UNIVERZA NA PRIMORSKEM
FAKULTETA ZA MATEMATIKO, NARAVOSLOVJE IN INFORMACIJSKE TEHNOLOGIJE

Borut Fonda

BIOMEHANSKE ZNAČILNOSTI KOLESARJENJA V KLANEC

Magistrsko delo

Koper, julij 2012

UNIVERZA NA PRIMORSKEM
FAKULTETA ZA MATEMATIKO, NARAVOSLOVJE IN INFORMACIJSKE TEHNOLOGIJE

APLIKATIVNA KINEZIOLOGIJA

BIOMEHANSKE ZNAČILNOSTI KOLESARJENJA V KLANEC

Magistrsko delo

MENTOR
Doc. dr. Nejc Šarabon

Avtor dela
BORUT FONDA

Koper, julij 2012

ZAHVALA

Iskrena hvala mentorju Dr. Nejcu Šarabonu za vse kar je naredil za moj raziskovalni, akademski in osebni razvoj.
Hvala podjetju S2P, znanost v prakso za hitro, strokovno in tehnično pomoč pri vseh opravljenih raziskavah.
Hvala vsem profesorjem na Aplikativni kineziologiji, ki so dvignili nivo mojega strokovnega in znanstvenega znanja.
Hvala družini, punci in prijateljem za podporo pri vseh študijskih in ob-študijskih dejavnosti.

Ime in PRIIMEK: Borut FONDA
Naslov magistrskega dela: Biomehanske značilnosti kolesarjenja v klanec
Kraj: Koper
Leto: 2012
Število listov: 22 Število slik: 2 Število tabel: 0
Število prilog: 1 Št. strani prilog: 1
Število referenc: 25
Mentor: doc. dr. Nejc Šarabon, dipl. fiziot., prof. šp. vzg.
UDK:
Ključne besede: biomehanika, energetika, mišična aktivnost, kolesarjenje

Povzetek: Zmagovalci večjih kolesarskih tekmovanj so običajno kolesarji, ki prevladujejo med kolesarjenjem v klanec. Na drugi strani se amaterski kolesarji pogosto izogibajo kolesarjenju v klanec, saj zaradi spremembe drže in delovanja nasprotujočih sil povzroči neugodje. Razumevanje motoričnega obnašanje med kolesarjenjem v klanec je zato izziv poiskati praktično uporabne optimizacijske rešitve. Glavnino magistrskega dela predstavljata članka objavljena v znanstvenih revijah. Namen preglednega članka je bil narediti pregled relevantnih raziskav področja biomehanike in energetike kolesarjenja v klanec. Skupaj smo analizirali več kot 40 člankov iz znanstvenih in strokovnih revij, ki so poročali o energetskih zahtevah, silah na pedalih, ekonomičnosti in učinkovitosti, mišični aktivnosti ter učinkovitosti in udobju optimizacij med kolesarjenjem v klanec. Glavni namen raziskovalne študije je bil preučiti vzorce mišične aktivnosti med kolesarjenjem v 20 % klanec (1) z običajno postavitvijo sedeža in (2) s prilagojenim položajem sedeža (tj. premik sedeža naprej in nagib sedeža spredaj navzdol). V primerjavi s kolesarjenjem po ravnini, 20 % klanec značilno spremeni tako časovno aktivnost, kakor tudi amplitudi aktivnosti izbranih mišic. Največje spremembe so se odražale na mišicah, ki prečkajo kolčni sklep. Ko je bil položaj sedeža optimiziran med kolesarjenjem v klanec, so bili vzorci mišične aktivnosti nespremenjeni v primerjavi s kolesarjenjem po ravnini. Po opravljenem pregledu literature lahko sklenemo, da se morajo nadaljnje raziskave osredotočiti na realne pogoje na terenu ter na pogoje, kjer se bodo preiskali vplivi večjih naklonin. Hkrati ostaja potreba po večjem razumevanju obremenitev sklepov na podlagi katerih bi se iskale optimizacije za izboljšanje učinkovitosti in varnosti med kolesarjenjem v klanec.

Name and SURNAME: Borut FONDA
Title of master thesis: Biomechanical characteristics of uphill cycling
Place: Koper
Year: 2012
Number of pages: 22 Number of pictures: 2 Number of tables: 0
Number of enclosures: 1 Number of enclosure pages: 1
Number of references: 25
Mentor: doc. dr. Nejc Šarabon
UDK:
Key words: biomechanics, energetics, muscle activity, cycling

Abstract: The winners of the major cycling races 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 behaviour during uphill cycling is needed in order to find an optimum solution that can be applied in practice. Core of this thesis are two articles published in scientific journals. The purpose of a review article was to review the relevant research in the fields of biomechanics and energetics during cycling uphill. Altogether we have analysed 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. The main purpose of the research study was to examine patterns of muscle activity during cycling at 20 % slope (1) with normal bike geometry settings and (2) with an adjusted seat position (i.e. forward move of the saddle and tilting the saddle down in front). Compared to level terrain cycling, 20 % slope significantly altered the timing of muscle activity, as well as the amplitude of activity of selected muscles. The largest changes were reflected in the muscles crossing the hip joint. When seat optimization was used during uphill cycling, the muscle activity patterns were unchanged compared with level terrain cycling. After completing a literature review, we concluded that further research should focus on the outdoor conditions and on the steeper slope conditions. At the same time it remains a need to better understand the joint loads for improvements of performance and safety during uphill cycling.

KAZALO VSEBINE

KAZALO SLIK

1 UVOD

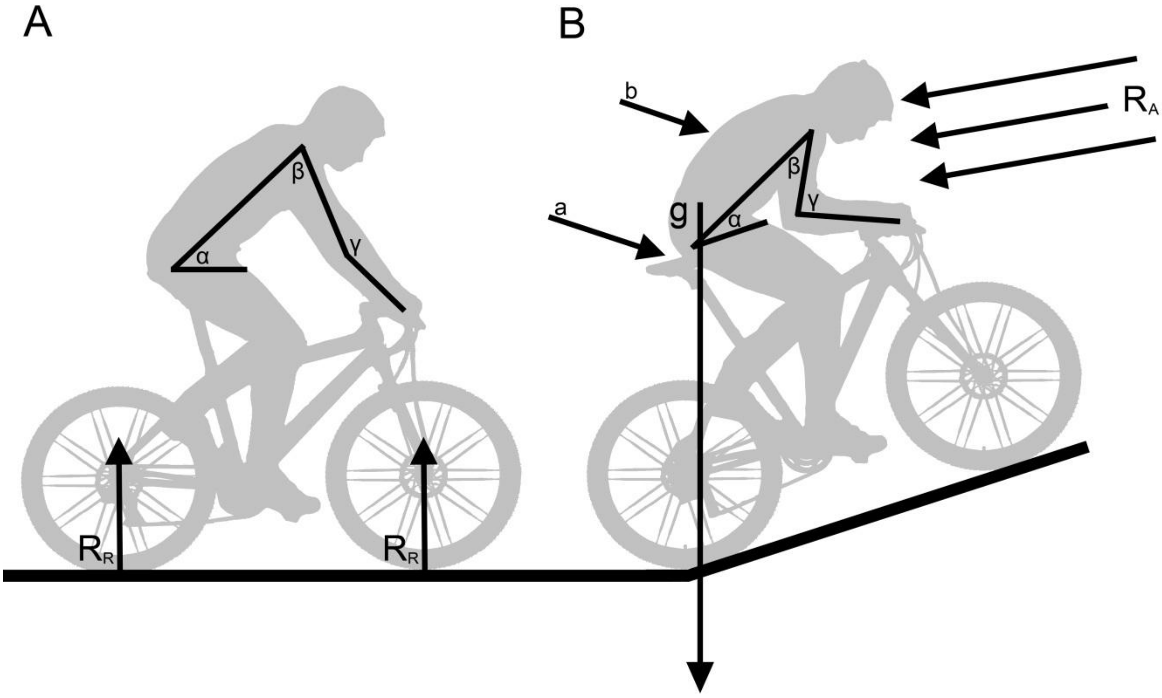
Prva kolesa so bila narejena v devetnajstem stoletju. Tehnologija za izdelavo koles se je v tistem času stalno razvijala in kolesarji so njihovo praktično uporabo kmalu preusmerili tudi v tekmovalne namene. Prva kolesarska tekma je tako zabeležena leta 1868 v okolici Pariza. Ta dogodek je bil pravi hit in kmalu so sledile še druge tekme drugje po svetu. Kolesarske tekme so hitro pridobivale na popularnosti, tako v Evropi, kot tudi v Združenih državah Amerike. Kasnejši prvi organizator znamenite Dirke po Franciji, Henri Desgrange, je leta 1891 postavil prvi hitrostni rekord v eni uri kolesarjenje s povprečno hitrostjo preko 35 kilometrov na uro.

Prva kolesa so bila izdelana iz lesa, nato iz železa ter so tehtala med 15 in 25 kilogramov. Danes so vrhunska kolesa izdelana iz karbona, aluminija in/ali titana ter najboljša tehtajo tudi manj kot 7 kilogramov. Izrazito se je spremenila oblika koles in posledično tudi položaj telesa med kolesarjenjem (Jeukendrup, 2002). Kolesarjenje dandanes predstavlja veliko več, kot le sredstvo prevoza. Postalo je izredno priljubljena rekreativna dejavnost in vse več je tudi zanimanja za kolesarstvo kot vrhunski šport. Z vse večjim ukvarjanjem s kolesarstvom, se je povečala tudi potreba po podrobnejšem razumevanju značilnosti obremenitev in odzivov telesa med to kompleksno gibalno/športno aktivnostjo.

Razvoj koles in kolesarske opreme je v zadnjih letih močno napredoval in ne kaže, da bi se napredek ustavil. Ker smernice razvoja postavljajo vrhunski tekmovalci, proizvajalci koles in kolesarske opreme razvoj le-teh prilagajajo tekmovalnim razmeram. Večina kolesarske opreme je posledično zasnovana za čim hitrejšo vožnjo, ergonomsko-zdravstveni vidik pa je zapostavljen. Avtorju te naloge ni znano, da bi na trgu obstajala kolesarska oprema, ki bi omogočala kolesarjem varno in brezskrbno kolesarjenje, hkrati pa bi jo uporabljali tudi tekmovalci za povečanje tekmovalne uspešnosti.

