THE INFLUENCE OF LATERAL FOOT DISPLACEMENT ON CYCLING EFFICIENCY AND MAXIMAL CYCLING POWER

A thesis submitted to the Kent State University College of Education, Health and Human Services in partial fulfillment of the requirements for the degree of Master of Science

By
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May 2014
The purpose of this study was to examine an experimental pedal-shoe interface. This allows the foot to undergo lateral displacement along the pedal axis. The lateral movement which mimics in-line skating was believed to increase cycling efficiency and maximum power production. The objective of this investigation was to determine if pedals that allow for lateral displacement of the foot during the down stroke increase maximum power output and cycling efficiency compared to a standard pedal.

The participants in this study performed cycling protocols using control pedals (C) and two experimental pedals (PS, PL) that allowed the foot to traverse laterally either 15mm (PS) or 32mm (PL). Visit one consisted of maximal oxygen consumption (VO$_2$) and ventilatory threshold (VT) test followed by a familiarization trial with experimental pedals. Visit two consisted of a submaximal pedaling at 90 RPM for 5 minutes at 30%, 60%, & 90% VT in all pedal conditions. Visit three involved five second maximal power sprints at 10% body weight resistance with all three pedal conditions.

During the submaximal protocols heart rate (HR), (VO$_2$) and respiratory exchange ratio (RER) were not significantly different between pedal conditions. Furthermore, cycling efficiency was not different at VT intensities in all pedal conditions. Maximal sprint power was also not different between the three conditions nor was the pedaling rate
at which max power was achieved. These results suggest that there are no significant differences in cycling efficiency or power output when using pedals that allow for lateral displacement.
ACKNOWLEDGMENTS

I would like to first thank my committee chairman, committee members, and all Exercise Physiology faculty members for their support and guidance of my thesis journey.

I greatly appreciated the assistance that my thesis chairman, Dr. John McDaniel, whose encouragement and support made my thesis possible through unforeseen delays, problems and solutions. I would like to thank my advisor, Dr. Ridgel, whose guidance through my master’s degree made my thesis possible. I would also like to thank Dr. Glickman who is always there to support Exercise Physiology students. Special thanks to Dr. Kingsley who participated as a committee member later the thesis preparation process. I would also like to thank Keith Burns and Brandon Pollack with their assistance in the protocol of the investigation and data collection support and encouragement.
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CHAPTER I
INTRODUCTION

Cycling efficiency and maximal cycling power are largely influenced by neuromotor control patterns (Leirdal & Ettema, 2011). Specifically, the coordination of muscles affects the direction, magnitude, and duration of force applied to the pedal. Efficiency is greatest when the muscle activation is coordinated such that the percentage of force applied perpendicular to the crank (i.e. effective force) is maximized (Ericson & Nisell, 1988). In addition, coordinating muscle activation and maximizing effective force has a large influence on the ability to produce maximal cycling power. The lower limbs of an individual may be capable of producing high forces, but power will be compromised if the muscle actions are not coordinated appropriately. There are also many other factors that influence cycling efficiency and maximal cycling power including muscle fiber type, fiber recruitment within the muscle, power-velocity relationships. These other factors partially explain why cycling efficiency is maximal between 60-70 revolutions per minute (RPM) (Chavarrren & Calbet, 1999; Emanuele & Denoth, 2012; Passfield & Doust, 2000) while maximal power is produced at approximately 110-120 RPM (Emanuele & Denoth, 2012).

Cycling efficiency and maximal power production may also be influenced by the positioning of three interfaces where the cyclist interact with the bicycle: the saddle, the handlebar, and the pedals (Wozniak Timmer, 1991). The interface of the pedals is argued to be most important because it allows force to be distributed to the pedals and transferred into powering the bicycle into motion. More efficient pedals have been
designed with a cleat interface in which the shoe locks onto the pedal so the cyclist can generate power on the upstroke thereby increasing effective force, cycling efficiency and maximal cycling power (Cannon, Kolkhorst, & Cipriani, 2007; Ostler, Betts, & Gore, 2008). Although current day commercially available pedals ‘lock’ the shoe onto the pedal, most models allow some degree of rotation or ‘float’ primarily designed to increase comfort but not necessarily cycling performance. These current pedals, however, do not allow for any other foot displacement that may enhance cycling efficiency, power or comfort.

