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ORIGINAL ARTICLE

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Determinants of maximal cycling power: crank length, pedaling rate and pedal speed

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Abstract The purpose of this investigation was to determine the effects of cycle crank length on maximum cycling power, optimal pedaling rate, and optimal pedal speed, and to determine the optimal crank length to leg length ratio for maximal power production. Trained cyclists ($n = 16$) performed maximal inertial load cycle ergometry using crank lengths of 120, 145, 170, 195, and 220 mm. Maximum power ranged from a low of 1149 (20) W for the 220-mm cranks to a high of 1194 (21) W for the 145-mm cranks. Power produced with the 145- and 170-mm cranks was significantly ($P < 0.05$) greater than that produced with the 120- and 220-mm cranks. The optimal pedaling rate decreased significantly with increasing crank length, from 136 rpm for the 120-mm cranks to 110 rpm for the 220-mm cranks. Conversely, optimal pedal speed increased significantly with increasing crank length, from 1.71 m/s for the 120-mm cranks to 2.53 m/s for the 220-mm cranks. The crank length to leg length and crank length to tibia length ratios accounted for 20.5% and 21.1% of the variability in maximum power, respectively. The optimal crank length was 20% of leg length or 41% of tibia length. These data suggest that pedal speed (which constrains muscle shortening velocity) and pedaling rate (which affects muscle excitation state) exert distinct effects that influence muscular power during cycling. Even though maximum cycling power was significantly affected by crank length, use of the standard 170-mm length cranks should not substantially compromise maximum power in most adults.

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Introduction

Previous investigators have reported that maximal cycling power is affected by cycle crank length (Inbar et al. 1983; Too and Landwer 2000; Yoshihuku and Herzog 1990, 1996) and that the optimal crank length is related to leg length (Inbar et al. 1983). Inbar et al. (1983) reported that peak cycling power for the Wingate anaerobic test varied by 8% for crank lengths of 125–225 mm. Since Inbar et al. (1983) reported their findings, it has been reported that the resistance used in the Wingate anaerobic test does not elicit maximum short-term cycling power (Dotan and Bar-Or 1983; Patton et al. 1985). Thus, their findings regarding the effects of crank length must be interpreted cautiously. Yoshihuku and Herzog (1990, 1996) modeled mathematically the effects of crank length on maximal power, optimal pedaling rate, and optimal pedal speed. They reported that maximum power varied by 0–10% for crank lengths of 130–210 mm, depending on the definition of optimal muscle length, and that optimal pedal speed was nearly independent of crank length. Their model, however, featured stepwise muscle activation and relaxation and may not have been affected by reduced muscle excitation, which normally occurs during activation and relaxation periods (Caiozzo and Baldwin 1997; Martin et al. 2000). More recently, Martin et al. (2000) reported that impulse and power were similar for crank lengths of 145–220 mm, but did not report values for maximum power, optimal pedaling rate, or optimal pedal speed. Thus, it seems that the exact effects of crank length on maximum power, optimal pedaling rate, and optimal pedal speed remain to be determined. Therefore, the purposes of this investigation were to determine the effects of crank length on the maximum cycling power, optimal pedaling rate, and optimal pedal speed of human subjects, and to determine the optimal crank length for maximum power production.

Methods

Trained male cyclists [$n=16$, mean (SD) age: 29 (7) years, height: 179 (6) cm, mass: 73 (7) kg] volunteered to participate in this investigation. The procedures were explained and the subjects provided written informed consent to participate. This investigation was approved by the Institutional Review Board at The University of Texas at Austin.

Maximal cycling was performed using crank lengths of 120, 145, 170, 195, and 220 mm. Familiarization trials were performed with all crank lengths during the week prior to data collection. On each experimental data collection day, subjects performed a 5-min warm-up of steady-state cycling at 100 W, and four maximal cycling power tests at one crank length. A randomized counterbalanced design with four ordering sequences was used for the presentation of the crank lengths to eliminate any presentation-order effect.

