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ORIGINAL ARTICLE

Changing relative crank angle increases the metabolic cost of leg cycling

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Abstract

Purpose Historically, the efficiency of leg cycling has been difficult to change. However, arm cycling research indicates that relative crank angle changes can improve efficiency. Therefore, we investigated if leg cycling with different relative crank angles affects efficiency.

Methods Ten healthy, male, recreational bicycle riders (27.8 ± 8.2 years, mean ± SD, mass 69.8 ± 3.2 kg) pedaled a pan-loaded cycle ergometer at a fixed power output of 150 watts at a cadence of 90 RPM. Each subject completed six, 5-min trials in random order at relative crank angles of 180°, 135°, 90°, 45°, 0°, and 180°. We averaged rates of oxygen uptake ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$), and respiratory exchange ratio (RER) for the last 2 min of each trial.

Results Crank angles other than 180° required a greater metabolic cost. As relative crank angle decreased from 180°, metabolic power monotonically increased by 1.6% at 135° to 8.2% greater when the relative crank angle was 0° ($p < 0.001$).

Conclusions We find that, unlike arm cycling, radically changing the relative crank angle on a bicycle from an out-of-phase (180°) to in-phase (0°) position decreases leg cycling efficiency by ~8%. We attribute the increase to changes in cost of breathing, muscle co-activation, trunk stabilization, power fluctuations, and possibly lifting the legs during the upstroke. Our findings may have relevance in the rehabilitation of patients recovering from stroke or spinal cord injury.

Keywords Asynchronous · Synchronous · Bicycle · Efficiency · Ventilation

Abbreviations

ANOVA	Analysis of variance
$\dot{V}CO_2$	Rate of carbon dioxide production
$\dot{V}O_2$	Rate of oxygen uptake
RER	Respiratory exchange ratio
RPM	Revolutions per minute
RR	Respiratory rate
STPD	Standard temperature pressure dry
V_t	Tidal volume
$\dot{V}_E$	Ventilation rate
VEQ	Ventilatory equivalent
W	Watt

Introduction

An early ancestor of the modern bicycle, the Laufmaschine (ca. 1820), was propelled by the feet alternately pushing on the ground (Herlihy 2004) and required less metabolic energy than walking or running (Minetti et al. 2001). However, it was not long before faster and more efficient bicycles with various forms of rotary cranks evolved, rendering the Laufmaschine obsolete. Due to reduced rolling and aerodynamic resistances, modern bicycles require far less mechanical power than historical bicycles with rotary cranks. However, the gross efficiency (mechanical power/metabolic power) has hardly changed (Minetti et al. 2001), probably because the human movement pattern (alternating leg extensions) acting on rotary cranks has remained almost

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invariant. Is it possible to substantially alter the efficiency of cycling by utilizing novel leg movement patterns?

Changing crank length alters the leg movement patterns and modestly affects cycling efficiency. Morris and Londeree (1997) compared three different crank lengths (165, 170, and 175 mm), and found that each individual had their own optimal crank length for which their oxygen uptake was least. In a related study, Zamparo et al. (2002) tested a novel rotary crank that changed length throughout the pedaling cycle. They found a significant increase in delta efficiency between the two bicycle cranks from 23.0% (standard crank) to 24.8% (variable length crank).

In terms of drivetrain mechanical advantage, non-circular chainrings produce a similar mechanical effect as varying crank length, but they do not change the leg movement pattern. Positioning the long axis of oval or elliptical chainrings to be vertical when the cranks are horizontal creates in effect a larger gear ratio when the maximal leg extension force can be applied. However, Hull et al. (1992) studied riders using circular vs. non-circular chainrings at average power outputs of 189 W and 266 W and found no difference in metabolic efficiency. Furthermore, Peiffer and Abbiss (2010) tested cyclists over a 10 km time trial, and found no improvement in performance with non-circular chainrings compared to standard circular rings.

Like the purported benefits of novel cranks and chainrings, cycling enthusiasts and manufacturers have long claimed that rigid-soled cycling shoes and shoe-pedal attachments are more efficient, because they allow riders to pull up during the pedal stroke. However, numerous researchers have shown this notion 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”. Furthermore, Ostler et al. (2008), Mornieux et al. (2008), and, most recently, Straw and Kram (2016) have all consistently shown, in several different experimental configurations, that shoes and pedals do not improve cycling efficiency.

