

Undergraduate Honors Thesis

Could a kangaroo win the Tour de France?
The effect of relative crank angle on metabolic efficiency in cycling

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Introduction

The rapid evolution of bicycles in the 1800s increased the speed of human powered transportation and decreased the metabolic power required. From the Laufmaschine (a 2-wheeled vehicle propelled directly with the feet on the ground), to direct-drive high-wheelers, to the rotary cranks and chain drive of modern bicycles, the mechanical power required decreased an astounding 300% compared to walking (Minetti et al., 2001). However, the gross efficiency (mechanical power/metabolic power) of pedaling these machines hardly changed (Minetti et al., 2001). In the ensuing paragraphs, I will review the various biomechanical and technological factors (cadence, crank length, chainring shape, shoe-pedal interface) and their effects on cycling efficiency.

Physiologically, one factor that does affect efficiency is the pedaling cadence. In general, most studies report an upside-down U-shaped relationship with a distinct optimal cadence that maximizes efficiency. A. V. Hill, the 1922 Nobel Prize winner, was among the first to relate muscle physiology to cycling. Hill explained that animals have an optimal speed, “cadence” at which their muscles act most efficiently. He posited that for “ a given length of crank, there is a certain optimum frequency of pedaling which gives the highest mechanical efficiency” (Hill, 1950). Later, Hagberg et al. (1981) tested Hill’s idea with competitive cyclists using a different gear ratios while riding at 20mph on a treadmill at various inclines. They found that the average energetically optimal cadence was 91RPM. Coast & Welch (1985) extended the Hagberg et al. study across a range of power outputs (100 to 300 watts) and a wide range of cadences (40-120RPM). They again confirmed the

upside-down U-shape relationship between efficiency and cadence. Further, they found that the optimal pedaling cadence increased linearly with power output. Looking back on A. V. Hill's ideas, it becomes clear why cadence has an effect on efficiency. Unless the muscle is contracting at its optimal speed, efficiency will not be maximized. However, that implies that when cadence is optimized, changes in technology should have little effect on cycling efficiency.

A few studies have also quantified how crank length affects efficiency. Morris & Londeree (1997) compared the efficiency of three different crank lengths (165mm, 170mm, and 175mm) at 68% of their $\dot{V}O_2$ max. They found that each subject had their own optimal crank arm length. In a related study, Zamparo et al., (2002) developed a novel crank that changes length throughout the pedaling cycle. Essentially, the crank arms were longest when they were horizontal, parallel to the ground and shortest when perpendicular to it. Zamparo et al. found the experimental bicycle crank to significantly increase efficiency by 2%.

Non-circular chain rings produce a similar effect as varying crank arm length. The long axis of an elliptical chainring is positioned to be vertical when the crank arms are horizontal and creates a larger gear ratio. Hull et al. (1992) studied riders using circular and non-circular chainrings at both 60, and 80% of their maximal $\dot{V}O_2$ and found no difference in efficiency between the two chainrings. They concluded, "for cycling events where efficiency is a determinant of performance, non-circular chain rings do not offer any advantage...". Further, Peiffer et al. (2011) tested cyclists over a 10km time trial, and found no increase in performance with non-circular chainrings compared to the standard circular rings.

Cycling enthusiasts and manufacturers have long claimed that rigid-soled cycling shoes and clipless pedals are “more efficient” because they allow riders to pull up during the pedal stroke. However, numerous researchers have shown this to be incorrect. Most notably, Korff et al. (2007) recorded a significant 5.9% *decrease* in gross efficiency when they instructed subjects to focus on pulling up during the pedal stroke as compared to “pedaling in circles”. Further, Ostler et al. (2008) compared the efficiency of cycling with tennis shoes on both flat pedals vs. classic toe clips and straps at different power outputs (60-240 watts) at a cadence of 90RPM. They concluded there was no difference efficiency between the two types of pedals. Mornieux et al., (2008) compared athletic shoes on flat pedals to cycling specific shoes and clipless pedals in competitive cyclists. They too found no significant differences in the rates of oxygen consumption. Recently, we (Straw & Kram, 2016), reported that cycling efficiency did not differ when riders wore flexible running shoes with flat pedals vs. rigid-soled cycling shoes with clipless pedals. Thus, the evidence to date is unequivocal that shoes and pedals do not improve efficiency.

