ELSEVIER

Journal of Biomechanics 40 (2007) 1262–1267

JOURNAL OF BIOMECHANICS

www.elsevier.com/locate/jbiomech
www.JBiomech.com

Is economy of competitive cyclists affected by the anterior–posterior foot position on the pedal?

J.R. Van Sickle Jr[a], M.L. Hull[a,b,*]

[a]*Biomedical Engineering Graduate Group, One Shields Avenue, University of California, Davis, CA 95616, USA*
[b]*Department of Mechanical Engineering, One Shields Avenue, University of California, Davis, CA 95616, USA*

Accepted 29 May 2006

Abstract

The primary purpose of this investigation was to test the hypothesis that cycling economy, as measured by rate of oxygen consumption ($\dot{V}O_2$) in healthy, young, competitive cyclists pedaling at a constant workrate, increases (i.e. $\dot{V}O_2$ decreases) when the attachment point of the foot to the pedal is moved posteriorly on the foot. The $\dot{V}O_2$ of 11 competitive cyclists (age 26.8 ± 8.9 years) was evaluated on three separate days with three anterior–posterior attachment points of the foot to the pedal (forward = traditional; rear = cleat halfway between the head of the first metatarsal and the posterior end of the calcaneous; and mid = halfway between the rear and forward positions) on each day. With a randomly selected foot position, $\dot{V}O_2$ was measured as each cyclist pedaled at steady state with a cadence of 90 rpm and with a power output corresponding to approximately 90% of their ventilatory threshold (VT) (mean power output 203.3 ± 20.8 W). After heart rate returned to baseline, $\dot{V}O_2$ was measured again as the subject pedaled with a different anterior–posterior foot position, followed by another rest period and then $\dot{V}O_2$ was measured at the final foot position. The key finding of this investigation was that $\dot{V}O_2$ was not affected by the anterior–posterior foot position either for the group ($p = 0.311$) or for any individual subject ($p \geqslant 0.156$). The $\dot{V}O_2$ for the group was 2705 ± 324, 2696 ± 337, and 2747 ± 297 ml/min for the forward, mid, and rear foot positions, respectively. The practical implication of these findings is that adjusting the anterior–posterior foot position on the pedal does not affect cycling economy in competitive cyclists pedaling at a steady-state power output eliciting approximately 90% of VT.

Keywords: Economy; Energy expenditure; Efficiency; Oxygen consumption; Ankle; Plantar flexor; Triceps surae; Muscle

1. Introduction

The two most important physiological factors in determining a rider's maximum average power output, and therefore velocity, are the rider's cycling economy and the rider's $\dot{V}O_2$ at lactate threshold (Coyle, 1995). Economy is defined as the caloric energy expenditure at a given workrate. At a given workrate, economy is a useful indicator of the gross efficiency defined as the ratio of the work accomplished per unit time to the caloric energy expenditure per unit time. Economy is dictated by the energy demands placed on the rider, which in turn are dictated by the force demands required of the muscles. Reducing the muscular forces at a given power output may translate into improvements in performance (Coyle, 1995).

One means for decreasing the force developed by the ankle plantarflexors is to move the foot on the pedal anteriorly. By equilibrating the moment about the ankle joint created by the pedal reaction force, the ankle plantarflexors act primarily to transfer the power produced by the hip and knee extensors to the crank (Raasch et al., 1997; Zajac et al., 2002) and hence contract largely isometrically. The force developed by the plantarflexors to transfer this power is substantial. For example, at a crank angle of 90° (i.e. crank

---

*Corresponding author. Tel.: +1 530 752 6220; fax: +1 530 752 4158.
E-mail address: mlhull@ucdavis.edu (M.L. Hull).

0021-9290/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2006.05.026

horizontal and forwards), the equilibrating force in the Achilles tendon for a size 9 ft in the traditional anterior–posterior position while pedaling at 90 rpm and 250 W is approximately 650 N. Consequently, moving the cleat rearward on the shoe would move the foot anteriorly on the pedal thus reducing the moment developed by the pedal reaction load about the ankle joint (Ericson et al., 1985b; Gonzalez and Hull, 1989) and decreasing the force required by the ankle plantarflexors to equilibrate this moment (Ericson et al., 1985a; van Sickle, 2003). This reduction in force could translate into an increase in economy. Because the effect of anterior–posterior foot position on economy in cycling is unknown, the primary objective of this study was to test the hypothesis that gross metabolic energy expenditure as indicated by $\dot{V}O_2$ in competitive cyclists decreases when the attachment point of the foot to the pedal is moved posteriorly on the foot. If the gross metabolic energy expenditure is not affected for the competitive cycling population, then a second objective was to determine whether effects are evident for individual subjects. This latter objective was of interest because pedaling mechanics differ between subjects (Coyle et al., 1991) so that the energy expenditure of individual subjects might be affected even if energy expenditure of the population was not.