Z vidika tekmovalne uspešnosti ima vpliv vožnje navkreber (v kolesarski stroki uporabljen termin »v klanec«) izreden pomen, saj se velika večina tekmovanj odloča ravno v teh pogojih. Na primer, zmagovalci vseh treh največjih etapnih dirk (Dirka po Franciji, Dirka po Španiji in Dirka po Italiji) so bili v zadnjem desetletju običajno kolesarji, ki so dominirali v etapah s ciljem na vrhu klanca. Če vožnja v klanec tekmovalcem predstavlja ključni del tekmovanj, pa rekreativnim in amaterskim kolesarjem pogosto pomeni nelagodje. Namreč, med kolesarjenjem v klanec je potrebno položaj telesa prilagoditi gravitacijskim zahtevam, da se ohrani dovolj oprijema na zadnjem kolesu in se hkrati prepreči dvigovanje prednjega kolesa. Prilagoditve drže so običajno z zmanjšanjem kota v kolku, ramenih in komolcih ter izrazitim pomikom naprej in povečanim upogibom hrbta (Slika 1). Slednje poveča sile na vretenca in lahko vodi do bolečine v spodnjem delu hrbta (Salai, Brosh, Blankstein, Oran, & Chechik, 1999). Istočasno se poveča tudi aktivnost mišic zgornjih udov in poraba kisika (Clarys, Alewaeters, & Zinzen, 2001; Fonda & Šarabon, 2010).

Slika 1: Primerjava telesne drže med kolesarjenjem po ravnini (A) in med kolesarjenjem v klanec (B).



R_A, zračni upor; R_R, sila trakcije podlage; g, sila gravitacije; α, kot v kolku; β, kot v ramenih; γ, kot v komolcih; a, položaj na sedežu; b,upogib hrbta..

Med kolesarjenjem po ravnini mora kolesar premagovati dve glavni retropulzivni sili (Slika 1). To sta sila trakcije podlage in sila zračnega upora (di Prampero, Cortili, Mognoni, & Saibene, 1979). Mehansko delo (W_C) se izračuna iz obeh retropulzivnih sil in hitrosti vetra(Enačba 1),

$$W_C = a + b \cdot v^2$$ Enačba 1

kjer sta *a* in *b* konstanti, *v* pa je hitrost vetra.

Mehanska moč (P_C) se izračuna iz produkta mehanskega dela in konstantne hitrosti kolesarjenja (s) (Enačba 2).

$$P_C = W_C \cdot s \qquad \text{Enačba 2}$$

Med kolesarjenjem v klanec mora kolesar premagati še silo gravitacije (g), ki takrat postane glavna retropulzivna sila. Sila zračnega upora se zaradi manjše hitrosti zmanjša, sila trakcije podlage pa ostane nespremenjena. Mehanska moč je torej seštevek moči potrebnih za premagovanje gravitacije, trakcije podlage in zračnega upora (Enačba 3),

$$P_C = a \cdot s + b \cdot s^3 + M \cdot g \cdot s \cdot \sin\gamma \qquad \text{Enačba 3}$$

kjer je M masa kolesarja skupaj s kolesom in opremo, γ pa naklon terena v stopinjah.

Iz teh podatkov je razvidno, da ima kolesarjenje v klanec drugačne energetske zahteve kot kolesarjenje po ravnini. Največja sprememba se verjetno izraža v zračnem uporu, ki se močno zmanjša zaradi manjše hitrosti. Iz podatkov v preteklosti je znano, da je aerodinamična drža med kolesarjenjem po ravnini manj učinkovita, kot normalna pokončna. Iz teh podatkov so raziskovalci (Welbergen & Clijsen, 1990) izračunali ob katerem naklonu je za kolesarja bolj priporočljivo, da se vrne v pokončni položaj. Na primeru enega kolesarja so ob brezvetrnih pogojih prišli do zaključka, da je točka, kjer je bolj učinkovita pokončna drža, ko je naklon večji od 7,5 %.

Zanimivo je, da so kolesa in oprema narejena v smeri, da kar najbolj ustrezajo kolesarjenju po ravnini. To pomeni raven sedež, aerodinamično postavljeno krmilo, itd. (Pruitt, 2006). Skratka, kolo pri vožnji v klanec ne omogoča posebnih prilagoditev, da bi bilo kolesarjenje učinkovitejše in/ali udobnejše. Sila gravitacije na kolesarja pri vožnji v klanec vpliva izrazito bolj retropulzivno, kot pri kolesarjenju po ravnini, kar se odraža v nekaterih telesnih prilagoditvah. Za primer so lahko kar kolesarju dokaj nepomemben člen, t.j. roke. Med kolesarjenjem po ravnini delujejo kot opora, s katero smo naslonjeni na krmilo. Pri rahlem vzponu to vlogo izgubijo in praktično nimajo pomembnejše vloge, medtem ko pri strmih vzponih zagotavljajo oporo, ampak v ravno nasprotni smeri, kot to počnejo pri ravninskem kolesarjenju (Clarys idr., 2001). Pri gorskih kolesarjih to postane še bolj izrazito, ko se morajo pri premagovanju strmih vzponov še spretno izogibati oviram na progi. Takrat se celoten položaj telesa prilagaja razmeram in je precej drugačen od tistega optimalnega, kakršen je med kolesarjenjem po ravnini.

1.1 Predmet in problem

Predmet magistrskega dela je preučevanje biomehanskih lastnosti kolesarjenja v klanec, s poudarkom na med-mišični koordinaciji in optimizaciji geometrije kolesa. Razlog za raziskavo med-mišične koordinacije predstavlja slabo raziskano področje, saj so v preteklosti študije, ki so preučevale med-mišično koordinacijo med kolesarjenjem dokaj ozko usmerjene in nezadostno pojasnjujejo vplive naklonine, še posebej večjih naklonov (Duc, Bertucci, Pernin, & Grappe, 2008; Li & Caldwell, 1998; Sarabon, Fonda, & Markovic, 2011). Dodatno razlog za raziskavo predstavlja tudi način optimizacije telesne drže preko nastavitve položaja sedeža s ciljem povečanja učinkovitosti in udobja (Fonda & Šarabon, 2010).

Znano je, da se mehanska učinkovitost med kolesarjenjem spreminja med različnimi kadencami (Gaesser & Brooks, 1975), položajih telesa (Ryschon & Stray-Gundersen, 1991), postavitvah stopala (Disley & Li, 2012), in tipih mišičnih vlaken (Coyle, Sidossis, Horowitz, & Beltz, 1992). Mehanska učinkovitost ima med kolesarjenjem v ponovljivih pogojih nizko stopnjo variabilnosti in zazna tudi manjše spremembe (Millet, Tronche, Fuster, & Candau, 2002). Med kolesarjenjem v klanec avtorji niso poročali o značilnih razlikah v učinkovitosti (Leirdal & Ettema, 2011; Millet idr., 2002). Omeniti velja, da v navedenih študijah niso uporabili naklonov večjih od 11 %. Enako, kot za učinkovitost kolesarjenja, so isti avtorji poročali, da ni razlik v ekonomičnosti (Millet idr., 2002) med kolesarjenjem v klanec v primerjavi s kolesarjenjem po ravnini.

Pri preučevanju sil, ki jih kolesar aplicira na pedala, največjo težavo predstavlja oprema za merjenje sil. Slednja mora biti natančna ter hkrati ne sme ovirati poganjanja pedal. Nekateri avtorji so poročali, da ni razlik v profilih navora v gonilki med kolesarjenjem v klanec v primerjavi s kolesarjenjem po ravnini (Caldwell, McCole, Hagberg, & Li, 1998). Nasprotno so dokazali Hansen, Jørgensen, Jensen, Fregly, in Sjøgaard (2002), ki so ugotovili značilne razlike v vzorcu navora gonilke med pogojem, ki laboratorijsko simulira kolesarjenje v klanec v primerjavi s kolesarjenjem po ravnini. Podatke o navorih gonilke in silah na pedalih moramo interpretirati s veliko mero previdnosti, saj rezultati laboratorijskih študij ne odražajo realnih pogojev (Bertucci, Grappe, & Groslambert, 2007). Bertucci, Grappe, Girard, Betik in Rouillon (2005) so poročali, da sprememba naklona v realnih pogojih značilno vpliva na navor gonilke. Področje navorov v sklepih med kolesarjenjem v klanec ostaja slabo raziskano področje. Avtorju te naloge je znano, da je bila do sedaj opravljena zgolj ena študija, ki je poročala o spremembah navorov plantarne fleksije gležnja in ekstenzije kolena med kolesarjenjem v klanec z 8 % naklonom (Caldwell, Hagberg, McCole, & Li, 1999).

Pri kolesarjenju v klanec je bilo ugotovljeno, da se aktivacija večine mišic spodnjega uda statistično značilno ne spreminja (Duc idr., 2008). Povišana aktivnost med kolesarjenjem v klanec je bila opazna le pri mišicah m. gluteus maksimus in m. erector spinae (Duc idr., 2008). Te rezultate moramo interpretirati s previdnostjo, saj v študiji ni bila uporabljena konstantna kadenca in se je pri večini subjektov znižala med kolesarjenjem v klanec, kar je posledično lahko privedlo do nižjih vrednosti mišične aktivnosti, kot sicer (McGhie & Ettema, 2010). Podobne rezultate sta dobila tudi Li in Caldwell (1998), ki pri spremembi naklona iz 0 na 8 % nista zaznala značilnih razlik v vzorcu mišične aktivnosti. Opazila pa sta povečano aktivnost m. gluteus maksimus in m. rectus femoris med kolesarjenjem v stoje. Povečana aktivnost m. gluteus maksimus je verjetno posledica zagotavljanja večje togosti kolčnega sklepa in stabilizacije medenice med tovrstnim kolesarjenjem. Med kolesarjenjem v klanec z večjim naklonom (20 %) so raziskovalci ugotovili, da se vzorci mišične aktivnosti značilno spremenijo v večini mišicah, ki potekajo preko kolčnega sklepa, ter v m. tibialis anterior (Sarabon idr., 2011). Spremembe v času aktivnosti so bile opažene pri m. rectus femoris, m. vastus medialis, m. vastus lateralis in m. biceps femoris. Isti raziskovalci so poročali, da med kolesarjenjem v 10 % klanec ne prihaja do statistično pomembnih razlik v aktivnosti mišic spodnjega uda (Sarabon idr., 2011).