In perhaps the most novel cycling efficiency experiment, Bressel et al. (1998) investigated the idea of altering the pedaling direction. In backwards locomotion (running and walking) research has quantified the greater metabolic cost (Flynn et al. 1994). Therefore, backward pedaling would be expected to be much more expensive metabolically. However, when Bressel et al. (1998) compared the metabolic cost of forward vs. backward pedaling they found no significant increase in the metabolic cost.

Reviewing all of these studies led me to ask: Is the efficiency of cycling essentially invariant and determined simply by the efficiency of the muscles? Thinking outside the box, for my thesis research, I intentionally tried to *decrease* cycling efficiency by altering the angle between the cranks from the standard 180° out-of-phase position. I tested the null hypothesis that there would be no difference in the metabolic cost of cycling when the relative crank angle was altered.

Methods

Subjects

Ten healthy, male, recreational bicycle riders (27.8 ± 8.2 yr, mean \pm SD, mass 69.8 ± 3.2 kg) participated after providing written informed consent as per the University of Colorado Boulder Institutional Review Board. The inclusion criteria were: age 18-45 yrs, good general health, neurologically intact, and a self-report of cycling a minimum 150 miles (241km) or 8 hours per week. Participants reported riding an average of 336 ± 120 km/week. I asked the subjects to fast for two hours prior to testing.

Equipment

Subjects rode a custom, pan-loaded cycle ergometer (Nobilette, Longmont CO) equipped with a standard Monark flywheel (9.53 kg, 0.51 m radius). I had the rear cog welded onto the flywheel to create a fixed gear, non-freewheeling set-up. The ergometer had a Shimano Octalink ® bottom bracket, which allowed me to set the relative crank arm angles at 45 degree increments. For the experiment, I set the

relative crank angles at 180°, 135°, 90°, 45°, and 0° (Figure 1). The crank arm length was 172.5mm. Subjects used their own rigid-soled cleated cycling shoes and clipless pedals during the experiment.

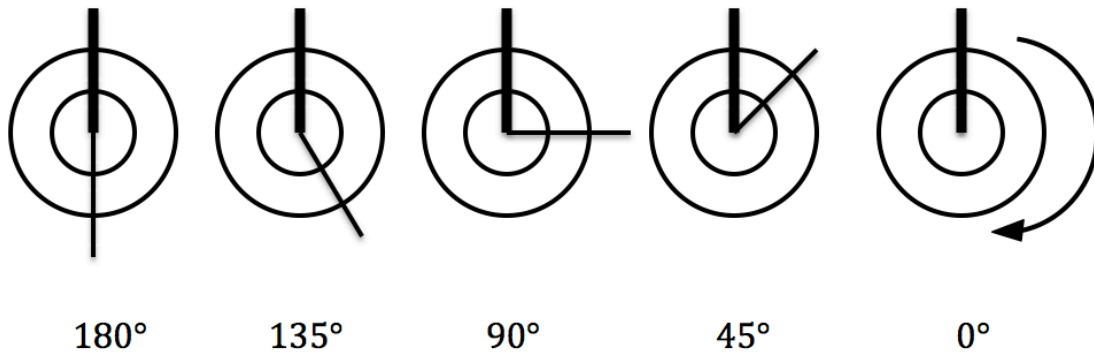


Figure 1. Relative crank angles used in this study. The crank arm of the dominant leg is indicated at top dead center by the thick lines. The thinner lines indicate the contralateral crank arm. The arrow indicates the direction of pedaling.

Protocol

To determine leg dominance, I asked the participants to kick a soccer ball and deemed the leg that struck the ball to be dominant (Teng & Powers, 2014). I set the crank positions by placing their dominant leg at top dead center (TDC) and set the contralateral crank arm accordingly (Figure 1). Subjects warmed-up for 10 minutes with light pedaling and stretching.

Each subject completed six, 5-minute trials. The first and last trials were at a relative crank angle of 180°. I randomized the order of the middle trials (135°, 90°, 45°, and 0°). I extended the last 180° trial to 10 minutes in order to further evaluate

neural adaptation. I suspected that the perturbations to the crank angle during the testing protocol might affect the coordination patterns. The last 180° condition allowed me to evaluate that possibility. During all the trials, I required subjects to maintain a cadence of 90 RPM using visual feedback from a handlebar mounted cadence meter. At 90RPM, with a gear ratio of 3.71 and a pan load of 1.68kg (16.5 N) applied to the flywheel at a radius of 0.255m equates to a mechanical power output of 150 watts (W). Subjects remained seated with their hands on the tops of the ergometer's racing style handlebars. Following each trial, subjects rested for 5-minutes. This obviated fatigue and allowed time to alter the ergometer relative crank angle for the following trial. All trials comprised a single experimental session.

