BIOMECHANICS AND ENERGETICS OF UPHILL CYCLING: A REVIEW

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Review
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Abstract:

The winners of the major cycling 3-week stage races (i.e. Giro d'Italia, Tour de France, Vuelta a Espana) are usually riders who dominate in the uphill sections of the race. Amateur cyclists, however, will often avoid uphill terrain because of the discomfort involved. Therefore, understanding movement behavior during uphill cycling is needed in order to find an optimum solution that can be applied in practice. The aim of this review is to assess the quality of research performed on biomechanics and the energetics of uphill cycling. Altogether we have analyzed over 40 articles from scientific and expert periodicals that provided results on energetics, pedal and joint forces, economy and efficiency, muscular activity, as well as performance and comfort optimization during uphill cycling. During uphill cycling, cyclists need to overcome gravity and in order to achieve this, some changes in posture are necessary. The main results from this review are that changes in muscular activity are present, while on the other hand pedal forces, joint dynamics, and cycling efficiency are not substantially altered during seated uphill cycling compared to cycling on level terrain. In contrast, during standing uphill cycling, all of the previously mentioned measures are different when comparing either seated uphill cycling or level terrain cycling. Further research should focus on outdoor studies and steeper slopes.

Key words: *performance, efficiency, biomechanics, physiology, optimization*

Introduction

Cycling has been the subject of discussion in many of the published scientific reviews (Ericson, 1986; Wozniak Timmer, 1991; di Prampero, 2000; Jeukendrup & Martin, 2001; Atkinson, Davison, Jeukendrup, & Passfield, 2003; Faria, Parker, & Faria, 2005; Bini & Diefenthaeler, 2009; Hug & Dorel, 2009). Research in cycling has generally concentrated either on a set of particular and practically relevant problems such as enhancing performance (Jeukendrup & Martin, 2001; Faria, et al., 2005), improving rehabilitation protocols (Ericson, 1986), improving comfort (Gámez, et al., 2008), and preventing the harmful effects caused by cycling (Burke, 1994; de Vey Mestdagh, 1998; Silberman, Webner, Collina, & Shiple, 2005), or on the more basic aspects of locomotion during cycling (Too, 1990; Coyle, et al., 1991; di Prampero, 2000; Bini & Diefenthaeler, 2009; Fonda & Sarabon, 2010a).

All of the previously mentioned reviews were mainly focused on studies that included level terrain cycling with little or no emphasis on uphill cycling. From a racing point of view, uphill cycling can often be the deciding factor that determines the winner (Bertucci, Grappe, Girard, Betik, & Rouillon 2005; Hansen & Waldeland, 2008). This can be deduced from the fact that in previous years, the winners of the major 3-week stage races (i.e. Giro d'Italia, Tour de France, Vuelta a Espana) have generally been riders who excelled in the hilly climbing sections of the races. On the other hand, in leisure cycling, if cyclists are sufficiently trained to cope with hills, uphill terrains often cause discomfort due to different mechanical loads on the spine. Consequently, many leisure cyclists tend to avoid hills (Fonda, Panjan, Markovic, & Sarabon, 2011).

During uphill cycling, riders need to overcome gravity, which increases the demands for mechanical power. Because of the inclination of the surface, they need to adapt their posture for two primary reasons: first, to avoid lifting the front wheel and, second, to ensure that they keep a stable position on the saddle, so that they do not slide off (Figure 1). Mountain bikers have to succeed in overcoming even more demanding terrain conditions: they need to ensure that there is enough traction on the rear wheel while simultaneously making sure the front wheel stays on the ground. To accomplish this, the mountain bikers have to shift their body forward on the saddle and flex their trunk (by leaning forward). This change in posture alters some of the characteristics of pedaling. Such changes can be reflected in (1) different mechanical demands (di Prampero, 2000), (2) changed economy and efficiency (Moseley & Jeukendrup, 2001), (3) altered cycling kinematics and kinetics (Bertucci, et al., 2005), and (4) modified neuromuscular activation patterns (Sarabon, Fonda, & Markovic, 2011). Changes can also be reflected in health-related issues during cycling. For example, lower back pain is one of the most common cycling injuries (Marsden & Schwellnus, 2010) and based on previous research (Salai, Brosh, Blankstein, Oran, & Chechik, 1999) we can assume that the lower back pain issue can intensify when cyclists adjust their posture due to uphill terrain characteristics (e.g. increased tensile forces on lumbar vertebra).

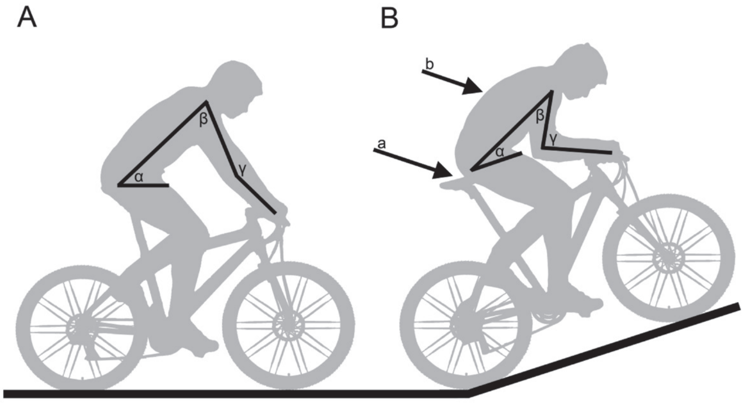

Figure 1. Differences in posture between level terrain (A) and uphill cycling (B). The hip angle (α), shoulder angle (β), and elbow angle (γ) are all smaller during uphill cycling. The position on the saddle is shifted forward (a) and the back is more rounded (b) during uphill cycling.

Understanding movement patterns during uphill cycling is necessary when searching for optimal solutions or enhancements, which can be then applied in practice. In the first part of this paper we will focus on the equations of motion of cyclists during uphill cycling and try to address some of the practical implications in this field. The next chapter focuses on economy and efficiency during uphill cycling. Patterns of kinetics and kinematics during uphill cycling are subsequently presented, with an emphasis on pedal forces, joint moments and joint movements. Neuromuscular alterations during uphill cycling are presented in the next part. In the final part, some of the practical solutions for improving uphill cycling are addressed. The paper concludes by summarizing the applied values of the presented experimental data and with some directions for future research in the field.

When searching through the available literature, we focused on professional and scientific papers from the following databases: Pubmed, ScienceDirect, and Springerlink. We combed through them by using keywords such as *biomechanics*, *energetics*, *equation*, *forces*, *joints*, *EMG* (i.e. electromyography) and *performance*, while including the words *uphill* and *cycling*. We noted over 40 professional and scientific papers. In the review tables (Table 1, Table 2 and Table 3) we have included 13 articles that directly reported studies on biomechanics and/or energetics of uphill cycling.