2. Methods

Eleven subjects, nine males and two females, were recruited from the local cycling community (Table 1). All subjects had a minimum of 2 years of competition, and 4 years cycling experience; their average age was 26 years.

After obtaining approval of the experimental protocol by the Institutional Review Board and after obtaining written informed consent of each subject, all testing was performed using a bicycle (Model 1500, Trek, Madison, WI) mounted on a Velodyne cycling ergometer (Frontline Technology, Irvine, CA). The Velodyne ergometer provided constant power outputs that could be adjusted incrementally and maintained independent of pedaling rate. The test bicycle was adjusted to match the dimensions of the subject's own bicycle. The dimensions measured for this purpose included the following: (1) seat height, (2) knee over pedal spindle (seat fore-aft position), (3) stem height (in relation to seat), and (4) nose of saddle to handlebar clamp distance.

Table 1
Subject data

Subject	Gender	Age (years)	Height (m)	Weight (kg)	Level
Subject 1	M	24	1.816	74.9	Cat 2
Subject 2	M	22	1.803	69.9	Cat 4
Subject 3	M	50	1.765	79.9	Mas 45+
Subject 4	M	36	1.854	78.1	Cat 3
Subject 5	F	21	1.702	59.9	Cat 3
Subject 6	M	21	1.778	83.1	Cat 4
Subject 7	M	22	1.753	74.9	Cat 4
Subject 8	M	22	1.880	87.2	Cat 4
Subject 9	F	22	1.778	64.5	Cat 3
Subject 10	M	27	1.867	79.9	Cat 3
Subject 11	M	28	1.854	78.1	Cat 4

To modulate the force demand of the ankle plantarflexors, the cleat was mounted in three different anterior–posterior positions. The traditional, or forward, position with the cleat beneath the head of the first metatarsal was used as a baseline reference. The other two positions were the rear position, halfway between the head of the first metatarsal and the posterior end of the calcaneous, and a mid position, halfway between the rear and forward positions. The progressive rearward mounting of the look-style cleat was accomplished by mounting the cleat on a lightweight (135 g), longitudinally slotted plate affixed to the bottom of lightweight (650 g for size 43) cycling shoes (SH-R100, Shimano, Irvine, CA). Because the effective leg length was decreased for the more rearward cleat positions, the seat height was necessarily lowered so that the subjects could reach the pedals. The seat height and handlebar heights were lowered by the amounts necessary to maintain the same patterns of motion (measured using a video-based motion analysis system) for the hip and knee for each foot position for each subject.

2.1. Experimental design

All testing was performed at a power output designed to elicit approximately 90% of the rate of oxygen consumption associated with ventilatory threshold (VT) of each of the 11 competitive cyclists who volunteered to be test subjects. VT was used instead of a strict percentage of $\dot{V}O_{2\,max}$ because VT is a better predictor of athletic performance (Coyle, 1995). VT provides a reference for the metabolic pathways being used by the body (i.e. right at the beginning of an exponential increase in arterial CO_2 pressure, which is $PaCO_2$) (Coyle, 1995). Accordingly, each subject worked at approximately the same relative level of effort. VT was determined using gas exchange and the "V-slope" method (Wasserman et al., 1994). The protocol involved breath-by-breath measurement of $\dot{V}CO_2$, plotted against the simultaneous $\dot{V}O_2$ (Physio-Dyne Max-1, Physio-Dyne Instruments Corp., Quogue, NY).

The VT test was designed to take approximately 14 min (Wasserman et al., 1994). The subjects began by riding for 3 min at 100 W. The loading was incrementally increased 25 W/min either for the next 12 min to elicit a respiratory exchange ratio ($RER = \dot{V}CO_2/\dot{V}O_2$) of at least 1.1 or until the subject could no longer continue. The power output needed to elicit a $\dot{V}O_2$ of approximately 90% of each subject's VT was determined.

