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Pedal force effectiveness in cycling: A review of constraints and training effects

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REVIEW ARTICLE

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Pedal force effectiveness in Cycling: a review of constraints and training effects

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Abstract

Pedal force effectiveness in cycling is usually measured by the ratio of force perpendicular to the crank (effective force) and total force applied to the pedal (resultant force). Most studies measuring pedal forces have been restricted to one leg but a few studies have reported bilateral asymmetry in pedal forces. Pedal force effectiveness is increased at higher power output and reduced at higher pedaling cadences. Changes in saddle position resulted in unclear effects in pedal force effectiveness, while lowering the upper body reduced pedal force effectiveness. Cycling experience and fatigue had unclear effects on pedal force effectiveness. Augmented feedback of pedal forces can improve pedal force effectiveness within a training session and after multiple sessions for cyclists and non-cyclists. No differences in pedal force effectiveness were evident between summarized and instantaneous feedback. Conversely, economy/efficiency seems to be reduced when cyclists are instructed to improve pedal force effectiveness during acute intervention studies involving one session. Decoupled crank systems effectively improved pedal force effectiveness with conflicting effects on economy/efficiency and performance.

Keywords: pedal forces, pedaling technique, cycling performance, workload, pedaling cadence, body position

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Introduction

During cycling, lower limb movement in the sagittal plane is constrained to a circular path by the geometry of the bicycle (i.e. cranks and pedals). Within these constraints the cyclist can vary pedaling technique by changing the kinematics of their lower limbs (thigh, shank and foot) and the activation of muscles. Technique in cycling can be assessed through measurement of joint kinematics (Bini et al. 2010; Chapman et al. 2008b; Hasson et al. 2008) and muscle activation patterns (Bini et al. 2008; Candotti et al. 2009; Dorel et al. 2009b). Alternatively, pedal force effectiveness (ratio of the force perpendicular to the crank and the total force applied to the pedal) has also been used as a gold standard measure of technique in cycling (Dorel et al. 2009a; Dorel et al. 2009b; Rossato et al. 2008). However, there has been criticism recently regarding using pedal force effectiveness exclusively for feedback as pedal force effectiveness may not provide a full representation of pedaling technique of cyclists (Bini and Diefenthaeler 2010). Pedaling technique is probably too complex to be summarized by force effectiveness alone given that technique strategies may not be fully translated into better force effectiveness. However, cyclists can improve power output if they improve force effectiveness, but they cannot improve power output exclusively by improvements in pedaling technique (Bini and Diefenthaeler 2010). For a similar pedaling technique (e.g. focus on pushing down forces applied at the downstroke phase) power output can be improved by increasing magnitude of force application (assuming similar directions of the force). However, changing technique to a more circling action (i.e. greater force effectiveness for similar magnitude of forces) power output can be improved, but only because force effectiveness is improved. In a mechanical perspective, applying pedal forces perfectly perpendicular to the crank in the direction of crank motion (force effectiveness equal to 100%) is only possible if a perfect circling action is performed by the cyclist.

Existing evidence is conflicting regarding the relationship between pedal force effectiveness and performance in cycling. Most research suggests that when the effectiveness of the force applied on the pedal is optimized, the economy/efficiency (i.e. ratio between mechanical energy produced and physiological energy demand) is reduced (Korff et al. 2007; Mornieux et al. 2008). No research has been conducted to quantify the relationship between symmetry in pedal forces and performance. We chose to review the use of pedal force effectiveness during cycling as pedal force systems are now commercially available to monitor cycling training and performance. Therefore, it is important to analyze what we know and what we still need to learn in terms of pedal force effectiveness to better advise cyclists and coaches.

The purpose of this review was to summarize current knowledge on pedal force effectiveness during cycling and how it is affected by task constraints such as workload, pedaling cadence, body position, fatigue and cycling ability. Limitations and benefits of measuring and using pedal force effectiveness feedback exclusively are discussed throughout the article. Interventions to improve force effectiveness and cycling performance are also considered to identify interactions between technique training and performance.

Methods

Academic databases (MEDLINE, SCOPUS, ISI Web of Knowledge, EBSCO, and GOOGLE SCHOLAR) were searched for peer-reviewed journals, books, theses, and conference proceedings since 1960 with the keywords pedal force effectiveness, workload, pedaling cadence, saddle position, cycling, fatigue, and symmetry. Articles were not included when they could not be retrieved without at least an English abstract. Journal articles (82), book chapters (4), and conference articles (10) were included in this review based on exclusion criteria of articles that were not related to pedal force measurements.

Results

Most studies measuring pedal forces have been restricted to one leg but a few studies have reported bilateral asymmetry in pedal forces. Pedal force effectiveness is increased at higher workload level and reduced at higher pedaling cadences. Changes in saddle position resulted in unclear effects in pedal force effectiveness, while lowering the upper body reduced pedal force effectiveness. Cycling experience and fatigue had unclear effects on pedal force effectiveness. Augmented feedback of pedal forces can improve pedal force effectiveness within a single training session and after multiple sessions for cyclists and non-cyclists. No differences in pedal force effectiveness were evident between summarized and instantaneous feedback. Conversely, economy/efficiency seems to be reduced when cyclists are instructed to improve pedal force effectiveness during acute intervention studies involving one session (Korff et al. 2007; Mornieux et al. 2008). Decoupled crank systems effectively improved pedal force effectiveness with conflicting effects on economy/efficiency and performance.

Table 1. Scientific papers reporting different systems to measure the force applied on the pedals during cycling.

Reference	Sensor type	Force components and moments	Cleats type	Application
Guye (1896)	Pressure[A]	Normal (Fz)	No cleats	Unknown[B]
Sharp (1896)	Pressure[A]	Normal (Fz)	No cleats	Laboratory
Hoes et al. (1968)	Strain gauge	Normal (Fz)	Toe clips	Laboratory
Sargeant & Davies (1977)	Strain gauge	Normal (Fz)	Toe clips	Laboratory
Dal Monte et al. (1973)	Strain gauge	Normal (Fz) and anterior-posterior (Fx)	Toe clips	Laboratory
Hull & Davis, (1981)	Strain gauge	Normal (Fz), anterior-posterior (Fx) and medio-lateral (Fy), and related moments	Toe clips	Laboratory
Harman et al. (1987)	Strain gauge	Normal (Fz) and anterior-posterior (Fx)	Unknown[B]	Laboratory
Newmiller et al. (1988)	Strain gauge	Normal (Fz) and anterior-posterior (Fx)	Clip in	Laboratory
Broker & Gregor (1990)	Piezoelectric	Normal (Fz), anterior-posterior (Fx) and medio-lateral (Fy), and related moments	Toe clips and Clip in	Laboratory
Álvarez & Vinyolas (1996)	Strain gauge	Normal (Fz) and anterior-posterior (Fx)	Clip in	Road
Boyd et al. (1996)	Strain gauge	Normal (Fz), anterior-posterior (Fx) and medio-lateral (Fy), and related moments	Clip in	Laboratory
Nabinger et al. (2002)	Strain gauge	Normal (Fz), anterior-posterior (Fx) and medio-lateral (Fy), and related moments	Clip in	Laboratory
Reiser Ii et al. (2003)	Strain gauge	Normal (Fz) and anterior-posterior (Fx)	Clip in	Laboratory
Chen et al. (2005)	Load cell	Normal (Fz) and anterior-posterior (Fx)	Unknown[B]	Road
Mornieux et al. (2006)	Cycle ergometer mounted on a force plate	Normal (Fz), anterior-posterior (Fx) and medio-lateral (Fy), and related moments	Toe clips	Laboratory
Stapelfeldt et al. (2007)	Hall effect sensor	Normal (Fz) and anterior-posterior (Fx)	Selectable	Laboratory
Valencia et al. (2007)	Piezoresistive force sensor attached to the pedal	Normal (Fz) and anterior-posterior (Fx)	Selectable	Laboratory
Dorel et al. (2008)	Strain gauge	Normal (Fz) and anterior-posterior (Fx)	Clip in and toe clips	Track
Chunfu (2009)	Strain gauge	Normal (Fz)	N.A[C]	N.A[C]