Maximal cycling power was measured using the inertial load method (Martin et al. 1997), which determines the torque and power delivered to an ergometer flywheel across a range of pedaling rates. The ergometer was fitted with bicycle-racing handlebars, cranks, pedals, and seat, and was fixed to the floor. Each subject wore cycling shoes fitted with a cleat that locked into a spring-loaded binding on the pedal.

A slotted disc was mounted on the flywheel and an infra-red photodiode and detector were mounted on the ergometer frame on opposite sides of the disc. The slots were spaced at $\pi/8$ radians ($\Delta\theta$) along the perimeter of the disc, and they alternately passed or interrupted the infra-red light beam. The detector circuit was programmed to emit a square pulse at each interrupt. The time between consecutive interrupts (Δt) was recorded by a dedicated microprocessor with a clock accuracy of ± 0.5 µs. Flywheel angular velocity was calculated as $\Delta\theta/\Delta t$. The time-angular velocity data were low-pass filtered at 8 Hz using a fifth-order spline (Woltring 1986). Power for each revolution of the pedal cranks was calculated as the rate of change in flywheel kinetic energy for each complete revolution of the cranks (beginning with either leg). Maximum power was identified as the highest power for a complete revolution within each bout (i.e., the apex of the power-pedaling rate curve). Pedaling rate, in revolutions per minute (rpm), was calculated as the reciprocal of the time (min) required to complete each revolution of the pedal cranks. Pedal speed (PS; m/s) was calculated from pedaling rate (PR; rpm) and crank length (CL; m) as: $\mathrm{PS} = 2\pi \times \mathrm{PR} \times \mathrm{CL}/60$. Optimal pedaling rate and optimal pedal speed were defined as those values at which maximum power occurred.

In the present investigation, specific changes were made to the original protocol of Martin et al. (1997), including the length of the crank, the inertial load ($\mathrm{IL} = 0.5 \times \mathrm{I} \times \mathrm{GR}^2$: where IL is the inertial load, I is the moment of inertia of the flywheel, and GR is the gear ratio), and the number of crank revolutions. The inertial load was varied by adjusting the gear ratio so that the inertial resistance at the pedal ($\mathrm{IR}_P = \mathrm{IL}/\mathrm{CL}$) was similar for all crank lengths (Table 1). The inertial loads used in this investigation do not correspond to outdoor cycling; rather, they were chosen specifically to elicit maximum power during our power test. The number of crank revolutions performed in each test was varied to match the total work across all of the crank lengths (e.g., 6.5 revolutions for the 220-mm cranks; 9.0 revolutions for the 120-mm cranks). This approach allowed the subjects to reach optimal pedaling frequency within approximately 2 s, and to complete the test in approximately 3–4 s. Seat height was set to match each subject's accustomed riding position and was adjusted so that the distance from the top of the saddle to the pedal axle (in its most extended position) was constant for all crank lengths.

Leg length, femur length, and tibia length were recorded using a fiberglass measuring tape and an anthropometer. Leg length was defined as the difference between standing height and seated height. Femur length was defined as the length from the greater trochanter to the cleft of the knee joint. Tibia length was defined as the length from the cleft of the knee to the lateral maleolus.

Repeated measures analysis of variance was used to determine whether crank length significantly affected maximum cycling power, optimal pedaling rate, or optimal pedal speed. If significant ($P < 0.05$) main effects of crank length were detected, the Bonferoni post hoc procedure was used to determine which crank lengths differed. Second-order polynomial regression analysis was performed to determine the optimal crank length (as a ratio of leg length, femur length, and tibia length) for maximum power. For that regression analysis, maximum power for each test was scaled as a proportion of that subject's maximum value for any crank length. Data are presented as the mean (SEM), unless stated otherwise.