Subsequent to the VT test, the subjects were tested in the different foot positions on each of 3 days to reduce the standard error in $\dot{V}O_2$ measurements and test days were spaced during a period of 2 weeks to reduce any effects of concurrent training. The testing of each subject occurred at a regular time of day within a 2-h window to control for any effect of the time of day on test results (Hill et al., 1992; Hill, 1996). All foot positions were tested each day, keeping the protocol identical and randomizing the foot position order. On each day preceding a test day, the subjects rested from their regular training regimen so that fatigue as a result of training load immediately prior to the test day did not affect test results (Sherman et al., 1984). The order of the foot positions was randomized for each subject to minimize any carry over effects.

The testing each day began by measuring the subject's resting heart rate in a sitting position after allowing the subject to rest comfortably for 5 min. The subject then warmed up for 17 min with the foot in the forward position. The warm up consisted of 10 min at 125 W, 5 min at 90% VT, and 2 min at 100 W. The entire warm up was ridden at 90 rpm. A metronome, as well as a visual cadence indicator, was used to regulate the cadence. Following the warm up, the subject was allowed to recover until their heart rate returned to within 20 beats per minute (bpm) of the previously measured resting value. To allow for adaptation to the different foot positions, each subject then rode for 10 min at 125 W and 90 rpm under each position to be tested. Upon completion of the adaptation period, the subject was allowed to recover until their heart rate fell to within 20 bpm of their resting value. The subject then began pedaling at 125 W and 90 rpm, and the resistance was steadily increased over 1 min up to the power output corresponding to approximately 90% of their VT for the forward foot position. The subject continued riding for 7 min at 90% of their VT and 90 rpm. Data were collected for the last 3 min of the interval while the subject was at steady state (Riley and Cooper, 2002). After the subject's heart rate fell to within 20 bpm of their resting value, the next randomly selected foot position was tested.

2.2. *Energy expenditure measurement and data analysis*

Oxygen uptake was determined using open-circuit metabolic procedures. Expired gasses were collected using a triple-J valve with mouthpiece, and analyzed for volume and concentration using a metabolic gas analyzer. $\dot{V}O_2$ was calculated from breath-by-breath collection with averages over each minute. The averaged value from the last 3 min of each trial was used to minimize variability.

To address the two objectives of the study, statistical analyses were performed. To test the hypothesis that moving the cleat rearward on the pedal decreased $\dot{V}O_2$ for the competitive cycling population, a one-factor repeated measures ANOVA on repeated observations for all subjects was used. To determine whether moving the cleat rearward on the pedal decreased $\dot{V}O_2$ for individual subjects, a one-factor ANOVA on repeated observations for each subject was used. In each of these analyses, the single factor was the anterior–posterior foot position at three levels (forward, mid, and rear) and the dependent variable was $\dot{V}O_2$ averaged over the last 3 min of each trial. If significant effects were detected ($p<0.05$), then a post hoc Tukey pairwise comparison was used to identify which foot positions significantly affected $\dot{V}O_2$. SAS (Release 8.02, Cary, NC) was used for all statistical calculations.

3. Results

The foot position did not significantly affect $\dot{V}O_2$ for the sample of subjects tested ($p = 0.311$) (Table 2). Indeed the differences in the $\dot{V}O_2$ averaged over all of the subjects for the mid and rear positions from the forward position were small (Fig. 1). The average difference in $\dot{V}O_2$ between the mid and forward positions was only 10 ml/min or 0.4% relative to the forward position. The average difference in $\dot{V}O_2$ between the rear and forward positions was greater than that between the mid and forward positions but was still limited to only 41 ml/min or 1.5% relative to the forward position (Fig. 1).

When the data were analyzed on a per subject basis, the foot position did not significantly affect $\dot{V}O_2$ for any of the subjects ($p>0.156$). Only three of the 11 subjects (subjects 1, 6, 10) showed a consistent trend in $\dot{V}O_2$ with foot position when averaged over the 3 days but these trends were not strong enough to be significant statistically.

