# How can Uphill Cycling be beneficial for sportsman

**Robert Abraham**

**Kerala University**

**Kerala**

**Abstract**

The victors 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 raceway.Amateur cyclists, however, will often avoid uphill terrain because of the irritation involved.Thus, understanding movement behavior during uphill cycling is called for in parliamentary procedure to obtain an optimum solution that can be used in practice.The purpose of this reexamination is to evaluate the caliber of research performed on biomechanics and the energetics of uphill cycling.All told we have analyzed over 40 articles from scientific and expert periodicals that provided results on energetics, pedal and joint forces, economy and efficiency, muscular action, as well as operation and comfort optimization during uphill cycling.During uphill cycling, cyclists need to defeat gravity and in order to accomplish this, some changes in posture are necessary.The principal outcomes of this review are that changes in muscle action 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 criteria are different when comparing either seated uphill cycling or level terrain cycling.Further inquiry 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 prac-tically relevant problems such as enhancing per-formance (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.

During uphill cycling, riders need to overcome gravity, which increases the demands for mechanical power. Because of the inclination of the surface, they demand to adjust their position for two principal reasons: first, to avoid lifting the front wheel and, second, to ensure that they hold a static posture on the saddle, hence that they do not slip away (Figure 1).Mountain bikers have to succeed in getting the best.

Even more demanding terrain conditions: they need to assure that there is enough traction on the back wheel while simultaneously making sure the front wheel rests on the land.To achieve this, the mountain bikers have to transfer their body forward on the saddle and flex their trunk (by leaning forward).This alteration in posture alters some of the characteristics of pedaling.Such modifications can be reflected in (1) different mechanical demands (DI Prampero, 2000), (2) changed economy and efficiency (Mo-Shelley & 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 instance, 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 position due to uphill terrain characteristics (e.g.Increased tensile forces on lumbar vertebra).

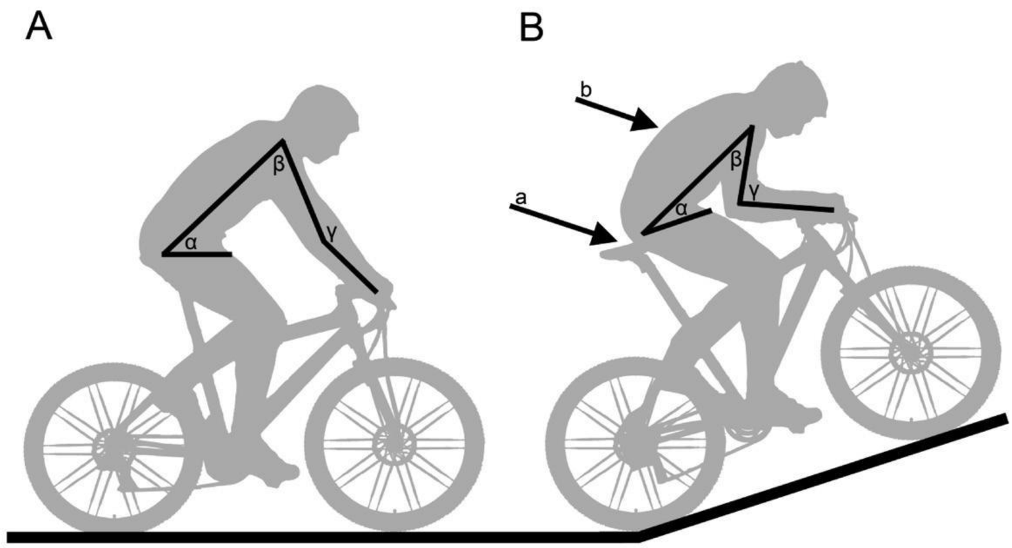

*Figure 1. Differences in posture between level terrain (A) and uphill cycling (B). The hip angle (α), shoulder angle (β), and elbow angle (γ) are all smaller during uphill cycling. The spot on the saddle is shifted forward (a) and the book binding is more rounded (b) during uphill cycling.*

Understanding movement patterns during up-hill cycling is necessary when looking for optimal solutions or enhancements, which can be then used in practice session.In the source part of this report, we will centralize on the equations of movement of cyclists during uphill cycling and try to come up to some of the practical implications in this country.The next chapter focuses on the economic organization and efficiency during uphill cycling.Patterns of kinetics and kinematics during uphill cycling are subsequently introduced, with an emphasis on pedal forces, joint moments and joint efforts.Neuromuscular alterations during uphill cycling are presented in the following part.In the concluding section, some of the practical solutions for improving uphill cycling are addressed.The story concludes by summarizing the applied values of the presented experimental data and with some directions for future research in the field.

