EFFECT OF CHANGES IN CRANK ARM LENGTH AND LOAD ON POWER PRODUCTION IN RECUMBENT CYCLING

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The purpose of this study was to determine the trend in peak power (PP), mean power (MP), and minimum power (MINP) with changes in load when cycling in a recumbent position. Fifteen female participants were randomly assigned to one of three crank arm length (CAL) conditions (110, 180, or 250 mm) and tested on a Monark Cycle ergometer with 5 loads varying from 75-165 gm/kg of body mass. The Wingate Anaerobic Cycling test was performed in a recumbent position (75° seat tube angle, backrest perpendicular to the ground). Curve estimation with regression analysis on incrementing loads revealed: (1) a quadratic trend in PP; (2) a quadratic trend in MP and MINP for the 110 and 180 mm CAL; and (3) a linear trend in MP and MINP for the 250 mm CAL. These trends suggest there is an optimal load for different CALs to maximize power production.

KEY WORDS: recumbent, cycling, crank-arm length, load, power

INTRODUCTION: It is well documented that recumbent human powered vehicles with an aerodynamic fairing, 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 110.65 km/hr (68.73 mph), established in 1992 by a single rider on a recumbent bicycle named the Cheetah (Kor, 1992), 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 not only focus on the aerodynamics, but also to examine the variables that affect power production in recumbent cycling and the interactions that would maximize power. Investigations of recumbent cycling and power production have examined changes in seat-tube angle (Too, 1991), trunk/backrest angle (Too, 1994), seat to pedal distance (Too, 1993), and CAL (Too, 1996).

Too (1991), examining a systematic change in seat tube angle (0°, 25°, 50°, 75°, and 100°) with a load of an 85 gm/kg of body mass (BM), reported a 75° seat tube angle to yield the largest PP and MP, with a parabolic curve (quadratic trend) to best describe the change in PP and MP with changing seat tube angles. Using a 75° seat-tube angle and an 85 gm/kg load, Too (1994) investigated the effect of 3 trunk angles (60°, 90°, and 120°) on power production. A 90° trunk angle was reported to yield the largest PP and MP, and that a parabolic trend best described PP and MP with changes in trunk angle. Using a 90° trunk angle, a 75° seat tube angle, and an 85 gm/kg load, Too (1993) examined the effect of seat-to-pedal distance (90%, 95%, 100%, 105%, and 110% of total leg length) on power production. A quadratic and linear function was reported to best describe the trend in PP and MP with changing seat-pedal-distance. In addition, Too (1996) examined changes in CAL (110, 145, 180, 230, and 265 mm) with a 75° seat tube angle, a 90° trunk angle, a 100% seat-to-pedal distance, and a load of 85 gm/kg BM. A 110 and 180 mm CAL was reported to yield the largest PP and MP, respectively; and that a linear and quadratic trend was reported to best describe the change in PP and MP, respectively, with increasing CAL (Too, 1996).

Based on muscle force-length and force-velocity-power relationships, changes in CAL and load will affect joint angles, muscle length, force, torque, and power production in cycling. Since the literature involving traditional cycling positions and power output have reported an interaction between CAL, load, and pedaling cadence (Hull & Gonzalez, 1988; Yoshihiku & Herzog, 1990), it can be assumed that similar interactions will occur in a recumbent cycling position. Therefore the purpose of this investigation was to determine what trends exist (if any) with systematic changes in load on power production with changes in CALs. Any trends in power production will provide information regarding loads and CALs to maximize power production during recumbent cycling.

METHODS: Fifteen healthy volunteer female participants (mean age = 22.3 ± 4.25 yr., weight = 60.6 ± 9.45 kg, height = 165 ± 9.8 cm) were randomly assigned to one of three CAL conditions (110 mm, 180 mm, or 250 mm) and tested with 5 different loads. The 5 loads used in the 110 mm CAL condition were 75, 90, 105, 120, and 135 gm/kg BM. The loads used in the 180 mm CAL condition were 90, 105, 120, 135, and 150 gm/kg BM**;** whereas the loads used in the 250 mm CAL condition were 105, 120, 135, 150, and 165 gm/kg BM. All five participants in each CAL condition were tested with the designated loads according to a randomly determined sequence and with a minimum of 24 hours rest between test sessions.
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 (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 was adjusted to 100% of total leg length for each subject as measured from the right femur to the ground (Too, 1991). Two adjustable crank arms, allowing for manipulations from 0 to 300 mm, were used for the 110, 180, and 250 mm CAL conditions (Too, 2000).
Each subject was strapped to the seat-backrest at the trunk and hips, and pedal toe-clips were used. 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 was instantaneously applied using calibration weights, and the subject pedaled 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 and used in conjunction with 16 reflective markers on the ergometer flywheel, was used to monitor and record flywheel revolutions during the test. PP was calculated from the highest average flywheel speed during any consecutive 5 seconds; MP was determined from the mean flywheel speed for the entire 30-second test, and MINP was calculated from the lowest mean flywheel speed during any consecutive 5 seconds. Curve estimation with regression analysis on incrementing loads was used to determine the trend in PP, MP, and MINP with the 110, 180, and 250 mm CAL.

