The Effect of Crank Length on Delta Efficiency In Recumbent Cycling

Tyler Baker and Dr. Mark Archibald
Grove City College
Grove City, PA 16127
Email: bakertk1@gcc.edu

Abstract

This study investigated the effect of bicycle crank length (CL) on delta efficiency (DE) in recumbent cycling ergometry. Crank lengths of 170mm, 140mm and 115mm were used in this study. Focus was placed on cranks that are shorter than the typical 170mm cranks, due to reported and potential benefits of short crank arms. Benefits include reduced space requirements for pedaling, improved vehicle aerodynamics, and a potential reduction in joint stress. A volunteer group of 12 males and 9 females n = 21, [mean (SD)] age [27.5 (14.6)], and xseam [102.8 cm (5.6 cm)] were selected to ride on a recumbent cycling ergometer with a typical hip angle of approximately -11°. To determine delta efficiency, cycling power and metabolic power output was measured for each subject at 3 power levels for each of the three cranks being tested. The mean DE for the 115mm, 140mm and 170mm cranks was 0.30 ±0.07 0.31 ±0.07 0.30 ±0.07 respectively. No statistically significant effect of crank length on DE was found at the α =.05 level of significance (p = 0.84) for the crank lengths tested. Delta efficiency is insensitive to crank length over the range tested.
Introduction

Cycling for transport, recreation, and training is usually conducted at sub-maximal exertion levels. Efficiency is thus a better metric for assessing the overall biomechanical system performance than maximum power. Crank arm length is an important system parameter, which has an effect on many system variables including joint angle ranges, leg inertial loads during pedaling, pedal force, cadence, and muscle excitation frequency. An important vehicular parameter directly related to crank length is the space required for pedaling, which has an effect on vehicle design parameters and aerodynamics. Anecdotal evidence in bike forums and periodicals indicates that some cyclists – including the authors – prefer short cranks when cycling recumbent vehicles where the crank is located higher than the seat. This study evaluates the effects of crank length on delta efficiency in recumbent cycling with high crank position.

This study is limited to normal and short crank arm lengths. Known advantages of short crank arms include reduced aerodynamic drag and reduced joint angle range. Recumbent cycles, particularly those with high cranks, reduce aerodynamic drag. Short cranks can further reduce drag by reducing frontal area and allowing a lower, more streamlined fairing. Shorter cranks also reduce the hip, knee, and ankle joint ranges of motion during pedaling, although the maximum angles also depend on seat position. When the seat position is adjusted such that the maximum leg extension is constant with respect to crank length, knees bend to a less acute angle with shorter cranks. The leg muscles exert a force on the joints through a smaller range of joint angles. Some individuals with knee problems have reported that the movement of smaller
cranks makes pedaling more enjoyable because of decreased stress on the knees. Longer crank arms increase forces on tendons in the knee which can cause knee pain and injury¹.

Several measures of efficiency have been proposed⁸. Gross efficiency is defined as the ratio of mechanical energy delivered to total metabolic energy expended. Gross efficiency tends to increase with workload so there is no linear relationship between work rate and energy expenditure. Net efficiency and work efficiency use resting energy expenditure or unloaded cycling, respectively, as a baseline. Moseley and Jeukendrup report that baseline energy expenditure is not likely to stay constant during changing environmental conditions, oxygen uptake, or pedaling cadence. Delta efficiency (DE) is defined as the change in mechanical energy delivered divided by the change in metabolic energy expended. An alternative, but equivalent definition of DE is the slope of the curve resulting when mechanical energy delivered is plotted against metabolic energy expended. DE may provide the most valid estimate of muscular efficiency, as it removes the effects of homeostasis on energy expenditure³. In this study delta efficiency is used to assess the effects of crank length on recumbent cycling.
The effects of crank arm length on cycling performance has been studied by several investigators but is not yet fully understood. The difficulty is likely due to the complex interaction of crank length with other system parameters, coupled with varying definitions of optimal performance. Danny Too lists several factors that interact with crank-arm length to determine cycling performance. These factors include anthropometric dimensions such as height, leg length, and thigh-to-leg ratio; seat-to-pedal distance, cycling position, load/resistance/gear ratio, cadence, training effects, inter-individual variation and intra-individual variation\textsuperscript{11}. Performance metrics have also varied, including peak and mean power in a 30 second Wingate test, time to fatigue, and various cost functions. Relatively few studies have specifically addressed recumbent cycling.