Results

The maximum power of our subjects varied by 4% across the range of crank lengths tested, from 1149 (44) W for the 220-mm cranks to 1194 (47) W for the 145-mm cranks (Fig. 1). Maximum power produced when using the 145- and 170-mm cranks was significantly greater ($P < 0.05$) than that produced with the 120- and 220-mm cranks. Optimal pedaling rate decreased significantly ($P < 0.05$) with increasing crank length (Fig. 2) from 136 (3) rpm for the 120-mm cranks to 110 (3) rpm for the 220-mm cranks. The optimal pedaling rate for the 195-mm cranks did not differ from that of the 170- or 220-mm cranks, but the values for all other lengths differed. Optimal pedal speed increased significantly ($P < 0.05$) with increasing crank length,

Table 1 Ergometer settings for the five crank lengths tested

Length	Gear ratio	Inertial load (kg·m^2)	[a]Pedal inertial resistance (kg·m)
120 mm	5.77:1	6.45	53.8
145 mm	6.38:1	7.88	54.4
170 mm	6.98:1	9.46	55.6
195 mm	7.59:1	11.2	57.3
220 mm	7.89:1	12.1	54.9

[a] The inertial resistance at the pedal for the various crank lengths do not match exactly because of the constraint of using bicycle chain rings and cogs with integer numbers of teeth

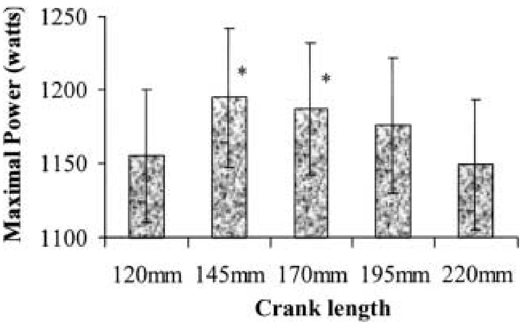

Fig. 1 Maximum power. Power varied by 4%, and power produced at the 145- and 170-mm cranks was greater than that produced at the 120- and 220-mm cranks (*$P < 0.05$)

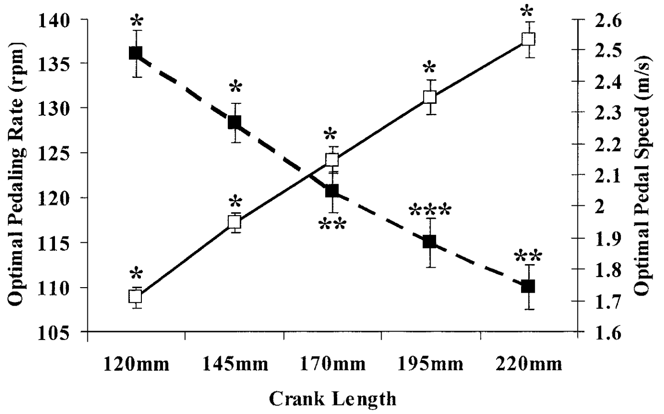

Fig. 2 Optimal pedaling rate and optimal pedal speed. Optimal pedaling rate (■) decreased with increasing crank length (*differs from all other crank lengths; **differs from all lengths except 195 mm; ***differs from the 120- and 145-mm crank lengths). Optimal pedal speed (□) increased with increasing crank length and the values for all cranks differed (*)

from 1.71 m/s for the 120-mm cranks to 2.53 m/s for the 220-mm cranks; the value for each crank differed from all others (Fig. 2).

Significant second-order polynomial relationships ($P < 0.001$) were observed between power and crank length relative to leg length [84 (4) cm], femur length [45 (2) cm], and tibia length [41 (3) cm]. The crank length to leg length (Fig. 3) and crank length to tibia length ratios accounted for 20.5% and 21.1% of the variability in maximum power, respectively, whereas the crank length to femur length ratio accounted for only 7.1% of the variability. The optimal crank length for maximum power was 20% of leg length or 41% of tibia length.