Equations of uphill cycling

During level terrain cycling at constant speed, the amount of energy wasted against gravitational forces with each pedal stroke is minimal, although inertial forces have been reported to have some influence on pedal forces (Kautz & Hull, 1993). Therefore, a cyclist performs almost all of the mechanical work (W_C) against two main opposing forces (Equation 1): the rolling resistance (R_R) and the air resistance (R_A), whose resultant is the total resistance (R_T) (van Ingen Schenau & Cavanagh, 1990). R_R is the energy loss as the wheels roll along the surface and it depends substantially on the mass of the bicycle and rider system, the acceleration of gravity, and a coefficient describing the inflation pressure of the tires, the characteristics of the surface and the type of the tires (di Prampero, Cortili, Mognoni, & Saibene, 1979). The R_A is a function of the frontal plane area of the cyclist and the bike, the air density and the air velocity. At higher speeds, R_R becomes a progressively smaller fraction of R_T. In practice, the estimation of the frontal plane area can be done either by using elaborate tests, such as a rolldown (de Groot, Sargeant, & Geysel, 1995), tractive towing (di Prampero, et al., 1979) or wind-tunnel experiments (Kyle, 1991), or by more simplified methods, such us using photographic weighing or planimetry (Olds & Olive, 1999). It is also common to measure the R_A first (using, for example, a wind tunnel) and then calculating the frontal plane area from that estimate.

$$W_C = a + b \cdot v^2 \quad \text{Equation 1}$$

$$C_C = W_C \cdot \eta^{-2} \quad \text{Equation 2}$$

In Equation 1, W_C is the mechanical work performed per unit of distance, v is the air speed and, a and b are constants for R_R and R_A per unit of distance, respectively. The energy cost (C_C) of cycling depends on overall cycling efficiency (η) (Equation

2). The mechanical efficiency of cycling is not far from 25%; however, it depends upon the cadence (pedal frequency) which increases from 42 to 60 rpm as the power output is increased from 50 to 300 W (di Prampero, 1986, 2000; Ericson, 1988). However, well-trained cyclists usually opt for higher pedaling frequencies (Kohler & Boutellier, 2005). In general, during uphill cycling, cyclists develop high forces at low cadences that are likely to be more economical; in contrast, on flat ground, they increase their cadence because their aerodynamic posture does not allow for high force production (Mognoni & di Prampero, 2003). In contrast, Dorel, Couturier, and Hug (2009) showed that cyclists can apply greater forces at the power phase of the crank cycle with an aerodynamic posture compared to an upright posture. The reason why competing cyclists opt for higher pedal frequencies instead of the optimal rate was discussed by di Prampero in his review (di Prampero, 2000) with plausible explanations in the reduced anaerobic energy releases to compensate for the slight fall in efficiency. Higher cadences were then explained by overall muscle activation (MacIntosh, Neptune, & Horton, 2000), reduced joint moments (Marsh, Martin, & Sanderson, 2000) and consequently lower resistive force to sustain similar power output.

The mechanical power (P_C) required to cycle at a constant speed is given by the product of W_C and the speed (s) (Equation 3), while the metabolic power (E_C) is defined as the product of C_C and s (Equation 4). Both, P_C and E_C, are expressed in Watts, since according to SI units, C_C is expressed in J/m and s in m/s.

$$P_C = W_C \cdot s \qquad \text{Equation 3}$$

$$E_C = C_C \cdot s \qquad \text{Equation 4}$$

Equations 1, 2, 3 and 4 become practical when all data is known. By using the commercially available power meters (e.g. SRM® or Cycleops Power Tab®) the power output and velocity are known, therefore the R_T can be calculated as external power output divided by the velocity (Grappe, et al., 1999; Lim, et al., 2011). With a constant tire pressure and a change in body position, only R_A is altered. This technique could be extremely valuable in helping cyclists, coaches and scientists to predict and improve cycling performance (Lim, et al., 2011).

During uphill cycling, at a given power output, the R_A becomes a relatively smaller fraction of the R_T and the main opposing force becomes acceleration due to gravity. Opposing forces during uphill cycling are summarized in Figure 2.

The mechanical work performed against gravity (W_{CG}) when cycling uphill is given by the product of the overall moving mass (M), the acceleration due to gravity (g) and vertical displacement (h). When expressed per unit of distance covered along the road (*d*) (Equation 5), mechanical work

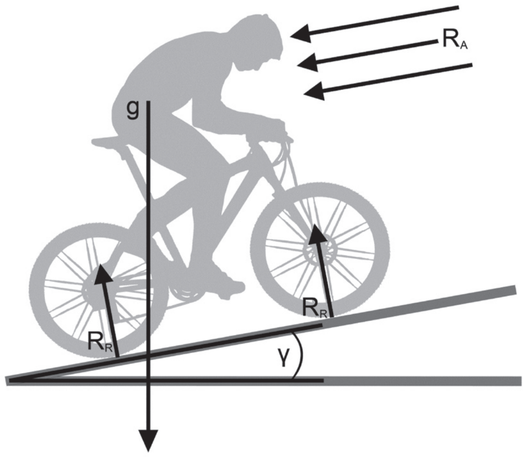

Figure 2. Main opposing forces during uphill cycling. Where g is acceleration due to gravity; R_A is aerodynamic drag, R_R are tractive resistive forces, and γ is angle of the terrain.

can be expressed as the product of M, g and sinus γ (Equation 6), where γ is the angle of the road slope.

$$W_{CG} = M \cdot g \cdot h \cdot d^{-1} \qquad \text{Equation 5}$$

$$W_{CG} = M \cdot g \cdot \sin \gamma \qquad \text{Equation 6}$$

A more detailed description of the W_C can be achieved by including the R_R and R_A in the calculations (Equation 7).

$$W_C = a + b \cdot s^2 + M \cdot g \cdot \sin \gamma \qquad \text{Equation 7}$$

The C_C can be calculated by substituting a and b in Equation 7 with the constants for metabolic energy dissipated against R_R (α, since $\alpha = a \cdot \eta^{-1}$) and R_A (β, since $\beta = b \cdot \eta^{-1}$), respectively, and dividing the last term by η (Equation 8). The E_C can be further estimated by the same principle used during level terrain cycling as a product of C_C and s (Equation 9). The mechanical efficiency has been shown not to change during uphill cycling (Millet, Tronche, Fuster, & Candau, 2002).

$$C_C = \alpha + \beta \cdot s^2 + M \cdot g \cdot \sin \gamma \cdot \eta^{-1} \qquad \text{Equation 8}$$

$$E_C = \alpha \cdot s + \beta \cdot s^3 + M \cdot g \cdot s \cdot \sin\gamma \cdot \eta^{-1} \qquad \text{Equation 9}$$

With these equations, we can estimate some of the important practical values. For example, in his review, di Prampero (2000) estimated the maximal incline of the slope that the cyclist could overcome. This is possible if the subjects' maximal E_C is known and the lowest speed value at which the cyclist does not lose his/her balance is assigned. However, these estimations can only be made for a smooth terrain and with the use of an appropriate gear system to ensure optimum pedal frequency at a very low speed.