When looking through the available literature, we centered on professional and scientific papers from the following databases: Pubmed, Sci-enceDirect, and Springerlink. We combed through them by using keywords such as *biomechanics*, *energetic*, *equation*, *forces*, *joints*, *EMG* (i.e. electro-myography) and performance, while admitting the words uphill and cycling.We watched 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 biomechan-ics 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 in-fluence on pedal forces (Kautz & Hull, 1993). Therefore, a cyclist performs almost all of the mechanical work (WC) against two primary fighting forces

(Equation 1): the rolling resistance (*RR*) and the air resistance (*RA*), whose result is the total resistance (*RT*) (van Ingen Schenau & Cavanagh, 1990). *RR is the energy loss as the wheels roll along the surface and it depends substantially on the stack of the bike and rider system, the acceleration of gravity, and a coefficient describing the inflation pressure of the tires, the characteristics of the airfoil and the type of the tires (DI Prampero, Cortili, Mognoni, & Saibene, 1979).*The RA is a map of the frontal plane area of the cyclist and the bike, the air density and the air velocity.At higher speeds, RR becomes an increasingly smaller fraction of RT.In the exercise, the appraisal of the frontal plane area can be performed 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 as 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 counting on the frontal plane area from that thought.

$$W_C = a + b \cdot v^2 \qquad \text{Par 1}$$

$$C_C = W_C \cdot \eta^{-2} \qquad \text{Par 2}$$

In Equation 1, WC is the mechanical work performed per unit of distance, v is the air speed and, a and b are constants for RR and RA per unit of dis-tance, respectively. The energy cost ($C_C$) of cycling depends on the overall cycling efficiency ($\eta$)

Equations 1, 2, 3 and 4 become practical when all information is recognized. By using the commercially available power meters (e.g. SRM® or Cycleops Power Tab®) the power output and velocity are known, so the RT can be worked out 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 exceedingly valuable in helping cyclists, coaches and scientists predict and better cycling performance (Lim, et al., 2011).

During uphill cycling, at a given power output, the RA becomes a comparatively modest fraction of the RT and the main opposing force becomes acceleration due to gravitational attraction. Opposing forces during uphill cycling are summarized in Figure 2.

The mechanical work performed against gravity (WCG) when cycling uphill is given by the product of the overall moving mass (M), the speedup due to gravity (g) and vertical displacement (h). When expressed per unit of distance covered along the road (*d*) (Equation 5), mechanical work can be extracted as the product of M, g and sinus γ (Equation 6), where γ is the angle of the road side.

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

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

A more elaborate description of the WC can be achieved by including the RR and RA in the calculations (Equation 7).

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

The CC can be estimated by substituting a and b in Equation 7 with the constants for metabolic energy dissipated against RR (α, since α = a · η-1) and RA (β, since β = be · η-1), respectively, and splitting the last term buy η (Equation 8). The *EC* can be further estimated by the same principle used during level terrain cycling as a product of *CC* and s (Equation 9). The mechanical efficiency has been demonstrated not to change during uphill cycling (Millet, trance, Fuster, & Candau, 2002).

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

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

With these equations, we can judge some of the important practical values.For instance, in his review, DI Prampero (2000) estimated the maximal slope of the side that the cyclist could over-do.This is possible if the subjects' maximal EC is known and the lowest speed value at which the bicyclist does not lose his/her balance is attributed.Nevertheless, these appraisals can only be prepared for a smooth terrain and with the utilization of an appropriate gear system to ensure optimum pedal frequency at a very low velocity.

Standard racing position. The $E_C$ for the upright position is 20% higher than for the racing position (Welbergen & Clijsen, 1990). With this data, the authors calculated that the incline where air resistance was no longer the determining factor was close to 7.5%.This data could benefit both coaches and cyclists regarding the position they should take during the uphill sections of a subspecies.