[A] No details about the measurement system characteristics.
[B] No details about pedal-shoe interface characteristics.
[C] The system was only analyzed using theoretical loads (finite elements).

Discussion

Measuring pedal forces

Over the last 30 years technology has allowed pedal force measurement to advance to the stage where it is now possible to measure three components of force (Fx, Fy and Fz) and three associated moments (Mx, My and Mz) (Hull and Davis 1981). Systems have been used during cycling on the road (Álvarez and Vinyolas 1996; Dorel et al. 2008) and off-road (Rowe et al. 1998). A summary of the systems used to measure forces applied during cycling is provided in Table 1.

The component of the force applied on the pedal in the frontal plane (medio-lateral) is presented in Figure 1.

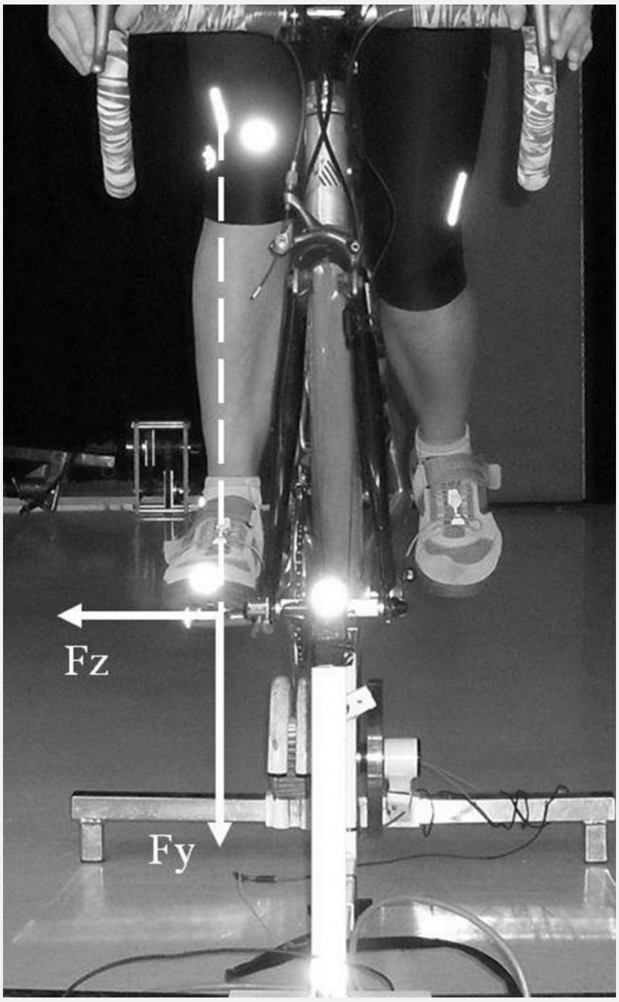

Figure 1. Frontal view image of one cyclist illustrating the normal and medio-lateral components of the force applied on the pedal. Dotted arrow shows the projection of the pedal in the frontal plane and highlights the medial-displacement of the knee. Image provided by the first author.

The medio-lateral component (Fz), does not contribute to bicycle propulsion and is usually ignored despite suggestions that inter-segmental forces at the knee joint may be associated with injury (Ericson et al. 1984; Ruby et al. 1992).

The total force applied on the pedal in the sagittal plane can be computed by the two components on the pedal surface (normal - Fy and anterior-posterior - Fx). A percentage of the total force on the pedal will be directed perpendicular to the crank (effective force). To compute the effective force, pedal angle in relation to the crank has been acquired using angular potentiometers (Hull and Davis 1981), videography (Rossato et al. 2008) or digital encoders (Martin and Brown 2009). By trigonometry, normal and anterior-posterior forces were converted into components tangential to the crank. Effective force can produce propulsive or retarding force on the crank depending on the direction of the force applied on the pedal during the crank revolution (see Figure 2).

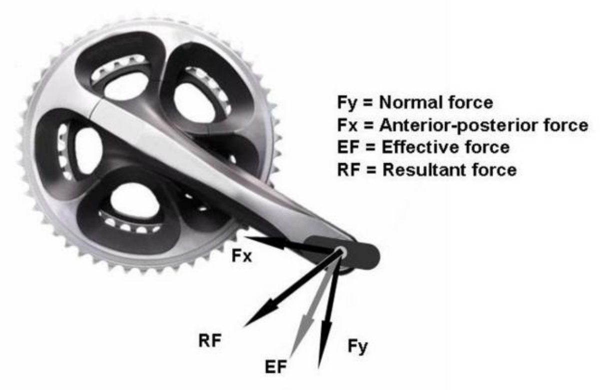

Figure 2. Diagram of the normal (Fy) and anterior-posterior (Fx) components of the total force applied on the pedal (resultant force – RF) in the sagittal plane. The effective component (EF) of the resultant force applied on the sagittal plane is also shown.

Pedal force effectiveness during cycling has been defined as the ratio of the force perpendicular to the crank (effective force) and the total force applied to the pedal (resultant force). This ratio has been defined as the index of effectiveness, which is the ratio of the impulse of the effective force to the impulse of the resultant force over a complete crank revolution (see equation 1) (LaFortune and Cavanagh 1983).

$$IE = \int_{0}^{360} EF dt / \int_{0}^{360} RF dt$$

Equation 1. Index of effectiveness (IE) is the ratio of the impulse of the effective force (EF) to the impulse of the resultant force (RF) over a complete crank revolution (LaFortune and Cavanagh 1983).