An experimental pedal design that allows for lateral displacement of the foot represents a radical departure from current bicycle pedals. Specifically, this design allows for lateral displacement of 15mm or 32mm during the pedal cycle. The exact phase at which this displacement occurs can be set by the researcher (Goldstein, 2011).

The experimental pedals were partially designed based off of inline skating and speed skating biomechanics and the concept that increased leg muscle activation/recruitment due to the lateral movement may improve cycling efficiency and power production. Currently there is limited information regarding the influence of lateral foot displacement on cycling efficiency or maximal cycling power. The only report to date (Goldstein, 2011) indicated that lateral displacement did not influence efficiency. However, this investigation did not use trained cyclists and observed at excess post-exercise oxygen consumption (EPOC) at only one intensity level.

The purpose of the proposed study was to determine if the lateral displacement of the foot (15mm and 32mm) throughout the pedal stroke allows for reduced metabolic
costs [(VO₂, respiratory exchange ratio (RER), and heart rate (HR)], increased cycling efficiency and increased maximal cycling power compared to normal pedaling mechanics. It is hypothesized that cyclists will have improved cycling efficiency and greater maximal power when using the lateral displacement pedals compared to control pedals. The results from this investigation will help sports scientists and coaches determine whether or not competitive road cyclists should use the lateral displacement pedals.
CHAPTER TWO  
METHODOLOGY

Participants (n=11) consisted of healthy competitive trained cyclists (9 males, 2 females, age = 39±7 years, weight = 72±8.4 kg, height =1.72±0.11 meters). Cyclists had to be regularly training 10 + hours per week and racing road cycling and/or triathlon events. All procedures were approved by Kent State University IRB and all participants were required to sign a consent form prior to their participation. Each participant reported to the Kent State University Applied Physiology Laboratory on three occasions. During the first session participants completed a VO₂ max test followed by a familiarization trial of the experimental lateral displacement pedals. During visits 2 and 3 the subjects participated in submaximal and maximal sprint cycling protocols, respectively. All testing took place in a thermoneutral environment. Subjects were instructed to refrain from strenuous exercise 24 hours prior to each visit (the day before the test may include light intensity cycling or exercise), consume their normal diet, and abstain from alcohol and caffeine. Four hours prior to visit two participants refrained from food or beverage other than water to ensure more consistent metabolic processes. As power output is influenced by factors such as body position, bike geometry, and pedaling cadences (de Groot et al., 1994), during all testing procedures participants were able to adjust the Velotron bicycle to fit their geometry.
**Visit 1**

In the first session, subjects’ height (Charder DigiStad HM210D stadiometer) and weight (Health-O-Meter Physician Balance Beam Scale) were measured. After the initial measurements were taken, the participant warmed up on the Velotron ergometer at self-selected pace using standard control pedals. Participants underwent an incremental progression to exhaustion designed to estimate ventilatory threshold (VT) and maximal oxygen consumption (VO\textsubscript{2} max). The protocol consisted of 20 watts for the first minute and increased 25 watts every minute thereafter until the subjects reached volitional fatigue while maintaining a self-selected revolutions per minute (RPM) (Amann, Subudhi, & Foster, 2004). Expired air was collected and analyzed with a Parvomedics metabolic cart (Parvomedics, Provo, Utah) to determine VO\textsubscript{2} max and VT (Yoon, Kravitz, & Robergs, 2007). VT researchers determined by VE/VO\textsubscript{2} increase to detect anaerobic threshold (Caiozzo et al., 1982). Specifically, researchers identified the point at which VE increased at a greater rate than oxygen consumption. After recovering from the VO\textsubscript{2} max test, the participants began a familiarization trial with the experimental lateral displacement cycling pedals. This trial includes practicing clipping-in, clipping-out & becoming acquainted with the slight change in cycling biomechanics.