Metabolic Energetics

I collected each participants' expired gases and calculated the STPD rates of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) using an open-circuit expired-gas analysis system (TrueOne 2400; ParvoMedics, Sandy, UT). Before each experiment, I calibrated the gas analyzers and pneumotach using reference gases and a calibrated 3-L syringe respectively. I averaged $\dot{V}O_2$, $\dot{V}CO_2$, and respiratory exchange ratio (RER) for the last 2 minutes of each 5 minute trial as well as minutes 9-10 of the final 180° trial. I planned to exclude any participants whose RER values exceeded 1.0, but all values remained below 1.0. From the $\dot{V}O_2$ and $\dot{V}CO_2$ measurements, I calculated metabolic power using the Brockway equation (Brockway, 1987). I recorded the respiratory rate, RR (=breathing frequency, breaths/minute), ventilation rate \dot{V}_E (L/min) and tidal volume V_t (L) using the Parvo

metabolic cart. In order to evaluate whether or not the subjects were hyperventilating during the trials, I calculated the ventilator equivalent, VEQ ($=\dot{V}_E/\dot{V}O_2$, both in L/min).

Statistics and Sample size

I estimated that I would be able to detect <1.6% differences in oxygen consumption given a sample size of 10 (Frederick, 1983). I used R software (www.rstudio.com) to run one-way repeated measure ANOVAs for the effect of relative crank angle on oxygen consumption rate, metabolic power, and RER. If I found significance following an ANOVA, I ran Bonferroni's pairwise t-tests to determine which conditions were different. Furthermore, I ran dependent t-tests to compare the physiological variables between minutes 4-5 of the first 180° trial, minutes 4-5 of the second 180° trial and minutes 9-10 of the second 180° crank positions. I set statistical significance at $p < 0.05$. I report all values as means \pm S.E. unless noted otherwise.

Results

I reject my first null hypothesis; crank angles other than 180° required slightly greater metabolic power. As I decreased the relative crank angle from 180°, metabolic power monotonically increased by 1.6% at 135° ($p < 0.002$) and by 8.2% when the relative crank angle was 0° ($p < 0.001$), (Table 1)(Figure 2). Similarly, at reduced relative crank angles, the increases in the rates of oxygen consumption ($\dot{V}O_2$) ranged from 1.9% at 135° to 7.7% at 0° ($p < 0.001$)(Table 1.). According to the slope of the regression equation for metabolic power vs. relative crank angle, a 10° change in crank angle from 180° increased metabolic power by 3.0 Watts or 0.35%

(Figure 3).

Table 1. Metabolic data for all crank angle positions, averaged during minutes 4-5 (n=10). Asterisks indicate significantly different from initial 180° condition

Relative Crank Angle (°)	Metabolic Power (W)	Gross Efficiency (%)	$\dot{V}O_2$ (L/min)	RER
180°	851 ± 10	17.6 ± 0.2	2.53 ± 0.03	0.81 ± 0.03
135°	865 ± 7*	17.4 ± 0.1*	2.58 ± 0.02*	0.79 ± 0.04*
90°	888 ± 11*	16.9 ± 0.2*	2.64 ± 0.03*	0.79 ± 0.03
45°	903 ± 16*	16.7 ± 0.3*	2.68 ± 0.05*	0.81 ± 0.04
0°	921 ± 15*	16.3 ± 0.3*	2.72 ± 0.04*	0.83 ± 0.04
180°	861 ± 10	17.4 ± 0.2	2.57 ± 0.03	0.77 ± 0.03*

Although I anticipated that metabolic power might be greater during minutes 4-5 of the second vs. first 180° trials, there was no significant difference ($p=0.31$). Further, I suspected that if metabolic power was greater during minutes 4-5 of the second 180° trial, it might decrease during the subsequent 5 minutes of “re-adaptation”. In fact, metabolic power slightly increased (1.8%) during the minutes 9-10 of the second 180° trial compared to minutes 4-5 ($p=0.003$).

