The Effects of Bicycle Crank Arm Length on Oxygen Consumption

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Catalogue Data

Key words: optimal crank arm length, leg length, efficiency
Mots-clés: longueur optimale du bras de manivelle, longueur de jambe, efficacité

Abstract/Résumé
The purpose of this investigation was to determine the effects of various crank arm lengths on oxygen consumption for trained cyclists. Secondary purposes were, if optimal crank arm lengths existed, to determine if these lengths could be predicted based on an individual’s leg length. Six trained cyclists completed four experimental protocols riding at a workload of approximately 68% of $\dot{V}O_2\text{ max}$ using crank arm lengths of 165, 170, and 175 mm. During each protocol, the cadence, oxygen consumption, and distance traveled were determined, and values were combined to give a $\dot{V}O_2 \cdot m^{-1} \cdot \text{min}^{-1}$ value. The values then were placed in either a high, medium, or low efficiency category. Significant differences were found among the three protocols. No significant correlations were found between each subject’s most efficient crank arm length and leg length. The results of the study suggest that each subject has a most efficient crank arm length, but it does not appear that optimal crank arm length can be predicted by leg length.

Le but de cette étude est d’évaluer les effets de diverses longueurs de bras de manivelle sur la consommation d’oxygène de cyclistes entraînés. Dans l’éventualité de l’identification d’une longueur optimale, il s’agit aussi d’établir si cette dernière est associée à la longueur de la jambe de l’athlète. Six cyclistes entraînés participent donc à quatre séances expérimentales au cours desquelles ils donnent un effort équivalent à 68% du $\dot{V}O_2\text{ max}$ pour chacune des longueurs de manivelle suivantes: 165, 170, et 175 mm. À chacune des séances, les valeurs de consommation d’oxygène et de distance parcourue sont combinées pour obtenir...
Introduction

While pedaling a bicycle at a certain workload, work efficiency may be varied by adjusting crank arm length. The possibility of optimal crank arm lengths for individuals, as well as various methods to predict them, have been a subject of discussion (Borysewicz, 1985; LeMond & Gordis, 1987). Longer crank arms allow a work rate to be maintained with less force application through the use of the longer lever arm. However, the increase in crank arm length increases the range of motion of the leg. Biomechanical models have suggested that because of the change in the range of motion of the leg with a change in crank length, optimal crank arm length may be dictated by the leg length of the cyclist (Hull & Gonzalez, 1988).

The effects of crank arm length on oxygen consumption have been examined in studies by Carmichael (1981) and Conrad (1983). The results of Carmichael showed significant differences in oxygen consumption with a greater than 10 mm change in crank arm length, whereas Conrad failed to show any change in oxygen consumption with a change in crank arm length. However, in both studies, riding periods for each crank arm length were only a few minutes in length and may not have represented long-term exercise bouts similar in length to that of a competitive road race. Furthermore, neither study allowed subjects any significant time to train with the various crank arm lengths before assessing their efficiency, thus forcing the muscles of the lower extremities to work through unfamiliar ranges of motion.

The purpose of this study was to determine the effects of various crank arm lengths on oxygen consumption while pedaling at a constant work rate and cadence. A second purpose was to determine if each individual had an optimal crank arm length that produced the lowest oxygen consumption per unit of work. Finally, the investigation sought to determine the existence of any relationship between leg length and optimal crank arm length.

Methods

SUBJECTS

Six members of a group of local competitive cyclists volunteered to take part in this study. Each subject had been competing for a minimum of 2 years. Four cyclists possessed a racing license issued by the United States Cycling Federation and varied in ability from being competitive at the State Championship level to a two-time qualifier for the United States Olympic Trials. Two subjects were accomplished triathletes who had qualified for the United States Triathlon Federation National Championships the previous season. All subjects were currently riding at least 225 km per week. Each subject was informed of the purposes of the study, possible risks and benefits, and study protocol as approved by the University of Missouri Human Subjects Committee. No specific information was given to the subjects regarding the investigators' hypotheses.
SUBJECT PREPARATION

Each subject reported to the Human Performance Laboratory for preliminary testing, including determination of weight, anthropometrical measurements, and maximal oxygen consumption. Following the preliminary tests, the first experimental crank arm length was installed on each subject’s bicycle. For 2 weeks following the installation of each experimental crank lengths, subjects rode at least 225 km per week to allow them to habituate to the new crank arm lengths. After each 2-week habituation period, the subject returned to the lab for a total of four laboratory assessments using the three experimental crank arm lengths.

