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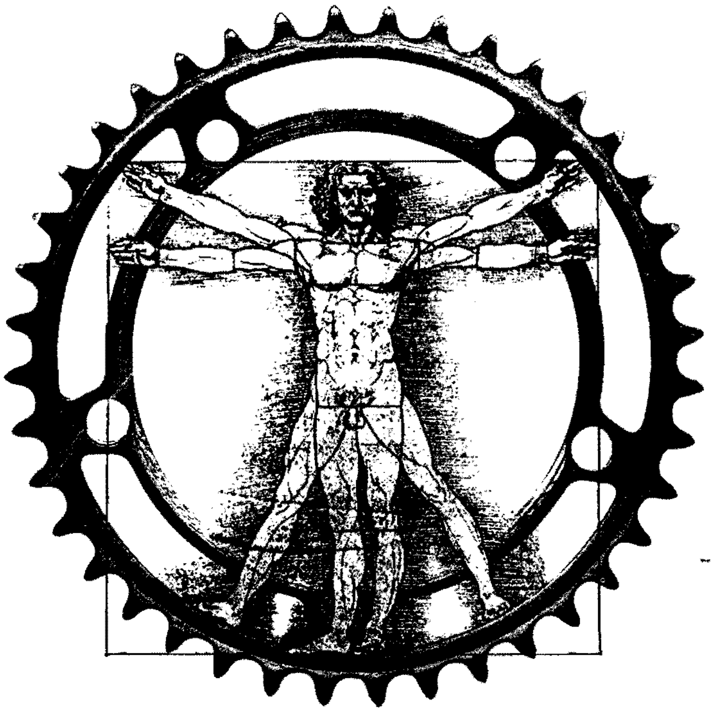

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Determination of the crank-arm length to maximize power production in recumbent-cycle ergometry

Danny Too and Chris Williams

ABSTRACT

The purpose of this study was to determine the crank-arm length that would maximize peak, mean and minimum power outputs in a recumbent cycling position. Nineteen male volunteers were each tested with five pedal-crank-arm lengths (110, 145, 180, 230 and 265 mm) according to a randomized sequence on a free-weight Monark cycle ergometer. The 30-second Wingate Anaerobic Cycling test was performed in a recumbent position (75° seat-tube angle, backrest perpendicular to the ground) against a resistance of 85 g/kg of the subject's body mass (5.0 J/crank rev/kg BM). Curve estimation with regression analysis revealed that the crank-arm lengths to maximize peak power, mean power and minimum power are 124 mm, 175 mm and 215 mm, respectively.

INTRODUCTION

It is well documented that recumbent human-powered vehicles with aerodynamic fairings, having a smaller drag coefficient and cross-sectional area, are faster than the standard racing bicycle (Kyle, 1982). However, with the current speed record of 117.06 km/hr 72.74 mph), established in 2000 by a single rider (Sam Witting -ham) on a Varna recumbent bicycle "Mephisto", designed and built by Georgi Georgiev, it becomes questionable whether a more aerodynamically effective human-powered vehicle can be designed. If future speed records are to be attained, it is necessary to focus not only on the aerodynamics, but also to examine the variables that affect power production in recumbent cycling and the interactions that would maximize it. Investigations in this area of recumbent cycling and power production have included an examination of changes in seat-tube angle (Too, 1991) and trunk/backrest angle (Too, 1994).

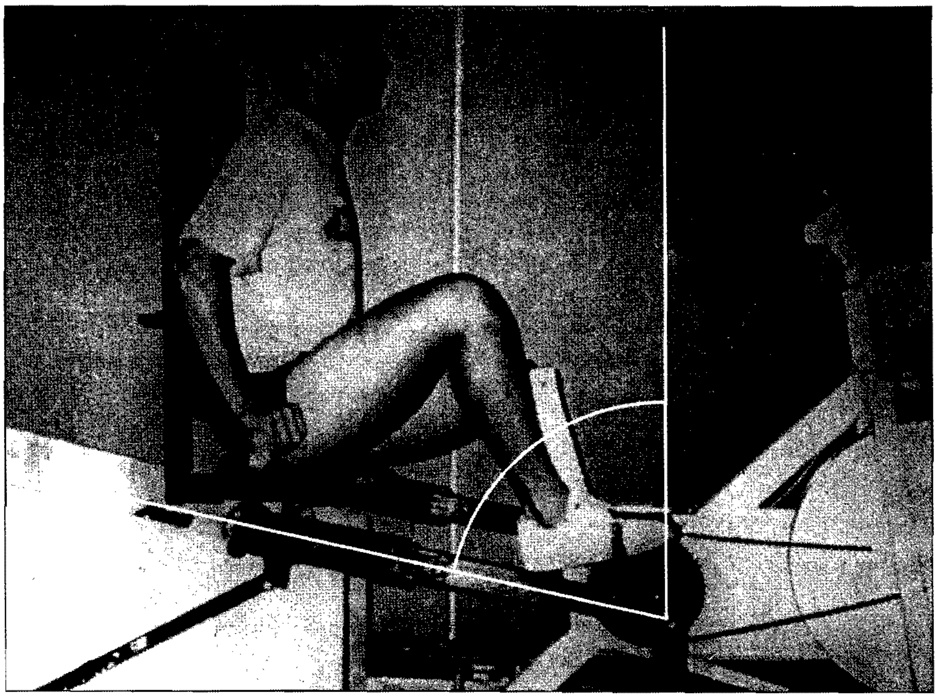
Figure 1. Recumbent position with a 75 degree seat-tube angle