**Visit 2**

Following the initial session, participants returned to the laboratory for sub-maximal endurance testing utilizing the control pedal (C), experimental 15mm short spindle (PS), experimental 32mm long spindle (PL). After a ten minute warm-up and 5
minute rest period participants sat quietly on the Velotron ergometer while gas exchange was measured for 2 minutes (baseline). Participants then pedaled through a submaximal cycling protocol that consisted of three 5 minute stages (5 minutes at 30% VT; 5 minutes at 60% VT, 5 minutes at 90% VT) at a pedaling rate of 90 RPM. This 15 minute protocol was then repeated for each pedal condition, presented in a counterbalanced fashion, with a 5 minute rest period that allowed for the technician to switch pedals on the ergometer. While cycling, the subject’s heart rate (HR), VO$_2$, (RER) was recorded. Metabolic cost in kilocalories (kcal) was calculated using the thermal equivalent of oxygen for nonprotein respiratory equivalent: kcal/min = VO$_2$ x (1.2341 x RER + 3.124) (Kuntz, 1901). Metabolic watts were then calculated using the factor of 69.7 watts/kcal/min. The protocol was repeated three times in each pedal condition. The participants then performed a ten minute cool-down. Visit two ended with a familiarization of the sprint trials they will perform during visit 3.

**Visit 3**

For the last visit participants performed a series of 5 second maximal power sprints. Participants began by performing a ten minute warm-up followed by 6 maximal sprints. The protocol was designed for participants to maintain 90 RPM at 100 watts for 20 seconds followed by 5 second maximal power sprint with the load set at 10% body mass utilizing the Velotron Wingate software (Racermate, Chicago, Illinois). Following each sprint the participant rested for 3 minutes until a total of 6 sprints were performed (2 sprints per pedal condition which were presented in counterbalanced fashion). Following
the completion of 4 subjects a malfunction occurred with the long spindle experimental pedals and that pedal was no longer usable. As a result, the remaining subjects performed two sprints with resistance set at 10% body mass followed by a single sprint at 5% and 15% body mass with the remaining two pedal conditions (C, PS). The variables collected were max power and pedaling rate at which max power occurred.

The protocols proposed were used previously to evaluate VO$_2$ max (Amann et al., 2004), VT (Yoon et al., 2007) cycling efficiency (Coast, Cox, & Welch, 1986; Hopker et al., 2013; McDaniel, Durstine, Hand, & Martin, 2002; Takaishi, Yasuda, Ono, & Moritani, 1996) and maximal cycling power (Hachana, Attia, Nassib, Shephard, & Chelly, 2012; Hodges et al., 2003; McGawley & Bishop, 2006; Racinais et al., 2006; Tomaras & MacIntosh, 2011; Watt, Hopkins, & Snow, 2002). Thus these protocols are well established in the literature and the use of healthy highly trained cyclists minimized any risk that could occur with strenuous physical activity. It was determined that two familiarization trials were optimal for collecting reliable data & no significant difference exists between trials 2, 3, 4, 5 in previous reports (McGawley & Bishop, 2006). Furthermore, when maximal power sprints are separated with proper rest in between it allows for adequate, precise data (Watt et al., 2002).

**Data Analysis**

The dependent variables assessed across the submaximal and maximal tests were VO$_2$, HR, RER, metabolic cost, gross efficiency, maximal power production and pedaling rate at which max power occurred. Subjects were divided into two groups based on
whether they used all three pedal conditions, or due to the defect with PL, were only tested on C and PS. All statistical analyses were performed using statistical analysis software (SPSS, Version 20.0, Chicago, IL). In regards to the submaximal protocols, averaged values across the last minute of each stage were analyzed. Due to the limited number of subjects completing all pedal conditions, and our primary focus on the main effect of the pedal, we restricted the analysis to 1-way repeated measures analysis of variance (ANOVA) for each exercise intensity. The level of significance was set a-priori at $p<0.05$. All data are reported as mean±SD.
CHAPTER THREE
ANALYSIS OF THE FINDINGS

Descriptive Statistics

11 subjects \((n= 9 \text{ males, 2 females})\) were participated in this investigation. The average \(\text{VO}_2\) max for the subjects was 56.2\(\pm\)5.5. On average their ventilatory threshold occurred at 70.3\(\pm\)24.3\% of their \(\text{VO}_2\text{max}\) and 238\(\pm\)26 watts.