Discussion

The main findings of this investigation were: (1) cycle crank lengths that varied by 83% elicited a mere 4% variation in maximum cycling power, (2) optimal pedaling rate decreased with increasing crank length, whereas optimal pedal speed increased with increasing crank length, and (3) the optimal crank length for maximum power was 20% of leg length or 41% of tibia length. The variation in maximum power was only half as large as the 8% reported by Inbar et al. (1983), and was within the range predicted by the mathematical models of Yoshihuku and Herzog (1990, 1996). Part of the difference between the 4% variation in maximum power in the present investigation and the 8% variation in peak power reported by Inbar et al. (1983) may be due to differences in measurement techniques. As mentioned earlier, it has been shown that the Wingate anaerobic test does not elicit maximum power (Dotan and Bar-Or 1983; Patton et al. 1985). Rather, the standard Wingate anaerobic test resistance (75 g/kg) allows subjects to reach pedaling rates that are on the descending limb of the power/pedaling rate relationship, where small differences in pedaling rate may have a large effect on power. In contrast, in the present investigation, the inertial load method was used to determine the apex of the power/pedaling rate relationship, and thus, our values truly represent maximum cycling power for each crank length. In addition, Inbar et al. (1983) used a single resistance for the various crank lengths tested and thus varied the resistance at the pedal. For example, a Monark ergometer, with a resistive load of 5.25 kg (i.e., a load of 0.075 kg/kg body mass for a 70-kg subject) will produce a resistive force of 289 N at the pedal for 170-mm cranks, 410 N for 120-mm cranks, and 224 N for 220-mm cranks. Thus, by using a constant flywheel resistance for various crank lengths, Inbar et al. (1983) altered dramatically the resistive force at the pedal. Our solution to this interaction between crank length and pedal force was to equate the "inertial resistance at the pedal" (i.e., inertial load divided by the crank length) for the various crank lengths tested. Thus, our methods varied the resistive torque in order to hold constant the resistive force at the pedal.

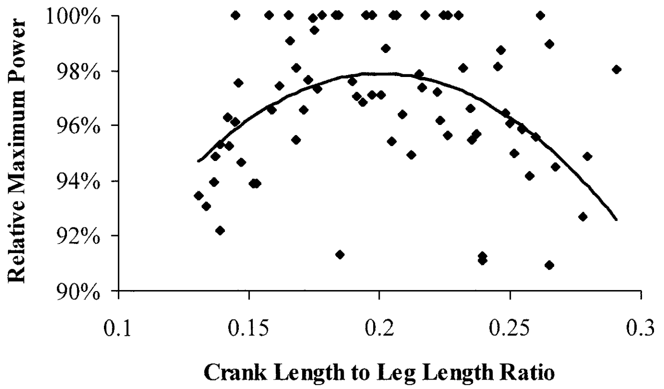

Fig. 3 Maximum power versus leg length to crank length ratio. The relationship of maximum power (expressed as a percent of each subjects best performance) with the crank length to leg length ratio (CL/LL) was parabolic, and the regression equation was: proportion of maximum power = $-6.83(\mathrm{CL/LL})^2 + 2.77\mathrm{CL/LL} + 0.698$; $P < 0.001$, $R^2 = 0.205$, SE = 2.4%. The optimal crank length was 20% of leg length

The model of Yoshihuku and Herzog (1990, 1996) predicted that crank lengths ranging from 130 to 210 mm would elicit 0–10% variation in maximum power, depending on the definition of optimal muscle length. When optimal muscle length was defined as the average of each whole muscle's length during the cycle (Yoshihuku and Herzog 1990, 1996: model 1), predicted power varied by less than 1%. When optimal fiber length was based on the cross-bridge theory (Yoshihuku and Herzog 1996: models 2a and 2b), power varied by approximately 10%. The 4% variation observed in the present data falls within the predictions of those two models, and the power produced by our subjects (1149–1194 W) was similar to the power predicted by the model (922–1284 W for two legs).