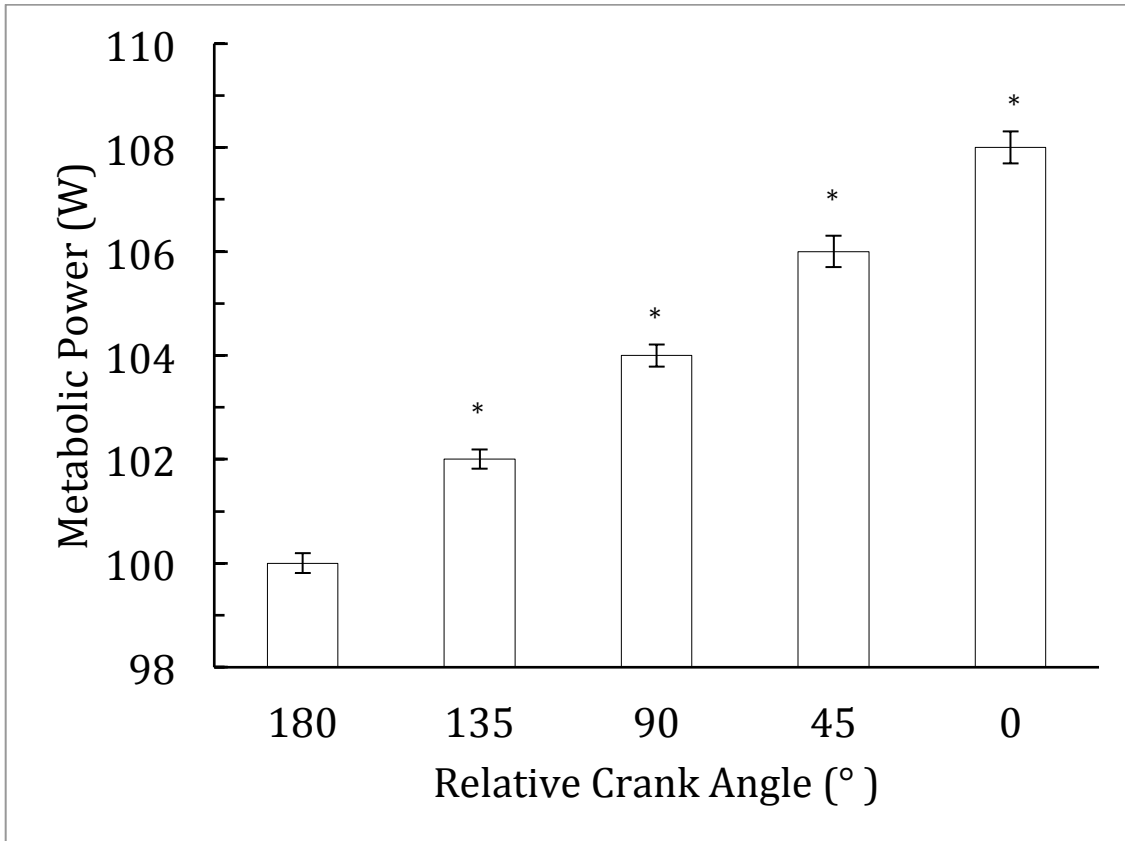


Figure 2. Differences in metabolic power between crank angle conditions, normalized to the first 180° trial. Asterisks indicate different from first 180° condition.