The index of effectiveness is the most used measure of technique in cycling because more skilled cyclists have higher pedal force effectiveness (Bohm et al. 2008; Hasson et al. 2008; Holderbaum et al. 2007). However, other studies have reported that pedal force effectiveness may not fully represent joint kinetic and kinematic patterns associated with changes in pedaling technique (Bini and Diefenthaeler 2010; Korff et al. 2007; Mornieux et al. 2008). The reason is that cyclists change joint kinetics and kinematics towards an improved technique (e.g. greater knee and hip joint flexor moments at the upward phase) but they do not necessarily convert these greater moments into better force effectiveness (Bini and Diefenthaeler 2010).

The pedal cycle is usually divided into two phases (propulsive or downward and recovery or upward) or four quarters. Average normal and anterior-posterior forces from one male competitive cyclist (20 years old, 375 W of maximal aerobic power output and 65 ml·kg^{-1}·min^{-1} of VO_{2Max}) and hypothetical ideal force application are presented in Figure 3 (unpublished data). The ideal force direction is based on the assumption that all the force applied to the pedal should be converted into effective force in favor of crank motion.

Radial forces at the bottom (or top) dead centres of crank revolution (commonly observed in cyclists) do not create angular motion, and therefore, do not help produce crank motion. Inertial moment from the cyclist's leg may result in angular motion. Although related to inertial components of leg segments, the radial force applied on the pedal is not free of energy cost because energy is spent to convert potential energy at the top dead centre to kinetic energy towards the bottom dead centre (Kautz and Hull 1993). If the cyclist is riding with no resistance on the bicycle wheel, energy is still required to keep pedaling resulting in internal work production (Minetti 2011). Potential energy is stored in muscle-tendon units at the top and bottom dead centres and is converted to kinetic energy at the upstroke and downstroke phases. Changing the motion of the limb from downward to upward does not require energy from the ipsilateral leg. However, the connection with the contralateral leg (which will spend energy lifting the other leg) and the inertial effect (or potential to kinetic energy conversion) will create angular motion at the bottom dead centre transition. The reason for the extra metabolic energy to reduce radial forces and increase tangential forces on the crank is likely due to an additional recruitment of muscles (i.e. knee and hip flexors) that would not be used by cyclists for this particular task (Mornieux et al. 2010).

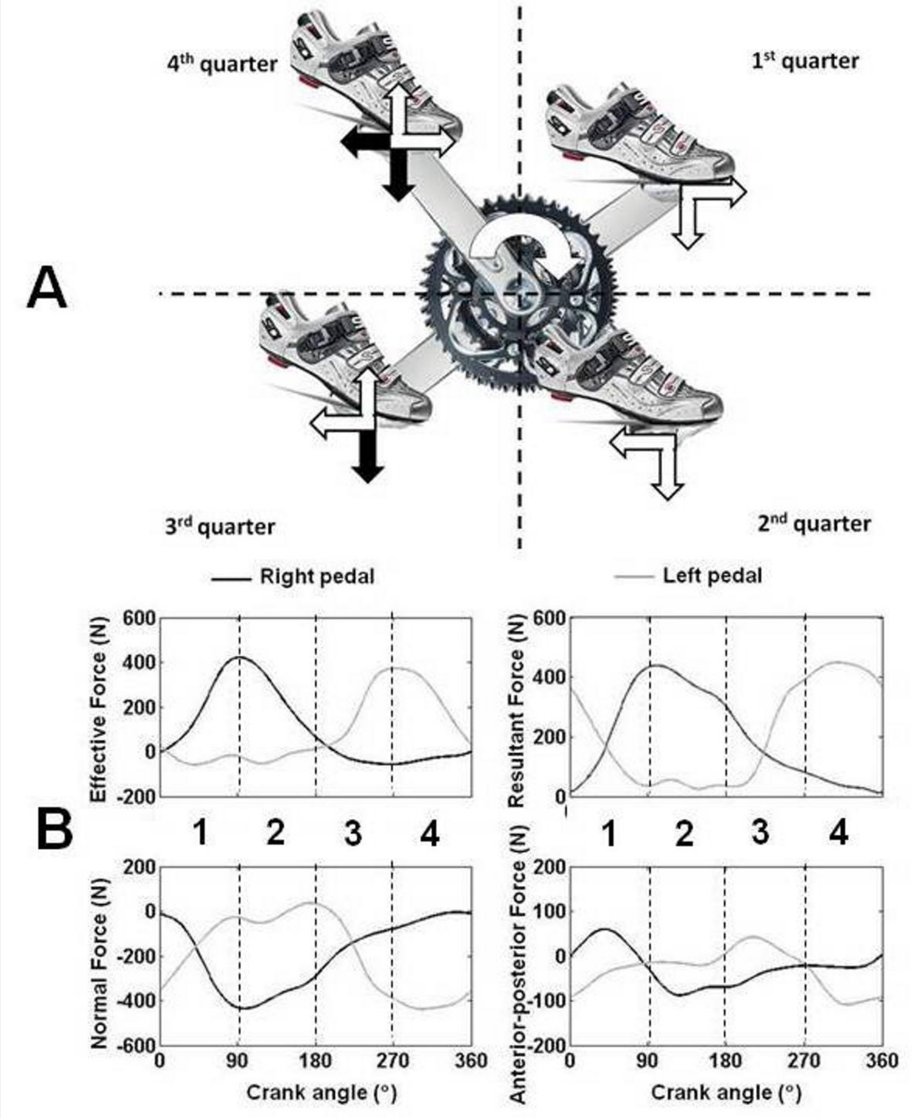

Figure 3. Representative diagram of pedal force directions at the four quarters of a pedal revolution. White arrows indicate ideal pedal force application to optimize force effectiveness and black arrows show normal and anterior-posterior pedal force application for one male competitive cyclist riding at 90 rpm and 350 W (unpublished data from our laboratory). Plots of right (black line) and left (grey line) normal and anterior-posterior force of one male competitive cyclist riding at 90 rpm and 350 W. Right and left effective (EF), resultant (RF), normal (Fy) and anterior-posterior (Fx) forces. For effective force, positive values indicate propulsive effective force. For normal force, positive values indicate force applied to pull the pedal, and for anterior-posterior force, positive values indicate a forward force applied to the pedal.

Pedal force application from the example cyclist was different from the hypothetical ideal force application presented in Figure 3. For normal force, propulsion is maximized by applying a downward force during the propulsive phase (from the top dead centre to bottom dead centre) and an upward force during the recovery phase (from the bottom dead centre to the top dead centre). Similarly for the anterior-posterior force, propulsion is maximized with anterior force during the first and the fourth quarters, and posterior force during the second and the third quarters. However, these idealized force profiles are not observed in cyclists (Korff et al. 2007; Mornieux and Stapelfeldt 2012; Mornieux et al. 2008).

In the propulsive phase the resultant force is consistent between cyclists (variance ratio = 0.063 [CV% = 10%]) but in the recovery phase normal force is more variable between cyclists (variance ratio = 0.204; CV% = 31%) (Hug et al. 2008), possibly because some cyclists try to pull the pedal upward to improve force effectiveness (Mornieux et al. 2008). Upward pulling of the pedal is possible during the recovery phase because most cyclists use a system (clipless or clip in) where the shoe is attached to the pedal by a cleat. Differences in anterior-posterior force between cyclists predominantly occur during the recovery phase, when some cyclists try to pull the pedal backwards (Coyle et al. 1991; Kautz et al. 1991).