Our results demonstrate that optimal pedaling rate decreases with increasing crank length, whereas optimal pedal speed increases with increasing crank length (Fig. 2). Even though both of these variables are rate terms, they may represent distinct physiological phenomena. Specifically, pedal speed constrains the shortening velocity of uniarticular muscles (Martin et al. 2000; Yoshihuku and Herzog 1990), whereas pedaling rate affects muscle excitation (Caiozzo and Baldwin 1997; Martin et al. 2000). Caiozzo and Baldwin (1997) reported that the incomplete excitation associated with activation and relaxation kinetics reduced force output, and that those kinetics exerted increasingly greater effect at higher frequency. Consequently, average excitation for a complete cycle was reduced with increasing frequency. Thus, our data suggest that the optimal conditions for maximum cycling power interactively depend upon crank length, muscle shortening velocity (constrained by pedal speed), and muscle excitation state (influenced by cycle frequency).

The interactive effects of crank length on optimal pedaling rate and pedal speed also extend to the entire power/velocity relationship. Specifically, the power/pedaling rate relationships for all five crank lengths (Fig. 4A) were similar in shape, but the relationships for the shorter cranks were shifted to the right (higher pedaling rate). The power/pedal speed relationships were also similar in shape (Fig. 4B), but the relationships for the longer cranks were shifted to the right (higher pedal speed). The combined effects of pedaling rate and pedal speed can be accounted for by using the product of the two as an expression of "cyclic velocity" (Martin et al. 2000). When power was plotted against cyclic velocity, the relationships for all five cranks tended to become aligned (Fig. 4C), suggesting that pedal speed (muscle shortening velocity) and pedaling rate (muscle excitation state) interactively constrain muscular power across a wide range of pedaling rates and pedal speeds.

Our results for optimal pedaling rate and optimal pedal speed contrast with those predicted by Yoshihuku and Herzog (1990, 1996). Their model predicted that optimal pedal speed would be nearly constant for crank lengths of 130–210 mm (2.5–2.8 m/s), but that optimal pedaling rate would vary by over 100% (110–232 rpm). As mentioned previously, their model featured stepwise activation and deactivation and therefore was not sensitive to the reduced muscle excitation associated with increasing pedaling rate. Yoshihuku and Herzog (1990) acknowledged that particular limitation of their model, but suggested that it would mainly affect power at very high pedaling rates. Our results suggest that the effect of pedaling rate on muscle excitation is more pervasive and affects power across a wide range of pedaling rates.

The selection of optimal cycle crank length for maximal power production may be of interest to competitive cyclists and to researchers who use cycle ergometry as a laboratory-based performance measure. Our data demonstrate that the optimal crank length for maximal power was 20% of leg length or 41% of tibia length. For our subjects, the mean optimal crank length calculated as a proportion of leg length [169 (2) mm] was similar to that calculated as a proportion of tibia length [170 (3) mm]. Both of these are quite similar to the standard length of bicycle and ergometer cranks (170 mm). Optimal crank length (i.e., 20% of leg length) varied from 151 mm for our shortest-legged (75.7 cm leg length) subject to 183 mm for our longest-legged subject (91.4 cm