Furthermore, by using the results from Equation 8 in Equation 4, and knowing E_C, the velocity can be calculated on every specific slope (Welbergen & Clijsen, 1990). Welbergen and Clijsen (1990) estimated the incline at which the cyclist would benefit from an upright position when compared to the standard racing position. The E_C for the upright position is 20% higher than for the racing position (Welbergen & Clijsen, 1990). With this information, the authors estimated that the incline where air resistance was no longer the limiting factor was approximately 7.5%. This information could benefit both coaches and cyclists regarding the posture they should adopt during the uphill sections of a race.

Efficiency and economy during uphill cycling

Cycling efficiency

Cycling efficiency has been described as the ratio of work accomplished to energy cost, which depends on the cadence (Gaesser & Brooks, 1975), feet position (Disley & Li, 2012), body position (Ryschon & Stray-Gundersen, 1991), and muscle fiber type (Coyle, Sidossis, Horowitz, & Beltz, 1992). Several calculations for efficiency have been proposed, mainly differentiated by a baseline correction factor that is used to correct the estimate of the energy expenditure and therefore of the measured level of efficiency (Gaesser & Brooks, 1975; Millet, et al., 2002). Gross cycling efficiency has been demonstrated to be highly correlated with cycling performance and has a low variability and detects smaller changes in exercise efficiency over several trials (Millet, et al., 2002).

Millet et al. (2002) examined the cycling gross efficiency during level 5.3% uphill seated and 5.3% uphill standing conditions. The gradient does not appear to be a factor that influences cycling efficiency at the same power output. Similarly, Leirdal and Ettema (2011) found no significant differences in gross efficiency, force effectiveness and dead center size between the level and 11% uphill cycling conditions. However, it is likely that the efficiency would be altered during steeper slopes, mainly because of the decrease in cadence (Swain & Wilcox, 1992).

Cycling economy

The term is used as a measure of oxygen consumption per unit of power output (Moseley & Jeukendrup, 2001). It can also be expressed as the oxygen consumption required to cycle at a given speed (Swain & Wilcox, 1992). The factors that influence cycling economy vary with the conditions under which cycling is performed (Table 1). Swain and Wilcox (1992) showed that a well-trained cyclist is more economical when using a higher pedaling frequency during seated uphill cycling than using a lower pedal frequency in either the seated or standing position. In contrast, Harnish, King and Swensen (2007) showed that trained cyclists are equally economical using high or low cadences, although they found a significant increase in ventilation (6%) and breathing frequency (8%) during standing uphill cycling when compared to the seated position. That could be explained by the rhythmic pattern of breathing in coordination with the locomotion during pedaling while standing.

The results obtained by Millet et al. (2002) showed that there are no significant differences in economy during uphill cycling (seated and standing) compared to level terrain. However, heart rates were found to be higher (6%) during standing uphill cycling as opposed to the seated position.

Increased ventilation during standing uphill cycling was accompanied by an increase in breathing frequency, which seems to be related to the rhythmic pattern of pedaling. Uphill cycling does not appear to be a factor that influences cycling efficiency, although more research is necessary, especially during steeper slopes, to confirm these conclusions.

Table 1. A review of studies on efficiency and economy during uphill cycling

Publication	Cyclists	Slope	Findings
Millet et al. (2002)	8 well-trained cyclists	5.3%	Gross cycling efficiency and economy were not significantly different among the level seated, uphill seated, or uphill standing position.
Harnish et al. (2007)	8 well-trained cyclists	5%	Ventilation and breathing frequency were significantly higher during standing compared to seated uphill cycling. Trained cyclists are in general equally economical using high or low cadences during uphill cycling.
Swain and Wilcox (1992)	14 well-trained cyclists	10%	Cyclists were more economical using a high cadence (84 rpm) in seated position than by using a low cadence (41 rpm) in either the seated or standing position.
Hansen and Waldeland (2008)	10 well-trained cyclists	10%	Trained cyclists performed better standing rather than seated at the highest intensities. The intensity of exercise that characterized the transition from seated to standing was found to be approximately 94% of maximal aerobic power. At lower power outputs, there was no difference between seated or standing uphill cycling.
Leirdal and Ettema (2011)	10-well trained cyclists	11%	There was no difference in gross efficiency, force effectiveness and dead centre size between a level and inclined cycling condition.

Kinematics and the kinetics of uphill cycling

Pedal and crank kinetics during uphill cycling

Alterations in kinetic patterns of pedal force and crank torque due to various changes during cycling have only been investigated in a few studies. A major problem is the equipment needed to evaluate the forces and torque on the pedal or crank. Instrumented pedals (Álvarez & Vinyolas, 1996; Hoes, Binkhorst, Smeekes-Kuyl, & Vissers, 1968; Reiser, Peterson, & Broker, 2003) which normally measure the forces applied at the foot/pedal interface were used to: study the kinetics under different cadence and workload conditions (Kautz, Feltner, Coyle, & Baylor, 1991), as an input for inverse dynamics to evaluate joint moments (Redfield & Hull, 1986), or to assess the determinants of performance in cycling (Coyle, et al., 1991). Caldwell, McColle, Hagberg and Li (1998) studied the crank torque profile while moving uphill (8%) and level terrain cycling and found no significant differences in the general crank torque profile when comparing at the same cadence in a seated condition. According to Bertucci et al. (2005), the reasons for this can be found in the crank inertial load, which is lower during uphill cycling because it depends on the gear ratio and the mass of the cyclist (Hansen, Jørgensen, Jensen, Fregly, & Sjøgaard, 2002). Hansen et al. (2002) observed that the crank torque profile was modified by varying the crank inertial load. They showed that when cycling with a high crank inertial load, peak torque was significantly higher. Crank-to-torque profiles observed during laboratory conditions are probably affected by the crank inertial load and the data should thus be interpreted with caution. The latter was confirmed by Bertucci, Grappe and Groslambert (2007) who found alterations in the crank torque profile during laboratory conditions compared to outdoor road conditions. However, their data should be taken with caution, as they used the SRM torque analysis system, which has been shown to underestimate peak torque from bilateral measures (Bini, Hume, & Cerviri, 2011). Minor effects on the crank torque profile could also be present due to the mechanical properties (i.e. stiffness and damping) of the bicycle ergometer.

The pedal and crank kinetics during uphill cycling studies are presented in Table 2.

In outdoors conditions, and at the same cadences (80 rpm), Bertucci et al. (2005) reported that the crank torque profile was slightly modified during uphill cycling compared to a level terrain. The highest difference was observed at 45° of the crank cycle (30.7 vs. 22.8 Nm for level and uphill terrain, respectively), although no differences were observed for peak values. These results vary from those of Hansen et al. (2002) who found differences in peak torque during cycling with a high and low crank inertial load. The differences could be explained by the fact that the study of Hansen et al. (2002) was conducted on a motorized treadmill with good control over the velocity, while in the field study of Bertucci et al. (2005) the cycling velocity was more prone to oscillations. According to the data gathered by Bertucci et al. (2007) the peak torque and minimal torque both occur 5° later in the crank cycle, even though the values of the torque were very similar.