Potreba po optimizaciji drže telesa obstaja tako med tekmovalci, kot tudi med rekreativci. V opravljeni študiji predstavljamo sedežno oporo (Slika 2), ki pomakne sedež naprej in spremeni njegov naklon. S to optimizacijo se izboljša udobje, poveča ekonomičnost in zmanjša aktivnost mišic rok (Fonda & Šarabon, 2010).

Slika 2: Nastavljiva sedežna opora.

Večina kolesarskih tekmovanj se odloči med kolesarjenjem v klanec, zato obstaja potreba pri raziskovanju novih pristopov in izboljšav. Razumevanje med-mišične koordinacije med kolesarjenjem v klanec ostaja nepojasnjeno, zato je v eksperimentalnem članku predstavljena študija mišične aktivnosti med kolesarjenjem v klanec in hkrati poskus optimizacije geometrije kolesa. Ostala področja kolesarjenja v klanec so raziskana bolje, čeprav na nekaterih delih še vedno nezadostno, ter so povzeta v preglednem članku.

1.2 Cilj magistrskega dela

Cilj magistrskega dela je preučiti biomehanske lastnosti kolesarjenja v klanec ter hkrati opraviti študijo mišične aktivnosti za optimizacijo geometrije kolesa med kolesarjenjem v 20 % klanec.

1.3 Hipoteze študije

H1: med-mišična koordinacija med kolesarjenjem v 20 % klanec se bo statistično značilno razlikovala od tiste pri kolesarjenju po ravnini.

H2: med-mišična koordinacija se bo med kolesarjenjem v 20 % klanec s spremenjeno geometrijo kolesa približala tisti med kolesarjenjem po ravnini.

1.4 Oblika magistrskega dela

Skladno s pravilnikom o magistrskem delu v študijskem programu druge stopnje Aplikativna kineziologija na Univerzi na Primorskem, Fakulteti za matematiko, naravoslovje in informacijske tehnologije, je magistrsko delo sestavljeno iz dveh člankov objavljenih oz. sprejetih v objavo v revijah s faktorjem vpliva, povezujeta pa jih skupen uvod in zaključek. Prvi avtor obeh člankov sem avtor tega magistrskega dela, Borut Fonda. V preglednem članku (Fonda & Sarabon, 2012), objavljen v reviji Kinesiology, se je uporabila deskriptivna metoda, v drugem članku, objavljen v reviji Journal of electromyography and kinesiology (Fonda, Panjan, Markovic, & Sarabon, 2011), pa gre za eksperimentalno metodo raziskovanja.

2 PREGLEDNI ČLANEK

NASLOV: Biomechanics and energetics of uphill cycling: a review

AVTORJI: Borut Fonda, Nejc Šarabon

LETO: 2012

REVIJA: Kinesiology

LETNIK: 44

ŠTEVILKA: 1

STRANI: 5-17

BIOMECHANICS AND ENERGETICS OF UPHILL CYCLING: A REVIEW

Borut Fonda[1] and Nejc Šarabon[1,2]

[1]S2P Ltd., Laboratory for Motor Control and Motor Behaviour, Ljubljana, Slovenia
[2]University of Primorska, Science and Research Centre, Institute for Kinesiology Research, Koper, Slovenia

Review
UDC: 577.35:612.766:796.61:796.015

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).

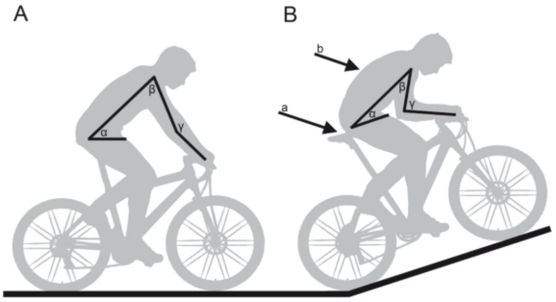


Figure 1. Differences in posture between level terrain (A) and uphill cycling (B). The hip angle (α), shoulder angle (β), and elbow angle (γ) are all smaller during uphill cycling. The position on the saddle is shifted forward (a) and the back is more rounded (b) during uphill cycling.

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.

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

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

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.

$P_C = W_C \cdot s$ Equation 3

$E_C = C_C \cdot s$ 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.

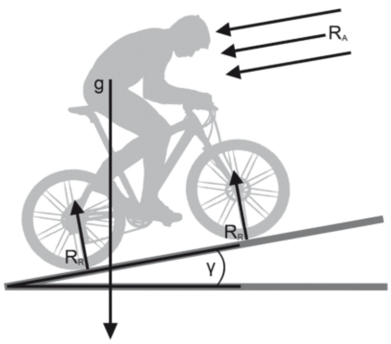


Figure 2. Main opposing forces during uphill cycling. Where g is acceleration due to gravity; R_A is aerodynamic drag, R_R are tractive resistive forces, and γ is angle of the terrain.

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

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

$W_{CG} = M \cdot g \cdot \sin \gamma$ 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).

$W_C = a + b \cdot s^2 + M \cdot g \cdot \sin \gamma$ 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).

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

$E_C = \alpha \cdot s + \beta \cdot s^3 + M \cdot g \cdot s \cdot \sin\gamma \cdot \eta^{-1}$ 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 & Lee, 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

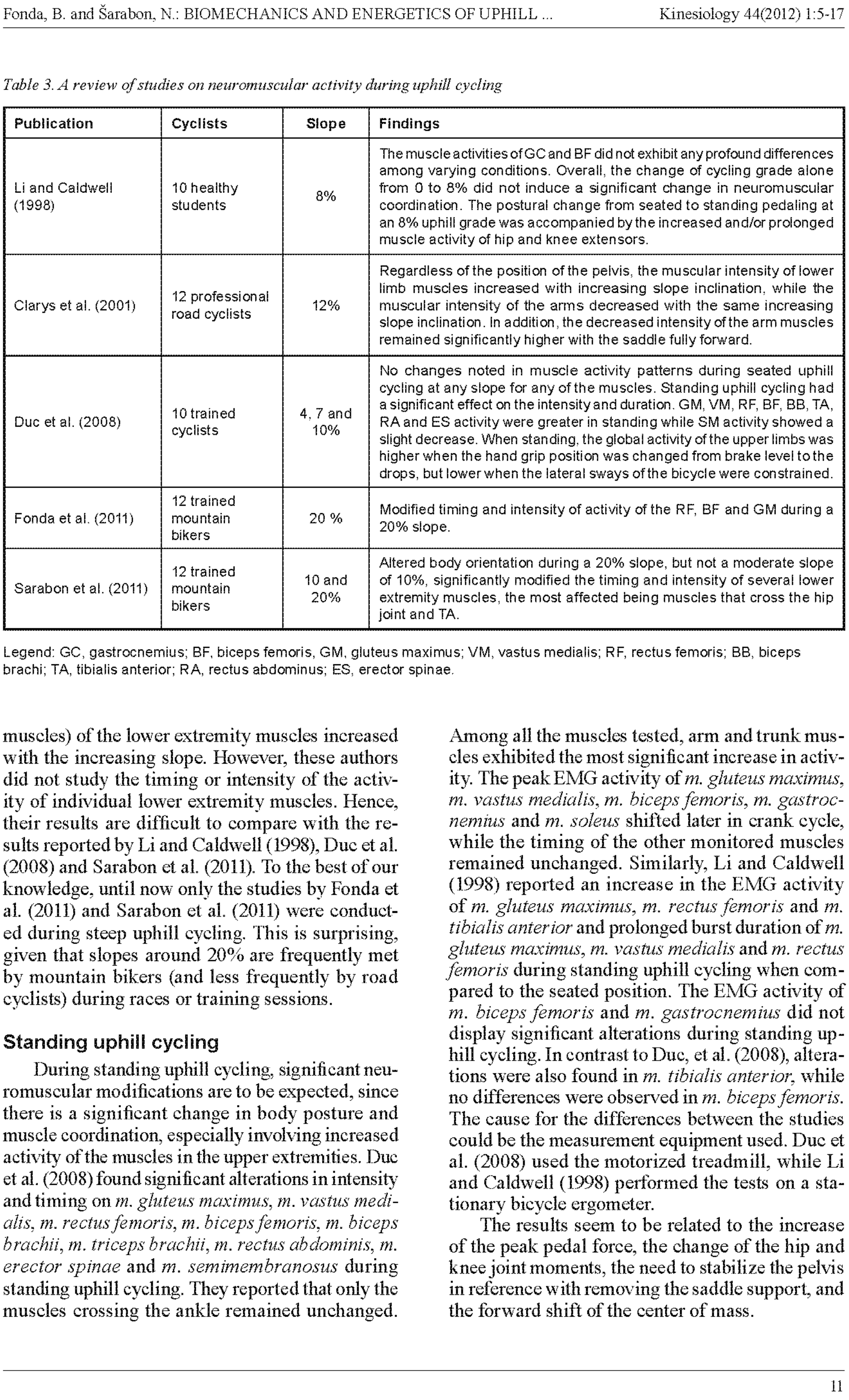


Table 3. A review of studies on neuromuscular activity during uphill cycling

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.