Most of the effective force is produced during the propulsive phase with the highest force generated at approximately 90° (Coyle et al. 1991). Propulsive effective force is rarely observed during the recovery phase and most studies reported negative effective force during the recovery phase (Dorel et al. 2009b; Rossato et al. 2008; Sanderson and Black 2003) which indicates that the effective component of pedal force is in the opposite direction to the crank movement, thereby resulting in resistive force for the contralateral leg (Coyle et al. 1991). This resistive force can be seen in Figure 3 where the effective force is negative during the third and the fourth quarters of crank revolution.

Separate analyses of pedal force effectiveness during the propulsive and the recovery phases has been performed using the index of effectiveness for each phase (i.e. integral limits from the top dead centre to the bottom dead centre) (Rossato et al. 2008). According to Mornieux et al. (2008), higher pedal force effectiveness is found during the propulsive phase, compared to the recovery phase, with lower effectiveness during the recovery phase possibly related to an inability of the cyclists to generate effective force from the knee and hip joint flexors at higher workloads similar to those observed during racing.

Pedal force effectiveness can also be calculated over a complete pedal revolution by the instantaneous "ratio of effectiveness", which has been used to assess different parts of the pedal cycle (Sanderson 1991). When the ratio of effectiveness is close to 1, a greater percentage of the resultant force is transferred as effective positive force. Conversely when the ratio of effectiveness is close to -1, most of the resultant force is transferred as effective force in the opposite direction of crank movement, resulting in resistive force for the contralateral leg. Typical values for the ratio of effectiveness are shown in Figure 4 using unpublished data from Rossato et al. (2008) for eight elite cyclists right pedal forces.

The ratio of effectiveness was close to 1 during the propulsive phase and close to -1 during the recovery phase indicating that the ipsilateral leg was directing most of the force applied on the pedal to generate propulsive torque on the crank (positive effective force). Conversely, during the recovery phase, most of the force applied on the pedal was creating resistive force for the crank (negative effective force). Similar ratios of effectiveness have been previously reported (Sanderson 1991; Sanderson and Black 2003).

Limitations on the exclusive use of force effectiveness analysis have been suggested because force effectiveness mixes muscular and non-muscular components (Leirdal and Ettema 2011a) and does not fully represent cyclists pedaling technique (Bini and Diefenthaeler 2010). An alternative analysis (decomposition method) separates the muscular and non-muscular components (mass and inertia) of pedal and intersegmental joint forces (Kautz and Hull 1993). A limitation of this method is the mechanical dependence of non-muscular components on the muscular component pattern where muscular action will affect non-muscular components, and vice versa. For practical application, the decomposition method requires the analysis of joint kinematics to determine joint moments, which are not always possible. Analysis of muscle moments from net moments is prone to errors due to limitations of the inverse dynamics technique (i.e. absence of co-contraction in the model). Another approach (ratio between the mechanical work at the top and bottom dead centers by the overall mechanical work of crank revolution) has provided conflicting relationships with economy/efficiency in recent studies (Leirdal and Ettema 2011a, b). Loras et al. (2009) assessed non-muscular component by measuring forces during unloaded cycling. However, this method is limited because a residual muscular component is still required to move the legs along with inertial components. Therefore, an ecologically valid, sensitive and reliable method of analysis of pedal force effectiveness to better represent cyclists pedaling technique is still required.

Most previous studies were conducted assuming symmetry between the right and left pedal forces. However, pedal force symmetry of non-injured athletes has ranged between ~2% (Smak et al. 1999) to ~3% (Bini et al. 2007). In injured non-athletes, pedal force asymmetry up to 400% has been reported between the non-injured and injured leg (Hunt et al. 2003; Mimmi et al. 2004). Further analysis should explore the degree of symmetry of each force component during the pedal cycle and whether the force symmetry is related to

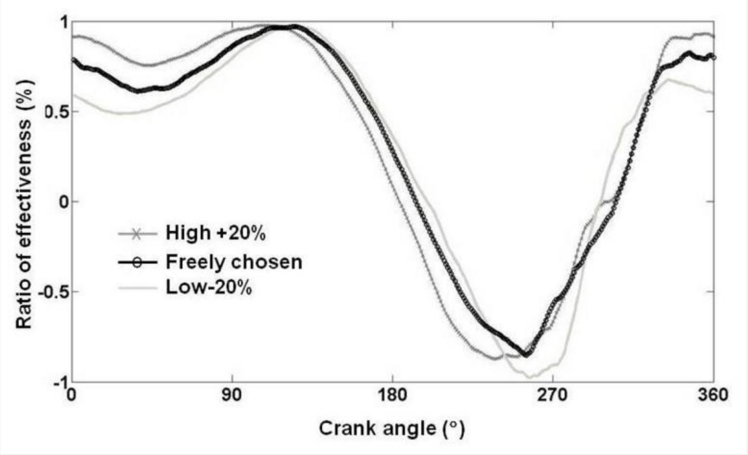

Figure 4. Average ratio of effectiveness for eight cyclists pedaling at 80% of their maximal power output. Freely chosen cadence was determined by the cyclists. "Low-20%" indicates pedaling cadence 20% lower than the freely chosen cadence and "High+20%" indicates pedaling cadence 20% higher than the freely chosen cadence. Unpublished data from previous research (Rossato et al. 2008).

cycling ability, or other factors. Currently, few studies have presented asymmetries in crank torque for uninjured cyclists (Carpes et al. 2007; Daly and Cavanagh 1976).

Constraints on force effectiveness

Pedal force effectiveness depends on constraints that could be workload level (Kautz et al. 1991; Zameziati et al. 2006), pedaling cadence (Candotti et al. 2007; Patterson and Moreno 1990), body position on the bicycle (Bini et al. 2009; Diefenthaeler et al. 2006; Diefenthaeler et al. 2008; Dorel et al. 2009a), fatigue (Diefenthaeler et al. 2007; Dorel et al. 2009b) and cycling experience/ability (Candotti et al. 2007; Sanderson 1991) (see Table 2).

On cycle ergometers, workload is measured by the average power output (in Watts) or the total mechanical work over time (in Joules) and calculated from the torque and angular velocity of the cranks. Crank torque depends on the mechanical characteristics of the bicycle (crank arm length) and on the effective force. The longer the crank arm length, the higher the torque for the same angular velocity and effective force.

Most studies assessed pedal force effectiveness during laboratory controlled trials at aerobic levels of workload (submaximal cycling). Pedal forces acquired during sprint cycling (5 s) conducted on a cycle ergometer were only reported by Dorel et al. (2010). Therefore, little is known about the effects of supramaximal (or anaerobic) workload levels for cycling variables (e.g. body position on the bicycle, fatigue and cycling experience/ability).