RESULTS: With changes in load, the mean ± SD values of PP, MP, and MINP for the 3 CALs are presented in Table 1.

Table 1 Peak Power, Mean Power, and Minimum Power with Changes in Load and Crank arm Length

		LOAD (gm/kg of body mass)						
CAL (mm)	Power (W)	75	90	105	120	135	150	165
	PP	568 ± 89	678 ± 155	647 ± 82	606 ± 80	577 ± 216		
110	MP	345 ± 101	370 ± 116	353 ± 101	279 ± 110	170 ± 108		
	MINP	223 ± 96	222 ± 128	211 ± 120	175 ± 107	48 ± 76		
	PP		488 ± 57	542 ± 51	511 ± 75	462 ± 101	435 ± 91	
180	MP		317 ± 57	312 ± 59	291 ± 58	225 ± 98	156 ± 81	
	MINP		217 ± 42	199 ± 50	197 ± 43	125 ± 115	34 ± 54	
	PP			488 ± 79	514 ± 71	512 ± 117	490 ± 79	479 ± 113
250	MP			366 ± 63	359 ± 72	362 ± 82	330 ± 69	317 ± 97

MINP	277 ± 41	262 ± 60	265 ± 58	243 ± 66	220 ± 62

Based on regression analysis of power production with incrementing loads and different CAL, several trends were determined (see Figure 1). PP is best described by a quadratic trend for all three CAL, although the trends were not significant ($\underline{p} > 0.05$). MP with the 110 and 180 mm CAL is best described by a quadratic equation ($\underline{p} < 0.01$), whereas MP with the 250 mm CAL is best characterized by a linear equation ($\underline{p} < 0.05$). MINP with the 110 and 180 mm CAL is best represented by a quadratic function ($\underline{p} < 0.05$), whereas MINP with the 250 mm CAL is best described by a linear function ($\underline{p} < 0.05$). The specific regression equations for the various measures of power with incrementing loads, using different CALs are as follows:

Peak Power:
110 mm CAL (quadratic trend, p = 0.29): $PP = -0.091x^2 + 18.8x - 311$ (standard error = 35)
180 mm CAL (quadratic trend, p = 0.17): $PP = -0.058x^2 + 12.6x - 165$ (standard error = 24)
250 mm CAL (quadratic trend, p = 0.17): $PP = -0.050x^2 + 7.9x - 1$ (standard error = 9)
Mean Power:
110 mm CAL (quadratic trend, p = 0.001): $MP = -0.103x^2 + 18.7x - 480$ (standard error = 3)
180 mm CAL (quadratic trend, p = 0.004): $MP = -0.055x^2 + 10.5x - 184$ (standard error = 6)
250 mm CAL (linear trend, p = 0.03): $MP = -0.851x + 462$ (standard error = 10)
Minimum Power:
110 mm CAL (quadratic trend, p = 0.03): $MINP = -0.088x^2 + 15.9x - 479$ (standard error = 18)
180 mm CAL (quadratic trend, p = 0.02): $MINP = -0.069x^2 + 13.6x - 456$ (standard error = 14)
250 mm CAL (linear trend, p = 0.02): $MINP = -0.881x + 372$ (standard error = 9)

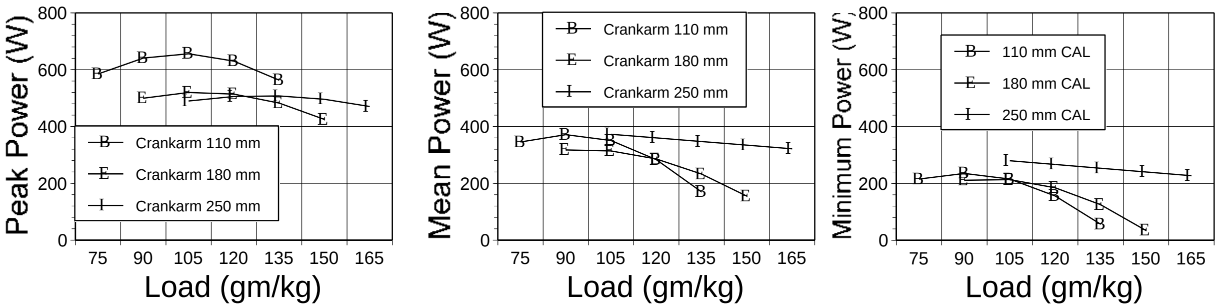

Figure 1 - Predicted power production with incrementing load for the 110, 180, and 250 mm CAL.

From Table 1 and the trends in Figure 1, several observations can be made: (1) PP is generally greater than MP, and MP greater than MINP regardless of CAL and load; (2) PP is greater with the 110 mm CAL than with the 180 or 250 mm CAL regardless of load; (3) MINP is greater with the 250 mm CAL than with the 110 or 180 mm CAL regardless of load; and (4) as load increases, power production appears to be favored with longer CALs. Based on the trend of PP, MP, and MINP for the different CALs with comparable loads (105, 120, and 135 gm/kg of body mass), It would appear that there is an interaction between CAL, load, and power production.