EXPERIMENTAL DESIGN

The experimental protocol involved testing each subject riding on his own bicycle while using three crank arm lengths (165, 170, and 175 mm). These three lengths were chosen because the crank arm lengths used by competitive road racers usually fall within the 165 mm to 175 mm range. The testing order of the three crank arm lengths was assigned randomly. Each subject reported to the lab on Week 1 of the treatment period to have the first randomly assigned experimental crank arm length installed. After 2 weeks of training at 225 km per week, the subject returned to the lab to undergo the first experimental lab session. Upon termination of the first experimental lab assessment, the second crank arm length was installed, followed by an identical 2-week habituation period and second experimental assessment. An identical protocol was followed for the third experimental crank arm length.

Two days following the third experimental protocol, subjects returned to the lab and repeated the experimental protocol with the third assigned crank arm length. This extra assessment was done to establish reliability of the measurements.

EXPERIMENTAL PROTOCOL

Subjects refrained from cycling on the day preceding their experimental assessments in the lab. The subjects were 3 hr postprandial and were required to keep records of all foods consumed within 48 hr of the test. Subjects were instructed to maintain similar diets within this time period and diet analyses were performed to ensure that subjects’ glycogen levels were similar for all experimental assessments (Nutritionist II, San Bruno CA). After a 5-min warm-up, each subject began riding at a cadence of 90 rpm and a predetermined gear size that would elicit approximately 65% of VO₂max. The subject exercised for 105 min pedaling in the seated position. Beginning at 0 min, expired air was collected for alternating 15-min time periods. A total of four 15-min air collection periods occurred during the protocol, starting at 0, 30, 60, and 90 min. Each air collection period was alternated with a 15-min off-line period. Heart rate was continuously monitored throughout the test. Laboratory temperature was maintained between 21 and 23 °C for all tests.

During the off-line period, the subjects continued to pedal at the same work rate, but were allowed occasional, brief periods when, for reasons of comfort, they could pedal in the standing position. Time spent standing during each off-line period of the first experimental protocol, as well as cadence during such time, were recorded and standardized during the remaining experimental protocols. The
subjects were allowed to drink water ad libitum during the off-line periods of the first experimental protocol. Volume of water consumed, as well as the time when it was consumed, were recorded and standardized during the remaining experimental protocols.

APPLICATION OF WORK RATE

The work rate was provided through the use of a Top Gear Team Mag Turbo magnetic trainer. When a bicycle is placed on a magnetic trainer, the rear wheel rests on an axle that rotates in close proximity to a magnetic field. As the subject pedals, the rear wheel turns, causing the axle to spin. The resistance of the magnetic field against the spinning axle provides the resistance to the subject. The work rate is a function of the angular velocity of the rear wheel and, therefore, can be varied by changing the velocity of the rear wheel. Changing the velocity of the rear wheel can be accomplished by either changing the cadence or by changing gear size. Because cadence remained constant during all protocols of the study, work rates were varied with changes in gear sizes only.

Gear size is determined by the linear distance the bicycle will travel with one revolution of the crank and is calculated by dividing the number of teeth on the front chaining by the number of teeth on the rear sprocket and multiplying the product by $2\pi r$, where $r$ = the radius of the rear wheel. The resulting product is the linear distance the bicycle will travel through one revolution of the crank. Work rate was kept consistent among the trials by maintaining a consistent gear. Tire pressure was kept consistent across trials to avoid changing the nature of the interface between the tire and the axle of the magnetic trainer. Subsequent tests to determine the consistency power outputs of this type of bicycle-trainer interface have been performed using the Schoberer Resistance Monitor (SRM). The SRM uses a series of strain gauges in a specially built bicycle crank to measure work rate and has been verified to be accurate within $\pm 2.5\%$. When these precautions are taken, the day-to-day variations in work rate for the bicycle-trainer setup were less than 2%.

$\dot{V}O_2$MAX AND MAXIMAL HEART RATE

$\dot{V}O_2$max and maximum heart rate (HRmax) were determined by using a continuous graded exercise test with each subject’s own bicycle connected to a Top Gear Team Mag Turbo magnetic trainer. Starting work rates were at the discretion of the subject. Subjects were instructed to treat the test as though it was the final moments of a time trial event. A time trial, with which all subjects had experience, involves a steady increase in work rate in the last several minutes until the last 45 s to 1 min, during which the rider is at maximum work output. To vary the work rate, cadence was kept constant at 90 rpm, and gear sizes were varied by the subject. Gear size was increased every 90 seconds by 0.20 m · pedal rev$^{-1}$. Termination of the test occurred at volitional exhaustion, with criteria for a valid test being a plateau in $\dot{V}O_2$, with an increase in gear size and an $R$ value of greater than 1.1. This protocol allowed the subject to use familiar equipment with a familiar position on the bike as opposed to that position that would have been encountered on a normal cycle ergometer. We have used this protocol in pilot work and have found it to provide results similar to other cycling protocols (Burke, 1977).
DETERMINATION OF WORK RATE