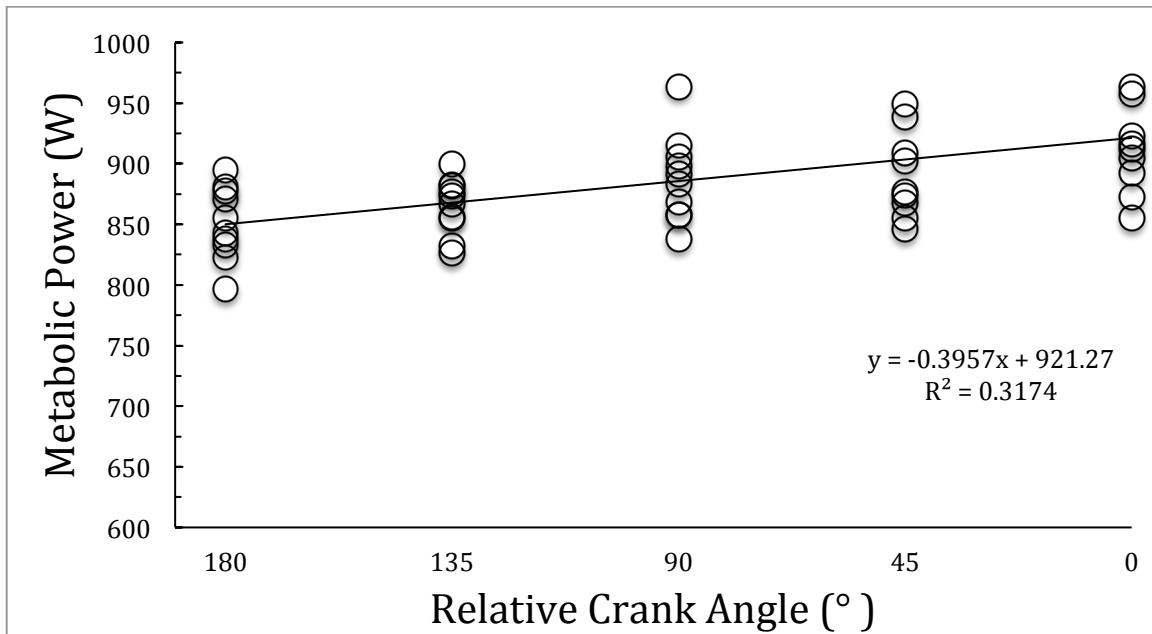


Figure 3. Linear regression of metabolic power in (W) vs. relative crank angles. Means +/- SEM.

After the repeated measures ANOVA indicated a main effect of relative crank angle on both metabolic power and oxygen consumption rate, I used Bonferroni's pairwise t-tests to detect differences between relative crank angles. This indicated significant differences in metabolic power (W) between the 180° condition and at 135°, 90°, 45°, 0°. Similarly, I found significant differences in $\dot{V}O_2$ between 180° condition and 135°, 90°, 45°, 0° (All $p < 0.015$).

I also investigated the changes in ventilation rate ($\dot{V}E$) across the different crank angles and found significant increases of 4.7% at 135° and 21.6% at 0° ($p < 0.001$) (Figure 4.). After completing a Bonferroni's post-hoc test, I found significant differences again between the 180° condition and 135°, 90°, 45°, 0°. (Table 2.)