**Efficiency and economy during uphill cycling**

**Cycling efficiency**

Cycling efficiency has been described as the ratio of work accomplished atan 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 suggested, mainly distinguished by a baseline correction factor that is used to adjust the estimate of the energy expenditure and hence of the measured degree of efficiency (Gaesser & Brooks, 1975; Millet, et al., 2002).Gross cycling efficiency has been shown to be highly correlated with cycling performance and delivers a low variance 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 substantial differences in gross efficiency, force effectiveness and dead center size between the level and 11% uphill cycling conditions.Nevertheless, it is probable that the efficiency would be altered during steeper slopes, primarily because of the decrease in cadence (Swain & Wilcox, 1992).

**Use the economy cycle**

The term is employed as a measure of oxygen con-Sumption per unit of power output (Moseley & Jeukendrup, 2001).It can likewise be stated as the oxygen consumption required to pedal at a given speed (Swain & Wilcox, 1992).The ingredients that influence cycling economy vary with the conditions under which cycling is performed (Table 1).Swain and Wilcox (1992) demonstrated 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 side.In contrast, Harnish, King and Swensen (2007) indicated that trained cyclists are equally economical using high or low cadences, although they set up a substantial increase in ventilation (6%) and breathing frequency (8%) during standing uphill cycling when compared to the seated view.That could be excused by the rhythmic practice of breathing in coordination with the locomotion during pedaling while standing.

The solutions obtained by Millet et al.(2002) indicated that there are no important conflicts in the economy during uphill cycling (seated and standing) compared to level terrain.Nevertheless, heart rates were found to be higher (6%) during standing uphill cycling as opposed to the seated view.

Increased ventilation during standing uphill cycling was accompanied by an increase in breathing frequency, which seems to be associated 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 critique of studies on efficiency and economy during uphill cycling*

| Publishing | Bicyclists | Side | 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% | Breathing 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 applying 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 in 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 dispute Between seated or standing uphill cycling. |
| Leirdal and edema (2011) | 10-well coached cyclists | 11% | There was no difference in gross efficiency, force effectiveness and dead Center 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 stud-ies. 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, Grape 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

**Joint moments and kinematics during uphill cycling**

The studies on joint kinematics and kinetics during cycling were mainly performed on level ter-rain (Leirdal & Ettema, 2011; Bini & Diefenthaeler, 2010; Bini, Tamborindeguy, & Mota, 2010; Bini, Diefenthaeler, & Mota, 2010; Ericson, Bratt, Nisell, Németh, & Ekholm, 1986). Despite being practical-ly important, these biomechanical studies of uphill cycling are relatively unknown. The authors of this review were only aware of one study that had ex-amined 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. | 8 elite | 8% | Overall patterns of pedal and crank kinetics were similar between level and 8% uphill cycling in a seated position. Higher |

| | | | |
|---|---|---|---|
| (1998) | cyclists | | 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 in-creased 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 mo-ment 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 condi-tions with only significant alterations in the peak extensor moment during seated uphill conditions, as compared to standing uphill conditions.

## 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 movementby 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 ac-tivity can be altered when changing the seat height (Ericson, et al., 1985; Sanderson & Amoroso, 2009), power output (Ericson, et al., 1985; Suzuki, Watan-abe, & Homma, 1982), pedaling technique (Can-non, Kolkhorst, & Cipriani, 2007), cadence (Nep-tune, Kautz, & Hull, 1997) and/or posture (Savel-berg, 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 cy-cling) can alter the angle/torque relationship of the involved muscles (Hof, 2002; Lunnen, Yack, & Le-Veau, 1981) and therefore, potentially affect neu-romuscular 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 & Cald-well, 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.

*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

muscles) of the lower extremity muscles increased with the increasing slope. However, these authors did not study the timing or intensity of the activ-ity of individual lower extremity muscles. Hence, their results are difficult to compare with the re-sults 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 conduct-ed 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 neu-romuscular 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 medi-alis*, *m. rectus femoris*, *m. biceps femoris*, *m. biceps brachii*, *m. triceps brachii*, *m. rectus abdominis*, *m. erector spinae* and *m. semimembranosus* duringstanding uphill cycling. They reported that only the muscles crossing the ankle remained unchanged.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.

**References**

Álvarez, G., & Vinyolas, J. (1996). A new bicycle pedal design for on-road measurements of cycling forces. *Journalof 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.