Figure 5 shows the normal, anterior-posterior, effective and resultant force components applied on the right pedal during three stages of an incremental maximal cycling test (75%, 90% and 100% of the maximal aerobic power output) from eleven competitive male cyclists (Bini et al. 2007). At higher workload levels, the peak of the effective force was ~20% greater during the propulsive phase (between 0° and 180° of crank angle) and ~110% lower (less negative) during the recovery phase (between 180° and 360° of crank angle). Increases in the effective force are usually due to higher resultant and normal forces during the propulsive phase. At 100% of the maximal aerobic power output there was a ~58% reduction in the forward (positive) pedal force component and a ~175% increase in the backward (negative) pedal force component.

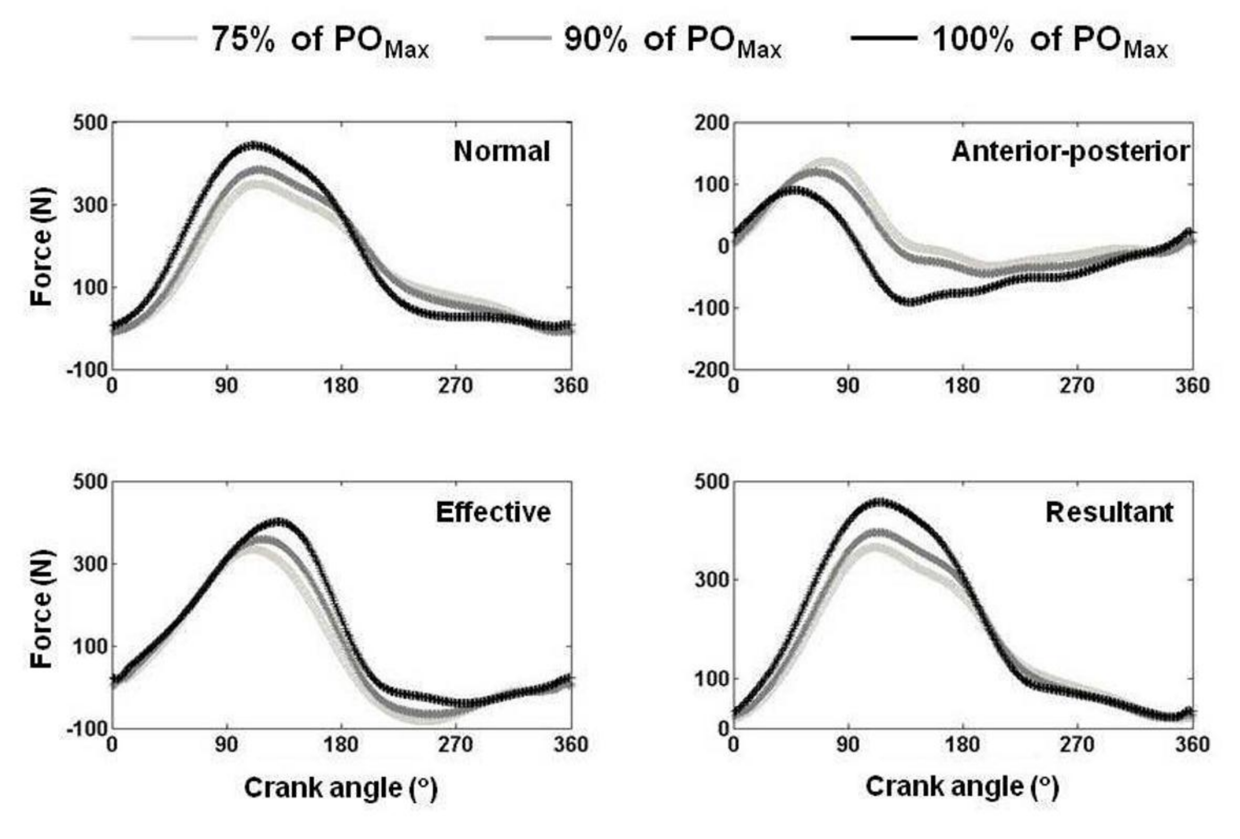

Figure 5. Average normal (Fz), anterior-posterior (Fx), effective (EF), and resultant (RF) forces applied to the right pedal from eleven cyclists during three stages of an incremental test (75, 90 and 100% of the maximal power output). Propulsive effective force is positive. Positive normal force is force applied to pull the pedal. Positive anterior-posterior force is forward force applied to the pedal. Unpublished data from previous research (Bini et al. 2007).

Table 2. Scientific papers related to effects of workload, pedaling cadence, body position, fatigue and cycling ability on pedal force effectiveness.

Reference	Independent variable	Subjects	Measurement System	Main results and notes
Dal Monte et al. (1973)^{A}	Workload	Not defined.	Two pedals with tension transducer for recording normal (Fz) and anterior-posterior (Fx) pedal force components in the sagittal plane.	Qualitative increased pedal force application at higher workload and during standing cycling. Qualitative asymmetry results for pedal forces.
Daly & Cavanagh (1976)	Bilateral symmetry, workload and pedaling cadence	Twenty male non-cyclists with undefined age.	Strain gauge deformation based system to measure effective force in both cranks.	Higher within day (0.87) and lower between days (0.47) reliability in force symmetry. Undefined effects of workload and pedaling cadence in force symmetry because of high variability.
Ericson & Nisell (1988)	Workload, pedaling cadence and saddle height	Six male non-cyclists between 20 and 31 years.	Piezoeletric sensors attached to the left pedal for measurement of three pedal force components (normal-Fz, anterior-posterior -Fx and medio-lateral -Fy). Pedal and crank angle measurements from video images.	Improved pedal force effectiveness (three times) when workload was increased without effects of pedaling cadence or saddle height.
Patterson & Moreno (1990)	Pedaling cadence	Eleven recreational cyclists between 21 and 44 years.	Strain gauge deformation based system to measure normal (Fz) and anterior-posterior (Fx) pedal force components in the sagittal plane (right and left).	66% higher force effectiveness when changing from 100 to 200 watts of workload. 1.5 lower force effectiveness when cadence increased from 50 to 110 rpm.
Kautz et al. (1991)	Workload	Fourteen male trained cyclists with 23 ±3 years of age.	Strain gauge deformation based system to measure normal (Fz) and anterior-posterior (Fx) pedal force components in the sagittal plane (right pedal).	42 % higher pedal force effectiveness at the power phase and 3% lower pedal force effectiveness at the recovery phase when changing the workload from 60 to 90% of maximal oxygen uptake.
Coyle et al. (1991)	Cycling performance level	Fourteen male trained cyclists with 23 ±3 years of age.	Strain gauge deformation based system to measure normal (Fz) and anterior-posterior (Fx) pedal force components in the sagittal plane (right pedal).	8% lower pedal force effectiveness for the best performance group compared to the ones who does not have the best performance.
Sanderson (1991)	Pedaling cadence and cycling expertise	Seven trained cyclists 30 ±11 years old and 38 male recreational cyclists 26 ±7 years old.	Strain gauge deformation based system to measure normal (Fz) and anterior-posterior (Fx) pedal force components in the sagittal plane (right pedal).	44% lower pedal force effectiveness changing from 60 to 100 rpm, 16% lower pedal force effectiveness when changing from 80 to 100 rpm. 56% greater pedal force effectiveness changing from 100 W to 235 W.
Black et al. (1993)	Workload	Five trained cyclists with undefined age and gender.	Piezoeletric system to measure the three pedal force components (normal-Fz, anterior-posterior -Fx and medio-lateral-Fy) and the three moments on the X, Y, and Z axis of the right pedal surface (Mx, My, and Mz). Pedal angle measured by potentiometer and optical sensors to calculate the crank angle.	100% increase in pedal force effectiveness in the end of the test.
Amoroso et al. (1993)	Fatigue	Eleven competitive cyclists with undefined age and gender.	Piezoeletric system to measure the three pedal force components (normal-Fz, anterior-posterior -Fx and medio-lateral-Fy) and the three moments on the X, Y, and Z axis of the right pedal surface (Mx, My, and Mz). Pedal angle measured by potentiometer and optical sensors to measure crank angle.	No significant difference in pedal force effectiveness.