Joint moments and kinematics during uphill cycling

The studies on joint kinematics and kinetics during cycling were mainly performed on level terrain (Leirdal & Ettema, 2011; Bini & Diefenthaeler, 2010; Bini, Tamborindeguy, & Mota, 2010; Bini, Diefenthaeler, & Mota, 2010; Ericson, Bratt, Nisell, Németh, & Ekholm, 1986). Despite being practically important, these biomechanical studies of uphill cycling are relatively unknown. The authors of this review were only aware of one study that had examined joint kinetics and kinematics during uphill cycling (Caldwell, Hagberg, McCole, & Li, 1999).

In their study, Caldwell et al. (1999) reported that 8% uphill cycling showed a significant increase in the magnitude of the peak ankle plantarflexor

Table 2. A review of studies on pedal and crank kinetics during uphill cycling

Publication	Cyclists	Slope	Findings
Caldwell et al. (1998)	8 elite cyclists	8%	Overall patterns of pedal and crank kinetics were similar between level and 8% uphill cycling in a seated position. Higher peak pedal force, shift of crank torque to later in the crank cycle. A modified pedal orientation was observed during seated and standing uphill cycling.
Bertucci et al. (2005)	7 male cyclists	9.25%	The torque was 26% higher at a 45° crank angle in a seated uphill situation compared to level terrain. At lower cadences, during uphill cycling the peak torque value was significantly (42%) higher compared to higher cadences during level terrain cycling.
Alvarez and Vinyolas (1996)	1 male cyclist	8-9%	No visual differences between level terrain and seated uphill cycling. More drastically increased pedal forces were observed during standing uphill cycling.

(25%) and knee extensor (15%) *moments*, and a shift of these *peak moments* to earlier in the crank cycle (12° and 15°, respectively). During standing uphill cycling, the ankle plantar flexor moment increased by 160% and was shifted forwards by 45° in the crank cycle, when compared to the uphill seated position. The knee extensor profile showed an extended bimodal profile with a shift towards the late down stroke period, although the peak moment occurred slightly earlier (3°). The knee flexor moment in the two seated conditions (uphill and level) showed a significant increase compared to standing uphill cycling. The patterns for the hip joint showed the most similarities across all conditions with only significant alterations in the peak extensor moment during seated uphill conditions, as compared to standing uphill conditions.

Changes during uphill standing conditions are related to the removal of the saddle as a base of support for the cyclist. As a consequence, there are higher forces on the pedals, the forward shift in pedal orientation, and the more forward hip and knee position (Caldwell, et al., 1998). The transition from a seated to a standing position provokes large changes to the range of motion of the joints of the lower limbs. According to Shemmell and Neal (1998), the range of motion at the knee during standing uphill cycling (28.7±8.8°) decreased significantly from that of a seated position (73.0±6.4°). This significant change could be primarily attributed to the forward translation of the body in relation with the bicycle and also by the fact that some degree of bicycle tilt is introduced into the movement. Changes to the position of the body also appear to affect the range of motion in the other joints of the lower limbs. The range of motion at the hip joint (68.8±6.7°) is increased from the sitting position (42.8±4.9°) and the range of motion for the ankle joint (40.5±6°) is increased from that of the seated position (25.7±14.1°).

Although only slight and non-significant changes in pedal forces were present during seated uphill cycling, an increase in the peak pedal force during standing uphill cycling seems to be related to the removal of saddle support with which the body weight increases the force production. The forward translation of the body in relation to the bicycle provokes a smaller range of motion in the knee, which confirms the previous hypotheses that more work is done by using body weight.

Neuromuscular aspect of uphill cycling

Neuromuscular aspects in cycling have been studied extensively (Dorel, Couturier, & Hug, 2008; Ericson, et al., 1985; Hug & Dorel, 2009; Hug, et al., 2008). Studies have examined the neuromuscular activation and adaptation of the cycling movement by observing the timing and intensity of muscular activity using surface electromyography (EMG) (for a review see Hug and Dorel, 2009).

The timing and the intensity of muscular activity can be altered when changing the seat height (Ericson, et al., 1985; Sanderson & Amoroso, 2009), power output (Ericson, et al., 1985; Suzuki, Watanabe, & Homma, 1982), pedaling technique (Cannon, Kolkhorst, & Cipriani, 2007), cadence (Neptune, Kautz, & Hull, 1997) and/or posture (Savelberg, Van de Port, & Willems, 2003). Changing the body posture either by changing the bicycle setup (geometry settings) or by adapting the posture due to the terrain characteristics (e.g. during uphill cycling) can alter the angle/torque relationship of the involved muscles (Hof, 2002; Lunnen, Yack, & LeVeau, 1981) and therefore, potentially affect neuromuscular patterns in the lower extremities.

Despite the relatively wide body of knowledge concerning neuromuscular activation when cycling on a level surface, there are only a few published reports on the effects of uphill cycling (Li & Caldwell, 1998; Clarys, Alewaeters, & Zinzen, 2001; Duc, Bertucci, Pernin, & Grappe, 2008; Fonda & Sarabon, 2010b; Fonda, et al., 2011; Sarabon, et al., 2011). The findings from the published studies are presented in Table 3.

Seated uphill cycling

Sarabon et al. (2011) and Fonda et al. (2011) reported changes in muscle activity patterns during steep uphill conditions (20%). The majority of changes were observed in muscles that cross the hip joint, as well as the *m. tibialis anterior*. Significant changes in muscle activation timing during 20% uphill cycling, when compared to level terrain, were observed in the *m. rectus femoris* (15° later onset and 39° earlier offset). The range of activity during 20% uphill cycling compared to level terrain was also significantly modified in *m. vastus medialis*, *m. vastus lateralis* (8° and 5° shorter, respectively) and *m. biceps femoris* (17° longer). Furthermore, a reduction of the EMG activity level was observed for *m. rectus femoris* and *m. tibialis anterior* during 20% uphill cycling compared to a level terrain (25% and 19%, respectively), while the opposite effect was observed for *m. gluteus maximus* (12%). No significant changes were observed during 10% uphill cycling compared to level terrain.

The absence of changes in muscles` activation patterns during uphill cycling on moderate slopes (up to 10%) appears to be consistent among different studies. Specifically, Duc et al. (2008) and Li and Caldwell (1998) found no significant differences in the intensity and timing of muscle activity patterns for individual muscles during seated uphill cycling compared with level terrain cycling. Conversely, Clarys et al. (2001) reported that global integrated EMG (the average of the four monitored

Table 3. A review of studies on neuromuscular activity during uphill cycling

Publication	Cyclists	Slope	Findings
Li and Caldwell (1998)	10 healthy students	8%	The muscle activities of GC and BF did not exhibit any profound differences among varying conditions. Overall, the change of cycling grade alone from 0 to 8% did not induce a significant change in neuromuscular coordination. The postural change from seated to standing pedaling at an 8% uphill grade was accompanied by the increased and/or prolonged muscle activity of hip and knee extensors.
Clarys et al. (2001)	12 professional road cyclists	12%	Regardless of the position of the pelvis, the muscular intensity of lower limb muscles increased with increasing slope inclination, while the muscular intensity of the arms decreased with the same increasing slope inclination. In addition, the decreased intensity of the arm muscles remained significantly higher with the saddle fully forward.
Duc et al. (2008)	10 trained cyclists	4, 7 and 10%	No changes noted in muscle activity patterns during seated uphill cycling at any slope for any of the muscles. Standing uphill cycling had a significant effect on the intensity and duration. GM, VM, RF, BF, BB, TA, RA and ES activity were greater in standing while SM activity showed a slight decrease. When standing, the global activity of the upper limbs was higher when the hand grip position was changed from brake level to the drops, but lower when the lateral sways of the bicycle were constrained.
Fonda et al. (2011)	12 trained mountain bikers	20 %	Modified timing and intensity of activity of the RF, BF and GM during a 20% slope.
Sarabon et al. (2011)	12 trained mountain bikers	10 and 20%	Altered body orientation during a 20% slope, but not a moderate slope of 10%, significantly modified the timing and intensity of several lower extremity muscles, the most affected being muscles that cross the hip joint and TA.