Submitted: March 18, 2012
Accepted: May 15, 2012

Correspondence to:
Nejc Šarabon, Ph.D.
University of Primorska, Science and Research Centre
Institute for Kinesiology Research
Garibaldijeva 1, 6000 Koper, Slovenia
Phone: +386 40 429 505
E-mail: nejc.sarabon@zrs.upr.si

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*

3 RAZISKOVALNI ČLANEK

NASLOV: Adjusted saddle position counteracts the modified muscle activation patterns during uphill cycling

AVTORJI: Borut Fonda, Andrej Panjan, Goran Marković, Nejc Šarabon

LETO: 2011

REVIJA: Journal of electromyography and kinesiology

LETNIK: 21

ŠTEVILKA: 5

STRANI: 854-860

Journal of Electromyography and Kinesiology 21 (2011) 854–860

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Adjusted saddle position counteracts the modified muscle activation patterns during uphill cycling

Borut Fonda[a], Andrej Panjan[a], Goran Markovic[a,c], Nejc Sarabon[a,b,*]

[a] *S2P Ltd., Laboratory for Motor Control and Motor Behavior, Bled, Slovenia*
[b] *University of Primorska, Science and Research Centre, Institute for Kinesiology Research, Koper, Slovenia*
[c] *Motor Control and Human Performance Laboratory, School of Kinesiology, University of Zagreb, Zagreb, Croatia*

ARTICLE INFO

Article history:
Received 22 November 2010
Received in revised form 26 May 2011
Accepted 26 May 2011

Keywords:
Cycling
Electromyography
Bicycle geometry
Muscular coordination

ABSTRACT

The main aim of this project was to study muscle activity patterns during steep uphill cycling (UC) (i.e., with a gradient of 20%) with (1) normal saddle geometry and (2) with adjusted saddle position ASP (i.e., moving the saddle forward and changing the tilt of the saddle by 20%). Based on our preliminary case study, we hypothesized that: (1) during 20% UC muscle activity patterns would be different from those of level cycling (LC) and (2) during 20% UC with ASP muscle activity patterns would resemble those of LC. Twelve trained male cyclists were tested on an electromagnetically braked cycle ergometer under three conditions with the same work rate (80% of maximal power output) and cadence (90 rpm): level (LC), 20% UC and 20% UC with ASP. Electromyographic signals were acquired from m. tibialis anterior (TA), m. soleus (SO), m. gastrocnemius (GC), m. vastus lateralis (VL), m. vastus medialis (VM), m. rectus femoris (RF), m. biceps femoris (BF) and m. gluteus maximus (GM). Compared to LC, 20% UC significantly modified both the timing and the intensity of activity of the selected muscles, while muscles that cross the hip joint were the most affected (RF later onset, earlier offset, shorter range of activity and decrease in peak amplitude of 34%; BF longer range of activity; GM increase in peak amplitude of 44%). These changes in EMG patterns during 20% UC were successfully counteracted by the use of ASP and it was interesting to observe that the use of ASP during 20% UC was perceived positively by all cyclists regarding both comfort and performance. These results could have a practical relevance in terms of improving performance during UC, together with reducing discomfort.

1. Introduction

Many physiological and biomechanical studies were dedicated to research into cycling performance and safety improvements (Coyle et al., 1991; Too, 1990; Wozniak Timmer, 1991). A body of literature resulting from research into the interaction between certain cycling conditions and biomechanical parameters of cycling has already been published, for a review see Fonda and Sarabon (2010a). This research concentrated on particular problems such as: on enhancing performance (Faria et al., 2005; Jeukendrup and Martin, 2001); on improving rehabilitation protocols (Ericson, 1986); on improving comfort (Gámez et al., 2008); and on preventing harmful effects caused by cycling (Burke, 1994; Silberman et al., 2005; de Vey Mestdagh, 1998). Many authors focused on the relation between body posture during cycling and bicycle geometry with the aim of facilitating positive effects during cycling. In their attempts to optimize the cyclist's posture, researchers modified saddle position, handlebar position, crank length, etc. (Burke, 1994; Gnehm et al., 1997; Grappe et al., 1998; Harnish et al., 2007; Jobson et al., 2008; Nordeen-Snyder, 1977; Silberman et al., 2005; de Vey Mestdagh, 1998).

The majority of the above mentioned studies focused on level terrain cycling (LC) although cycling in other conditions, for example uphill cycling (UC), is typical of both racing and leisure cycling. From the racing point of view, UC can be the deciding factor that determines the winner (Bertucci et al., 2005; Hansen and Waldeland, 2008; Li and Caldwell, 1998), on the other hand, in leisure cycling uphill terrains often bring discomfort and consequently many leisure cyclists try to avoid hills. During UC, cyclists need to adapt their posture for two main reasons: first, they have to avoid lifting the front wheel and secondly, they have to ensure that they keep a stable position on the saddle so that they do not slide off. Mountain bikers have to succeed in overcoming more demanding requirements in providing enough traction on the rear wheel while at the same time preventing the front wheel from lifting. To accomplish that they have to move forward on the saddle and flex the trunk (leaning forward). Adapting the posture in this way, consequently changes the muscle length/force ratio (Lunnen et al., 1981; Hof, 2002; Enoka, 2008). Such changes should be reflected

---

[*] Corresponding author at: University of Primorska, Science and Research Centre, Institute for Kinesiology Research, Garibaldijeva 1, 6000 Koper, Slovenia. Tel.: +386 40 429 505.
E-mail addresses: nejc.sarabon@zrs.upr.si, nejc.sarabon@s2p.si (N. Sarabon).

1050-6411/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jelekin.2011.05.010

in (1) modified neuromuscular activation patterns (Chapman et al., 2008; Farrokhi et al., 2008) and (2) altered cycling kinematics and kinetics (Ercison et al., 1988; Price and Donne, 1997).

Regarding UC kinematics and kinetics, previous research provided conflicting findings. Bertucci et al. (2005) observed an increase in torque during UC compared to LC. In contrast, Caldwell et al. (1998) studied the kinematic and kinetic parameters of the lower extremities during level and 8% UC, but found almost no alterations in the values of the selected parameters (i.e., force exerted on the pedal, pedal orientation and torque). Regarding neuromuscular coordination during UC, two studies (Duc et al., 2008; Li and Caldwell, 1998) found no significant differences in intensity and timing of muscle activity patterns for individual muscles. Conversely, Clarys et al. (2001) reported that global integrated EMG (average of all monitored muscles) of the lower extremity increases with increasing slope. Notably, all the aforementioned studies have been conducted on slopes ⩽12% and used only limited methodological approaches to analyze the differences between various conditions. Thus, more research is needed to advance our knowledge about muscle function and mechanics during UC.

When considering health-related issues during cycling, low back pain is certainly one of the most common ones (Marsden, 2010). In their fluoroscopic/biomechanical and clinical study Salai et al. (1999) showed that tilting the saddle forward by 10–15° can significantly decrease the tensile forces on lumbar vertebra and therefore reduce low back pain during cycling. Based on their research we can assume that the low back pain issue can become even worse when cyclists adjust their posture due to uphill terrain characteristics (increased tensile forces on lumbar vertebra).

In this study, a novel bicycle geometry optimization was used with the goal of enhancing performance and comfort of cycling during uphill conditions. With an adjusted tilt and longitudinal position of the saddle we wanted to bring the posture during UC closer to the posture during LC and achieve a more comfortable position during UC. Our aim was to study muscle recruitment patterns during steep (i.e., 20%) UC with and without adapted saddle positions. Based on our preliminary case study, we hypothesized that muscle activity patterns would change during 20% UC compared to LC (Fonda and Sarabon, 2010b). Since the most substantial changes in body position during UC happen in the hip joint, we expected that the most prominent differences between LC and UC will be present in the muscles that cross the hip joint. We also hypothesized that an adapted saddle position during 20% UC would result in more similar muscle activity patterns compared to LC.

2. Methods

2.1. Subjects

Twelve male, highly trained mountain bikers whose physical and physiological characteristics are presented in Table 1 volunteered to participate in this study. Details about the study were presented to them in an interview before the start of the experiment. The study was approved by the National Medical Ethics Committee and all the subjects signed a statement of informed consent at their enrollment.

2.2. Protocol

Two test sessions were conducted in the following order: (1) an incremental test until exhaustion in order to standardize the intensity for the main experiment and (2) an experimental test with three different cycling conditions: (a) level, (b) 20% slope and (c) 20% slope with adjusted saddle position. The main experiment was carried out at least three days after the first test to exclude fatigue effects.

Table 1
Physical and physiological characteristics.

	Mean ± SD
Age	22.6 ± 6.9 years
Body height	180.3 ± 5.4 cm
Body weight	71.0 ± 8.9 kg
VO_2 max	63.1 ± 13.1 ml·kg^{-1} min^{-1}
Years of racing	7.6 ± 2.7 years
Max power output	401.6 ± 37.2 W

VO_2 max, maximal oxygen uptake.

During the first session, each subject performed an incremental test, starting at 100 W increasing by 30 W every 2 min. The test was terminated when the subject could no longer maintain the goal power output. The maximal power was noted as the power output which was maintained for at least 1 min (Duc et al., 2008; Lepers et al., 2000; Sekir et al., 2002). This test was performed to standardize the intensity for the main experiment.

During the second session all subjects completed a standardized 10-min warm-up at the increasing intensity from 30% to 70% of the maximal power output. After the warm-up, they were asked to perform three 2-min trials at 80% of their maximal power output from the first session at a constant cadence of 90 rpm. All cycling trials were performed in randomized order to avoid any systematic bias. Between the trials there was a 5-min active break; easy pedaling at 100 W. All cyclists were instructed to adapt their body posture as they would in real life racing conditions.

2.3. Material

Both test sessions were performed on the same electro-magnetically braked cycle ergometer (Tacx, Wassenaar, Netherlands, model Flow). Inclination in the second session was simulated with a custom made slope platform. Bicycle geometry optimization was achieved with a specially designed adjustable saddle post (ASP; Fig. 1). With the ASP the position of the saddle can be moved forward and the tilt of the saddle can be changed to the equivalent of a slope of 20%. Each subject performed both tests with his own racing bicycle in which the ASP was inserted.

EMG signals were acquired from m. tibialis anterior (TA), m. soleus (SO), m. gastrocnemius (GC), m. vastus lateralis (VL), m. vastus medialis (VM), m. rectus femoris (RF), m. biceps femoris (BF) and m. gluteus maximus (GM) with wireless EMG device (Noraxon, Scottsdale, USA, model TeleMyo 2400 G2) via bipolar surface electrodes placed according to the SENIAM standards. All the electrodes and the wires were fixed on the skin with adhesive tape and elastic sleeve to avoid artifacts. A crank trigger (optical sensor, Leuze Electronic, Owen, Germany) was placed at 180° of the crank cycle. The acquisition of the EMG and the crank trigger signals were carried out at a sampling rate of 4000 Hz.

After a subject completed the measurements of the main experiment, he was asked to grade on a scale from 1 to 3, his subjective feeling about comfort and performance when using ASP. Grade 1 meant that the subject preferred riding with normal saddle position and would not choose the ASP during a race, 2 meant that the subject could not decide between normal or adjusted saddle position and 3 meant that the subject preferred using ASP during UC and would also choose that saddle position during a race.