Too (1991), examining a systematic change in seat-tube angle (0°, 25°, 50°, 75° and 100°), reported the largest peak power and mean power to be found with the 75° seat-tube angle and a parabolic curve (quadratic trend) best describing the change in peak power and mean power with changing seat-tube angles. Seat-tube angle was defined by the angle formed between the seat tube and a vertical line (perpendicular to the ground) passing through the crank spindle. Using a 75° seat-tube angle, Too (1994) investigated the effect of three trunk/seat-backrest angles (60°, 90° and 120°) on power production. A parabolic trend in peak power and mean power was found with changes in trunk/seat-backrest angle, with the largest peak power and mean power reported using the 90° trunk angle.

Based on muscle force-length and force-velocity power relationships, changes in crank-arm length will affect joint angles, muscle length, force, torque and power production in cycling. Since the literature involving traditional upright cycling positions have reported an effect on power output with changes in crank-arm length (Hull & Gonzalez, 1988; Inbar, Dotan, Trousil & Dvir, 1983; Too & Landwer, 2000), it can be assumed that power production will also be affected in a recumbent cycling position with different crank-arm lengths. Therefore the purpose of this study was to determine the trend in power production with changes in crank-arm length, and the crank-arm length that would maximize peak power, mean power and minimum power in a recumbent cycling position.

METHOD

Nineteen healthy volunteer male participants (mean age = 24.8 ± 4.4 yr., weight = 81.76 ± 11.84 kg, height = 1.80 ± 0.08 m) subjects were tested with a free-weight Monark cycle ergometer (Model 814E) at five pedal-crank-arm lengths (110, 145, 180, 230 and 265 mm), as defined by the distance between the center of the crank spindle and pedal spindle. (The normal crank-arm length for a Monark cycle ergometer is 170 mm). To accomplish this, two adjustable crank arms allowing for manipulations from 0 to 300 mm were used (Too & Landwer, 2000). All subjects were

		Crank-arm length (mm)				
		110	145	180	230	265
PP(W)	M	1139	1144	1097	1025	916
	SD	206	214	223	193	167
MP(W)	M	802	845	845	819	762
	SD	177	192	168	166	134
MINP(W)	M	555	598	619	627	612
	SD	141	156	145	148	117
MAXPED(rpm)	M	174.1	171.7	167.5	153.1	135.2
	SD	11.7	10.7	12.4	11.1	11.3
MINPED(rpm)	M	82.0	88.4	91.9	92.7	91.4
	SD	12.7	12.2	12.0	12.3	9.1

PP = peak power; MP = mean power; MINP = minimum power
MAXPED = maximum pedaling rate;
MINPED = minimum pedaling rate

Table 1. Peak power, mean power, minimum power, maximum and minimum pedaling rate with changes in crank arm length

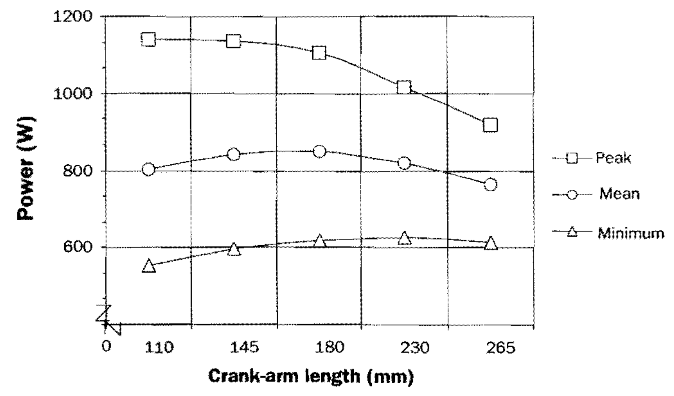

Figure 2. Predicted peak power, mean power and minimum power with increasing crank-arm length.

tested in each of the five pedal-crank-arm-length conditions, with the order of testing randomly assigned. There was a minimum of 24 hours of recovery between test sessions. For each condition, pedal toe clips were worn, and the subject was strapped to the seating apparatus at the hip and trunk.