Legend: GC, gastrocnemius; BF, biceps femoris, GM, gluteus maximus; VM, vastus medialis; RF, rectus femoris; BB, biceps brachi; TA, tibialis anterior; RA, rectus abdominus; ES, erector spinae.

muscles) of the lower extremity muscles increased with the increasing slope. However, these authors did not study the timing or intensity of the activity of individual lower extremity muscles. Hence, their results are difficult to compare with the results reported by Li and Caldwell (1998), Duc et al. (2008) and Sarabon et al. (2011). To the best of our knowledge, until now only the studies by Fonda et al. (2011) and Sarabon et al. (2011) were conducted during steep uphill cycling. This is surprising, given that slopes around 20% are frequently met by mountain bikers (and less frequently by road cyclists) during races or training sessions.

Standing uphill cycling

During standing uphill cycling, significant neuromuscular modifications are to be expected, since there is a significant change in body posture and muscle coordination, especially involving increased activity of the muscles in the upper extremities. Duc et al. (2008) found significant alterations in intensity and timing on *m. gluteus maximus*, *m. vastus medialis*, *m. rectus femoris*, *m. biceps femoris*, *m. biceps brachii*, *m. triceps brachii*, *m. rectus abdominis*, *m. erector spinae* and *m. semimembranosus* during standing uphill cycling. They reported that only the muscles crossing the ankle remained unchanged. Among all the muscles tested, arm and trunk muscles exhibited the most significant increase in activity. The peak EMG activity of *m. gluteus maximus*, *m. vastus medialis*, *m. biceps femoris*, *m. gastrocnemius* and *m. soleus* shifted later in crank cycle, while the timing of the other monitored muscles remained unchanged. Similarly, Li and Caldwell (1998) reported an increase in the EMG activity of *m. gluteus maximus*, *m. rectus femoris* and *m. tibialis anterior* and prolonged burst duration of *m. gluteus maximus*, *m. vastus medialis* and *m. rectus femoris* during standing uphill cycling when compared to the seated position. The EMG activity of *m. biceps femoris* and *m. gastrocnemius* did not display significant alterations during standing uphill cycling. In contrast to Duc, et al. (2008), alterations were also found in *m. tibialis anterior*, while no differences were observed in *m. biceps femoris*. The cause for the differences between the studies could be the measurement equipment used. Duc et al. (2008) used the motorized treadmill, while Li and Caldwell (1998) performed the tests on a stationary bicycle ergometer.

The results seem to be related to the increase of the peak pedal force, the change of the hip and knee joint moments, the need to stabilize the pelvis in reference with removing the saddle support, and the forward shift of the center of mass.

Performance and comfort optimization during uphill cycling

Body position

The effect of the body position has already been partly discussed in the section "Equations of uphill cycling". Welbergen and Clijsen (1990) conducted a study where they examined the effect of body position (upright and racing position) on maximal power and oxygen consumption. They concluded that the trunk angle had a significant effect on the maximal power output delivery in a 3-minute test, with the highest amount of power produced in the upright position. Based on that data, they estimated that if a cyclist's maximal power is assumed to be 20% lower in a racing position, the incline at which the cyclist would benefit by being in the upright position is approximately 7.5%. At this point, by neglecting wind speed, air resistance is no longer the most limiting factor.

The standing position is often employed during uphill cycling, especially at lower cadences. It has been reported that oxygen consumption is lower during uphill cycling in a seated compared with a standing position at around 45% of maximal oxygen consumption. This indicates that performance during uphill cycling at such a low intensity is optimized by using the seated rather than the standing position (Ryschon & Stray-Gundersen, 1991). Knowing more about which position favours performance for more intense cycling would be helpful for cyclists and their coaches. Therefore, Hansen and Waldeland (2008) conducted a study to examine the transition from the seated to the standing position. Their results showed that cycling in a standing position resulted in a significantly better performance than seated cycling at the highest power output (around 165% of maximal aerobic power) while the seated-to-standing transition was identified at 94% of maximal aerobic power. Below this intensity, seated cycling is energetically more economical than standing.

Saddle position

When considering health-related issues during cycling, lower back pain is certainly among the most common issues (Marsden & Schwellnus, 2010). In their fluoroscopic/biomechanical and clinical study, Salai et al. (1999) showed that tilting the saddle forward by 10 to 15° can significantly decrease the tensile forces on lumbar vertebrae and therefore reduce lower back pain during cycling. Based on their research, we can assume that lower back pain could become even worse if cyclists adjust their posture due to uphill terrain characteristics (increased tensile forces on lumbar vertebrae). During uphill cycling, especially on steeper slopes, cyclists need to prevent themselves from sliding off the saddle and have to ensure that they keep a stable and balanced position. Additionally, by leaning and moving forward, the area on which the cyclist sits is reduced. Therefore, the saddle loses all its ergonomic characteristics and provokes discomfort. It would be beneficial for their comfort if cyclists would tilt the saddle forward, thus allowing for the anterior rotation of the pelvis, which helps keep the lumbar lordosis during cycling and subsequently decreases the tensile forces on the lumbar vertebrae. By tilting the saddle, the level of support on which cyclists sit would also increase.

In a study by Fonda et al. (2011), a novel bicycle geometry optimization was used with the goal of enhancing the performance and comfort of cycling during uphill conditions. With an adjusted tilt and the longitudinal position of the saddle they wanted to bring the posture during uphill cycling closer to the posture acquired during level terrain cycling and achieve a more comfortable position (Figure 3). The use of the adjusted saddle position during a 20% slope counteracted the neuromuscular changes, suggesting that the applied adjustment of the tilt and therefore the position of the saddle was successful in bringing the posture during uphill cycling closer to that of the posture during level terrain cycling. Specifically, neither the timing nor the intensity of the activity of the studied muscles differed between 20% uphill cycling with an adjusted saddle position and level terrain cycling. The exceptions concerned the onset of *m. vastus medialis* and offset of *m. biceps femoris*, where statistically significant changes were observed during 20% uphill cycling with an adjusted saddle position versus level terrain cycling. However, these changes were rather small (1.5-6%), and probably not practically relevant. Another interesting finding was that the use of an adjusted saddle position during 20% uphill cycling was positively perceived by all the participating cyclists in terms of both their comfort and their performance. These results could have practical relevance in terms of improving performance during uphill cycling, as well as reducing the prevalence of lower back pain associated with cycling. Based on pilot studies (S2P, Ltd., personal communication), the adjusted saddle position was found to be transformative in reducing oxygen consumption (6%) and therefore increasing the economy of uphill cycling. That was later confirmed by a reduction (30-60% decrease) of muscle activity in the upper extremities (*m. brachioradialis*). Both parameters were measured during 20% uphill cycling in laboratory conditions. Nevertheless, the adjusted saddle position requires further investigation, especially in outdoor conditions.