\(\text{VO}_2\) Responses

\(\text{VO}_2\) was not different between pedal conditions at 30\% VT (C 18.6\(\pm\)2.2; PS 16.7\(\pm\)2.2; PL 18.2\(\pm\)3.4 ml/kg/min, \(P=0.321\)); 60\% VT (C 29.5\(\pm\)3.8; PS 27.6\(\pm\)4.3; PL 28.3\(\pm\)4.1ml/kg/min, \(P=0.329\)); nor 90\% VT (C 41.4\(\pm\)6.2; PS 39.7\(\pm\)6.5; PL 41.4\(\pm\)4.6 ml/kg/min, \(P=0.264\)).

![Figure 1: VO2 Responses.](image_url)
HR Responses

Heart rate was not significantly different between pedal conditions at 30% VT (C 98.0±12.3; PS 100.3±13.9; PL 101.7±12.7 bpm, \( P=0.69 \)), 60% VT (C 128.7±13.6, PS 139.6±14.3; PL 127.4±16.2 bpm, \( P=0.57 \)), nor 90% VT (C 146.2±13.6, PS 148.4±13.4, PL 148.6±15.0 bpm, \( P=0.11 \)).

\[ \text{Figure 2: HR Responses.} \]

Respiratory Exchange Ratio

RER also did not have significant differences between pedal conditions at 30% VT (C 0.84±.06, PS 0.84±.06, PL 0.83±.07, \( P=0.83 \)), 60% VT (C 0.88±.03, PS 0.87±.03, PL 0.88±.04, \( P=0.40 \)), nor 90% VT (C 0.96±.06, PS 0.94±.02, PL 0.95±.03, \( P=0.79 \)).
Metabolic Cost

Repeated measures analysis also indicate that metabolic cost also did not have significant differences between pedal conditions at 30% VT (C 6.48±0.88; PS 5.94±1.80; PL 6.56±1.42, \( P=0.34 \)), 60% VT (C 10.3±1.70, PS 9.83±2.26, PL 10.3±1.91, \( P=0.30 \)), nor 90% VT (C 14.8±2.72, PS 14.4±3.00, PL 15.4±2.50, \( P=0.23 \)).
Gross Efficiency

Gross efficiency also did not have significant differences between pedal conditions at 30% VT (C 16±2.1%, PS 17±2.3%, PL 16±1.7%, \( P=0.39 \)), 60% VT (C 20±3.6%, PS 21±3.2%, PL 20±2.3%, \( P=0.31 \)), nor 90% VT (C 21±4.4%, PS 22±3.6%, PL 20±2.6%, \( P=0.24 \)).
Individual Maximal Power Sprints (load = 10% body mass)

Maximal power sprints had no significant difference exist in the pedal conditions sprinting against 10% load (C 846±144, PS 827±138, PL 832 ±130 watts, $P=0.50$).

*Figure 6: Individual Maximal Power Sprints (load = 10% body mass)*

Average Maximal Power Sprints (load = 10% body mass)

Average maximal power sprints had no significant difference exist in the pedal conditions sprinting against 10% load (C 846±144, PS 827±138, PL 832 ±130 watts, $P=0.50$).
Maximal Sprint RPM

RPM during maximal power sprints at 10% load was not different across pedal conditions (C 113.7±7.4, PS 114.2±8.2, PL 112.5±6.7 RPM, P=.531).

Figure 7: Average Maximal Power Sprints (load = 10% body mass)

Figure 8: Maximal Sprint RPM.
Individual Maximal Sprints (load = 5% and 15% body mass)

Due to malfunction of PL participants 5-11 completed 5% BW & 15% BW sprints in the control and short pedal condition. Similar to the maximal power production with 10% body mass load, no significance differences in maximal sprint power were observed when the resistance was set at 5% or 15% body mass.