The recumbent cycling position used for all test sessions, was defined by a 75°angle formed between the bicycle seat tube and a vertical line passing through the crank spindle (see figure 1; Too, 1991). To obtain this seating position, a variable seating apparatus, allowing for manipulations in seat-tube angle, backrest angle and seat-to-pedal distance was used and interfaced to a Monark cycle ergometer (Model 814E). The seat backrest was kept perpendicular to the ground and the seat-to-pedal distance adjusted to 100% of the total leg length of each subject, as measured from the right femur to the ground (Too, 1991). The test protocol involved a computerized 30-second Wingate Anaerobic Cycling Test. To initiate the test, the subject pedaled the cycle ergometer with no load. Once the ergometer's inertial resistance had been overcome, the appropriate load (85 g/kg of the subject's body mass) was instantaneously applied using calibration weights, and the subject pedaled as hard and as fast as possible for 30 seconds. A Sports Medicine Industry (SMI) opto-sensor (Model 2000) with a sampling rate of 50 Hz, interfaced with a Zenith 386 micro-computer, in conjunction with 16 reflective markers on the ergometer flywheel, was used to monitor and record flywheel revolutions during the test. Peak power was calculated from the highest average flywheel speed during any consecutive five seconds, mean power was determined from the mean flywheel speed for the entire 30-second test, and minimum power was calculated from the lowest mean flywheel speed during any consecutive five seconds (which was always the last five seconds). The different power variables were calculated using the following equation:

Peak power (watts) = [load (N)] × [distance covered by flywheel with one revolution (1.615 meters per revolution) × average number of recorded flywheel revolutions for five seconds (rpm)]/[1 min/60 sec].

Additionally, maximum and minimum pedaling rates were calculated from flywheel speed recorded for peak power and minimum power, respectively. The equation used in this calculation was:

Pedaling rate (rpm) = average flywheel rpm for five seconds / 3.7 flywheel revolution per pedal-crank revolution (Gledhill and Jamnik, 1995).

This would be equivalent to a 52/14 gear ratio. Curve estimation with regression analysis was used to determine: (1) the trend in peak power, mean power and minimum power with changes in crank-arm length; and (2) the crank-arm length that would maximize peak power, mean power and minimum power during a 30-second test.

RESULTS

With changes in crank-arm lengths, the mean ± SD values of peak power, mean power, minimum power, maximum and minimum pedaling rates are presented in table 1.

Based on regression analysis the change in peak power, mean power and minimum power with increasing crank-arm length, appears to be best described by a parabolic curve, represented by the equation: $y = -x^2 + x + C$ (where y represents power and x represents crank-arm length) as shown in figure 2. The specific regression equations for the various measures of power were as follows:

Peak power (quadratic trend, $p = 0.006$): $y = -0.011x^2 + 2.8x + 972$ ($SE = 11$)

Mean power (quadratic trend, $p = 0.011$): $y = -0.011x^2 + 3.8x + 513$ ($SE = 5$)

Minimum power (quadratic trend, $p = 0.002$): $y = -0.007x^2 + 2.8x - 325$ ($SE = 2$).

From table 1, several observations can be made: (1) regardless of crank-arm length, peak power is greater than mean power, and mean power is greater than minimum power; (2) peak power is greatest with the 145-mm crank-arm length and least with the 265-mm crank-arm length; (3) mean power is greatest with the 145- and 180-mm crank-arm lengths and least with the 265-mm crank-arm length; (4) minimum power is greatest with the 230-mm and least with the 110-mm crank-arm length; and (5) maximal and minimal pedaling rates occur with the 110-mm crank-arm length. From regression equations, the predicted crank-arm lengths to maximize peak power, mean power and minimum power are 124 mm, 175 mm and 215 mm, respectively.