In an unusual cycling efficiency experiment, Bressel et al. (1998) investigated backwards pedaling. Many investigators have shown that backwards walking and running have a greater metabolic cost than forward locomotion (Flynn et al. 1994; Chaloupka et al. 1997; Wright and Weyand 2001; Hooper et al. 2004). Therefore, backward pedaling would also be expected to be much more metabolically costly. However, Bressel et al. (1998) found no significant difference in metabolic cost at a power output of 157 W.

In normal leg cycling, the relative position of the cranks and, therefore, the leg movements are 180° out-of-phase. However, numerous studies have compared the efficiency of different arm cycling movement patterns [left/right arms out-of-phase (180°) vs. left/right arms in-phase (0°)]. One study found a slightly greater efficiency for arm cycling out-of-phase (Goosey-Tolfrey and Sindall 2007) and several studies were either inconclusive or showed no difference in efficiency (Marincek and Valencic 1977; Hopman et al. 1995; Mossberg et al. 1999; Meyns et al. 2014). However, three studies have found that in-phase arm cycling is more efficient. For example, Dallmeijer et al. (2004) tested 13 subjects arm cycling at an average power output of 29 W in both the out-of-phase position and in-phase crank positions. They reported that efficiency was 13.3% greater for in-phase arm cycling. Building on that study, van der Woude et al. (2008) tested subjects arm cycling at higher power outputs (68.5 W out-of-phase, 81.6 W in-phase) and again found better efficiency with in-phase arm cycling (24.7% greater). Finally, in a study of 35 subjects with spinal cord injuries, Abel et al. (2003) found oxygen uptake to be ~4.4% lower (i.e., 4.4% greater efficiency) during in-phase rather than out-of-phase arm cycling at power outputs ranging from 30 to 90 W. To the best of our knowledge, there are no published reports of leg cycling efficiency with in-phase cranks.

Given the intriguing efficiency improvements in some arm cycling studies, we wondered if in-phase leg cycling is more efficient than the traditional out-of-phase leg cycling. Even a small increase in efficiency would have a dramatic effect on competitive cycling. Therefore, we investigated the extent to which cycling with different relative crank angles affects the efficiency of leg cycling. We tested the null hypothesis that there would be no difference in the metabolic cost of leg cycling when the relative crank angle was altered.

Methods

Subjects

Ten healthy, male, recreational bicycle riders (27.8 ± 8.2 years, mean ± 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 years, good general health, neurologically intact, and a self-report of cycling a minimum 150 miles (241 km) or 8 h per week. Subjects reported riding an average of 336 ± 120 km/week. We asked the subjects to fast for at least 2 h prior to testing.

Equipment

Subjects rode a custom (Nobilette, Longmont CO, USA), pan-loaded cycle ergometer (Vandewalle and Driss 2015) equipped with a standard Monark flywheel (9.53 kg, 0.255 m radius). We had the rear cog welded to the flywheel to create a fixed gear, non-freewheeling drivetrain which allowed subjects to more easily return the pedals from the bottom of the pedal stroke back to the top. The ergometer had a Shimano Octalink® bottom bracket, which allowed us to set the relative crank angle θ in 45 degree increments. For the experiment, we set the relative crank angles at 180°, 135°, 90°, 45°, and 0° (Fig. 1). Crank length was 172.5 mm. Subjects used their own rigid-soled, cleated cycling shoes, and clipless pedals during the experiment.

Protocol

To determine leg dominance, we asked the participants to kick a football (soccer ball) three times and deemed the leg that struck the ball to be dominant (Teng and Powers 2014). We set the relative crank angle by placing their dominant leg at top dead center and positioned the contralateral crank arm accordingly (Fig. 1). Subjects warmed-up for 10 min with light pedaling and stretching.

Each subject completed six, 5-min trials. The first and last trials were at the typical relative crank angle of 180°. We then randomized the order of the middle trials (135°, 90°, 45°, and 0°) for each subject. The last 180° trial was extended to 10 min in order to evaluate adaptation. We suspected that the perturbations to the crank angle during the testing protocol might have affected the coordination patterns and thus metabolic cost. The last 180° condition allowed us to evaluate that possibility. During all the trials, we required subjects to maintain a cadence of 90 RPM using visual feedback from a handlebar-mounted cadence meter. With a gear ratio of 3.71 and a pan load of 1.68 kg (16.5 N) applied to the flywheel at a radius of 0.255 m, a cadence of 90 RPM equates to a mechanical power output of 150 W. Subjects rode seated with their hands on the tops of the ergometer's racing style handlebars. Following each trial, subjects rested for 5 min. This obviated fatigue and allowed time to alter the ergometer relative crank angle for the following trial. All trials comprised a single experimental session.