2.4. Data analysis

All analyses were performed with the statistical package SPSS 17.0 and specially designed software with LabView (National Instruments, Austin, USA). The EMG signals were processed using

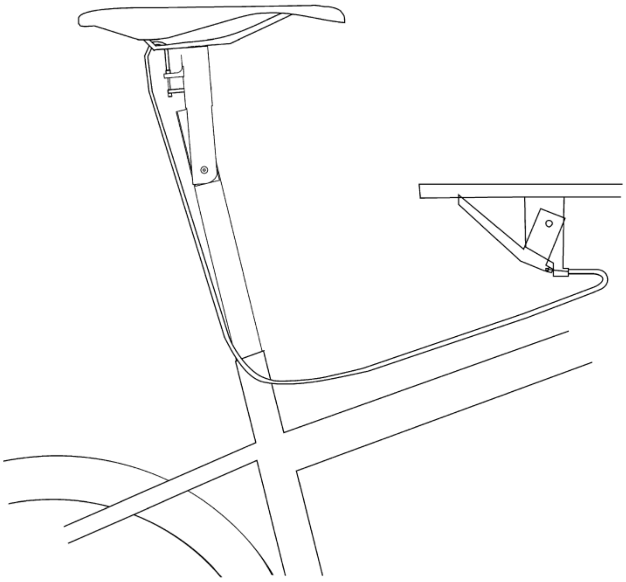


Fig. 1. Adjustable saddle post (ASP). ASP enables the cyclists to adjust the angle and the position of the saddle by putting it into three different positions: (i) horizontal position (normal), (ii) 10% angle of the saddle and (iii) 20% angle of the saddle. For our study we only used the normal and the 20% saddle position during uphill cycling. Note that forward movement of the saddle and optimized saddle angle does not alter the saddle height. The lever on the handlebar allows the position of the saddle to be modified safely.

the following steps: (1) zero alignment, (2) band-pass filtering, 20–750 Hz, Butterworth, 2nd order, (3) full-wave rectification and (4) smoothing with a RMS moving window of 25 ms to produce a linear envelope with cut-off frequency of 6 Hz. Averaged values for each of the muscles were calculated from the last 50 consecutive cycles in the 2-min trial, thereby using the digital trigger to indicate the beginning of the crank cycle. These averaged signals were then normalized to the maximal value recorded during level cycling and the time scale was transformed to crank angle scale. The top dead center (TDC; i.e., 360–0° shift) and the bottom dead center of the crank (BDC; i.e., 180°) were defined.

A threshold value of 25% of the maximal value derived from the level cycling condition was taken to determine the onset and offset of the main burst of activity (Duc et al., 2008; Li and Caldwell, 1998). The range of the active phase (RAN) was defined as the duration between the onset and the offset of the muscle activity. The active phase that was defined in this way was additionally analyzed using the following parameters: maximal amplitude of the linear envelope of the average signal (P_{AMP}), the crank position at which it was achieved (P_{POS}), and average root mean square of the active phase (RMS).

An important methodological problem for statistical analyses of the dependent variables related to crank cycle position (onset, offset, and P_{POS}) is the transit of the TDC, which is because of the numeric scale discontinuity (360–0°). With the initial inspection we found out that for all muscles the values of a single position parameter were grouped on interval that covered half of the crank cycle or less. After that, for the purpose of statistical analyzes only, we transformed the original data to eliminate discontinuity between 0° and 360° on a crank cycle scale. Transformation was done for each position parameter (onset, offset and P_{POS}) and each muscle individually as follows. First, the data for all 12 subjects and all cycling conditions relating to a single position parameter of a particular muscle were placed on a crank cycle scale. Second, minimum and maximum values that satisfied two conditions (minimum and maximum are adjacent two values and the distance between them is the largest among all the distances between pairs of adjacent points) were identified. Third, if discontinuity was on interval between minimum and maximum, values that were less than maximum were shifted by 360°, otherwise, values were not shifted.

All the above mentioned EMG parameters of the same muscle, except P_{AMP}, were statistically tested for differences between cycling conditions by repeated measure analysis of variance (RANOVA) and Tukey's corrected *post hoc* *t*-tests for pairwise comparisons relative to the level condition. For P_{AMP}, one-sample *t*-tests were performed for pairwise comparisons between the level condition and both uphill cycling conditions. The level of statistical significance was set at $p < 0.05$.

3. Results

3.1. EMG patterns of all muscles for all conditions for a representative subject are presented in Fig. 2

The data for onset, offset, and RAN for all muscles are presented in Fig. 3.

Regarding onset, we observed statistically significant differences between cycling conditions for VM and RF ($p = 0.048$ and 0.041). Pairwise comparisons revealed a delayed onset of VM during 20% UC with ASP as compared to LC for VM (mean ± SD for level vs. mean ± SD for uphill) (334 ± 11° vs. 339 ± 11°, $p = 0.027$), and of RF during the 20% UC compared to LC (273 ± 33° vs. 286 ± 29°, $p = 0.011$), respectively. Additionally, statistically significant differences in offset between cycling conditions were observed for RF and BF ($p = 0.048$ and 0.044). Pairwise comparisons showed earlier offset for RF during the 20% UC as compared to LC (105 ± 14° vs. 72 ± 59°, $p = 0.046$), while in BF the same parameter was delayed during the 20% UC with ASP (208 ± 27° vs. 221 ± 24°, $p = 0.017$). Finally, statistically significant differences in RAN between cycling conditions were observed for VM, VL, RF and BF ($p = 0.012$–0.033). Compared to LC, cycling up a 20% slope with normal bicycle geometry resulted in significantly shorter RAN in VM (148 ± 13° vs. 140 ± 16°, $p = 0.038$), VL (153 ± 46 vs. 148 ± 44°, $p = 0.013$), and most pronounced in RF (191 ± 35 vs. 147 ± 67°, $p = 0.032$), while RAN of BF was significantly prolonged (190 ± 61° vs. 207 ± 46°, $p = 0.028$). No statistically significant differences were observed for muscles' RAN pairwise comparisons between LC and 20% UC with ASP (all $p \geqslant 0.05$).

Results showed no statistically significant modulations of P_{POS} among the cycling conditions in any of the observed muscles (all $p \geqslant 0.05$) (Table 2). However, relative to the normalized LC condition, which was taken as 100% for each muscle, a significant P_{AMP} drop was present during 20% UC in RF (66.1 ± 22.8%, $p = 0.001$), while a significant P_{AMP} increase was observed in GM for the same condition (143.7 ± 13.6%, $p = 0.010$). This average change in P_{AMP} of 34% and 44%, respectively, was counteracted by the use of ASP, which resulted in non-significant pairwise comparisons between the LC and 20% UC with ASP ((84.8 ± 26.6% of LC, $p = 0.189$) and (100.1 ± 22.0% of LC, $p = 0.982$) for RF and GM, respectively).

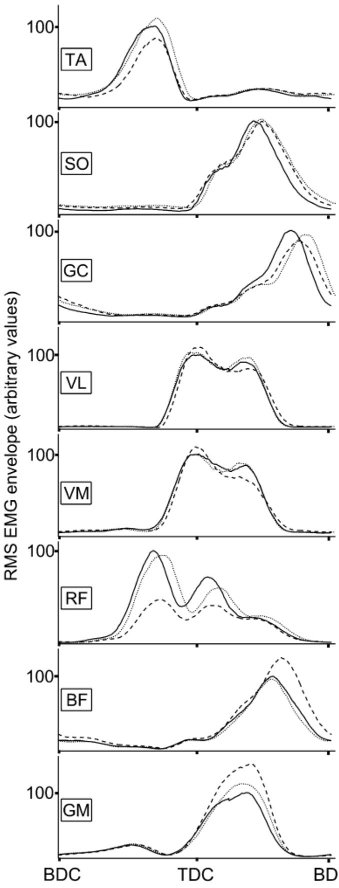


Fig. 2. Representative subject's EMG patterns of all monitored muscles for all cycling conditions. The graphs present muscle EMG patterns for all muscles for level (solid line), 20% slope (dashed line) and 20% slope with adjusted saddle position (dotted line). EMG patterns are expressed in arbitrary values as root mean square (RMS) linear envelope on a crank cycle scale; TDC = top dead center, BDC = bottom dead center.

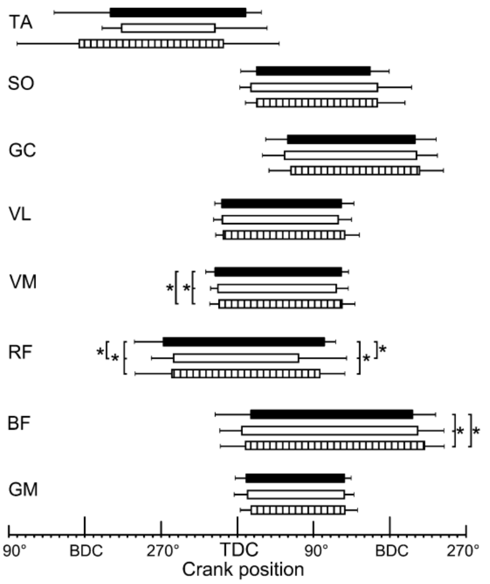


Fig. 3. Onset, offset and range (RAN) for each of the muscles for level (black), 20% slope (white), and 20% slope with ASP (striped) cycling. The 540° horizontal axis is used to ensure the continuous presentation for all the muscles. The left ends of the horizontal bars and the accompanied error bars represent means and standard deviations, respectively, for the onset values. The same analogy is used for the offset values on the right side of the horizontal bars. Statistical significance – for onset (left side of the bars) and offset (right side of the bars) – of RANOVA (connector line linking three bars) and paired *t*-tests (connector line linking two bars) is marked with "*" ($p < 0.05$) and "**" ($p < 0.01$). Statistical significances of differences for RAN are not marked on this graphic, but they are reported in the text.