4. Discussion

Improving cycling economy through biomechanical modifications of the bicycle-rider interface is a potential means for improving athletic performance. Changing the anterior–posterior foot position on the pedal had the potential to alter a rider's economy by substantially reducing the force of the ankle plantarflexors. The hypothesis tested in this study was that the gross metabolic energy expenditure of the cyclist would decrease when the attachment point of the foot to the pedal was moved posteriorly on the foot. The key findings were that $\dot{V}O_2$ for the rear and mid foot positions was not significantly different from that of the

Table 2
Rates of oxygen consumption for each subject (ml O_2/min)

	Day	Forward	Mid	Rear
Subject 1	1	3044	3003	2967
	2	3048	3093	3079
	3	3040	3027	3045
Subject 2	1	2737	2752	2722
	2	2559	2575	2554
	3	2774	2889	2829
Subject 3	1	2816	2953	2831
	2	3112	3075	3063
	3	2597	2543	2458
Subject 4	1	3159	3137	3142
	2	3109	3083	3114
	3	2812	2836	2822
Subject 5	1	2337	2281	2320
	2	2449	2424	2450
	3	2035	2002	2953
Subject 6	1	2860	2940	3035
	2	3003	2815	2963
	3	2926	2909	2926
Subject 7	1	2708	2582	2700
	2	2477	2424	2471
	3	2693	2738	2762
Subject 8	1	3006	2993	2973
	2	2871	2792	2840
	3	2721	2814	2844
Subject 9	1	2180	2112	2210
	2	2186	2157	2210
	3	1986	1968	1995
Subject 10	1	2920	2980	3030
	2	3061	3024	3111
	3	2990	3002	3080
Subject 11	1	2343	2343	2338
	2	2374	2374	2422
	3	2357	2329	2380

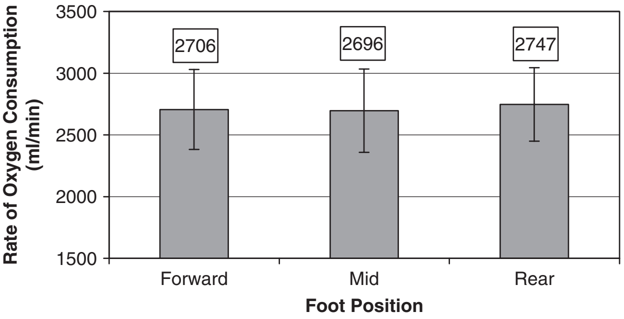

Fig. 1. Bar graph illustrating average rates of oxygen consumption across all subjects for the three foot positions. The error bars are ±1 standard deviation. The foot position did not significantly affect the rate of oxygen consumption ($p = 0.311$).

forward position for either the subject sample or for any individual subjects.

Because the null hypothesis was not rejected and because a small 1.5% difference in $\dot{V}O_2$ between the forward and rear positions existed for the subject sample which could translate into a performance difference, a post hoc power analysis based on the variability in the data collected and the small difference observed was conducted. In this analysis, the difference to detect, delta, was set at 41 ml O_2/min and the sample standard deviation, sigma (i.e. square root of the error term), was equal to 59 ml O_2/min. For a delta/sigma ratio $= 0.7$, the power of the statistical test was approximately 95% which indicates that there is a low probability of falsely accepting the null hypothesis. Accordingly, the null hypothesis that there is no difference in $\dot{V}O_2$ can be accepted with high confidence.

The results did not support the hypothesis notwithstanding the substantial decreases in the force demand placed on the ankle plantarflexors by moving the cleat posteriorly to the mid and rear positions. At constant power output, the intersegmental moment developed at the ankle joint is proportional to the distance between the attachment point of the shoe to the pedal and the ankle joint (Ericson et al., 1985b). Because only the ankle plantarflexors but not the dorsiflexors are active when the ankle intersegmental moment is maximum (Neptune et al., 1997), the corresponding force produced by the ankle plantarflexors is modulated in direct proportion to changes in the intersegmental ankle moment. The ankle intersegmental moment and hence force demand on the ankle plantarflexors decreased by approximately 30% and 65% for the mid and rear foot positions, respectively.

Because the results did not support the hypothesis, it is of interest to consider the implications to the mechanical kinetics of the muscles. Although the ankle plantarflexors act primarily to transfer the power produced by the hip and knee extensors to the crank (Raasch et al., 1997; Zajac et al., 2002), they also generate power in their own right contributing about 7.5% of the total work to complete one crank cycle (Zajac et al., 2002). Moving the cleat posteriorly on the foot not only reduced the force demand on the ankle plantarflexors to equilibrate the ankle joint moment developed by the foot-pedal reaction forces, but also reduced the ability of the ankle plantarflexors to generate power. Because the average power generated by the subjects was maintained constant, another muscle(s) would have to generate additional power to compensate for the loss in power of the ankle plantarflexors. Accordingly one possible explanation of the result in this study is that the increase in energy expenditure to redistribute power to another muscle(s) was equal to the loss in energy expenditure accompanying the reduced force of the ankle plantarflexors.