Average Maximal Sprints (load = 5% and 15% body mass)

Due to malfunction of PL participants 5-11 completed 5% BW & 15% BW sprints in the control and short pedal condition. Similar to the maximal power production with 10% body mass load, no significance differences in maximal sprint power were observed when the resistance was set at 5% or 15% body mass.
Figure 10: Average Maximal Power Sprints (load = 5% and 15% body mass).
CHAPTER FOUR
DISCUSSION AND IMPLICATIONS

The aim of this investigation was to determine if pedals that allowed for lateral displacement of the foot, designed based on speed skating biomechanics, reduced metabolic costs (VO$_2$, RER, and HR), increased cycling efficiency and increased maximal cycling power compared to pedals that result in normal pedaling mechanics. Although no significant benefits were realized in this investigation it has been concluded that the lateral displacement pedals are also not detrimental. Future research could uncover other potential benefits including the reduction of knee and ankle pain as well as fatigue.

Lateral Displacement During Submaximal Cycling

In general, utilizing pedals that allowed for lateral displacement during the pedal stroke did not influence the cardiovascular and metabolic variables measured in this investigation. VO$_2$, HR and RER all increased with exercise intensity, as expected. However there was no difference in these parameters across pedal conditions (Figure 1, 2 and 3). Metabolic cost, which is calculated based VO$_2$ and RER: Kcal = VO$_2$ x (1.2341 x RER + 3.124) (Kuntz, 1901) also did not differ between pedal conditions. Metabolic power was then calculated through the factor of 69.7 watts/kcal/min allowing us to ultimately determine gross cycling efficiency. Gross cycling efficiency was calculated
through mechanical power (watts) / metabolic power (watts) = gross efficiency.

Our data agrees with previous investigations in that gross efficiency ranged between 15.9±21.9 and increased with cycling intensity (Chavarren & Calbet, 1999). However, similar to the previously mentioned variables, no significant differences in gross efficiency existed between pedal conditions.

**Lateral Displacement During Sprint Cycling**

Unfortunately, as previously mentioned, a malfunction occurred with the long spindle experimental pedals and that pedal was not usable for 7 subjects. As a result, in addition to the two sprints with resistance set at 10% BW for the C and PS condition, those subjects also performed a single sprint at 5% BW and a single sprint at 15% BW for both pedal conditions. The variables collected were maximal power and pedaling rate at which maximal power occurred. Across all sprint protocols there were no significant differences between maximal power or pedaling rate at which maximal power occurred between pedal conditions (*Figure 8 and 9*).

The results observed in this investigation are similar to those reported by previous investigator (Goldstein, 2011). Specifically, they also reported that HR, VO₂, and gross efficiency were not different between pedal conditions. However, the subjects utilized in that study were not trained cyclists which would lead to large variances in the data. For example those subjects may have been relatively untrained with clipped-in pedals which could have led to inaccurate results. Cyclists who spend 10+ hours week training have a more finely tuned motor control pattern and we believed that they may be able to take
advantage of the lateral displacement offered by these pedals. Furthermore, their protocol consisted for only one submaximal intensity (150 watts for females, 175 watts for males). As previous reports indicate that motor recruitment and overall cycling biomechanics vary based on intensity (Coyle et al., 1991; Emanuele & Denoth, 2012; Mognoni & di Prampero, 2003; Wozniak Timmer, 1991) researchers felt a study that included more than one intensity level was needed to determine the potential benefits of these pedals.