Table 2. Continue

Sanderson & Black (2003)	Fatigue	Twelve competitive male cyclists 28 ±6 years old.	Piezoeletric system to measure right normal (Fz) and anterior-posterior (Fx) pedal force components in the sagittal plane (right pedal).	No fatigue effects on pedal force effectiveness.
Zameziati et al. (2006)	Workload	Ten male non-cyclists 26 ±1 years old.	Monark cycle ergometer attached on a force plate to allow the measurement of the three pedal force components (normal-Fz, anterior-posterior -Fx and medio-lateral-Fy) and the three moments on the X, Y, and Z axis of the right and left pedals surface.	Positive relationship (r = 0.79) between pedal force effectiveness and economy/efficiency. Positive relationship between pedal force effectiveness during the recovery phase and economy/efficiency (r = 0.66).
Diefenthaeler et al. (2006)	Saddle height and horizontal position	Three male competitive cyclists 26 ±4 years old.	Strain gauge deformation based system to measure normal (Fz) and anterior-posterior (Fx) pedal force components in the sagittal plane (right pedal).	5-7% lower pedal force effectiveness when moving the saddle forward and 2-7% lower pedal force effectiveness when moving the saddle up or down.
Diefenthaeler et al.(2007)	Fatigue	Eight male elite competitive cyclists (31 ±6 years old.	Strain gauge deformation based system to measure normal (Fz) and anterior-posterior (Fx) pedal force components in the sagittal plane (right and left).	No difference in pedal force effectiveness throughout the fatigue cycling test.
Candoti et al. (2007)	Pedaling cadence and cycling expertise	Nine male competitive cyclists 25 ±8 years old and eight male competitive triathletes 27 ±9 years old.	Strain gauge deformation based system to measure normal (Fz) and anterior-posterior (Fx) pedal force components in the sagittal plane (right pedal).	30% decrease in pedal force effectiveness when cadence changed from 60 to 105 rpm. 22% higher pedal force effectiveness for cyclists compared to triathletes. No significant differences between groups for higher cadence (90 and 105 rpm).
Korff et al. (2007)	Pedaling technique	Eight male competitive cyclists 35 ±6 years old.	Piezoeletric sensors attached on the right and left pedals for measurement of three pedal force components (normal-Fz, anterior-posterior -Fx and medio-lateral-Fy). Pedal and crank angle measurements by video images.	Two times higher pedal force effectiveness when changing from the preferred to the pulling technique.
Rossato et al. (2008)	Workload and pedaling cadence	Eight male competitive cyclists 24 ±3 years old.	Strain gauge deformation based system to measure normal (Fz) and anterior-posterior (Fx) pedal force components in the sagittal plane (right pedal).	13% higher pedal force effectiveness changing from 80% to 60% of peak power output. No significant changes in pedal force effectiveness between the preferred, the 20% faster and the 20% slower pedaling cadences.
Mornieux et al. (2008)	Pedaling technique	Eight elite cyclists and seven non-cyclists with undefined age.	Hall effect sensors attached in a custom made adaptor to measure normal (Fz) and anterior-posterior (Fx) pedal force components (right and left).	20% higher pedal force effectiveness on the recovery phase.
Bini et al. (2009)	Knee position relative to the bicycle frame	Three male competitive cyclists and three male competitive triathletes 29 ±9 years old.	Strain gauge deformation based system to measure normal (Fz) and anterior-posterior (Fx) pedal force components in the sagittal plane (right pedal).	No significant effects of knee position on pedal force effectiveness.
Dorel et al. (2009a)	Upper body position (trunk lean)	Twelve male competitive triathletes 31 ±8 years old.	Effective force measurement based on torque and crank arm measurement using the cycle ergometer system (right and left).	9.5% lower pedal force effectiveness at the recovery phase of crank revolution in the aero position, compared to the upright position.
Dorel et al. (2009b)	Fatigue	Ten competitive cyclists 21 ±3 years old.	Strain gauge deformation based system to measure normal (Fz) and anterior-posterior (Fx) pedal force components in the sagittal plane (right and left).	No significant fatigue effects in pedal force effectiveness.
Emanuele et al. (2011)	Upper body position (trunk lean)	Six male amateur cyclists 28 ±3 years old.	Strain gauge deformation based system to measure normal (Fz) and anterior-posterior (Fx) pedal force components in the sagittal plane (right and left).	No significant differences between the upright position and the position with hands on the drops of the handlebars.

[A] These studies did not indicate the number or characteristics of the subjects.

It is unclear why cyclists present lower pedal force effectiveness at lower workload levels. Studies showed that wide increases in workload level (i.e. from 60% to 98% of maximal aerobic power output) led to higher force effectiveness (Black et al. 1993; Zameziati et al. 2006), which was not observed when smaller differences in workload level (i.e. from 75% to 100% of maximal aerobic power output) were assessed (Bini and Diefenthaeler 2010). One possibility is that when improving pedal force effectiveness cyclists may increase activation of muscles that are less efficient (i.e. hip and knee flexors) which may increase energy expenditure and reduce economy/efficiency (Korff et al. 2007; Mornieux et al. 2008). Therefore, to maintain a lower oxygen uptake cyclists may postpone recruiting these less efficient muscles and rely on the knee and hip joint extensors to produce power (Fernandez-Pena et al. 2009). Indeed, differences in results from previous studies may also be because the 60% of maximal aerobic power output is potentially a very low intensity effort for trained cyclists.