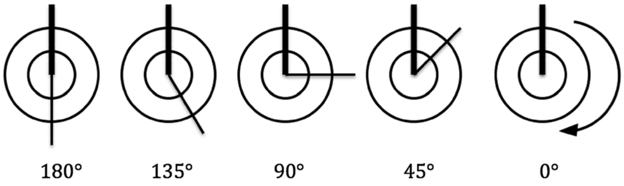

Fig. 1 Relative crank angles used in this study. The crank of the dominant leg is indicated at top dead center by the *thick lines*. The *thinner lines* indicate the contralateral crank. The *arrow* indicates the direction of pedaling

Metabolic energetics

We collected each participants' expired breaths and calculated the standard temperature and pressure, dry (STPD) rates of oxygen uptake ($\dot{V}O_2$), and carbon dioxide production ($\dot{V}CO_2$) using an open-circuit expired-gas analysis system (TrueOne 2400; ParvoMedics, Sandy, UT). Before each experiment, we calibrated the gas analyzers and pneumotach (flow meter) using reference gases and a calibrated 3-L syringe, respectively. We averaged $\dot{V}O_2$, $\dot{V}CO_2$, ventilation rate $\dot{V}_E$ (L/min), respiratory rate RR (=breathing frequency, breaths/min), tidal volume V_t (L), and respiratory exchange ratio (RER) for the last 2 min of each 5-min trial as well as for 9–10 min of the final 180° trial. If a subject's RER values had exceeded 1.0, we would have excluded his data from the study; however, all values remained below 1.0 (RER values ranged from 0.72 to 0.89). From the $\dot{V}O_2$ and $\dot{V}CO_2$ measurements, we calculated metabolic power using the Brockway equation (Brockway 1987). Finally, to evaluate if subjects were hyperventilating during the trials, we calculated the ventilatory equivalent, VEQ (=$\dot{V}_E/\dot{V}O_2$, both in L/min).

Statistics

We estimated a priori that we would be able to detect differences >1.6% in oxygen uptake given a sample size of 10 (Frederick 1983). We used R software (www.rstudio.com) to run one-way repeated-measures ANOVAs for the effect of relative crank angle on metabolic power, oxygen uptake rate, RER, and the ventilatory variables. If we found significance with an ANOVA, we ran Bonferroni's pairwise *t* tests to determine which conditions were different. Furthermore, we ran dependent *t* tests to compare the physiological variables for 4–5 min of the first 180° trial, 4–5 min and min 9–10 of the second 180° trial. We set statistical significance at $p < 0.05$. We report all values as mean ± SD unless noted otherwise.

Results

Leg cycling with crank angles other than 180° required greater metabolic power. As we decreased the relative crank angle from 180°, metabolic power monotonically increased by 1.6 ± 1.7% at 135° up to 8.2 ± 4.1% when the relative crank angle was 0° ($p < 0.001$) (Table 1; Fig. 2). Similarly, at reduced relative crank angles, the increases in $\dot{V}O_2$ ranged from 1.9 ± 1.5% at 135° to 7.7 ± 2.2% at 0° ($p < 0.001$) (Table 1). According to the slope of the linear regression, equation metabolic power increased by 4.0 W or 0.47% per 10° change in relative crank angle from 180° to 0° (Fig. 2). We applied both a linear fit as well as a sinusoidal fit, but upon finding essentially identical correlation coefficients for

Table 1 Metabolic data for all crank angle positions, averaged during 4–5 min (mean ± SE)

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 ± 0.05*
90	888 ± 11*	16.9 ± 0.2*	2.64 ± 0.03*	0.80 ± 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*

* Significantly different from the initial 180° condition ($p < 0.05$)