The use of an adjusted saddle position during 20% uphill cycling counteracted the changes in muscular activity, suggesting that the adjusted saddle could be successful in bringing the posture during uphill cycling closer to that of the level terrain.

Figure 3. An adjustable saddle position, which enables the cyclists to adjust the angle and position of the saddle by putting it into three different positions: (1) horizontal position (normal), (2) 10% angle of the saddle and (3) 20% angle of the saddle. Note that the forward movement of the saddle and optimized saddle angle does not alter the saddle height.

Further directions for research

Current studies are limited either to laboratory conditions or small to moderate slopes. Future biomechanical and physiological studies should be focused on outdoor conditions and steeper slopes. Due to the technical difficulties of measuring pedal forces without substantially affecting pedaling by abnormal pedal (weight, size, wires, etc.), one goal should be the development of a force pedal that does not alter the pedaling technique. Another limitation of the outdoor studies is the kinematical evaluation in measuring joint forces and movement. Different measurement equipment should therefore be used for evaluating joint movements.

Steeper slopes are common in mountain bike races, as well as in road racing. The majority of studies presented in this review were conducted on slopes of up to 12%. Further studies should also focus on steeper slopes (20%) in comparison to level terrain cycling.

Understanding motor behavior and physiological responses in such conditions will allow scientists to transfer knowledge into practice and enhance performance, comfort and safety during cycling. Since the large majority of races are won in the hilly sections of the race, scientists should also focus on bicycle geometry optimization specifically for these conditions (i.e. "bike-fitting") instead of for only "standardized" level terrain conditions.

Conclusions

Unlike level ground cycling, where wind resistance is a major opposing force, uphill cycling requires a great portion of power to overcome gravity. Posture during uphill cycling differs compared to level terrain as aerodynamics no longer play a crucial role as the main opposing force. In windless conditions, with a slope that is 7.5% or steeper, it is more economical to adopt an upright posture rather than just a normal posture with hands on the drops. The inclination of the terrain forces cyclists to adjust their posture to maintain a stable position and to increase their mechanical output. To accomplish this, cyclists usually shift forward on the saddle and flex the trunk (leaning forward). Seated uphill cycling does not appear to be a factor that influences cycling efficiency, pedal forces and joint dynamics, while the neuromuscular patterns are altered.

Sometimes, cyclists stand on the pedals to increase their mechanical output. Changing the posture by standing alters some of the characteristics of locomotion, such as economy and efficiency, kinematics and kinetics, and neuromuscular activation patterns. Increased ventilation during standing uphill cycling is accompanied by an increase in breathing frequency, which seems to be related to the rhythmic pattern of pedaling. Additionally, the forward translation of the body in relation to the bicycle provokes a smaller range of motion in the knee. Changes in muscle activity during standing uphill cycling seem to be related to the increase of the peak pedal force, the change of the hip and knee joint *moments*, the need to stabilize the pelvis in reference with removing saddle support, and a forward shift in the center of mass.

References

Álvarez, G., & Vinyolas, J. (1996). A new bicycle pedal design for on-road measurements of cycling forces. *Journal of Applied Biomechanics*, *12*(1), 130-142.

Atkinson, G., Davison, R., Jeukendrup, A., & Passfield, L. (2003). Science and cycling: Current knowledge and future directions for research. *Journal of Sports Sciences*, *21*(9), 767-787.

Bertucci, W., Grappe, F., Girard, A., Betik, A., & Rouillon, J.D. (2005). Effects on the crank torque profile when changing pedalling cadence in level ground and uphill road cycling. *Journal of Biomechanics*, *38*(5), 1003–1010.

Bertucci, W., Grappe, F., & Groslambert, A. (2007). Laboratory versus outdoor cycling conditions: Differences in pedaling biomechanics. *Journal of Applied Biomechanics*, *23*(2), 87-92.

Bini, R.R., & Diefenthaeler, F. (2009). Mechanical work and coordinative pattern of cycling: A literature review. *Kinesiology*, *41*(1), 25-39.

Bini, R.R., & Diefenthaeler, F. (2010). Kinetics and kinematics analysis of incremental cycling to exhaustion. *Sports Biomechanics*, *9*(4), 223-235.

Bini, R.R., Hume, P.A., & Cerviri, A. (2011). A comparison of cycling SRM crank and strain gauge instrumented pedal measures of peak torque, crank angle at peak torque and power output. *Procedia Engineering*, *13*, 56-61.

Bini, R.R., Diefenthaeler, F., & Mota, C.B. (2010). Fatigue effects on the coordinative pattern during cycling: Kinetics and kinematics evaluation. *Journal of Electromyography and Kinesiology*, *20*(1), 102-107.

Bini, R.R, Tamborindeguy, A.C., & Mota, C.B. (2010). Effects of saddle height, pedaling cadence, and workload on joint kinetics and kinematics during cycling. *Journal of Sport Rehabilitation*, *19*(3), 301-314.

Burke, E.R. (1994). Proper fit of the bicycle. *Clinics in Sports Medicine*, *13*(1), 1-14.

Caldwell, G., Hagberg, J., McCole, S., & Li, L. (1999). Lower extremity joint moments during uphill cycling. *Journal of Applied Biomechanics*, *15*(2), 166-181.

Caldwell, G.E., McCole, S.D., Hagberg, J.M., & Li, L. (1998). Pedal and crank kinetics in uphill cycling. *Journal of Applied Biomechanics*, *14*(3), 245-259.

Cannon, D.T., Kolkhorst, F.W., & Cipriani, D.J. (2007). Effect of pedaling technique on muscle activity and cycling efficiency. *European Journal of Applied Physiology*, *99*(6), 659-664.

Clarys, J.P., Alewaeters, K., & Zinzen, E. (2001). The influence of geographic variations on the muscular activity in selected sports movements. *Journal of Electromyography and Kinesiology*, *11*(6), 451-457.

Coyle, E.F., Feltner, M.E., Kautz, S.A., Hamilton, M.T., Montain, S.J., Baylor, A.M., Abraham, L.D., et al. (1991). Physiological and biomechanical factors associated with elite endurance cycling performance. *Medicine and Science in Sports and Exercise*, *23*(1), 93-107.