DISCUSSION: In this investigation, the trends observed in power production appear to be consistent with the interactions of load, pedaling rate, CAL, and power output that have been reported in the upright cycling literature (Hull & Gonzalez, 1988; Yoshihiku & Herzog, 1990). With increasing load for any given CAL, greater PP is produced if the same maximal pedaling rate can be reached and maintained. If the load exceeds some optimal or critical value and the maximal pedaling rate cannot be attained or sustained, there will be a decrement in PP as observed in the trends for the 110, 180, and 250 mm CALs. Although pedaling rate was not directly measured in this investigation, it can be calculated from the recorded flywheel revolutions. When Too (1996) reported a decreasing linear trend in PP with increasing CAL (from 110 to 265 mm) using a fixed load (85 gm/kg BM), it can be assumed that the load was large enough to maximize PP only for the 110 mm CAL. If greater loads (such as those in this investigation) were used, a quadratic trend in PP would be expected with increasing CALs. However, when the same fixed load (85 gm/kg BM) was used in upright cycle ergometry, a quadratic trend was found in PP with increasing CAL from 110 to 265 mm (Too, 2000). This difference in PP trend (linear vs. quadratic) between an upright and recumbent position would suggest that greater PP can be achieved in a recumbent cycling position (when compared to a standard upright cycling position) and may be attributed to greater pedal forces when using a seat-backrest to push against.

In this investigation, the greater PP obtained with the 110 mm CAL (when compared to the 180 and 250 mm CAL) can be attributed to the greater pedal rate that can be achieved with a shorter CAL. As the load increased from 105 to 135 gm/kg BM, the same maximum pedal rate for the 110 mm CAL apparently could not be maintained resulting in a decrement in PP. The trends in PP for the 3 CALs would suggest that if PP were extrapolated (using a load of 165 gm/kg BM) for the 110 and 180 mm CAL, PP for the 110 mm CAL would be less than that of the 180 and 250 mm CAL.

This appears to be supported by the smaller MP and MINP values of the 110 mm CAL when compared to those of the 180 and 250 mm CAL with a load of 135 gm/kg BM. The smaller MP and MINP values of the 110 mm CAL can be attributed to a decrement in pedaling rate due to fatigue in the latter part of the test. As the load increased, pedal rate and power production decreased, and even more so with shorter CALs and with the onset of fatigue. This interaction between load, CAL, and pedaling rate would be consistent with what would be expected based on muscle force-length and force-velocity-power relationships.

Although only females were selected (due to their relatively smaller body masses when compared to males, and to the maximum load limit of the ergometer) to participate in this investigation, similar trends in power production would be expected with males if similar loads and CALs were used.

CONCLUSION: The trends in PP, MP, and MINP with incrementing load for 3 CALs (110, 180, and 250 mm), would suggest there is an optimal load for different CALs to maximize power production in a recumbent cycling position. For human powered vehicle competitions of short duration, where maximal PP is necessary, a short CAL is recommended for use with the largest load that would not result in a decrement in maximal pedal rate. For competitions of longer duration where fatigue is a factor and greater MP and MINP becomes important, it is suggested that a long CAL is used with the largest load that would not result in a decrement in maximal pedal rate. The optimal load(s) for various competitions would be dependent on the force and power production capability of each individual.

REFERENCES:

Hull, M.L., & Gonzalez, H. (1988). Bivariate optimization of pedalling rate and crank arm length in cycling. *Journal of Biomechanics*, **21**, 839-849.

Kor, J. (1992). News flash! *Human Powered Vehicle News*, **9** September/October, 7.

Kyle, C.R. (1982). *Bicycling*, **23**, 59-66

Too, D. (1991). The effect of hip position/configuration on anaerobic power and capacity in cycling. *International Journal of Sports Biomechanics*, **7**(4), 359-370.

Too, D. (1993). The effect of seat-to-pedal distance on anaerobic power and capacity in recumbent cycling. *Medicine and Science in Sports and Exercise*, **25**(5), S68. (Abstract)

Too, D. (1994). The effect of body orientation on power production in cycling. *The Research Quarterly for Exercise and Sport*, **65**, 308-315.

Too, D. (1996). The effect of pedal crankarm length on power production in recumbent cycle ergometry. In T. Bauer (ed.) *Proceedings of the XIII International Symposium on Biomechanics in Sports* (pp. 350-353). Lakehead University Printing Services, Thunder Bay, Ontario, Canada.

Too, D. (2000). The effect of pedal crank arm length on joint angle and power production in upright cycle ergometry. *Journal of Sports Sciences*, **18**(3), 153-161.

Yoshihiku, Y., & Herzog, W. (1990). Optimal design parameters of the bicycle-rider system for maximal muscle power output. *Journal of Biomechanics*, **23**, 1069-1079.