During the lab assessment, cadence was maintained by the subject through the use of a Cateye Micro cycle computer, which provides the user with a digital cadence readout. An investigator monitored the cadence every 5 min. To assure no gross differences in total work performed existed between the experimental protocols, distance traveled during each expired air collection periods, as well as distance traveled during the entire testing session, was monitored through the use of the cycling computer and was recorded. Total distance ridden during each of the four collection periods was divided by 60 min to obtain the average speed in meters per minute.

EXPIRED AIR ANALYSIS

Expired air collection involved fitting a rubber mouthpiece connected to a low resistance Daniel's model valve in each subject's mouth. The nose was plugged with a nose clip. Expired air flowed through a 3.18 cm I.D. smooth plastic tube into a mixing chamber. Volume was measured using a Hewlett-Packard Model 47303A digital pneumotach. A small sample of air was taken from the mixing chamber and analyzed for gas concentration with an Ametek S-3A oxygen analyzer and a Beckman LB-2 carbon dioxide analyzer. Expired air temperature was measured in the mixing chamber using a YSI 43 TA tele-thermometer. Heart rate was monitored with a Burdick M 200 two-way channel EKG monitor. All instruments were connected to a Rayfield REP-400 software program to calculate VO₂. Calibration of the gas analyzers was performed prior to each test using calibration gas of verified concentration. Calibration of the pneumotach was performed prior to each test by pumping 20 L of air through the pneumotach with a 2.0 L calibration syringe at a rate similar to that of the exercising respiration rate.

ANTHROPOMETRY

Measurements of leg lengths were taken on the subject's dominant side. All measurements were taken by the investigator as follows:

- Total leg length: Measured from the iliac crest to the inferior border of the medial malleolus
- Upper leg length: Measured from the greater trochanter of the femur to the joint line of the knee on the lateral side
- Lower leg length: Measured from the joint line of the knee on the lateral side to the inferior border of the lateral malleolus

DATA TRANSFORMATION

Each subject was expected to complete 105 min of exercise with each of the three crank arm lengths plus a second session with the final crank arm length. Expired air was collected during four 15-min time periods starting at 0, 30, 60, and 90 min. Oxygen consumption during the collection periods was determined continuously and reported as averaged minute values. The individual oxygen consumption data were scanned to determine the effects of exercise duration on oxygen consumption. Though slight variations in oxygen consumption over the course of the expired air collection periods were observed, the changes were not consistent so as to
suggest a pattern; therefore, the data for each collection period were
combined for further analyses. Total distance traveled was determined for each
expired air collection period and used to determine an average speed per
minute.

The data were further transformed by taking the average oxygen consump-
tion from each protocol for each subject and dividing it by the respective velocity
for that protocol, giving a $\text{VO}_2 \cdot \text{m}^{-1} \cdot \text{min}^{-1}$ value. This procedure adjusted for
small deviations in the distance traveled among protocols. The data then were
categorized by taking each subject’s protocol that produced the lowest $\text{VO}_2 \cdot \text{m}^{-1} \cdot
\text{min}^{-1}$ and placing them into one category. The “middle” and “high” values were
treated in an equivalent manner. The categories are referred to as high, medium,
and low efficiency categories.

STATISTICAL ANALYSES

A two-way ANOVA with repeated measures on one variable was performed fol-
lowed by a Tukey post hoc analysis to determine significant differences between
the efficiency categories. A Pearson product-moment correlation was performed
to determine the relationship between optimal crank arm length and
anthropometrical variables. Two separate analyses were performed to determine
the reliability of the testing method. A one-way ANOVA was performed to test for
significant differences between the first and second administration of the final
crank length. Also, in a procedure similar to that used to categorize the experi-
mental crank length data, the test-retest data were also placed into high and low effi-
ciency categories and analyzed with a one-way ANOVA to determine significant
differences between the two groups.