Figure 1 Illustration of computation of delta efficiency

\[ DE = \frac{P_{e,2} - P_{e,1}}{P_{m,2} - P_{m,1}} \]
Hull and Gonzalez developed a biomechanical model of the lower limb in upright cycling. A cost function based on hip and knee moments was used to evaluate the effects of varying crank arm length and cadence. They were able to identify quasi-static and kinematic components of the joint moments, and demonstrated that an optimum crank length and cadence exists. For an average sized man, they found 145 mm crank arms and 110 RPM to be optimal. The optimal crank length decreases as cadence increases, but cadence affected the cost function more strongly than crank arm length. As power increased, optimal crank length decreased and cadence increased. Optimal crank length and cadence also depend on stature. Hull and Gonzalez noted that these results do not agree exactly with cycling practice. However, it is of interest that this purely mathematical model predicts trends that do generally agree with cycling practice. For example, the models show that the cost function is relatively insensitive to crank length, but more sensitive to cadence. Other studies, including the current study, support this general conclusion.

Optimal crank length depends strongly on joint angles and muscle length and velocity. Muscle force is optimized at resting length. As the rate of contraction of a muscle fiber increases, the force decreases. Power is maximized when the muscle force is approximately one-third of the maximum. Too and Landwer emphasized the importance of joint angles, muscle length, and the load/velocity relationships for cycling with different crank lengths and cycling positions. They concluded that optimal joint angles are both important and unknown.

Several studies have used the 30 second anaerobic Wingate test to assess the effect of crank length on power performance. Results indicate an inverse quadratic relationship between
power and crank length. Although the optimum value varies somewhat between studies, for upright cycling it appears that the standard 170 mm length is close. Inbar, et. al. used a 30 second anaerobic Wingate test and found that peak power (PP) and mean power (MP) in upright cycling both follow an inverse quadratic relationship with crank length. Peak power and mean power were maximized with 164 mm and 166 mm cranks, respectively. They also determined that the optimum crank length increased with leg length, with optimal leg length to crank arm length ratios of 6.36 and 6.28 for mean and peak power. Too and Lander conducted a similar study. In addition to determining PP and MP, joint angles were measured during the 30 second anaerobic Wingate test. The upper body was constrained at a 90 degree angle to the ground. Results again indicated an inverse quadratic relationship between power and crank length. In this case, quadratic regression showed optimal crank lengths of 171 mm and 197 mm for PP and MP respectively. Maximum hip, knee, and ankle joint angles remained relatively constant for different crank lengths, but the range of motion, particularly for the hip and knee angles, decreased with decreasing crank length.

A similar study was conducted using a 30 anaerobic Wingate test for the recumbent position. Subjects were tested in a recumbent position using a seat tube angle of 75 degrees and vertical backrest. In this case, the crank lengths for optimizing PP and MP were considerably shorter than for the upright study with optimal lengths (based on quadratic regression) of 124 mm (for PP) and 175 mm (for MP). Shorter cranks may be optimal for recumbent cycling events where high power for short duration is required. The importance of joint angles on power performance was also noted. Too also compared upright and recumbent results. Both PP and MP were significantly higher in the recumbent position as compared to
the upright cycling position. This suggests that the joint angles may be more effective in the recumbent position.