In considering which muscles are likely to provide the additional power, the principal candidates are the gluteus maximus and/or the vastii because these muscles produce the majority of the power in the downstroke region of the crank cycle and because the ankle plantarflexors act synergistically with the hip and knee extensors to transfer power to the crank (Raasch et al., 1997; Zajac et al., 2002). In an effort to determine which of these muscles provided the extra power, the electromyograms of the vastus lateralis, vastus medialis, and gluteus maximus were recorded with surface electrodes during the experiments (van Sickle, 2003). The methods and results of these measurements are summarized briefly below and are not presented in greater detail because the measurements were not central to test the hypothesis of the study and because the results were inconclusive. The activation of each muscle was computed as described previously (Raasch et al., 1997; Neptune and Hull, 1998) and it can be argued that the activation was a relative indicator of the muscle force for the conditions of these experiments (van Sickle, 2003). The activation was analyzed statistically using a single-factor repeated measures ANOVA where the independent variable was foot position at three levels and the dependent variable was the activation integrated over the crank cycle. There was no statistically significant increase in integrated activation for any of the muscles as the cleat position was moved posteriorly on the sole of the shoe ($p > 0.05$). An increase in activation may not have been detected because other muscles, which could not be monitored with surface electrodes, provided the additional power. For example, the vastus intermedius could have provided most of the additional power because it contributes the greatest to knee extension moment of the three vastii muscles (Zhang et al., 2003). Alternatively the additional power could have been distributed to either one or more of the muscles that were monitored but the increase was difficult to detect using activation computed from surface electromyography.

To confirm the large decrease in plantarflexor force of approximately 30% and 65% for the mid and rear positions expected from the equilibrium analysis, the electromyograms also were recorded for the three ankle plantarflexors (van Sickle, 2003). The integrated activation over the crank cycle for the mid and rear positions decreased by 27% and 54%, respectively, compared to the forward position and these decreases were statistically significant ($p < 0.0001$) (van Sickle, 2003). The dramatic decreases in integrated activation support the results from equilibrium that the force demand on the ankle plantarflexors was substantially decreased.

The result that the anterior–posterior foot position had a minimal effect on the economy in pedaling has an important practical implication. Many commercially available cycling shoes offer a small (±1 cm) range of adjustment of the anterior–posterior cleat position and this range could be readily increased if such an increase is warranted. Based on the results of this study however, there is no economy advantage to be gained in terms of energy cost by adjusting the anterior–posterior cleat position for cyclists riding at approximately 90% VT at a steady-state pedaling rate of 90 rpm.

Lowering the force demand of the ankle plantarflexors could be beneficial to injured athletes. For athletes with injuries to either the Achilles tendon or the muscles in the triceps surae group, it would be beneficial to reduce the load on this muscle–tendon complex while maintaining the ability to either exercise or possibly compete. Because a significant change in energy expenditure was not demonstrated for a more rearward cleat position, a more rearward position can be adopted without an expected decrease in steady-state performance due to increased energy expenditure.

Two biomechanical variables that were controlled so that they did not systematically affect the metabolic energy expenditure were the seat height and the handlebar height. Seat height was adjusted (i.e. lowered) as the cleat position was moved posteriorly on the sole of the shoe. Subjects could not reach the pedals at the bottom of the crank cycle with the posterior cleat positions because the effective length of the leg decreased due to the loss in foot length as the cleat position was moved posteriorly on the sole of the shoe. The seat was lowered for the mid position by 7 mm on average and for the rear position by 13 mm on average. The handlebar height was also lowered in conjunction with the seat height. These two adjustments served to maintain the patterns of motion of both the hip and knee constant as verified through motion analysis. Without maintaining the joint patterns of motion constant, the experiment design could have been confounded because changes in both anterior–posterior foot position and joint patterns of motion could have affected the energy expenditure (Shennum and deVries, 1976; Nordeen-Snyder, 1977; Grappe et al., 1998). Thus to isolate the anterior–posterior foot position as a single independent variable for study, the physical seat height and handlebar height were adjusted to maintain a constant 'effective' seat height.