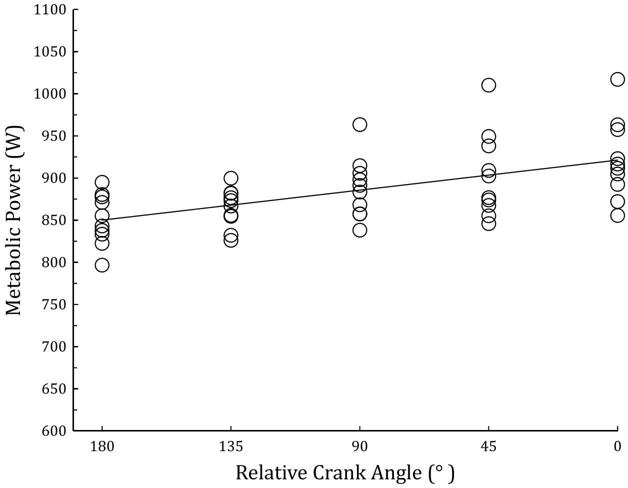

Fig. 2 Linear regression of metabolic power in (*W*) vs. relative crank angle (θ). *Symbols* indicate individual subject mean values. Linear regression equation: metabolic power (W) = $-0.3957\ \theta + 921$; $r^2 = 0.3174$, ($p < 0.001$)

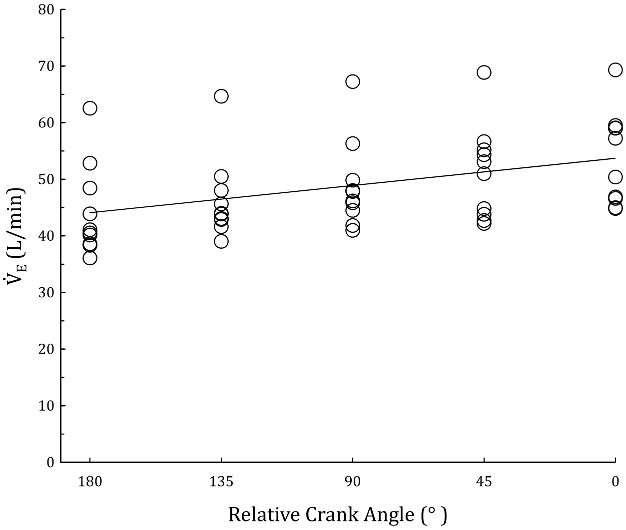

Fig. 3 Linear regression of ventilation rate ($\dot{V}_E$) vs. relative crank angle (θ). *Symbols* indicate individual subject mean values. Linear regression equation: $\dot{V}_E$ (L/min) = $-0.0534\ \theta + 53.706$; $r^2 = 0.1688$, ($p < 0.001$)

the two methods, we chose to present data from the linear fit model for simplicity (r^2: 0.317 linear and 0.313 sinusoidal).

Although we anticipated that metabolic power might be greater during 4–5 min of the second vs. first 180° trials due to the intervening trials at unfamiliar relative crank angles, there was no significant difference ($p = 0.31$). Furthermore, we suspected that if metabolic power was greater during 4–5 min of the second 180° trial, it might decrease during the subsequent 5 min of "re-adaptation". In fact, metabolic power slightly increased (1.8 ± 5.0%) during the 9–10 min of the second 180° trial compared to 4–5 min ($p = 0.003$).

After the repeated-measures ANOVA indicated a main effect of relative crank angle on both metabolic power and oxygen uptake rate, we used Bonferroni's pairwise *t* tests to detect differences between relative crank angles. The *t* tests indicated significant differences ($p < 0.001$) in metabolic power (*W*) between the 180° condition and 135°, 90°, 45°, and 0°. Similarly, we found significant differences in $\dot{V}O_2$ between the 180° condition and the 135°, 90°, 45°, and 0° conditions (all $p < 0.015$).

We also investigated if there were any changes in ventilatory variables across the different crank angles. In short, subjects overall ventilated more air per minute via more rapid and only slightly smaller breaths. As relative crank angle decreased, $\dot{V}_E$ increased significantly by 4.7% at 135° and by 21.6% at 0° ($p < 0.001$; Fig, 3). In addition, RR showed significant increases of 11.2% at 135° and of 23.3% at 0° ($p < 0.001$) (Table 2) and the breathing frequency was not a sub-multiple of pedaling rate at any relative crank angle. For both $\dot{V}_E$ and RR, the Bonferroni's post hoc test indicated significant differences between the 180° condition and the 135°, 90°, 45°, and 0° conditions (Table 2). V_T significantly decreased by 7.9% at 135° and 3.1% at 0° ($p < 0.001$) (Table 2). Finally, $\dot{V}EQ$, the ratio of $\dot{V}_E$ to $\dot{V}O_2$, significantly increased from 17.5 ± 2.9 at 180° to 19.8 ± 2.8 at 0° ($p < 0.001$) indicating a slight hyperventilation (Fig. 4). Bonferroni's post hoc tests indicated significant differences in $\dot{V}EQ$ between the 180° condition and the 90°, 45°, and 0° conditions.