The effect of pedaling cadence on pedal force effectiveness is uncertain (Ansley and Cangley 2009). When cycling at constant workload in the laboratory, cyclists can minimize resultant force application by riding at approximately 90 rpm (Candotti et al. 2007; Neptune and Herzog 1999; Patterson and Moreno 1990). Most studies have shown higher pedal force effectiveness at lower pedaling cadences (i.e. 60 rpm) when compared to self-selected cadences (Candotti et al. 2007; Ericson and Nisell 1988). Improved pedal force effectiveness at low cadence may be due to lower overall muscle activation (MacIntosh et al. 2000), lower joint moments (Marsh et al. 2000; Takaishi et al. 1998) and reduced co-activation of extensor/flexor groups (Candotti et al. 2009; Neptune and Herzog 1999). In contrast, Rossato et al., (2008) reported that pedal force effectiveness of cyclists did not differ at a cadence 20% higher than the self-selected cadence. Experienced cyclists typically pedal at high cadence (~100 rpm) resulting in reduced activation of the main driving muscles (i.e. vastus lateralis and gluteus maximus) (Lucia et al. 2004), lower joint moments (i.e. reduced resultant moments) (Marsh et al. 2000) and less effort perception (Ansley and Cangley 2009). Experienced cyclists may be able to sustain pedal force effectiveness while cycling at high pedaling cadences (Candotti et al. 2007; Rossato et al. 2008).

The configuration of bicycle components determines the position of the body on the bicycle, though it is acknowledged that different body positions can be obtained despite no change in bicycle geometry (e.g. by varying hand placement). Any change in body position resulting from a change in saddle height will affect knee angle (Nordeen-Snyder 1977; Sanderson and Amoroso 2009), muscle activation (Ericson et al. 1985; Jorge and Hull 1986), muscle length (Sanderson and Amoroso 2009), and oxygen uptake (Nordeen-Snyder 1977; Shennum and DeVries 1976). For trained cyclists, a 3% increase in saddle height resulted in 7% increase in force effectiveness (Bini et al. in press-a). Ericson & Nisell (1988) found that seat height changes (±8% of the ischial tuberosity to the floor) did not affect pedal force effectiveness of non-cyclists. It is likely that the experienced cyclists who were adapted to their bicycle configuration due to training were sensitive to the small changes in saddle height resulting in the acute effect on pedal force effectiveness, or it was simply a sub-optimal position.

In addition to the height of the saddle, the forward-backward position of the saddle changes ankle joint kinematics (Price and Donne 1997) and muscle activation (Ricard et al. 2006). However, moving forward or backward by ~3° did not affect force effectiveness in trained cyclists/triathletes (Bini et al. in press-b).

Trunk angle (upright versus the most aerodynamic position) has an effect on effective force (Dorel et al. 2009a). With the trunk in the most aerodynamic position the effective force was 9.5% lower during the recovery phase compared to the upright position (Dorel et al. 2009a). In the aerodynamic position, the angle between the trunk and thigh was smaller which reduced the activation and possibly the length of hip joint flexor muscles, thereby decreasing the ability to generate pulling force during the recovery phase (Dorel et al. 2009a). In contrast, Emanuele et al. (2011) observed no changes in effective force when cyclists used a position of the hands on the drops of the handlebars compared to the upright position (hands on the top of the handlebars). Increased hip power production and reduced knee joint power when the hands were on the drops were in contrast to findings from Dorel et al. (2009a). Further research is required to assess to what extent upper body flexion compromises hip and knee muscle actions and pedal force effectiveness.

Cyclists usually stand up on the bicycle to ride uphill to benefit from using their upper body mass to apply force on the pedal in the downstroke phase (Caldwell et al. 1998). Specifically, Caldwell et al. (1998) reported that the peak torque for the same workload level and pedaling cadence increased by ~30% and total pedal force increased by ~50% when standing compared to seated cycling uphill. Therefore any changes in torque profile would have come from changes in total pedal force with potential decreases in pedal force effectiveness. Consequently, the 30% higher (and delayed) peak torque and 50% greater total pedal force suggests reduced pedal force effectiveness when standing on the bicycle during uphill riding. Conversely, cycling at 75% of the workload of maximal oxygen uptake at 11% of incline has not changed pedal force effectiveness compared to level cycling for another study (Leirdal and Ettema 2011b).

Most studies failed to show a consistent change in pedal force effectiveness when cyclists were in a fatigued state (Diefenthaeler et al. 2007; Sanderson and Black 2003). Studies that did report changes with fatigue showed an increase in pushing down normal force during the propulsive phase (Amoroso et al. 1993; Dorel et al. 2009b), in resistive force during the recovery phase (Sanderson and Black 2003), and in the pulling backward force on the pedal surface during the recovery phase (Dorel et al. 2009b). For these studies, cyclists were either assessed at a fixed workload level of 300 W (Amoroso et al. 1993) or at 80% of maximal aerobic power output (Dorel et al. 2009b; Sanderson and Black 2003) during time to exhaustion testing. These results suggested that lower limb mechanics change to balance for fatigue and sustain pedal force effectiveness. Increased ankle dorsi-flexion (Amoroso et al. 1993; Sanderson and Black 2003), higher range of motion for the ankle joint (Bini et al. 2010) and reduced knee flexion angle (Bini et al. 2010) have been found during fatigue. The increased activation of hip extensor muscle activation (Dorel et al. 2009b) contrasted with the unchanged individual joint contribution to the absolute joint moments (Bini et al. 2010). Further research could assess changes in pedal forces during time trial events, when fatigue is postponed by pacing strategy.

It is unclear how experience in cycling affects pedal force effectiveness. From a cross-sectional perspective, differences were found between cyclists and non-cyclists (Mornieux et al. 2008), cyclists and triathletes (Candotti et al. 2007), but no differences were found between competitive and recreational cyclists (Sanderson 1991). If pedal force effectiveness is important for performance it may be expected that pedal force effectiveness would be related to competitive results within a cohort of cyclists. However, a study of 14 competitive cyclists reported that the cyclists who achieved better performance indices where the ones who had lower pedal force effectiveness but were able to apply higher normal force on the pedal (Coyle et al. 1991). Recent studies (Korff et al. 2007; Mornieux et al. 2008) have analyzed pedal force effectiveness and cycling efficiency with the aim of determining why there is a lack of relationship between pedal force effectiveness and performance in cycling. No relationship was found between economy/efficiency and pedal force effectiveness during sub maximal trials at constant aerobic power output, yet in the cycling community, it is advocated that better force effectiveness can be translated to higher economy/efficiency (Cavanagh and Sanderson 1986). Further research is needed to increase our understanding of the implications of cycling experience on pedal force effectiveness.

Technique training effects on cycling performance

Improved pedal force effectiveness should theoretically result in an increase in economy/efficiency but this has not been the case (Korff et al. 2007). However, cyclists still aim to improve pedaling technique via improving pedal force effectiveness. Research studies have provided visual feedback of pedal forces or have used assisting devices (e.g. decoupled cranks) to stimulate the cyclist to change their natural movement to improve pedal force effectiveness.