Results

Individual and average subject characteristic data are presented in Table 1. Submaximal oxygen consumption values expressed as a percentage of $\text{VO}_2\text{max}$ averaged 68.3% ($SD = 11.1\%$, range = 47% to 76%). Results of the data analyses

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>$\text{VO}_2\text{max}$ (ml $\cdot$ kg$^{-1}$ $\cdot$ min$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22</td>
<td>177.0</td>
<td>77.6</td>
<td>60.4</td>
</tr>
<tr>
<td>2</td>
<td>23</td>
<td>178.5</td>
<td>73.0</td>
<td>63.1</td>
</tr>
<tr>
<td>3</td>
<td>27</td>
<td>172.7</td>
<td>68.8</td>
<td>50.4</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>176.5</td>
<td>74.0</td>
<td>63.3</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>177.8</td>
<td>62.8</td>
<td>54.9</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>178.0</td>
<td>69.6</td>
<td>48.4</td>
</tr>
<tr>
<td>$M$</td>
<td>23.8</td>
<td>176.8</td>
<td>70.7</td>
<td>56.8</td>
</tr>
<tr>
<td>$SD$</td>
<td>1.7</td>
<td>2.1</td>
<td>5.1</td>
<td>5.9</td>
</tr>
</tbody>
</table>
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Table 2 Oxygen Consumption Efficiency Values and Categories

<table>
<thead>
<tr>
<th>Subject</th>
<th>High ( \dot{V}O_2 )</th>
<th>Medium ( \dot{V}O_2 )</th>
<th>Low ( \dot{V}O_2 )</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>CL</td>
<td>CL</td>
<td>CL</td>
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<tr>
<td>1</td>
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<td>4.60</td>
<td>4.80</td>
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<tr>
<td></td>
<td>170</td>
<td>175</td>
<td>165</td>
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<tr>
<td>2</td>
<td>4.85</td>
<td>5.06</td>
<td>5.37</td>
</tr>
<tr>
<td></td>
<td>175</td>
<td>170</td>
<td>165</td>
</tr>
<tr>
<td>3</td>
<td>5.81</td>
<td>6.03</td>
<td>6.03</td>
</tr>
<tr>
<td></td>
<td>165</td>
<td>175</td>
<td>170</td>
</tr>
<tr>
<td>4</td>
<td>5.53</td>
<td>5.81</td>
<td>5.90</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>165</td>
<td>175</td>
</tr>
<tr>
<td>5</td>
<td>5.55</td>
<td>5.57</td>
<td>5.92</td>
</tr>
<tr>
<td></td>
<td>165</td>
<td>175</td>
<td>170</td>
</tr>
<tr>
<td>6</td>
<td>4.56</td>
<td>4.81</td>
<td>4.89</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>165</td>
<td>175</td>
</tr>
</tbody>
</table>

Note. \( \dot{V}O_2 \) is in ml · m\(^{-1} \) · min\(^{-1} \). CL = crank length in millimeters. \( \dot{V}O_2 \) for each category is significantly different from other two categories \((p < .01)\).

Table 3 Subject Leg Lengths

<table>
<thead>
<tr>
<th>Subject</th>
<th>Total leg length (cm)</th>
<th>Upper leg length (cm)</th>
<th>Lower leg length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>92.0</td>
<td>41.5</td>
<td>42.5</td>
</tr>
<tr>
<td>2</td>
<td>93.0</td>
<td>42.5</td>
<td>43.0</td>
</tr>
<tr>
<td>3</td>
<td>91.0</td>
<td>40.5</td>
<td>41.0</td>
</tr>
<tr>
<td>4</td>
<td>88.5</td>
<td>38.5</td>
<td>41.5</td>
</tr>
<tr>
<td>5</td>
<td>94.0</td>
<td>43.7</td>
<td>42.3</td>
</tr>
<tr>
<td>6</td>
<td>92.8</td>
<td>41.5</td>
<td>42.5</td>
</tr>
<tr>
<td>( M )</td>
<td>91.9</td>
<td>41.4</td>
<td>42.1</td>
</tr>
<tr>
<td>( SD )</td>
<td>1.9</td>
<td>1.6</td>
<td>0.7</td>
</tr>
<tr>
<td>( r^a )</td>
<td>-.02</td>
<td>-.05</td>
<td>+.66</td>
</tr>
</tbody>
</table>

*Correlation with optimal crank arm length.

revealed significant differences among the high, middle, and low efficiency categories with respect to oxygen consumption \((p < .01)\) (Table 2). Post hoc analysis showed significant differences between each of the three efficiency categories. No significant differences in \( \dot{V}O_2 \) were observed with respect to testing order or the subject’s original crank arm length versus other lengths. ANOVAs performed on the first and second administration of the final crank length revealed no significant differences between the two data sets when compared in a test-retest \((p > .99)\) or in a high-low efficiency category manner \((p > .51)\).