Too and Landwer investigated the effect of crank arm length on cycling duration in the recumbent position\(^\text{12}\). Subjects pedaled at 60 RPM on a recumbent ergometer with a 75 degree seat tube and backrest perpendicular to the ground. The maximum time to fatigue occurred with 145 mm cranks, but was not significantly different from the time to fatigue with 180 or 230 mm cranks. Regression coefficients were not reported, but a quadratic regression using the reported data indicates a maximum time to fatigue would correspond to 184 mm cranks. The different results of the anaerobic power test and the fatigue test are likely due to force-load-speed characteristics required for the two tests. However, the relatively low cadences in fatigue tests favor the use of longer cranks. As cadence increases, the optimal crank length to delay fatigue decreases. Conversely, in anaerobic power tests such as the Wingate test, high power loads favor longer crank arms. As the power level decreases, the optimal crank length also decreases\(^\text{13}\). This emphasizes the relationship between pedal force, cadence, and crank arm length.

Method

A volunteer group of 12 males and 9 females \(n = 21\), [mean (SD)] age [27.5 (14.6)], and xseam [102.8 cm (5.6 cm)] was selected to participate in the study. Subject xseam was measured by having each individual sit with their legs extended horizontally and their back resting against the back of the chair 30 degrees from vertical. The distance from the bottom of the back of the bench to the ball of their foot with their toes pointed vertically was measured. Xseam is a common method of sizing recumbent bicycles. The subjects were intentionally selected to provide a diverse range of age, fitness level, and cycling experience.
experience was self rated on a scale of 1, 2, or 3 corresponding too seldom, weekly or daily bicycle riding. No professional or competitive cyclists participated in this study.

Subjects were tested on a custom made recumbent ergometer with a free motion flywheel (97×10³ kg s² / m³ inertia) as shown in Figure 1. The seat and crank are set such that the hip orientation angle for most subjects is approximately -11°, the body orientation angle is typically around 140° and the backrest is at an angle of 30° from horizontal. The velocity ratio between the flywheel and chainring is 2.75. The ergometer used in this study is equipped with a free motion flywheel to best simulate actual cycling. That is, the driven sprocket is attached to the flywheel with a one-way clutch. As in actual cycling, energy can only be transferred in one direction, from the crank to the flywheel.

![Figure 2 Ergometer with free motion flywheel illustration](image)

The ergometer power is determined by measuring the flywheel speed and torque. Torque is measured with force transducers (Omega Engineering LC101-100 and LC101-50) installed on both the tension and slack sides of the belt. Flywheel speed is measured with a magnetic reed.
switch. The state of the reed switch was digitally sampled at 2000 Hz, decimated to 20 Hz to be compatible with sample rates used for the remaining transducers. The ergometer power $P_e$ is computed from the belt tensions $F_{\text{tension}}$ and $F_{\text{slack}}$ and the flywheel radius $R$ by:

$$
P_e = (F_{\text{tension}} - F_{\text{slack}}) \times R \times 2\pi \omega
$$

Both force transducers and the magnetic reed switch were sampled at a rate of 20 hertz and digitized with an E-DAQ Lite data acquisition system from Somat, Inc. Fine control of belt tension, and hence ergometer load, is regulated with a hand knob. The subject’s power level is monitored in real time via a computer display.

Metabolic data was measured using aVO2000 metabolic testing system and Breeze software, both produced by Medgraphics. The respiratory exchange ratio (RER), breathing rate (BR), heart rate (HR), VO$_2$ and VCO$_2$ were collected continuously throughout the test. Metabolic data was averaged over three, six or nine consecutive breaths depending on the rate of respiration. Metabolic power $P_m$ was calculated from the subjects' RER and VO$_2$ using the following formula:

$$
P_m = \left[ VO_2 \times 1.24 \times \left( \frac{VCO_2}{VO_2} \right) + 3.81 \right] \times 0.068 \, \text{Watts}
$$

This equation is obtained by interpolating data from published tables and incorporating a conversion factor to obtain Watts$^{17}$. Subjects were briefed on the procedure and familiarized.
with the ergometer prior to testing. The seat was positioned for each crank length such that the
minimum knee angle was approximately 30° and the subject could pedal comfortably. All
participants used cycling shoes and clipless pedals. Subjects were given an opportunity to
stretch and warm up prior to and between tests. Sports snacks and drinks were provided to
subjects between and after tests.

