lactate concentrations in one sample of venous blood may not accurately reflect muscle lactate production. There is no evidence that either the rate of lactate production or the rate of efflux from the active muscles was identical in the three conditions; in a recent study in this laboratory (11) plasma lactate concentrations 4–10 min following exercise at a velocity of 140 rpm were significantly higher than at 60 rpm, although similar at 3 min.

A significant negative correlation ($r = -0.63$, $P < 0.006$) existed between maximal oxygen uptake and the FI for power output at a crank velocity of 60 rpm. A previous investigation from this laboratory reported a similar relationship (19) in a group of 18 young male subjects, who performed a maximal effort test on the constant velocity ergometer for 45 s at 60 rpm. These results suggest that the oxidative capacity of the muscles may be important in determining the extent of fatigue during maximal cycling exercise at slow crank velocities; this in turn may suggest a major involvement of Type I fibers in this type of activity.

The higher initial power output and greater rate of fatigue observed at the faster crank velocities may have resulted from an initial preferential recruitment of fast-twitch motor units. This may occur at the onset of activity under some circumstances (10). Results of animal experiments have demonstrated that individual fast-twitch motor units, and whole muscles with a high percentage of type II fibers, are capable of higher levels of tetanic tension, and are more susceptible to fatigue when stimulated electrically, than type I fibers (3). Studies on intact human muscle have reported that individuals with muscles containing a high proportion of type II fibers are capable of a faster maximal contraction velocity, and greater maximal force output (23), but are more prone to fatigue during repeated maximal dynamic contractions (24). Nilsson et al. (20) also demonstrated a strong correlation between an increase in the ratio of electromyographic activity to power associated with fatigue, and with a high percentage of type II fibers, prompting the suggestion that diminished force was due to a selective drop out of this type of fiber. A progressive reduction in motor unit activation has been observed during a maximal voluntary contraction of the adductor pollicis muscle, sustained for 60 s; however, it was not established whether the reduced firing frequency was restricted to the fast-twitch motor units (2).

In the present study evidence was obtained to tentatively suggest that the contribution of different fiber

types to whole muscle tension may have varied between slow and fast crank velocities. During fatigue at 60 rpm, peak power output was consistently generated when the pedal crank was at the forward horizontal (90°) position. However, in some subjects, during fatigue at 100 and particularly 140 rpm, peak power output was not developed until the pedal crank was between approximately 115 and 140°. This finding suggests a decrease in muscle contraction speed and rate of tension development, although it may also reflect changes in pedaling technique. These results could be attributed, at least in part, to a selective drop out and fatigue of type II muscle fibers. Moreover, it has recently been suggested by DiPrampo et al. (5) that a reduction in contractile speed rather than depletion of high-energy phosphates may be a major cause of fatigue during activities requiring maximal power output.

We have demonstrated that cycling activity of less than 6–7 s duration should be performed at crank veloc-

ities of at least 120 rpm to obtain maximal power output. For efforts of slightly longer duration (<20 s) the optimal velocity is somewhat less (~100 rpm), whereas for the successful maintenance of power output over greater periods of time the most economical rate is about 60 rpm or perhaps even less (4, 12). These results are in accordance with the observation that many racing cyclists choose to pedal at crank velocities above 110 rpm when they wish to attain maximal power output (28). However, even champion racing cyclists who trained for years at high pedaling rates were reported to be most efficient when performing at 60 rpm (17).

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