Discussion

Since no literature could be found examining the effect of changes in crank-arm length on cycling performance in a recumbent position, comparisons will be made with the literature available for an upright position. The parabolic curve observed in peak power and mean power with increasing crank-arm length is consistent with the trend for an upright position reported by: (1) Inbar *et al.* (1983) for five crank-arm lengths (125, 150, 175, 200 and 225 mm); and (2) Too and Landwer (2000) for five crank-arm lengths (110, 145, 180, 230 and 265 mm). From best-fitting parabolic curves, Inbar *et al.* (1983) described the peak power and mean power to occur at a crank-arm length of 166 mm and 164 mm, respectively; whereas Too and Landwer (2000) predicted peak power and mean power to be maximized with crank-arm lengths of 164 and 200 mm, respectively. This is quite in contrast with the predicted crank-arm lengths (124 and 175 mm) to maximize peak power and mean power, respectively, for a recumbent position.

The largest peak power (762.7 W) and mean power (615.9 W) values reported by Inbar *et al.* (1983), and those reported by Too and Landwer (2000; largest peak power and mean power values to be 968 W and 718 W, respectively) are less than the largest peak power (1144 W) and mean power (845 W) values recorded for the recumbent position in this investigation. In fact, except for the 265 mm crank-arm length condition, peak power values (and all mean power values) in the recumbent position were greater than the largest peak and mean power values reported by Inbar et al (1983) and by Too and Landwer (2000) for an upright position. The smaller peak power and mean power values reported by Inbar *et al.* (1983) may be attributed to a smaller load used (75 g/kg body mass) and/or to the different stature of the subjects tested (approximately 10.5 kg smaller, 73 mm shorter than the subjects of this investigation). However, the smaller peak and mean power values reported by Too and Landwer (2000) are probably attributed to differences in lower-limb joint angles (between an upright and recumbent position) and/or to a smaller force production potential in an upright position (since there is no seat-backrest to push against).

Based on the predicted crank-arm lengths to maximize the different power variables, and the trend of peak power, mean power and minimum power with changes in crank-arm length, it would appear that an interaction exists between crank-arm length and power production, with the optimal crank-arm length to maximize power dependent on load and pedaling rate. Since power is a function of both force and velocity, the optimal crank-arm length to maximize peak power would be one where the maximum pedaling rate is produced and maintained with the largest load that can be applied. Although manipulation of load was not examined in this investigation, changes in crank-arm length would alter the torque on the crank arm (when the same force is applied) and would be analogous to a change in load. Based on the force-velocity relationship, a longer crank-arm length resulting in a lower "load" experienced by the lower limbs will result in a greater linear velocity at the pedal (when compared to the same pedaling rate with a shorter crank-arm length). This was confirmed when the maximal pedaling rates determined for the different crank-arm lengths of this investigation were converted to maximal linear pedal velocity. The maximal linear pedal velocity was found to increase (although the maximal pedaling rate decreased) with increasing crank-arm lengths from 110 to 265 mm. Similarly, an increase in crank-arm length from 110 to 265 mm also resulted in an increase in minimum linear pedal velocity (as determined from the minimum pedaling rates) and is also consistent with that expected from force-velocity relationships. Since parabolic curves in power were observed with increasing crank-arm lengths, and the largest values for peak, mean and minimum power were found with three different crank-arm lengths, this would indicate that the optimal crank-arm length to maximize power is dependent on the type of power examined.

In this investigation, the optimal crank-arm lengths predicted to maximize peak, mean and minimum power with a load of 85 g/kg BM, were 124 mm, 175 mm and 215 mm, respectively. The interaction between crank-arm length, pedaling rates and load (as evidenced by parabolic curves for power), would suggest that the optimal crank-arm length for peak, mean and minimum power would change with different loads. Based on the force-velocity-power relationship, increased loads to maximize power, resulting in a decreased pedal rate would favor longer crank-arm lengths.

Changes in crank-arm length will affect not only the force-velocity-power relationship, but also the muscle force-length relationship. From the force-length curve, a muscle can produce its largest force at resting length, with a decrement in force at increasing or decreasing lengths. Systematic increments in crank-arm length (from 110 to 265 mm) for an upright cycling position have been reported to result in significant decrements in minimum hip and knee angle, and significant increments in hip and knee range of motion (Too and Landwer, 2000). Whether it is more advantageous to use a long crank arm or a short crank arm is unknown because there is a complex interaction among changes in joint angles, muscle length and muscle-moment-arm length to produce force and torque with changes in crank-arm length. This complexity is further increased when multi-joint muscles that cross the hip and knee, or knee and ankle are involved and interact with force-velocity-power relationships. Additional research into the interaction of crank-arm length, pedaling rate and load on power production is needed before the limits of performance in human-powered vehicles can be reached.