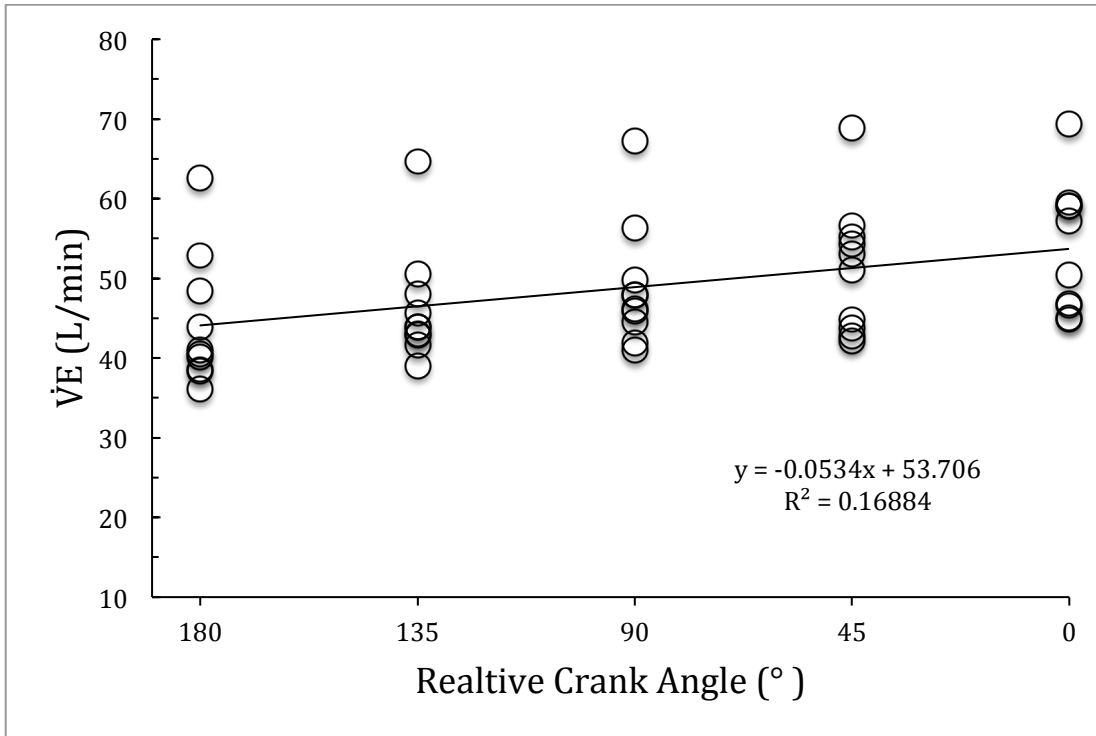


Figure 3. Ventilation rates across relative crank angles. ($p < 0.001$)

Table 2. Ventilation data for all relative crank angle positions (n=10).

Relative Crank Angle ($^\circ$)	\dot{V}_E (L/min)	RR (Breaths/min)	V_T (L)
180 $^\circ$	44.25 \pm 2.58	27.69 \pm 2.47	1.64 \pm 0.14
135 $^\circ$	46.33 \pm 2.28*	30.80 \pm 1.67*	1.51 \pm 0.11*
90 $^\circ$	48.86 \pm 2.46*	31.74 \pm 1.98*	1.56 \pm 0.14
45 $^\circ$	51.27 \pm 2.62*	33.34 \pm 1.73*	1.56 \pm 0.13
0 $^\circ$	53.79 \pm 2.60*	34.14 \pm 1.72*	1.59 \pm 0.14
180 $^\circ$	46.07 \pm 2.41*	30.77 \pm 1.82*	1.51 \pm 0.11*