Individual and average anthropometric data are presented in Table 3. Each subject’s optimal crank arm length was correlated to total leg length, upper leg length, and lower leg length. The highest correlation exhibited was between optimal crank arm length and lower leg length, \( r = .66 \), \( r_{\text{crit}} = .81 \) (Table 3).
Discussion

Results of the analyses showed that significant differences in oxygen consumption occurred with changes in crank arm length within the 165- to 175-mm range. However, the practical applications of the current study may be somewhat limited, as the lack of significant correlations of optimal crank arm length to anthropometrical variables leaves direct assessment of oxygen consumption as the only known method to determine which crank arm length is optimal for an individual.

The lack of significant correlations between most efficient crank arm length and anthropometrical or isokinetic work may be misleading. Previous work by Hull and Gonzalez in 1988 and Gonzalez and Hull in 1989 dealing with crank arm length, cadence, seat height, seat tube angle, and longitudinal foot position on the pedal demonstrated the importance of the interrelationship of several variables on biomechanical efficiency. The results of these studies point to the possibility that significant correlations may exist between optimal crank arm length and anthropometrical variables only when the proper combination of variables is present. For example, biomechanical models of Hull and Gonzalez (1988) demonstrated that optimal crank arm length changes with a change in pedaling cadence, and a previous study by Hagberg et al. (1981) reported that cyclists showed individual optimal cadences ranging from 72 to 102 rpm. In explanation of this wide range of optimal cadences, Hagberg et al. referred to work by Suzuki (1979), which suggested that optimal cadence may depend somewhat on muscle fiber composition with those subjects possessing a higher percentage of fast twitch fibers being more efficient at higher cadences. Therefore, absolute optimal crank arm length may not be revealed if a subject is not pedaling at an optimal cadence as dictated by a particular crank arm length and his or her muscle fiber composition.

The findings of Suzuki also may have direct ramifications on optimal crank arm length. Using a longer crank arm length increases the linear distance the foot must travel per revolution, thus requiring a concordant change in the velocity of the leg segments to maintain a given cadence. Thus, for any given cadence, contractile speed must increase when using a longer crank arm. Previous work by Koushermerick and Davies (1969) has shown that maximum muscular efficiency occurs when contractile velocity approaches one third of the maximum shortening velocity of the muscle fiber. Furthermore, Coyle et al. (1979) have demonstrated a rightward shift in the power versus velocity of contraction curve in subjects possessing high ratios of Type II muscle fibers, suggesting that those individuals with higher percentages of Type II fibers produce work more effectively at higher contractile speeds. Therefore, the effect of muscle fiber composition on optimal crank length also should be investigated.

Further investigations dealing with the practical applications of the current research findings should be pursued. While statistical analyses did reveal significant differences between the high, medium, and low efficiency categories, oxygen consumption values varied by only 7%. A performance test in which subjects have a set time period to perform as much work as possible or are required to complete a given amount of work in the shortest possible time period could be a more useful method of evaluating optimal crank length. Tests should be of varying length to imitate different competitive events as closely as possible, as work by Inbar et al. (1983) suggested that those crank arm lengths that are conducive to
quick power production are not the best choice for the maintenance of high power outputs.

The bicycle used by competitive cyclists has evolved over the last 100 years, and today the crank arm lengths used by competitive cyclists fall within the 165- to 175-mm range. However, this range represents a narrow sample of available crank arm lengths and the possibility of optimal crank arm lengths falling outside of this range has been proposed. Gonzalez and Hull (1989) suggested an optimal crank arm length/cadence combination of 145 mm and 110 rpm based on moment cost function analyses, a somewhat shorter crank arm length and higher cadence than those commonly used by competitive cyclists. However, the conclusions of Gonzalez and Hull did not take into account the effects of physiological criteria such as the force-velocity relationship of a muscle fiber type or the effect of muscle fiber type on the relationship between optimal contractile speed and maximal power output.

Other biomechanical analyses performed by Hull and Gonzalez (1988) indicated that optimal crank length is positively correlated with leg length. However, once again the findings of the current study do not support these conclusions. Thus far, research has been performed to determine optimal crank arm length from purely biomechanical and purely physiological perspectives while research studies integrating the two scientific disciplines is lacking. Research determining the effects of changes in body position, crank length, cadence, and pedaling technique on biomechanical and physiological pedaling efficiency, aerodynamics, and work production could be of great value in determining optimal methods of interfacing the rider to the bicycle.

In summary, the present study demonstrates that changes in crank arm length will elicit significant changes in oxygen consumption per unit of work. However, the lack of significant correlations between each subject’s most efficient crank arm length and leg lengths suggest that the use of these variables exclusively to predict optimal crank arm length may be invalid. The results of the current study also suggest that long protocols (e.g., 105 minutes) appear to be unnecessary to determine optimal crank arm length.

References


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