The results of the RMS analysis are displayed in Fig. 4. Statistically significant differences among the three cycling conditions were observed for GM, RF and TA (RANOVA, $p = 0.049$, 0.000 and 0.012, respectively). Pairwise comparisons revealed that the increase in RMS of GM (73.6 ± 3.8 vs. 82.0 ± 10.7, $p = 0.017$) and the decrease in RMS of RF (61.3 ± 4.9 vs. 45.8 ± 10.5, $p = 0.000$) and TA (71.4 + 5.6 vs. 57.9 ± 10.3, $p = 0.008$) took place during the 20% UC as compared to LC. No statistically significant differences were observed for 20% UC with ASP vs. LC comparisons for any of the observed muscles (all $p \geqslant 0.05$).

Finally, note that all subjects marked their subjective feeling about using the ASP during UC with grade 3 and commented that they would also use such an adjusted saddle position during the race.

4. Discussion

In the present study, we applied a novel technical tool which enables the cyclist to adjust the saddle position during cycling,

Table 2
Peak amplitudes and their crank positions.

	Level		20% Slope		20% Slope ASP	
	P_{AMP}	P_{POS}	P_{AMP}	P_{POS}	P_{AMP}	P_{POS}
TA	100 ± 0.0	291.3 ± 41.4	84.3 ± 21.0	256.1 ± 60.0	91.3 ± 18.4	271.3 ± 49.9
SO	100 ± 0.0	81.9 ± 17.8	104.3 ± 30.8	78.2 ± 19.6	109.6 ± 40.1	88.3 ± 20.5
GC	100 ± 0.0	138.0 ± 27.7	95.5 ± 9.5	139.4 ± 32.7	98.3 ± 13.0	146.4 ± 26.8
VL	100 ± 0.0	41.9 ± 26.7	95.3 ± 11.5	39.8 ± 25.1	99.3 ± 16.7	45.0 ± 31.4
VM	100 ± 0.0	40.3 ± 25.3	97.8 ± 9.0	43.6 ± 27.3	100.4 ± 14.4	47.5 ± 14.5
RF	100 ± 0.0	343.0 ± 40.8	66.1 ± 22.7**	342.2 ± 42.0	84.8 ± 26.6	333.9 ± 35.7
BF	100 ± 0.0	113.2 ± 29.2	108.3 ± 21.9	118.8 ± 26.5	100.3 ± 11.6	125.5 ± 23.5
GM	100 ± 0.0	79.6 ± 15.5	114.0 ± 13.5*	80.7 ± 12.6	100.1 ± 22.0	78.7 ± 14.5

P_{AMP}, peak amplitudes; P_{POS}, crank positions when P_{AMP} occurred (mean ± standard deviation); level, level terrain condition; 20% slope, 20% slope condition; 20% slope ASP, 20% slope conditions with adjusted saddle position. Amplitude values are expressed relative to the same muscle's values during level cycling condition.

* Statistically significant differences of the one-sample *t*-tests ($p \leqslant 0.05$).

** Statistically significant differences of the one-sample *t*-tests ($p \leqslant 0.01$).

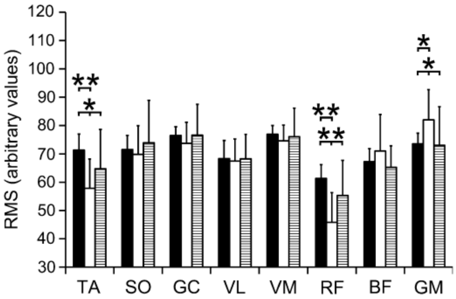


Fig. 4. EMG intensity analysis of the active phase. Charts present RMS of the active phase for all muscles for level (black), 20% slope (white), and 20% slope with ASP (striped) cycling, respectively. RMS values were calculated from the EMG signals normalized to the level cycling PAMP and are therefore presented in arbitrary values (mean, standard deviation). Statistical significance of RANOVA (lower connector line linking three bars) and paired *t*-tests (upper connector line linking two bars) is marked with "*" ($p < 0.05$) and "**" ($p < 0.01$).

and potentially: (1) optimize bicycle geometry and neuromuscular coordination and (2) improve performance and comfort during UC. Our main finding was that the use of the adjusted saddle post (ASP) during 20% UC counteracted significant changes in muscle activation patterns induced by the same UC compared to the normal saddle position. Another interesting finding was that the use of ASP during 20% UC was perceived positively by all the cyclists regarding both their comfort and their performance. These findings, together with their possible practical applications, will be discussed in the following paragraphs.

4.1. Effects of uphill cycling and adjusted saddle position on muscle activity patterns

As hypothesized, 20% UC resulted in significant alterations of the EMG patterns compared to LC, those muscles crossing the hip joint (i.e., RF, BF and GM) being the most affected. Given that changes in body position during UC are particularly evident in the hip joint, these findings are not surprising. Specifically, steep UC modified the timing and duration of the activity of quadriceps (particularly RF) and BF. For example, RAN for RF was reduced by 23%, but increased for BF by ~10% during steep UC compared to LC. The corresponding changes in RAN for VM and VL were of smaller magnitude (i.e., 3–6%). Furthermore, 20% UC induced a large drop in RF and TA EMG intensity and an even larger increase in GM EMG intensity. The observed changes in the EMG patterns suggest that the function of the lower limb muscles in UC was modified. In particular, reduced RAN for the quadriceps muscle and lower RF EMG intensity on one side, and prolonged RAN for BF and higher GM EMG intensity on the other side, suggest that the relative contribution of the hip and knee extensors to power production during the down stroke phase in UC is changed in favor of hip extensors. To which extent these changes in muscle function contribute to changes in mechanics and energetics of UC remains unknown. However, the fact that four muscles had consistent activity patterns during both steep UC and LC, whereas four other muscles showed altered activity profiles during steep UC, is indicative of a change in neuromuscular coordination during UC (Li and Caldwell, 1998).

Previous research that compared lower extremity muscle activity patterns in LC vs. UC reported inconclusive results. Li and Caldwell (1998) and Duc et al. (2008) examined neuromuscular modifications to cyclists from changes in gradient up to 10% and found no significant differences in intensity and timing of muscle activity patterns for individual muscles compared with cycling on level ground. In contrast, Clarys et al. (2001) reported that global integrated EMG (average of all monitored muscles) of the lower extremity during cycling increases with increasing the slope up to 12%. However, the latter authors did not study the timing or intensity of activity of individual lower extremity muscles. Hence, their results are difficult to compare with our results, as well as with the results reported by Li and Caldwell (1998) and Duc et al. (2008). Although our experiment differed from experiments conducted by Li and Caldwell (1998) and Duc et al. (2008) in some factors that could affect the EMG patterns during pedaling (e.g., cadence, type of bicycle; (Hug and Dorel, 2009)), we believe that the contrasting findings regarding the effect of slope on neuromuscular activation during cycling is mainly the result of a twofold difference in the steepness of the slope between previous studies and ours (i.e., 8–10% in previous studies vs. 20% in our study). Thus, we may conclude that slopes greater than 10% (and closer to 20%) are needed to substantially modify the muscle activity patterns during UC versus LC.

The above-discussed alterations of the EMG patterns and, possibly, of muscle functions during 20% UC were successfully counteracted by the use of ASP. Specifically, neither the timing nor the intensity of activity of the studied muscles differed between 20% UC with ASP and LC. The exceptions concerned the onset of VM and offset of BF, where statistically significant changes were observed during 20% UC with ASP versus LC. However, these changes were rather small (1.5% and 6% of the respective RAN; see also Fig. 2), and probably not practically relevant. This novel finding is in line with our second hypothesis, and suggests that applying the changes to the tilt and longitudinal position of the saddle was successful in bringing the posture during UC close to the posture during LC.

Few previous studies have examined the modifications in the activation pattern of lower extremity muscles induced by changes in bicycle geometry, in particular changes to saddle height (Ericson et al., 1985; Jorge and Hull, 1986; Sanderson and Amoroso, 2009). Overall, the results of these studies indicate that changes in bicycle geometry through adjustments of saddle height affect the EMG patterns during LC. However, since we used a different type of seat adjustment (i.e., moving the saddle forward and changing the tilt of the saddle) and applied it during UC, we cannot directly compare our results with those of the aforementioned studies.

To the best of our knowledge, only Clarys et al. (2001) studied the effects of different saddle positions on the patterns of lower limb muscle activity during UC. The authors manipulated the saddle position by simultaneously moving it forward and upward, or backward and downward. They reported no effect from changing the saddle position on the global integrated EMG of both upper and lower extremity muscles during UC up to 12%. However, due to serious limitations related to EMG analysis (i.e., lack of analysis of the activation pattern of individual muscles), the results of that study should be interpreted with caution. Clearly, more research is needed to verify the validity of our findings and to further advance our knowledge on biomechanics of UC.

4.2. Clinical and performance considerations

Studies focused on the optimization of bicycle geometry are primarily aimed at improving performance, increasing comfort and reducing musculoskeletal stress (i.e., injury prevention). However, a simultaneous achievement of these goals is a challenging task. For example, the users of racing or triathlon bicycles, assume a very low profile and lean non-physiologically on an aerobar. This decreases their air resistance and improves speed, but also decreases comfort and increases tensile forces on lumbar vertebra (Salai et al., 1999). The opposite is true for the use of urban/city bicycles. While improving performance has relevance mainly for competitive cyclists, comfort plays an important role in both competitive and leisure cycling. Notably, UC is one of the most uncomfortable parts of cycling. During UC, 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. Also 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.

In the current study, the cyclists were asked to grade their subjective feeling about the comfort and performance when using ASP, using a scale from 1 to 3. All of them marked their subjective feeling with grade 3 and commented that they would also use the ASP during a race. This important feedback suggests that the applied technical tool has the potential to simultaneously improve performance and increase comfort during UC. However, since we did not measure the physiological and/or performance parameters, this conjecture remains to be tested in future studies.

Our findings could also have clinical relevance. Namely, low back pain is common among cyclists, regardless of age, gender or type of bicycle. In their fluoroscopic/biomechanical study of cyclists, Salai et al. (1999) showed that low back pain can be attributed to the anatomical extension between the pelvis and the spine. This results in tensile forces along the anterior longitudinal ligament of the lumbar spine, which increase as the result of sitting on the saddle and reclining on the handlebar (Salai et al., 1999). Based on these results, the authors hypothesized that the adjustment of the saddle tilt could eliminate the low back pain in cyclists. They conducted a clinical investigation on 40 cyclists with chronic low back pain for whom they tilted the saddle forward by 10–15°. After 6 months, 72% of this group of cyclists reported that the pain during cycling was gone, 20% reported that the pain was very reduced and only 7% reported no change. From the perspective of the current study, these results suggest that the presented technical tool could also be effective in reducing low back pain during UC. Namely, compared with LC, UC requires the cyclist to lean his trunk further forward with a posterior rotation of the pelvis. Having in mind the data presented above, it is reasonable to assume that the lumbar tensile forces are even more pronounced in UC, but by using ASP during UC, we change the orientation of the pelvis, and probably reduce the tensile forces on lumbar vertebra. Future clinical studies should test this hypothesis.