SUMMARY

The predicted crank-arm lengths to maximize peak power, mean power and minimum power in a recumbent cycling position, using a resistance load of 85 g/kg body mass, were 124 mm, 175 mm and 215 mm, respectively. This would suggest that for human-powered vehicle competitions of short duration, where maximal peak power is necessary, a shorter crank-arm length is recommended. For competitions of longer duration where fatigue is a factor and the largest mean power and minimum power become important, it is suggested that longer crank-arm lengths be used.

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Bicycle pitchover characteristics

by Frederick H. Matteson

SUMMARY

Pitchover is explained and a graph developed showing boundaries versus slopes. Situations and road characteristics are discussed.

INTRODUCTION

Pitchovers, wherein the bicycle and rider rotate forward about the front wheel, have been a problem since the early days of cycling when the high-wheel, direct-drive bicycle, commonly referred to as the "Ordinary" and later, derisively, as the "Penny Farthing", was used. The position of the rider, high and forward with respect to the front axle, made these cycles likely to pitch forward particularly in descents with braking. It was this danger that led to the development of the chain-driven "safety bicycle" still in use today. Today's bicycles, with the rider well back between the wheels, are far safer, but pitchovers can and do still occur.

This article concerns the matter of hills. That steep hills are an expectation of touring cyclists is evident by the installation of triple chainwheels and wide-range gearing on touring machines. Before the time of the automobile steep roads were common in this country. Horses could climb steep hills, but cars had limited climbing ability. The author recalls seeing Ford Model T's stop at the bottom of a hill, turn around and back up because they could climb a steeper hill in reverse gear. Such a practice was not reasonable and the trend has been towards less-steep public roads in the United States. The process of building safe, high-speed roads has consisted of straightening and leveling, often at great expense and difficulty. Abroad, and in particular in lesser-developed lands or where there are fewer automobiles, even main roads may be unsealed, crooked and containing steep slopes. Safety features common

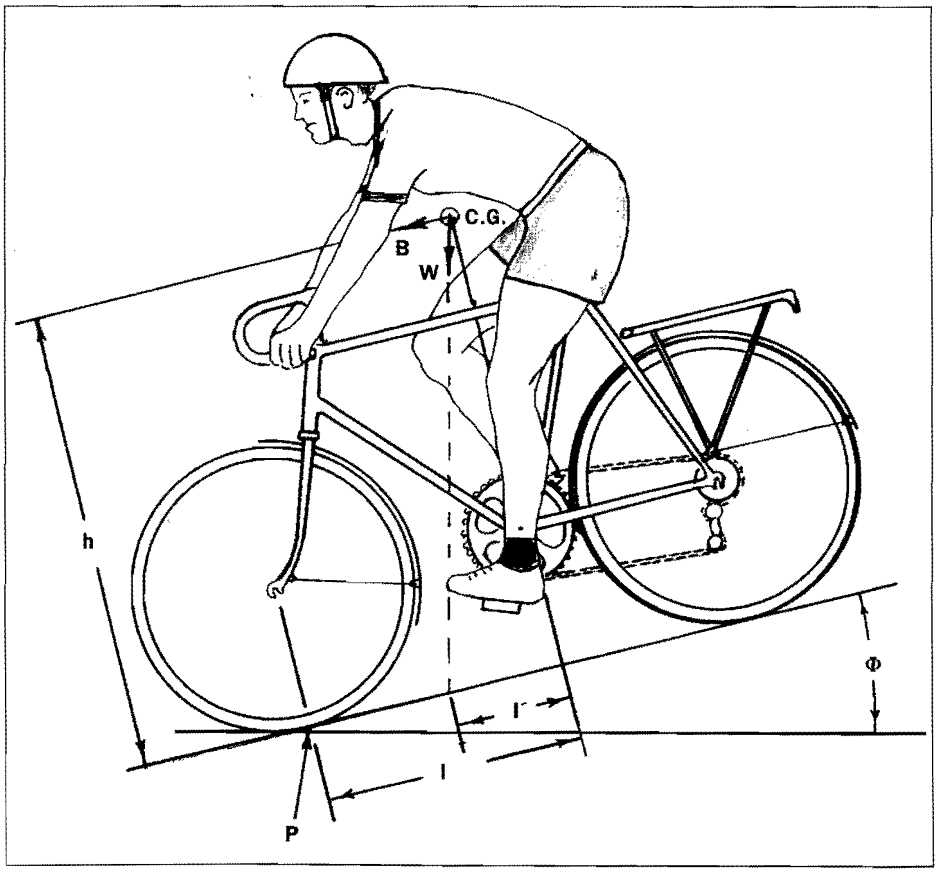

Figure 1. Sketch of forces and moment arms on bicycle and rider