Prior to each test, the subject self selected a comfortable cadence while pedaling at the
medium power level before the test began. Subjects were instructed to maintain their chosen
cadence for each of the three power levels in the test. A metronome and a digital readout
tachometer were provided to help subjects maintain cadence. Cadence was reselected by the
subject when the cranks were changed. Subjects were informed that most people prefer a higher
cadence for shorter cranks and a lower cadence for longer cranks. The actual cadence
maintained by the subject was measured during the test and later compared to the target cadence.
The mean square difference between target cadence and actual cadence was 4.8 %.

Subjects were tested using crank lengths of 115mm, 140mm and 170mm, given in
randomized sequence. For each crank a given subject maintained the same three power levels
given in increasing order. The three ergometer power levels used 30 watt increments and were
selected based on the subject’s age, gender and fitness level. Subjects were tested at one of the
following sets of three power levels: {30W 60W and 90W}, {45W 75W and 105W}, {60W 90W
and 120W}, {80W 110W and 140W} or {90W 120W and 150W}. Each power level was
maintained for 5 minutes total; 3 minutes for the subject to establish equilibrium in bodily
systems as measured by respiration and heart rate and 2 minutes of data collection at a constant
respiration and heart rate. After the 2 minutes of data collection at the third power level the power was decreased and the subject was given a brief cool down period. Succeeding each test, subjects were given a ten minute rest, offered a snack and asked to rate their perceived level of exertion for the crank length just tested. Average metabolic and ergometer power ($P_m$ and $P_e$) were calculated for each test. Delta efficiency was then calculated by:

$$\Delta E = \frac{P_e,2 - P_e,1}{P_m,2 - P_m,1}$$

Since each subject was tested at three power levels for each of the three cranks, six values of DE were obtained for each subject. The data was first analyzed using 2-way ANOVA to test for a significant effect due to crank length alone. To investigate effects of cadence, individual differences, and other variables, an N-way ANOVA model was used.

A preliminary, non-reported study tested 13 subjects with two crank lengths, 140 and 170 mm. Subjects in the preliminary study were tested for longer time intervals (8 minutes at each power level; 5 minutes for the subject to establish equilibrium in bodily systems at each power level and 3 minutes data acquisition.) Data from the preliminary study indicated that delta efficiency did not change in the last two minutes of data acquisition. Hence, the testing times were reduced in the final study. Overall results did not differ between the two studies.

Results
Data from a single subject is shown in Figure 3 as an example. The horizontal and vertical whiskers represent the standard deviation of metabolic and mechanical output power, respectively. Data was approximately linear for all subjects, as expected. Values are also tabulated in Table 1. Delta efficiency was calculated twice for each curve, using the three data points indicated.

**Figure 3** Example of the mechanical and metabolic power data collected for one subject
Table 1 Example of power data from one subject.

No significant difference in delta efficiency between the three crank lengths was found in this study. The mean (±std dev) DE for the 115mm, 140mm and 170mm cranks was 0.30 ± 0.065, 0.31 ± 0.071, 0.30 ± 0.065 respectively. A one-way ANOVA model found no statistically significant effect of crank length on DE at the $\alpha = .05$ level of significance ($p = 0.84$) for the lengths of cranks tested. Analysis of the preliminary study yielded similar results for the 140 and 170 mm cranks tested (0.27±0.12 and 0.27±0.074.) No effect due to crank length was found in the preliminary data ($p=.96$).

Table 2. 3-Way ANOVA Results

A three-way ANOVA model was used to investigate effects due to crank length, cadence, and individual subject variation. Table 2 shows the results. There was a significant effect on DE due to the subject ($p = .0099$), implying that individual differences between subjects was significant. Due to the range of subject’s age and level of fitness, this is expected. There was
also a slight, but not statistically significant, effect on DE due to cadence ($p = 0.082$). Analysis of covariance indicated a slight non-significant increase in DE with cadence (slope = $0.0005$, $p=.21$) when all data was considered. The slope increased for each crank length (slope = $-0.0007$, $-0.0001$, and $0.0008$ with $p=.19$, $.88$, and $.18$ for 115, 140, and 170 mm cranks, respectively), although the differences were not statistically significant. More experienced cyclists tended to pedal at higher cadences, increasing by an average of 9.4 rpm with each increase in experience level.