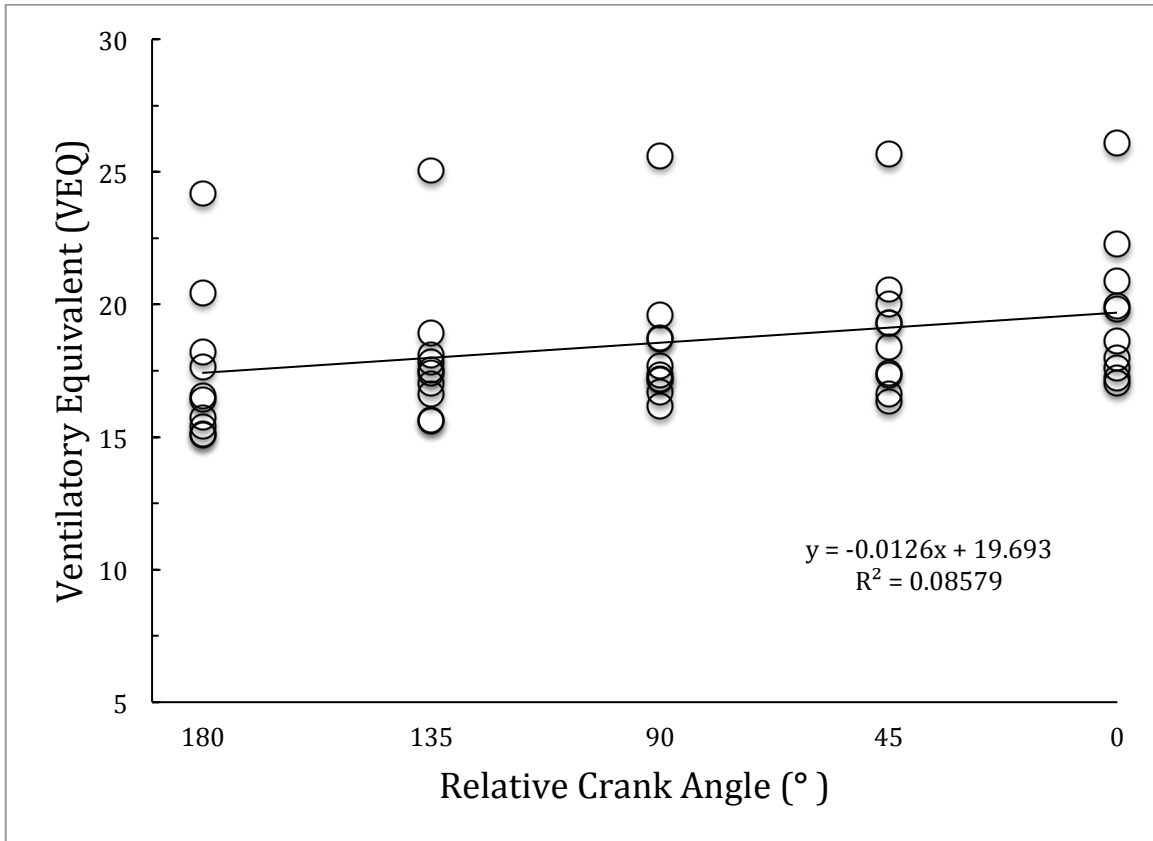


Figure 5. Ventilatory Equivalent ($\dot{V}EQ$) = $\dot{V}E$ (L/min)/ $\dot{V}O_2$ (L/min) across all relative crank angles.

Discussion

The aim of this study was to determine how inefficient I could make pedaling a bicycle by altering the relative crank angle. I reject my null hypothesis that there would be no change in efficiency. Surprisingly, I was only able to worsen efficiency by ~8% with the most extreme relative crank arm angle condition (0°).

Physiologically, I can explain this minimal ~8% decrease in efficiency. Building on the work of A.V Hill, McDaniel et al. (2002) concluded that mechanical power output by itself accounts for 95% of the difference in the metabolic cost of

cycling with different cranks lengths and cadences. Given that I kept cadence and crank length constant in my experiment, it is therefore reasonable to expect only minimal change in efficiency. Under the conditions I studied, the subjects' muscles were able to operate at their optimal spots on both the force-length curve for muscle (reflected by crank arm length) and force-velocity curve for muscle (reflected by cadence). The force-length curve explains physiologically at which sarcomere length myofilament overlap is optimized, i.e., the length at which our muscles can produce the most force. Further, the force-velocity curve for muscle explains how muscle contraction speed affects power output and efficiency during a fully activated concentric contraction.

One of the physiological parameters I recorded, the expiratory volumetric flow rate (\dot{V}_E) (a.k.a., "minute volume") yielded some confusing results (Table 2.). Compared to the baseline 180° relative crank angle, \dot{V}_E increased linearly, by 4% at 135° and by 17% at 0°. \dot{V}_E is calculated as the product of breathing frequency "respiratory rate" (RR) and tidal volume (V_T). The ANOVA indicated that the increase in \dot{V}_E was due to a significant increase in RR. To some extent, subjects were hyperventilating when pedaling with relative crank angles other than 180° (Figure 4.). However when a subject hyperventilates, the respiratory exchange ratio, RER typically increases. RER is the ratio of $\dot{V}CO_2 / \dot{V}O_2$. A greater RER either indicates that CO₂ is being produced more rapidly due to greater carbohydrate (vs. fat) metabolism or that CO₂ is being exhaled more quickly from CO₂ stores in the blood. However, my data indicated a lower, not higher, RER for the smaller relative crank angle conditions.

An alternative explanation may be related to forced ventilation associated with the more synchronous movements of the legs. When subjects rode the ergometer with the cranks at 180°, their legs were out-of-phase, meaning when the right leg was at the bottom of the pedal stroke, the left leg was at its highest point. Since the subjects rode with a flexed hip posture, leaning forward while grasping the brake hoods, the legs may have alternately applied an upward force on the viscera and consequently the diaphragm causing the lungs to exhale. However, when the legs were in-phase (0°), the subject may have had both legs applying an upward force on the diaphragm likely causing the increase in RR regardless of RER. The only contradicting evidence against my speculative explanation however, is that RR was not synchronized to cadence and I am unable to explain this phenomenon. According to Aaron et al. (1992) the greater \dot{V}_E would be expected to increase $\dot{V}O_2$ by just ~ 0.030 L O₂/min. However, I calculated a difference of 0.19L O₂ between the 180° and 0° conditions (Table 1.). That means that 15.8% of the greater $\dot{V}O_2$ at the relative crank angle of 0° degrees could be attributed to the greater \dot{V}_E .