5. Conclusions

Changing the cycling gradient from 0% to 20% resulted in significant alterations in the muscle activity patterns; those muscles crossing the hip joint being the most affected. The use of ASP during 20% UC counteracted these neuromuscular changes, suggesting that the applied adjustment of tilt and position of the saddle was successful in bringing the posture during UC close to that of the posture during LC. Another interesting finding was that the use of ASP during 20% UC was perceived positively by all the participating cyclists regarding both their comfort and their performance. These results could have a practical relevance in terms of improving performance during UC, as well as reducing the prevalence of low back pain associated with cycling.

References

Bertucci W, Grappe F, Girard A, Betik A, Rouillon JD. Effects on the crank torque profile when changing pedalling cadence in level ground and uphill road cycling. J Biomech 2005;38(5):1003–10.

Burke ER. Proper fit of the bicycle. Clin Sports Med 1994;13(1):1–14.

Caldwell GE, McCole SD, Hagberg JM, Li L. Pedal and crank kinetics in uphill cycling. J Appl Biomech 1998;14(3):245–59.

Chapman AR, Vicenzino B, Blanch P, Knox JJ, Dowlan S, Hodges PW. The influence of body position on leg kinematics and muscle recruitment during cycling. J Sci Med Sport 2008;11(6):519–26.

Clarys JP, Alewaeters K, Zinzen E. The influence of geographic variations on the muscular activity in selected sports movements. J Electromyogr Kinesiol 2001;11(6):451–7.

Coyle EF, Feltner ME, Kautz SA, Hamilton MT, Montain SJ, Baylor AM, et al. Physiological and biomechanical factors associated with elite endurance cycling performance. Med Sci Sports Exerc 1991;23(1):93–107.

Duc S, Bertucci W, Pernin J, Grappe F. Muscular activity during uphill cycling: effect of slope, posture, hand grip position and constrained bicycle lateral sways. J Electromyogr Kinesiol 2008;18(1):116–27.

Enoka RM. Neuromechanics of human movement. 4th ed. Champaign, IL: Human Kinetics; 2008.

Ercison MO, Nisell R, Nemeth G. Joint motions of the lower limb during ergometer cycling. J Orthop Sports Phys Ther 1988;9(8):273–8.

Ericson MO. On the biomechanics of cycling. A study of joint and muscle load during exercise on the bicycle ergometer. Scand J Rehabil Med Suppl 1986;16:1–43.

Ericson MO, Nisell R, Arborelius UP, Ekholm J. Muscular activity during ergometer cycling. Scand J Rehabil Med 1985;17(2):53–61.

Faria EW, Parker DL, Faria IE. The science of cycling: factors affecting performance – Part 2. Sports Med 2005;35(4):313–37.

Farrokhi S, Pollard CD, Souza RB, Chen YJ, Reischl S, Powers CM. Trunk position influences the kinematics, kinetics, and muscle activity of the lead lower extremity during the forward lunge exercise. J Orthop Sports Phys Ther 2008;38(7):403–9.

Fonda B, Sarabon N. Biomechanics of cycling: literature review. Sport Sci Rev 2010a;19(1/2):131–63.

Fonda B, Sarabon N. Inter-muscular coordination during uphill cycling in a seated position: a pilot study. Kinesiologia Slovenica 2010b;16(1):12–7.

Gámez J, Zarzoso M, Raventós A, Valero M, Alcántara E, López A, et al. Determination of the optimal saddle height for leisure cycling. Eng Sport 2008;7:255–60.

Gnehm P, Reichenbach S, Altpeter E, Widmer H, Hoppeler H. Influence of different racing positions on metabolic cost in elite cyclists. Med Sci Sports Exerc 1997;29(6):818–23.

Grappe F, Candau R, Busso T, Rouillon JD. Effect of cycling position on ventilatory and metabolic variables. Int J Sports Med 1998;19(5):336–41.

Hansen EA, Waldeland H. Seated versus standing position for maximization of performance during intense uphill cycling. J Sports Sci 2008;26(9):977–84.

Harnish C, King D, Swensen T. Effect of cycling position on oxygen uptake and preferred cadence in trained cyclists during hill climbing at various power outputs. Eur J Appl Physiol 2007;99(4):387–91.

Hof AL. EMG and muscle force. An introduction. Hum Mov Sci 2002;3(1/2):119–53.

Hug F, Dorel S. Electromyographic analysis of pedaling: a review. J Electromyogr Kinesiol 2009;19(2):182–98.
Jeukendrup AE, Martin J. Improving cycling performance. How should we spend our time and money. Sports Med 2001;31(7):559–69.
Jobson SA, Nevill AM, George SR, Jeukendrup AE, Passfield L. Influence of body position when considering the ecological validity of laboratory time-trial cycling performance. J Sports Sci 2008;26(12):1269–78.
Jorge M, Hull ML. Analysis of EMG measurements during bicycle pedalling. J Biomech 1986;19(9):683–94.
Lepers R, Hausswirth C, Maffiuletti N, Brisswalter J, Van Hoecke J. Evidence of neuromuscular fatigue after prolonged cycling exercise. Med Sci Sports Exerc 2000;32(11):1880–6.
Li L, Caldwell GE. Muscle coordination in cycling: effect of surface incline and posture. J Appl Physiol 1998;85(3):927–34.
Lunnen JD, Yack J, LeVeau BF. Relationship between muscle length, muscle activity, and torque of the hamstring muscles. Phys Ther 1981;61(2):190–5.
Marsden M. Lower back pain in cyclists: a review of epidemiology, pathomechanics and risk factors: review article. Int Sport Med J 2010;11(1):216–25.
Nordeen-Snyder KS. The effect of bicycle seat height variation upon oxygen consumption and lower limb kinematics. Med Sci Sports 1977;9(2):113–7.
Price D, Donne B. Effect of variation in seat tube angle at different seat heights on submaximal cycling performance in man. J Sports Sci 1997;15(4):395–402.
Salai M, Brosh T, Blankstein A, Oran A, Chechik A. Effect of changing the saddle angle on the incidence of low back pain in recreational bicyclists. Br J Sports Med 1999;33(6):398–400.
Sanderson DJ, Amoroso AT. The influence of seat height on the mechanical function of the triceps surae muscles during steady-rate cycling. J Electromyogr Kinesiol 2009;19(6):465–71.
Sekir U, Ozyener F, Gur H. Effect of time of day on the relationship between lactate and ventilatory thresholds: a brief report. J Sports Sci Med 2002;1:136–40.
Silberman MR, Webner D, Collina S, Shiple BJ. Road bicycle fit. Clin J Sport Med 2005;15(4):271–6.
Too D. Biomechanics of cycling and factors affecting performance. Sports Med (Auckland, N.Z.) 1990;10(5):286–302.
de Vey Mestdagh K. Personal perspective: in search of an optimum cycling posture. Appl Ergon 1998;29(5):325–34.
Wozniak Timmer CA. Cycling biomechanics: a literature review. J Orthop Sports Phys Ther 1991;14(3):106–13.

Borut Fonda is research and development assistant at company S2P, science to practice, Ltd., where he is continuous process of developing innovative technologies for sports and medicine diagnostics. He obtained his B.Sc., at the Faculty of Sport, University of Ljubljana, Slovenia. Now, he is a graduate student of Applied Kinesiology at University of Primorska, Slovenia. His main research focus is on studying neuromechanics, biomechanics, ergonomics and injury prevention during cycling.

Andrej Panjan is young researcher at Wise Technologies Ltd., Ljubljana, Slovenia, where he heads the Laboratory for Advanced Measurement Technologies. He is also member of the Laboratory for Motor Control and Motor Behavior at S2P, science to practice, Ltd., Bled, Slovenia. He obtained his B.Sc., (2009) degree in Computer and Information Science from University of Ljubljana, Slovenia. His primary research interests include kinesiology, artificial intelligence and signal processing for the purpose of use in kinesiology. Within these areas, he has (co)-authored 2 papers in peer-reviewed journals.

Goran Markovic is an Associate Professor of Kinesiology at the School of Kinesiology, University of Zagreb, Croatia, where he heads the Laboratory for Motor Control and Human Performance. He obtained the M.Sc., (2002) and Ph.D., (2004) degrees in Kinesiology from University of Zagreb, Croatia. He obtained post-doctoral training in Motor Control at the University of Delaware (2006/2007). His primary research interests include neuromuscular and mechanical aspects of human movement and performance, acute and chronic adaptation to exercise training and disuse, and optimizing sports performance. Within these areas, he has (co)-authored approximately 40 papers in peer-reviewed journals.

Nejc Sarabon is an Assistant Professor of Kinesiology at the Faculty of Mathematics, Natural Sciences and Information Technologies, University of Primorska, Koper, Slovenia. He upgraded his background in physical therapy and sport science with the Ph.D., and post-doc projects on the fields of motor control and motor behavior using primarily electrophysiological and biomechanical diagnostic approaches. His primary research interests include balance, sensory-motor integration processes, kinaesthesia and inter-muscular coordination. Within this areas, he has (co)-authored about 20 papers in peer-reviewed journals. Regarding his applied professional work he is primarily active on the field of physical conditioning and musculoskeletal injury prevention and rehabilitation.

4 SKLEP

Zmagovalci treh glavnih 3-tedenskih etapnih kolesarskih dirk (Giro d'Italia, Tour de France, Vuelta Espana) so običajno kolesarji, ki prevladujejo med kolesarjenjem v klanec. Na drugi strani se amaterski kolesarji pogosto izogibajo kolesarjenja v klanec, saj zaradi spremembe drže in delovanja retropulzivnih sil povzroči neugodje. Razumevanje motoričnega obnašanje med kolesarjenjem v klanec je zato potrebno, da bi se našle optimalne rešitve, ki jih je mogoče nato uporabiti v praksi.