Other Potential Benefits of Lateral Motion During Cycling

Although major performance benefits (i.e. maximal cycling power or cycling efficiency) may not have been realized with the experimental pedals, no disadvantages were observed either. In other words, maximal power and cycling efficiency were not reduced due to lateral foot displacement. Thus there are several questions regarding injury prevention, muscle activation and muscle fatigue that still need to be investigated before any global conclusions can be made. The lateral displacement pedals investigated result in an increased Q factor or horizontal distance between pedals. Increasing the Q factor could have potential benefits for individuals that develop lateral knee pain or discomfort when using a fixed cleat-pedal interface with limited range of motion. Specifically, increasing the Q factor may reduce the lateral forces placed on the knee during cycling. This is especially true for women with wider hips; the population that tends to develop knee pain associated cycling. It should be noted that previous reports indicated that gross efficiency increases as the Q factor narrows (Disley & Li, 2012).
This suggests that the lateral displacement pedals should have decreased cycling efficiency, although this was not observed in the current study.

Electromyography (EMG) is used for evaluating and recording the electrical activity produced by skeletal muscle and can be used to determine changes across muscle activation patterns. In regards to cycling, for example, in a previous investigation (Ericson et al., 1985) cyclists were observed in twelve different conditions at different work-loads, pedaling rate, saddle height and pedal foot positions. The lower extremity muscles that were engaged varied across the twelve conditions. Although significant difference were not found within cycling efficiency and maximal power in the current investigation, EMG could prove beneficial in determining whether muscle activation patterns were altered using the lateral displacement pedals compared to the control condition. For example, if lateral foot displacement resulted in greater muscle recruitment, utilized greater muscle mass but at lower muscle specific intensities, then it could be argued that the rate of fatigue for any given muscle would be reduced. This is an important concept because efficient muscle coordination decreases as fatigue and workload increases (Bini, Diefenthaler, & Mota, 2010; Dorel, Drouet, Couturier, Champoux, & Hug, 2009; Prilutsky & Gregory, 2000; Sanderson & Black, 2003). This could help increase performance and reduce fatigue and/or perceived effort given the same conditions (Prilutsky & Gregory, 2000).
Limitations of the Pedal Design

As previously mentioned the current lateral displacement pedals investigated have an increased Q factor or a horizontal width between bicycle pedals. Aerodynamic drag is affected by the frontal surface area of the rider and the bike and is largely influenced by body positioning. Therefore, it could be hypothesized that increasing the frontal surface area due to the lateral displacement of the foot and lower leg could lead to increased aerodynamic drag. This detriment obviously would not impact results in the lab, but would reduce performance on the road. Altered aerodynamics could be evaluated with wind tunnel testing (Debraux, Grappe, Manolova, & Bertucci, 2011). The lateral displacement pedal design may also reduce the speed at which cyclists can corner. Specifically, when cornering at high speeds the cyclists leans the bike. Lateral displacement of the pedal could result in the pedal contacting the ground.

Study Limitations

A limitation of the current study is that subjects had only 1 familiarization trial before the submaximal bouts and two familiarization trials before the sprint protocols. As hours are spent training for competition, trained cyclists focus on their pedaling technique. It is generally accepted that proper pedaling technique saves energy and yields higher gross efficiency (Leirdal & Ettema, 2011). (Korff, Fletcher, Brown, & Romer, 2011), suggested that short-term interventions in pedaling technique can change pedaling mechanics but do not correlate to efficiency during steady-state cycling. To make an effective change it may require weeks/months of training with these pedals.
before advantages are realized. A second limitation of the current investigation is that the timing of the lateral displacement pedal was preset such that the pedal would be most medially at the top of the crank cycle, move outward during the downstroke and return to medially during the upstroke. Although this paradigm was based on skating biomechanics (Chang, Turcotte, & Pearsall, 2009) it may not necessarily represent the most optimal pattern. A future investigation involving a free floating medial-lateral displacement pedal may allow each cyclist to determine the best lateral movement pattern for their individual biomechanics/body position.

**Conclusion**

The lateral displacement pedals that resemble skating biomechanics were studied to determine if reductions in metabolic costs (VO$_2$, RER, and HR), increased cycling efficiency and increased maximal cycling power would occur compared to normal pedaling mechanics. Though no significant results were determined from this study the lateral displacement pedals cause no harm nor benefit to a cyclist. Therefore with further research in product development, EMG testing may lead to undiscovered benefits.
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