Table 2 Ventilation data for all relative crank angle positions, averaged during 4–5 min (mean ± SE)

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

* Significantly different from the initial 180° condition ($p < 0.05$)

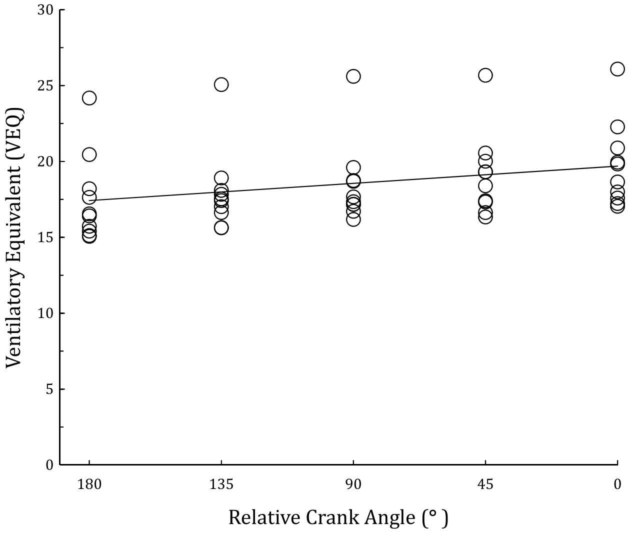

Fig. 4 Ventilatory equivalent (VEQ) = $\dot{V}_E$ (L/min)/$\dot{V}O_2$ (L/min) vs. relative crank angles (θ). *Symbols* indicate individual subject mean values. Linear regression equation: VEQ = −0.0126 θ + 19.693; $r^2 = 0.0857$, ($p < 0.001$)

Discussion

Although we hypothesized no difference in the metabolic cost at different relative crank angles, we found, in fact, that there was an increase. Therefore, we reject our null hypothesis. While pedaling in the most extreme relative crank arm angle condition (0°), efficiency decreased by ~8%. The increases in metabolic cost are likely related to increases in the metabolic cost of breathing, leg muscle co-activation, trunk stabilization, fluctuations in the angular velocity of the ergometer flywheel, and possibly lifting the legs during the upstroke.

To explore the possible increased metabolic cost of breathing, we investigated changes in $\dot{V}_E$ (Table 2). Compared to the baseline 180° relative crank angle, $\dot{V}_E$ increased linearly, by 4% at 135° to 17% at 0°. The increase in $\dot{V}_E$ was due to a significant increase in RR. Based on the increased VEQ, we surmise that the subjects were mildly hyperventilating when pedaling with relative crank angles other than 180° (Fig. 4). However, when a person hyperventilates, the respiratory exchange ratio (RER) typically increases. Since RER is the ratio of $\dot{V}CO_2/\dot{V}O_2$, a greater RER either indicates that CO_2 is being produced more rapidly due to greater carbohydrate (vs. fat) metabolism or that CO_2 is being “blown off” from stores in the blood and body. However, our data indicated that with mild hyperventilation at non-180° relative crank angle conditions, RER was inexplicably slightly lower not higher.