Namen preglednega članka (Fonda & Sarabon, 2012) je bil pregled relevantnih raziskav opravljenih na področjih biomehanike in energetike kolesarjenja v klanec. Skupaj smo analizirali več kot 40 člankov iz znanstvenih in strokovnih revij, ki so poročali o energetskih zahtevah, silah na pedalih, ekonomičnosti in učinkovitosti, mišični aktivnosti ter učinkovitosti in udobju optimizacij med kolesarjenjem v klanec.

Med kolesarjenjem v klanec morajo kolesarji premagati silo gravitacije in da bi to dosegli, so potrebne nekatere spremembe v položaju telesa. Glavni zaključek preglednega članka je, da raziskave poročajo o spremembah v mišični aktivnosti, medtem ko na drugi strani različni avtorji ne poročajo o spremenjenih silah na pedalih, dinamiki, kinematiki in kolesarski učinkovitosti med kolesarjenjem v klanec v primerjavi s kolesarjenjem po ravnini. Nasprotno temu, med kolesarjenjem v klanec v stoje, se prej omenjeni parametri značilno razlikujejo, ko primerjamo z bodisi kolesarjenjem v klanec v sede, bodisi s kolesarjenjem po ravnini.

Glavni namen raziskovalne študije (Fonda idr., 2011) je bil preučiti vzorce mišične aktivnosti med kolesarjenjem v 20 % klanec (1) z običajno postavitvijo sedeža in (2) s prilagojenim položajem sedeža (tj. premik sedeža naprej in spremenjen nagib sedeža za 20 %). Na podlagi naše predhodne pilotske študije (Fonda & Sarabon, 2010), smo predpostavili, (1) da bo med-mišična koordinacija značilno spremenjena med kolesarjenjem v 20 % klanec in (2) da bo s spremenjeno geometrijo kolesa med-mišična koordinacija enaka kot med kolesarjenjem po ravnini.

V primerjavi s kolesarjenjem po ravnini, 20 % klanec značilno spremeni tako časovno aktivnost, kakor tudi amplitudi aktivnosti izbranih mišic. Največje spremembe so se odražale na m. rectus femoris, m. biceps femoris in m. gluteus maksimus. Te spremembe med kolesarjenjem v klanec z običajno postavitvijo sedeža niso bile prisotne, ko je bil optimiziran položaj sedeža. Dodatno so merjenci v raziskavi poročali o pozitivnih občutkih, ko smo jih povprašali o udobju. Rezultati te študije bi lahko imeli praktičen pomena v smislu izboljšanja fizične zmogljivosti in povečanja udobja med kolesarjenjem v klanec.

Po opravljenem pregledu literature lahko sklenemo, da se morajo nadaljnje raziskave osredotočiti na realne pogoje na terenu ter na pogoje, kjer se bodo preiskali vplivi večjih naklonin. Ostaja tudi potreba po večjem razumevanju obremenitev sklepov ter na podlagi teh raziskav iskati optimizacije za izboljšanje učinkovitosti in varnosti med kolesarjenjem v klanec.

5 VIRI

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.

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.

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

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., 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.

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

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.

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. (2010). Inter-muscular coordination during uphill cycling in a seated position: a pilot study. *Kinesiologia Slovenica*, *16*(1), 12–17.

Fonda, B., & Sarabon, N. (2012). Biomechanics and Energetics of Uphill Cycling: A review. *Kinesiology*, *44*(1), 5–17.

Fonda, B., & Šarabon, N. (2010). Učinki Prilagojenega Položaja in Naklona Sedeža med Kolesarjenjem v Klanec. *Šport*, *58*(3/4), 40–45.

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.

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.

Jeukendrup, A. (2002). *High-Performance Cycling*. Human Kinetics.

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.

McGhie, D., & Ettema, G. (2010). The effect of cadence on timing of muscle activation and mechanical output in cycling: On the activation dynamics hypothesis. *Journal of Electromyography and Kinesiology,* 21(1), 18-24.

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.

Pruitt, A. L. (2006). *Andy Pruitt's Complete Medical Guide for Cyclists*. VeloPress.

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.

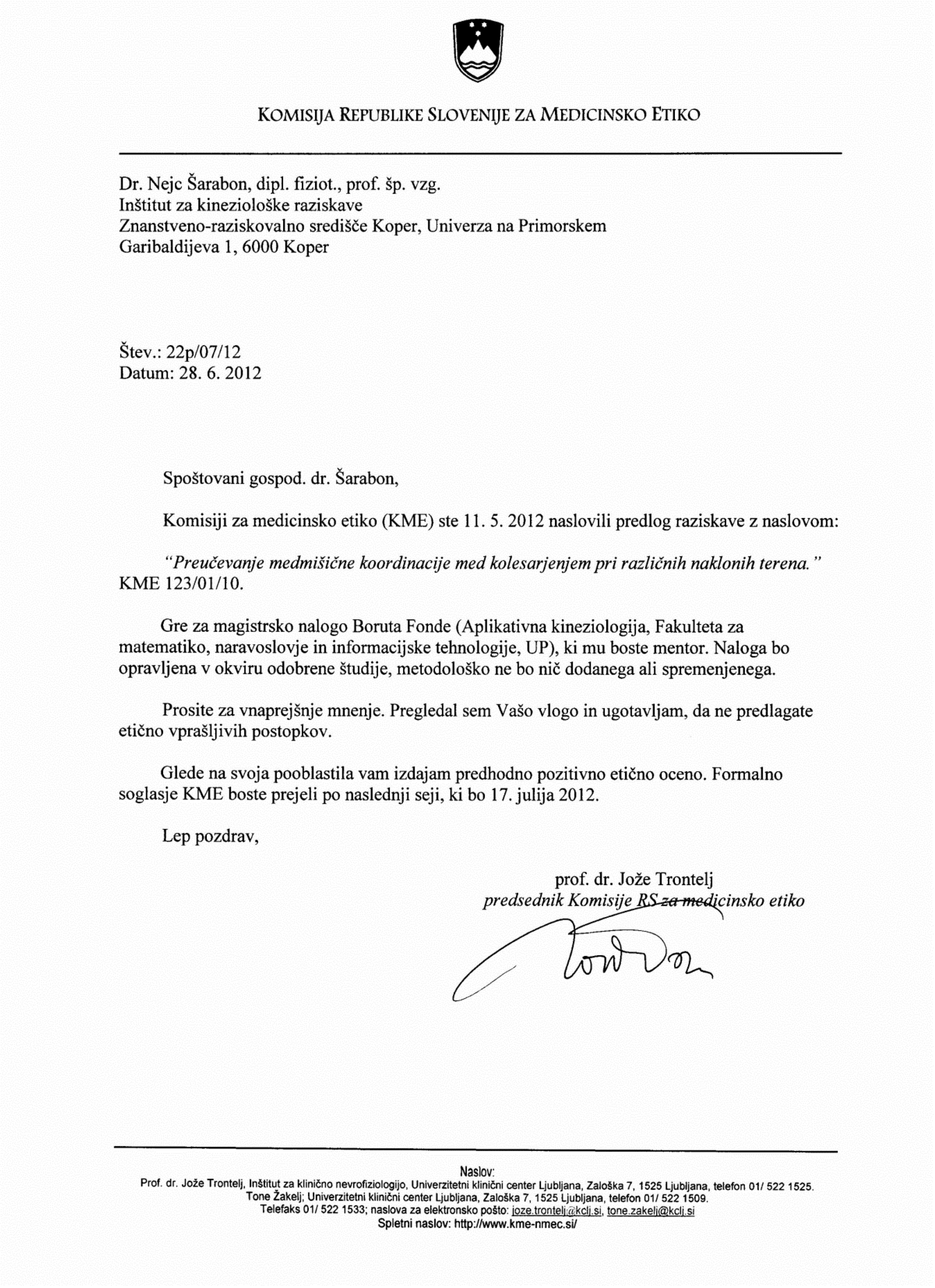
Sarabon, N., Fonda, B., & Markovic, G. (2011). Change of muscle activation patterns in uphill cycling of varying slope. *European Journal of Applied Physiology*. doi:10.1007/s00421-011-2236-1

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.

6 PRILOGE

KAZALO PRILOG

Priloga 1: Soglasje Komisije za medicinsko etiko



KOMISIJA REPUBLIKE SLOVENIJE ZA MEDICINSKO ETIKO

Dr. Nejc Šarabon, dipl. fiziot., prof. šp. vzg.
Inštitut za kineziološke raziskave
Znanstveno-raziskovalno središče Koper, Univerza na Primorskem
Garibaldijeva 1, 6000 Koper

Štev.: 22p/07/12
Datum: 28. 6. 2012

Spoštovani gospod. dr. Šarabon,

Komisiji za medicinsko etiko (KME) ste 11. 5. 2012 naslovili predlog raziskave z naslovom:

"Preučevanje medmišične koordinacije med kolesarjenjem pri različnih naklonih terena."
KME 123/01/10.

Gre za magistrsko nalogo Boruta Fonde (Aplikativna kineziologija, Fakulteta za matematiko, naravoslovje in informacijske tehnologije, UP), ki mu boste mentor. Naloga bo opravljena v okviru odobrene študije, metodološko ne bo nič dodanega ali spremenjenega.

Prosite za vnaprejšnje mnenje. Pregledal sem Vašo vlogo in ugotavljam, da ne predlagate etično vprašljivih postopkov.

Glede na svoja pooblastila vam izdajam predhodno pozitivno etično oceno. Formalno soglasje KME boste prejeli po naslednji seji, ki bo 17. julija 2012.

Lep pozdrav,

prof. dr. Jože Trontelj
predsednik Komisije RS za medicinsko etiko

Naslov:
Prof. dr. Jože Trontelj, Inštitut za klinično nevrofiziologijo, Univerzitetni klinični center Ljubljana, Zaloška 7, 1525 Ljubljana, telefon 01/ 522 1525.
Tone Žakelj; Univerzitetni klinični center Ljubljana, Zaloška 7, 1525 Ljubljana, telefon 01/ 522 1509.
Telefaks 01/ 522 1533; naslova za elektronsko pošto: joze.trontelj@kclj.si, tone.zakelj@kclj.si
Spletni naslov: http://www.kme-nmec.si/