Limitations

For all subjects, non-180 degree crank pedaling was a novel task. Allowing the riders to practice with different crank angles before the testing began may have decreased the observed differences in metabolic cost across the different crank angles. Another factor to consider is that, in order to eliminate dead spots in the pedaling motion (at the top and bottom of the crank cycle), I welded the fixed gear cog to the flywheel hub. This intentionally converted the bicycle ergometer into a

fixed gear system with no coasting. The new flywheel system eliminated the dead spots in the pedaling rotation, making it easier for the subjects to keep a set cadence. However, it is unknown what effects if any, a fixed gear vs. freewheeling ergometer has on cycling efficiency. I am unaware of any research relating the efficiency of fixed vs. freewheel cycling. Moreover, it is likely, given the dead spots in the pedal stroke when the cranks were at positions other than 180° , that the power output of the rider fluctuated during the pedal stroke even though the average mechanical power output remained 150W. In normal 180° cycling, the subjects pedaling pattern produced a nearly constant 150 W due to one leg always applying a downward force while the other leg was recovering. However, when the crank angle was set at 0° , the subjects were only able to apply a force to the pedals from the top of the pedal stroke to the bottom of the stroke (half the cycle). Moreover, with the implementation of a fixed gear, the flywheel's momentum moved the subjects' legs from the bottom of the cycle back to the top. However, there is a possibility that the crank angular velocity decreased during the entire second half of the crank cycle causing a decrease in power output and that confounded my results. It might have been useful to study multiple power outputs. However, due to the severity of some of the relative angles, my pilot data suggested that the upper limit for which subjects could maintain a cadence of 90RPM was 150W.

Future studies

In the future, I plan to investigate a variety of ideas stemming from this project. Recently, Garmin ® (Overland Park, KS, USA) donated a pair of their power measuring bicycle pedals to the Locomotion Lab. There is a possibility that I will

repeat the altered crank study with the new power measuring pedals as well as electromyography (EMG). The use of both of these pieces of equipment could lead to a better understanding of how the legs function throughout the pedal stroke. The data that I could collect using the Garmin ® pedals may help us to understand how power is distributed differently between the legs at crank angles other than 180°. EMG data could provide us with a better understanding of how the legs are reacting neurologically to the altered relative crank angles. Given a better understanding of how muscle activation changes with alterations to the crank, I feel compelled to explore the idea of using altered cranks in a rehabilitation setting.

Although my study is the first of its kind, i.e the metabolic testing of relative crank angles, I see the possibility of a potential application in the physical therapy/rehabilitation sector. It is plausible that a patient may require a form of rehabilitation that would involve a cycle ergometer with altered crank arms. Specifically, I believe that my research may be able to help the survivors of a stroke. Following a stroke, survivors are often left with gait issues. One highly researched and proven method for gait rehabilitation of stroke survivors involves split-belt treadmills (SBT) (Reisman et al., 2007) A SBT employs two treadmills side-by-side with smaller belts than a “gym” treadmill. A split-belt treadmill allows each of the subject’s legs to move independently of each other and at different speeds. SBT rehabilitation is thought to alter the movement patterns of one leg, invoking a coordinated response of muscle activity in both legs (Duysens et al., 1994) that also causes a perturbation in the subject’s gait. Reisman et al. (2007) was able to show that repeated bouts of walking on a SBT can normalize the walking pattern of a

patient who is only recently post-stroke. However, SBT rehabilitation is expensive and not widely available. Alternatively, the use of my modified bicycle ergometer appears to be a possible method of rehabilitation. If the use of an altered crank bicycle ergometer can produce similar effects as SBT, the cycle ergometer may present a cheaper and more accessible form of rehabilitation.

Continuing along the lines of rehabilitation and physical therapy, I believe there could be an application of non-180 degree crank configurations to amputee cyclists. I know that altering the relative crank angles in intact humans increases metabolic rate in most subjects but, altering relative crank angle only caused a small increase in metabolic cost. However, what I do not know is how alterations to the cranks would affect cyclists with leg amputations. There could be a situation in which someone with a leg amputation is not fully activating their remaining leg muscles when riding at 180°, and that moving the crank by some extent could improve muscle activation and intern increase efficiency. Finally, my research has shown there is a need to understand differences in fixed vs. freewheel cycling and I would like to investigate if one is more efficient than the other.

In conclusion, my thesis research has shown that, despite radically changing the relative crank angle, metabolic power increased by only ~8%, i.e. efficiency was nearly invariant. I would argue that attempts to substantially improve cycling efficiency using modifications to pedaling mechanics are likely futile.

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