In some forms of exercise such as rowing, the double pole technique in cross-country skiing, and galloping in quadrupeds, ventilation is constrained or induced by overall body movements (Siegmund et al. 1999; Lindinger and Holmberg 2011; Bramble and Carrier 1983). During the present cycling experiment, subjects rode with a flexed hip posture, leaning forward while grasping the handlebars. Thus, the legs might have alternately applied an upward force on the viscera and consequently the diaphragm, aiding exhalation. When the legs were in-phase (0°), the subjects may have had both legs simultaneously applying an upward force on the diaphragm, which might have caused an increase in tidal volume, but V_T actually slightly decreased. Furthermore, cadence was kept constant throughout the experiment and yet RR increased at non-180° relative crank angles. Additionally, recall that RR was not a sub-multiple of pedaling cadence at any of the relative crank angles tested. Overall, we are unable to explain the changes in ventilation we observed. According to Aaron et al. (1992), the greater $\dot{V}_E$ we observed can be expected to increase $\dot{V}O_2$ by just ~0.03 L O_2/min. We measured a sixfold greater increase (0.19 L O_2/min) between the 180° and 0° conditions (Table 1). Thus, just 15.8% of the greater $\dot{V}O_2$ at the relative crank angle of 0° could be attributed to the greater $\dot{V}_E$.

In addition to ventilatory changes, the riders surely altered their muscle activity patterns while riding non-180° relative crank angles. Based on the previous arm cycling studies, we suspect that because of the novelty of the cycling experiment, greater leg muscle co-activation likely occurred and played a role in the greater metabolic cost (decrease in efficiency) when pedaling at non-180° relative crank angles.

In addition, changes in angular velocity of the ergometer flywheel may have affected our results. Although we were not able to quantify the fluctuations in flywheel angular velocity, any fluctuation would increase the mechanical power required. In normal 180° cycling, the subject’s pedaling pattern produces a nearly constant power output of 150 W due to one leg always applying a downward force, while the other leg is recovering. However, in non-180° cycling, the flywheel accelerated and decelerated slightly during the push and recovery phase of each crank cycle, respectively. The fixed gear mitigated but did not prevent such angular velocity fluctuations.

Gravity is another factor to consider. In the standard 180° configuration, the weight of the left leg counterbalances the weight of the right leg and vice versa. Thus, no muscular effort is required to lift the weight of the upstroke leg. However, for the 0° relative crank angle condition, if we had used a freewheeling rear hub on the ergometer flywheel, hip-flexor muscle activation presumably would have been needed during the upstroke, consuming metabolic energy. In that configuration, during the downstroke, the weight of the legs would help to overcome the flywheel resistance without a metabolic cost. However, the hub on our ergometer flywheel was a fixed gear. This allowed the momentum of the flywheel to assist the lifting of the legs during the upstroke of the pedaling cycle. Overall, it is unclear if there is any additional net cost during fixed gear 0° relative crank angle cycling due to the need to lift the legs against gravity.

Why is out-of-phase leg cycling more efficient than in-phase, while the opposite is generally true for arm cycling? Dallmeijer et al. (2004) and van der Woude et al. (2008) seem to be in agreement that the differences in efficiency between out-of-phase arm cycling and in-phase arm cycling arise from utilization of trunk muscles. They suggest that during out-of-phase arm cycling, the trunk muscles are used to stabilize the core and thus consume energy without doing useful work. Furthermore, they suggest that during in-phase arm cycling, the trunk muscles contribute to the production of mechanical power and thus do not negatively affect the efficiency.

Limitations

For all subjects, non-180° degree crank pedaling was a novel task. Allowing the riders to practice further with different crank angles before the testing began might have decreased the observed differences in metabolic cost across the different crank angles. Recall that to eliminate dead spots in the pedaling motion, we welded a fixed gear cog to the flywheel hub. It is unknown what effects if any, a fixed gear vs. freewheeling gear has on cycling efficiency.

Future directions

While the idea of altering the relative crank angle of a bicycle may seem of only academic interest, it may prove useful in rehabilitation settings. Recently, there has been growing interest in the use of split-belt treadmill for the use of gait rehabilitation, especially for post-stroke patients (Reisman et al. 2013; Helm and Reisman 2015; Hoogkamer 2017). Altering the bicycle's relative crank angle might achieve the same beneficial muscle phasing and activation changes that occur during split-belt treadmill rehabilitation. Indeed, Alibiglou, Brown and coworkers have developed a motor-driven, split-crank cycle ergometer (Alibiglou et al. 2009) and are exploring how it can be used to aid with post-stroke recovery (Alibiglou and Brown 2011a, b). One notable advantage of cycling rehabilitation vs. treadmill rehabilitation is that it could be done earlier post-stroke, before patients are able to walk safely.

Conclusion

We find that, unlike arm cycling, radically changing the relative crank angle on a bicycle from an out-of-phase (180°) to in-phase (0°) position decreases leg cycling efficiency by ~8%.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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