In summary, the anterior–posterior foot position did not affect pedaling economy both for the population of competitive cyclists and for individuals within this population. Thus the substantial decrease in the force of the ankle plantarflexors that occurred when the cleat position was moved posteriorly on the sole of the shoe did not elicit a change in economy for steady-state cycling. From a cycling performance standpoint, there is no benefit in moving the cleat posteriorly on the sole of the shoe. From a clinical standpoint, the anterior–posterior foot position can be adjusted to lower the force transmitted through the Achilles tendon while minimally affecting the patient's ability to exercise, which may be beneficial to injured athletes.

Acknowledgement

The authors are grateful to Professor James Shaffrath of the Department of Exercise Biology for advice on the experimental design and measurement of human performance variables.

References

Coyle, E.F., 1995. Integration of the physiological factors determining endurance performance ability. Exercise and Sport Science Reviews 23, 25–63.

Coyle, E.F., Feltner, M.E., Kautz, S.A., Hamilton, M.T., Montain, S.J., Baylor, A.M., Abraham, L.D., Petrek, G.W., 1991. Physiological and biomechanical factors associated with elite endurance cycling performance. Medicine and Science in Sports and Exercise 23, 93–107.

Ericson, M.O., Nisell, R., Arborelius, U.P., Ekholm, J., 1985a. Muscular activity during ergometer cycling. Scandanavian Journal of Rehabilitation Medicine 17, 53–61.

Ericson, M.O., Ekholm, J., Svensson, O., Nisell, R., 1985b. The forces of ankle joint structures during ergometer cycling. Foot and Ankle 6, 135–142.

Gonzalez, H., Hull, M.L., 1989. Multivariable optimization of cycling biomechanics. Journal of Biomechanics 22, 1151–1161.

Grappe, F., Candau, R., Busso, T., Rouillon, J.D., 1998. Effect of cycling position on ventilatory and metabolic variables. International Journal of Sports Medicine 19, 336–341.

Hill, D.W., 1996. Effect of time of day on aerobic power in exhaustive high-intensity exercise. Journal of Sports Medicine and Physical Fitness 36, 155–160.

Hill, D.W., Borden, D.O., Darnaby, K.M., Hendricks, D.N., Hill, C.M., 1992. Effect of time of day on aerobic and anaerobic responses to high-intensity exercise. Canadian Journal of Sport Science 17, 316–319.

Neptune, R.R., Hull, M.L., 1998. Evaluation of performance criteria for simulation of submaximal steady-state cycling using a forward dynamic model. Journal of Biomechanical Engineering 20, 334–341.

Neptune, R.R., Kautz, S.A., Hull, M.L., 1997. The effect of pedaling rate on coordination in cycling. Journal of Biomechanics 30, 1051–1058.

Nordeen-Snyder, K.S., 1977. The effect of bicycle seat height variation upon oxygen consumption and lower limb kinematics. Medicine and Science in Sports 9, 113–117.

Raasch, C.C., Zajac, F.E., Ma, B., Levine, W.S., 1997. Muscle coordination of maximum-speed pedaling. Journal of Biomechanics 30, 595–602.

Riley, M.S., Cooper, C.B., 2002. Ventilatory and gas exchange responses during heavy constant work-rate exercise. Medicine and Science in Sports and Exercise 34, 98–104.

Shennum, P.L., deVries, H.A., 1976. The effect of saddle height on oxygen consumption during bicycle ergometer work. Medicine and Science in Sports 8, 119–121.

Sherman, W.M., Armstrong, L.E., Murray, T.M., Hagerman, F.C., Costill, D.L., Staron, R.C., Ivy, J.L., 1984. Effect of a 42.2-km footrace and subsequent rest or exercise on muscular strength and work capacity. Journal of Applied Physiology 57, 1668–1673.

van Sickle, J., 2003. How the anterior–posterior foot position on the pedal affects muscle force and energy expenditure in competitive cyclists. MS Thesis in Biomedical Engineering, University of California at Davis.

Wasserman, K., Stringer, W.W., Casaburi, R., Koike, A., Cooper, C.B., 1994. Determination of the anaerobic threshold by gas exchange: biochemical considerations, methodology and physiological effects. Zeitschrift für Kardiologie 83, 1–12.

Zajac, F.E., Neptune, R.R., Kautz, S.A., 2002. Biomechanics and muscle coordination in human walking. Part 1. Introduction to concepts, power transfer, dynamics, and simulations. Gait and Posture 16, 215–232.

Zhang, L.Q., Wang, G., Nuber, G.W., Press, J.M., Koh, J.L., 2003. In vivo load sharing among the quadriceps components. Journal of Orthopedic Research 21, 565–571.