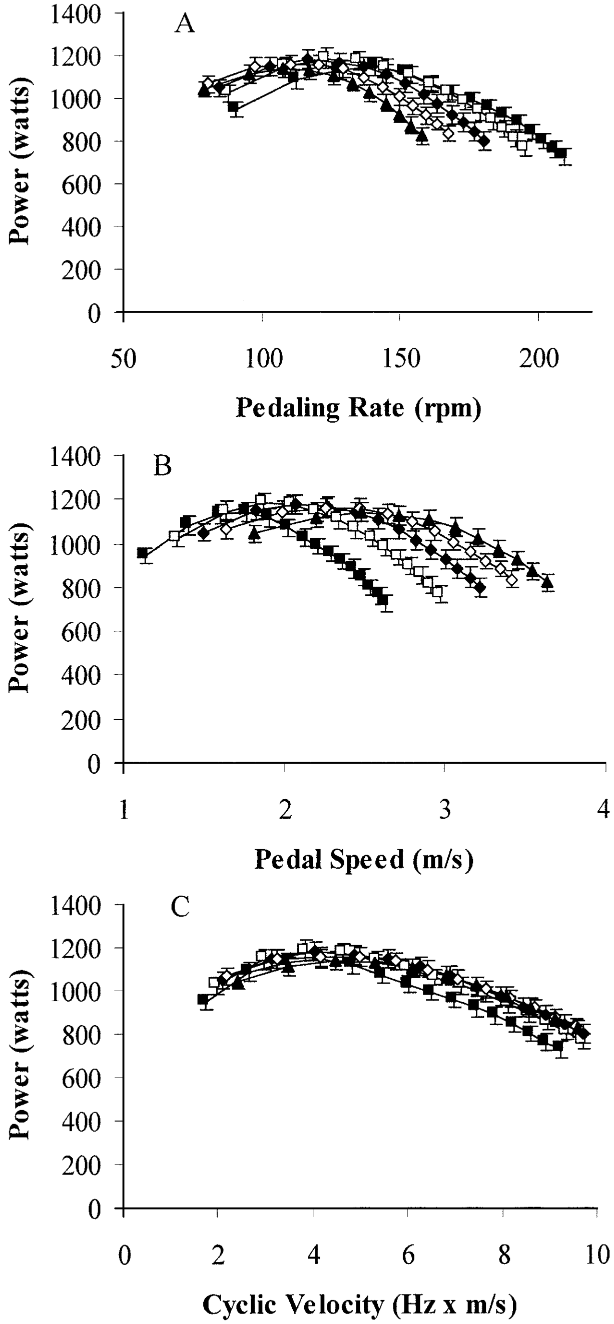

Fig. 4A–C Power/pedaling rate and power/pedaling speed relationships. The power/pedaling rate relationships (**A**) for all crank lengths (■120 mm, ❐145 mm, ◆ 170 mm, ◇ 195 mm, ▲ 220 mm) were similar in shape, but the relationships for the shorter cranks were shifted to the right (i.e., toward a higher pedaling rate). The power/pedal speed relationships were also similar in shape (**B**), but the relationships for the longer cranks were shifted to the right (i.e., toward a higher pedal speed). When power was plotted against the product of pedaling rate and pedal speed ("cyclic velocity", expressed as Hz × m/s; **C**), the relationships for all five cranks tended to converge onto one curve leg length). Even though the range in optimal crank length of our subjects was 32 mm, the regression equation (Fig. 3) indicated that standard (170 mm) length cranks would reduce power by less than 0.5%. Thus, standard laboratory or bicycle equipment should not substantially compromise maximum power for most adults.

The optimal length determined from this investigation agrees well with that reported by Inbar et al. (1983: 166 mm). Indeed, even though the methods employed by Inbar et al. (1983) were quite different from those used in the present study, the results are qualitatively similar. A seemingly major difference, however, is the reported correlation of maximum power with the leg length to crank length ratio. Inbar et al. (1983) reported a correlation coefficient of 0.99, whereas our value was 0.45. That difference is due, at least in part, to the fact that Inbar et al. performed regression on the mean values for each crank length, whereas values for all 16 subjects were included in our regression model. Indeed, when similarly analyzed, the present data yield a correlation coefficient of 0.94. This difference in analytical techniques has important implications. The analysis reported by Inbar et al. (1983) suggests that the crank length to leg length ratio accounted for approximately 98% of the variation in peak power, and that selection of optimal crank length is essential for maximum power production. Conversely, our analysis suggests that the same ratio accounted for only 20.5% of the variation in maximum power. Thus, even though our maximum power values were highly reproducible [coefficient of variation = 1.8 (0.2)%], the crank length to leg length ratio accounted for only one-fifth of the total variation. This suggests that the selection of crank length will have only a minor impact on maximal power production.