When cyclists are given feedback of pedal forces they can improve their force effectiveness (Broker et al. 1993; Sanderson and Cavanagh 1990; Ting et al. 1998). Visual (augmented) feedback of pedal force has been used in different phases of the pedal cycle (Hasson et al. 2008; Henke 1998; Holderbaum et al. 2007) without differences between summarized and real time feedback (Broker et al. 1993). Presentation of an ideal force diagram and the actual force (similar to the one presented in Figure 3) has been used as feedback (Hasson et al. 2008; Holderbaum et al. 2007). Cyclists were instructed to apply force on the pedal so their normal and anterior-posterior components of pedal force were closer to the ideal profile. Regardless of whether they focused only on the recovery phase or on specific quarters of pedal cycle, force effectiveness had similar improvements after training.

Changes in pedal force effectiveness with feedback occurs rapidly with one study reporting significant changes in novice cyclists after one session (Hasson et al. 2008). Sanderson & Cavanagh (1990) showed that after the first two days of training, recreational cyclists improved pedal force effectiveness (lower resultant force during the recovery phase). No marked differences between the second and the 10th training sessions indicated that a plateau exists in pedal force effectiveness development. Retention of force effectiveness was similar one week and three months after cessation of the training period (Broker et al. 1993).

Provision of visual feedback for trained (Henke 1998) and recreational cyclists (Sanderson and Cavanagh 1990) has resulted in improvements in force effectiveness ranging from 17% to 40%. Studies with non-cyclists (Broker et al. 1993; Hasson et al. 2008; Holderbaum et al. 2005; Holderbaum et al. 2007; Nishiyama and Sato 2005) have reported improvements in force effectiveness between 24% and 55%. However, Mornieux et al. (2008) compared pedal force effectiveness of cyclists and non-cyclists who were instructed to increase pulling upward forces during the recovery phase (one trial of feedback). Economy/efficiency reduced by 3% in non-cyclists and 10% in trained cyclists. Both groups reduced economy/efficiency by improving pedal force effectiveness, with worst results for trained cyclists. Long term adaptation to a specific motion (i.e. higher pushing forces during the propulsion phase) can result in neuromuscular adaptation for cyclists (Candotti et al. 2009; Chapman et al. 2008a), and changes in pedal force profile (Candotti et al. 2007), which may limit their acute adaptation to changing motion (i.e. pedaling with higher force effectiveness). Physiological adaptation of highly trained cyclists (Coyle et al. 1991) may support the hypothesis that cyclists are more efficient recruiting the quadriceps muscle group during a cycling task compared to non-cyclists (Takaishi et al. 1998). When improving pulling upward forces during the recovery phase, cyclists recruited “less efficient” muscles, which resulted in a reduced economy/efficiency (Edwards et al. 2009; Korff et al. 2007; Mornieux et al. 2008). However, Theurel et al. (2012) reported smaller reductions in sprint cycling power due to fatigue from 45 minutes of cycling at

75% maximal aerobic power output when cyclists received feedback to improve pedal force effectiveness. There was smaller economy/efficiency during the first 15 minutes of the test when using feedback, without differences in the following 30 minutes. Further research should be conducted using a control group (no feedback) to ascertain any learning effects, which were not addressed in this previous study.

To date only Mornieux & Stapelfeldt (2012) have assessed the effects of longer training (four weeks) using force effectiveness feedback for 12 sessions of 30 minutes at 60% maximal aerobic power output and 80 rpm pedaling cadence. No improvements in maximal aerobic power output occurred for the feedback group compared to the control group (no feedback during training). The feedback group did reduce force effectiveness during the propulsive phase of crank revolution (lower index of effectiveness) and increased force effectiveness during the recovery phase (greater index of effectiveness). It is therefore unlikely that improving pedal force effectiveness with training may enhance performance in cycling. Further research at higher workload levels (>60% maximal aerobic power output) and pedaling cadence (>80 rpm) for training may provide evidence of whether force feedback training may (or may not) be useful in improving cycling performance.

On a normal bicycle the cranks are diametrically opposed (180°) and fixed which links the forces at each pedal. In an attempt to encourage higher force effectiveness, novel systems have been developed where the cranks are decoupled. These Powercranks® (or Smartcranks®) require a pulling force during the recovery phase of the crank cycle, and at the bottom dead centre, because the crank is attached to the chain ring via a free bearing system. This higher pulling force on the recovery phase was previously related to higher force effectiveness using decoupled cranks (Bohm et al. 2008).

Only one study (Luttrell and Potteiger 2003) reported benefits after training with decoupled cranks in cycling economy/efficiency. Six novice cyclists trained using Powercranks® (Walnut Creek, CA) for six weeks at 70% of VO_{2Max} for one hour per day. After the training period, cyclists who trained using Powercranks® improved economy/efficiency by 2.3% during a one hour constant load test, compared to the group who trained using normal cranks. Changes in economy/efficiency may have been caused by changes in muscle activation profiles of knee and hip flexor groups. A study showing decreased activity of vastus lateralis and increased biceps femoris after two weeks of training for 30-45 minutes per session at undefined workload using Powercranks® provided some support for this suggestion (Fernandez-Pena et al. 2009). In contrast, a similar study with five weeks training twice per week at 80% of the individual's anaerobic threshold found no changes in economy/efficiency for ten trained cyclists (Bohm et al. 2008), even though force effectiveness did improve. It is unclear why the results from the two studies differed following such similar interventions. Possible lower fitness level of the "novice" cyclists from the study of Luttrell & Potteiger (2003) may explain the differences. Another study (Williams et al. 2009) found no changes in power output at lactate threshold, economy/efficiency during steady state cycling, and time trial performance, of well-trained cyclists following training using decoupled crank systems. Until more evidence is available it is difficult to assess the potential benefit of training with decoupled cranks.

There are several areas that research could contribute to improving the understanding of the relationship between optimal force effectiveness and performance. Establishing a "natural" range of symmetry of pedal forces should be the goal of future research and may explain the influence of symmetry in cycling performance and injury prevention. In addition, the effects of pedal force effectiveness training on economy/efficiency may be a focus of future research. Higher levels of workload (>60% maximal aerobic power output) and pedaling cadence (>80 rpm) for training should be used in future research, which may allow adaptation of the higher hip and knee flexors recruitment to pulling forces. Cycling experience may reduce adaptation to technique training. Comparison of competitive cyclists, triathletes and recreational cyclists may help identify populations likely to benefit from force effectiveness training. The use of decoupled crank systems should be investigated for longer training periods with different experience and ability levels in cycling.

Practical applications

Pedal forces are often based on the measurement of normal, anterior-posterior, effective and resultant force components, with analysis of pedal force effectiveness based on the computation of the index of effectiveness. Workload level and pedaling cadence affect pedal force effectiveness, but there are unclear effects of body position on the bicycle, fatigue state, cycling experience and ability on pedal force effectiveness.

Technique training, using either augmented feedback of pedal forces or decoupled cranks, increases pedal force effectiveness in short duration studies but evidence of augmented feedback efficacy in long term studies is lacking. The effects of technique training trying to improve force effectiveness on economy/efficiency and performance are unclear.

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