Additional analyses showed no observed effect on DE due to subject age, subject x-seam, and power level. While delta efficiency was determined to be the most applicable parameter for this study, gross efficiency was evaluated. An n-way ANOVA analysis with gross efficiency, crank length, power, and subject indicated no significant effect on gross efficiency due to crank length ($p=.11$). However, both power ($p=.005$) and subject ($p = 0$) had significant effects on gross efficiency. These findings were consistent with the literature.

All power measurements were based on measured cadence. It was of interest to evaluate how well subjects maintained the target cadence. It was found for all subjects and all crank lengths the mean difference between the mean actual cadence and the target cadence was $-1.15\%$. This indicates that test subjects were able to keep their actual cadence very close with their target cadence. It is noteworthy that the cadence tended to vary more for the shorter cranks than for the longer cranks. The mean ($\pm$ standard deviation) cadence was $-0.74 \pm 9.2 \%$ for 115 mm cranks, $-1.50 \pm 3.2 \%$ for 145 mm cranks and $-1.63 \pm 4.5 \%$ for 175 mm cranks.
Discussion

The primary finding of this study was that the crank lengths of 115, 140, and 170 mm have no effect on delta efficiency during recumbent ergometry with negative hip angles. Perceived benefits of short cranks are most applicable to vehicles in which the crank is higher than the seat, resulting in negative hip angles. Hence, this study was limited to this cycling position. Results may not be applicable to other cycling positions. Subjects included fit non-cyclists and recreational cyclists only. While some subjects were active recreational cyclists, none were highly trained. This was consistent with intent of the study.

Cadence was not controlled in this study. Cyclists choose a cadence based on load, comfort, and other factors. In this study subjects were allowed to choose a cadence for each crank length to better mimic actual cycling. Subjects preferred higher cadences with the shorter cranks, as was expected. In a study using upright cycling geometry, McDaniel found that DE increased with increased crank length. Pedal speed was found to be a better predictor of DE than crank length alone\(^7\), and DE increased with increasing crank length. Data in the current study is consistent with this finding as DE increased slightly with increasing pedal speed. The increase was not statistically significant (slope = .035, p=0.17). Regression analysis for data corresponding to each crank length was also not statistically significant, but did indicate an increasing slope with increasing crank length. It is possible that subjects self-selected cadences that would generate similar pedal speeds, thereby masking any significant effects.
Delta efficiency varied significantly between subjects. This variability may be attributed to the diversity of subject age, gender and fitness level. Subjects’ unfamiliarity with the ergometer and respiration mask may also contribute to the rather high variability in recorded values of delta efficiency. Five subjects clearly exhibited anomalous values of DE for the initial test. Although the second and third tests for these subjects appear normal, the subjects were not included in the results. In future studies, subjects should be given more familiarization time with the ergometer.

Conclusion

Crank arm length has no observed or statistically significant effect on DE for the lengths of cranks tested for recumbent vehicles with crank height higher than seat height. This study also found no effect on DE due to subject age, subject x-seam, and power level. Many studies have shown a relationship between power production and crank length. In most cases, the range of optimal crank lengths was fairly broad. This study is consistent with those findings. There may be some indications, although not statistically significant, that the 115 mm cranks were at the lower end of the optimal range.

The use of short cranks on vehicles with negative hip angles should not incur a penalty in terms of efficiency or power production. Shorter cranks may be preferred due to comfort or vehicle space restrictions. Smaller cranks allow a smaller, more aerodynamic fairing which may lead to increased overall performance. Shorter cranks may also reduce knee stress due to
cycling. Based on the results in this study, recumbent riders may choose their crank length without incurring a DE penalty.

References