Coyle, E.F., Sidossis, L.S., Horowitz, J.F., & Beltz, J.D. (1992). Cycling efficiency is related to the percentage of type I muscle fibers. *Medicine and Science in Sports and Exercise*, *24*(7), 782-788.

de Groot, G., Sargeant, A., & Geysel, J. (1995). Air friction and rolling resistance during cycling. *Medicine and Science in Sports and Exercise*, *27*(7), 1090-1095.

de Vey Mestdagh, K. (1998). Personal perspective: In search of an optimum cycling posture. *Applied Ergonomics*, *29*(5), 325-334.

di Prampero, P.E. (1986). The energy cost of human locomotion on land and in water. *International Journal of Sports Medicine*, *7*(2), 55-72.

di Prampero, P.E. (2000). Cycling on Earth, in space, on the Moon. *European Journal of Applied Physiology*, *82*(5-6), 345-360.

di Prampero, P.E., Cortili, G., Mognoni, P., & Saibene, F. (1979). Equation of motion of a cyclist. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, *47*(1), 201-206.

Disley, B. X., & Li, F.-X. (2012). The effect of Q Factor on gross mechanical efficiency and muscular activation in cycling. *Scandinavian Journal of Medicine & Science in Sports*. doi:10.1111/j.1600-0838.2012.01479.x

Dorel, S., Couturier, A., & Hug, F. (2008). Intra-session repeatability of lower limb muscles activation pattern during pedaling. *Journal of Electromyography and Kinesiology*, *18*(5), 857-865.

Dorel, S., Couturier, A., & Hug, F. (2009). Influence of different racing positions on mechanical and electromyographic patterns during pedalling. *Scandinavian Journal of Medicine & Science in Sports*, *19*(1), 44-54.

Duc, S., Bertucci, W., Pernin, J.N., & Grappe, F. (2008). Muscular activity during uphill cycling: Effect of slope, posture, hand grip position and constrained bicycle lateral sways. *Journal of Electromyography and Kinesiology*, *18*(1), 116-127.

Ericson, M. (1986). On the biomechanics of cycling. A study of joint and muscle load during exercise on the bicycle ergometer. *Scandinavian Journal of Rehabilitation Medicine. Supplement*, *16*, 1-43.

Ericson, M.O. (1988). Mechanical muscular power output and work during ergometer cycling at different work loads and speeds. *European Journal of Applied Physiology and Occupational Physiology*, *57*(4), 382-387.

Ericson, M.O., Bratt, A., Nisell, R., Németh, G., & Ekholm, J. (1986). Load moments about the hip and knee joints during ergometer cycling. *Scandinavian Journal of Rehabilitation Medicine*, *18*(4), 165-172.

Ericson, M.O., Nisell, R., Arborelius, U.P., & Ekholm, J. (1985). Muscular activity during ergometer cycling. *Scandinavian Journal of Rehabilitation Medicine*, *17*(2), 53-61.

Faria, E.W., Parker, D.L., & Faria, I.E. (2005). The science of cycling: Factors affecting performance - part 2. *Sports Medicine*, *35*(4), 313-337.

Fonda, B., Panjan, A., Markovic, G., & Sarabon, N. (2011). Adjusted saddle position counteracts the modified muscle activation patterns during uphill cycling. *Journal of Electromyography and Kinesiology*, *21*(5), 854-860.

Fonda, B., & Sarabon, N. (2010a). Biomechanics of cycling: Literature review. *Sport Science Review*, *19*(1/2), 131-163.

Fonda, B., & Sarabon, N. (2010b). Inter-muscular coordination during uphill cycling in a seated position: A pilot study. *Kinesiologia Slovenica*, *16*(1), 12-17.

Gaesser, G.A., & Brooks, G.A. (1975). Muscular efficiency during steady-rate exercise: Effects of speed and work rate. *Journal of Applied Physiology*, *38*(6), 1132-1139.

Gámez, J., Zarzoso, M., Raventós, A., Valero, M., Alcántara, E., López, A., Prat, J., et al. (2008). Determination of the optimal saddle height for leisure cycling (P188). *The Engineering of Sport*, *7*, 255-260.

Grappe, F., Candau, R., Barbier, B., Hoffman, M.D., Belli, A., & Rouillon, J.-D. (1999). Influence of tyre pressure and vertical load on coefficient of rolling resistance and simulated cycling performance. *Ergonomics*, *42*(10), 1361-1371.

Hansen, E.A., Jørgensen, L.V., Jensen, K., Fregly, B.J., & Sjøgaard, G. (2002). Crank inertial load affects freely chosen pedal rate during cycling. *Journal of Biomechanics*, *35*(2), 277-285.

Hansen, E.A., & Waldeland, H. (2008). Seated versus standing position for maximization of performance during intense uphill cycling. *Journal of Sports Sciences*, *26*(9), 977-984.

Harnish, C., King, D., & Swensen, T. (2007). Effect of cycling position on oxygen uptake and preferred cadence in trained cyclists during hill climbing at various power outputs. *European Journal of Applied Physiology*, *99*(4), 387-391.

Hoes, M.J., Binkhorst, R.A., Smeekes-Kuyl, A.E., & Vissers, A.C. (1968). Measurement of forces exerted on pedal and crank during work on a bicycle ergometer at different loads. *Internationale Zeitschrift Für Angewandte Physiologie, Einschliesslich Arbeitsphysiologie*, *26*(1), 33-42.

Hof, A.L. (2002). EMG and muscle force: An introduction. *Human Movement Science*, *3*(1-2), 119-153.

Hug, F., & Dorel, S. (2009). Electromyographic analysis of pedaling: A review. *Journal of Electromyography and Kinesiology*, *19*(2), 182-198.

Hug, F., Drouet, J.M., Champoux, Y., Couturier, A., & Dorel, S. (2008). Interindividual variability of electromyographic patterns and pedal force profiles in trained cyclists. *European Journal of Applied Physiology*, *104*(4), 667-678.

Jeukendrup, A.E., & Martin, J. (2001). Improving cycling performance: How should we spend our time and money? *Sports Medicine*, *31*(7), 559-569.

Kautz, S.A., Feltner, M.E., Coyle, E.F., & Baylor, A.M. (1991). The pedaling technique of elite endurance cyclists: Changes with increasing workload at constant cadence. *International Journal of Sport Biomechanics*, *7*(1), 29-53.

Kautz, S.A., & Hull, M.L. (1993). A theoretical basis for interpreting the force applied to the pedal in cycling. *Journal of Biomechanics*, *26*(2), 155-165.

Kohler, G., & Boutellier, U. (2005). The generalized force-velocity relationship explains why the preferred pedaling rate of cyclists exceeds the most efficient one. *European Journal of Applied Physiology*, *94*(1-2), 188-195.

Kyle, C.R. (1991). The effect of crosswind upon time trials. *Cycling Science*, *4*, 51-56.

Leirdal, S., & Ettema, G. (2011). The relationship between cadence, pedalling technique and gross efficiency in cycling. *European Journal of Applied Physiology*, *111*(12), 2885-2893.

Li, L., & Caldwell, G.E. (1998). Muscle coordination in cycling: Effect of surface incline and posture. *Journal of Applied Physiology*, *85*(3), 927-934.