In most of the models presented by Yoshihuku and Herzog (1990, 1996), the highest power was predicted for the 130-mm crank, suggesting that their model may have been more sensitive to muscle force/length characteristics than our human subjects. That is, predicted power was reduced by crank lengths that elicited muscle excursion beyond the optimal portion of the force/length relationship. Their model included force/length effects based on the model of Woittiez et al. (Woittiez et al. 1984). For cycling, however, the muscles undergo cyclic length changes and are stretched prior to each contraction. Data reported by Neptune et al. (Neptune and Herzog 2000) suggest that some portion of that stretch may occur after muscle activation. Specifically, they reported that muscle electromyographic burst onset for the gluteus maximus occurred as early as 54° before the top dead center of the cranks (i.e., during the leg flexion phase) when subjects pedaled at 120 rpm. The observation that muscles that act to extend the leg are activated during leg flexion suggest that they are subjected to active stretch. Muscle force/length characteristics for cycling may, therefore, be affected by stretch-enhanced force production, which dramatically affects the force/length characteristics. Specifically, Edman et al. (1978) reported that muscle force was nearly constant from resting length to 25% above resting length following stretch, whereas force was reduced by approximately 15% over that same range without stretch. In addition, Stevens (1993) reported that muscles produced more force when performing work-loops (activated 54° before shortening) than when performing traditional force/velocity measurements at the same velocity. Taken together, these investigations provide compelling support for the notion that stretch-enhanced force production affects muscular power during cycling. Thus, stretch-enhanced force production may account for at least some of the differences between our human data and the values predicted by the model of Yoshihuku and Herzog (1990, 1996).

A potential limitation inherent in our methods was that, by changing the inertial load in concert with crank length, we may have influenced the measurement of maximum power, optimal pedaling rate, or optimal pedal speed. However, the inertial load method used in this investigation relies solely on the reaction torque of the flywheel to provide resistance. Thus, at any pedaling rate, the measured power is exactly what the subject produced, regardless of the inertial load. In addition, extensive pilot testing in our laboratory has revealed that both the maximum power and optimal pedaling rate for 170-mm cranks were stable across a wide range of inertial load conditions. Consequently, we are confident that the methods used in this investigation allowed us to determine accurately maximum power, optimal pedaling rate, and optimal pedal speed for each crank length. Finally, the inertial loads used in this investigation were substantially lower than those experienced by a cyclist using a racing gear ratio and, thus, might not apply to road or track cycling. However, Fregly et al. (1996) reported that inertial load has little effect on pedaling coordination, suggesting that our ergometer results are indeed applicable to outdoor cycling, even though the inertial characteristics differ.

In summary, cycle crank lengths that varied by 83% elicited a mere 4% variation in maximum cycling power. Optimal pedaling rate decreased with increasing crank length, whereas optimal pedal speed increased with increasing crank length. The differing optimal conditions for these two rate terms suggest that pedal speed (which represents muscle shortening velocity) and pedaling rate (which influences muscle excitation) exert distinct effects that limit muscular power during cycling. The optimal crank length for maximal power was 20% of leg length [169 (2) mm] or 41% of tibia length [170 (3) mm]. Even though our results reveal an optimal crank length, it must be recognized that the crank length to leg length and crank length to tibia length ratios accounted for only 20.5% and 21.1% of the variability in maximum power exhibited by our subjects. Indeed, the use of 170-mm cranks would only reduce the power of our shortest- and longest-legged subjects by less than 0.5%, suggesting that standard laboratory or bicycle equipment should not substantially compromise maximum power for most adults.

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