Lim, A.C., Homestead, E.P., Edwards, A.G., Carver, T.C., Kram, R., & Byrnes, W.C. (2011). Measuring changes in aerodynamic/rolling resistances by cycle-mounted power meters. *Medicine and Science in Sports and Exercise*, *43*(5), 853-860.

Lunnen, J.D., Yack, J., & LeVeau, B.F. (1981). Relationship between muscle length, muscle activity, and torque of the hamstring muscles. *Physical Therapy*, *61*(2), 190-195.

MacIntosh, B.R., Neptune, R.R., & Horton, J.F. (2000). Cadence, power, and muscle activation in cycle ergometry. *Medicine and Science in Sports and Exercise*, *32*(7), 1281-1287.

Marsden, M., & Schwellnus, M. (2010). Lower back pain in cyclists: A review of epidemiology, pathomechanics and risk factors. *International Sport Medicine Journal*, *11*(1), 216-225.

Marsh, A.P., Martin, P.E., & Sanderson, D.J. (2000). Is a joint moment-based cost function associated with preferred cycling cadence? *Journal of Biomechanics*, *33*(2), 173-180.

Millet, G.P., Tronche, C., Fuster, N., & Candau, R. (2002). Level ground and uphill cycling efficiency in seated and standing positions. *Medicine and Science in Sports and Exercise*, *34*(10), 1645-1652.

Mognoni, P., & di Prampero, P.E. (2003). Gear, inertial work and road slopes as determinants of biomechanics in cycling. *European Journal of Applied Physiology*, *90*(3-4), 372-376.

Moseley, L., & Jeukendrup, A.E. (2001). The reliability of cycling efficiency. *Medicine and Science in Sports and Exercise*, *33*(4), 621-627.

Neptune, R.R., Kautz, S.A., & Hull, M.L. (1997). The effect of pedaling rate on coordination in cycling. *Journal of Biomechanics*, *30*(10), 1051-1058.

Olds, T., & Olive, S. (1999). Methodological considerations in the determination of projected frontal area in cyclists. *Journal of Sports Sciences*, *17*(4), 335-345.

Redfield, R., & Hull, M.L. (1986). On the relation between joint moments and pedalling rates at constant power in bicycling. *Journal of Biomechanics*, *19*(4), 317-329.

Reiser, R., Peterson, M., & Broker, J. (2003). Instrumented bicycle pedals for dynamic measurement of propulsive cycling loads. *Sports Engineering*, *6*(1), 41-48.

Ryschon, T.W., & Stray-Gundersen, J. (1991). The effect of body position on the energy cost of cycling. *Medicine and Science in Sports and Exercise*, *23*(8), 949-953.

Salai, M., Brosh, T., Blankstein, A., Oran, A., & Chechik, A. (1999). Effect of changing the saddle angle on the incidence of low back pain in recreational bicyclists. *British Journal of Sports Medicine*, *33*(6), 398-400.

Sanderson, D.J., & Amoroso, A.T. (2009). The influence of seat height on the mechanical function of the triceps surae muscles during steady-rate cycling. *Journal of Electromyography and Kinesiology*, *19*(6), e465-471.

Sarabon, N., Fonda, B., & Markovic, G. (2011). Change of muscle activation patterns in uphill cycling of varying slope. *European Journal of Applied Physiology*. doi:10.1007/s00421-011-2236-1

Savelberg, H.H.C.M., Van de Port, I.G.L., & Willems, P.J.B. (2003). Body configuration in cycling affects muscle recruitment and movement pattern. *Journal of Applied Biomechanics*, *19*(4), 310-324.

Shemmell, J., & Neal, R. (1998). The kinematics of uphill, out-of-the-saddle-cycling. *North American Congress on Biomechanics*. Presented at the North American Congress on Biomechanics, University of Waterloo, Waterloo, Ontario, Canada: Canadian Society for Biomechanics, American Society of Biomechanics.

Silberman, M.R., Webner, D., Collina, S., & Shiple, B.J. (2005). Road bicycle fit. *Clinical Journal of Sport Medicine: Official Journal of the Canadian Academy of Sport Medicine*, *15*(4), 271-276.

Suzuki, S., Watanabe, S., & Homma, S. (1982). EMG activity and kinematics of human cycling movements at different constant velocities. *Brain Research*, *240*(2), 245-258.

Swain, D.P., & Wilcox, J.P. (1992). Effect of cadence on the economy of uphill cycling. *Medicine and Science in Sports and Exercise*, *24*(10), 1123-1127.

Too, D. (1990). Biomechanics of cycling and factors affecting performance. *Sports Medicine*, *10*(5), 286-302.

van Ingen Schenau, G.J., & Cavanagh, P.R. (1990). Power equations in endurance sports. *Journal of Biomechanics*, *23*(9), 865-881.

Welbergen, E., & Clijsen, L.P. (1990). The influence of body position on maximal performance in cycling. *European Journal of Applied Physiology and Occupational Physiology*, *61*(1-2), 138-142.

Wozniak Timmer, C.A. (1991). Cycling biomechanics: A literature review. *The Journal of Orthopaedic and Sports Physical Therapy*, *14*(3), 106-113.

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BIOMEHANIKA I ENERGETIKA VOŽNJE BICIKLA UZBRDO: PREGLED ISTRAŽIVANJA

Pobjednici najvećih biciklističkih 3-tjednih etapnih utrka (npr. Giro d'Italia, Tour de France, Vuelta a Espana) su najčešće biciklisti koji dominiraju u segmentima utrke s usponima. Amaterski biciklisti, pak, često izbjegavaju uzbrdice zbog neugodnosti koju vožnja uzbrdo izaziva. Zbog toga je nužno poznavati i razumjeti kretanje tijekom vožnje bicikla uzbrdo da bi se izabralo optimalno motoričko ponašanje koje se može primijeniti u praksi. Cilj je ovoga rada ocijeniti kvalitetu istraživanja o biomehanici i energetskim zahtjevima bicikliranja uzbrdo. Ukupno smo analizirali 40 članaka iz znanstvenih i stručnih časopisa koji su istražili energetiku, sile pedaliranja i sile u zglobovima, ekonomičnost i učinkovitost mišićne aktivnosti te optimizaciju izvedbe i udobnosti tijekom vožnje bicikla uzbrdo. Za vožnje po uzbrdici biciklisti moraju svladati gravitaciju, a da bi u tome uspjeli, potrebne su određene promjene u položaju tijela. Glavni rezultat ovog preglednog rada jest zaključak da se mišićna aktivnost mijenja tijekom vožnje bicikla uzbrdo u sjedu usporedbi s vožnjom po ravnom terenu, dok se s druge strane, sile na pedalama, dinamika zglobova i učinkovitost vožnje ne mijenjaju značajno. Suprotno tome, tijekom vožnje bicikla uzbrdo u stojećem položaju sve ranije spomenute mjere su različite od onih zabilježenih u vožnji bicikla uzbrdo u sjedu ili u vožnji po ravnom terenu. Daljnja istraživanja trebala bi se usmjeriti na istraživanja provedena u vanjskim uvjetima i na strmijim usponima.

Ključne riječi: *uspješnost, učinkovitost, biomehanika, fiziologija, optimizacija*