Acute Effects of Small Changes in Bicycle Saddle Height on Gross Efficiency and Lower Limb Kinematics

Article *in* The Journal of Strength and Conditioning Research · March 2014

DOI: 10.1519/JSC.0b013e3182a1f1a9 · Source: PubMed

Ventura Ferrer
Centre d'Alt Rendiment Esportiu

Raúl Bescós
University of Plymouth

Pedro Galilea
Centre d'Alt Rendiment Esportiu

Oliver Valero
Autonomous University of Barcelona

ACUTE EFFECTS OF SMALL CHANGES IN BICYCLE SADDLE HEIGHT ON GROSS EFFICIENCY AND LOWER LIMB KINEMATICS

VENTURA FERRER-ROCA,[1,2] RAÚL BESCÓS,[3] ANDREU ROIG,[1] PIERO GALILEA,[1] OLIVER VALERO,[4] AND JUAN GARCÍA-LÓPEZ[2]

[1]Sport Science and Medical Unit, Performance and Health Research Group for High-Level Sports, High Performance Sport Center of Sant Cugat (CAR), Barcelona, Spain; [2]Department of Physical Education and Sports, Institute of Biomedicine (IBIOMED), University of Leon, Leon, Spain; [3]Department of Physiology, National Institute of Physical Education INEFC-Barcelona, Universitat de Barcelona (UB), Barcelona, Spain; and [4]Applied Statistics Service Universitat Autònoma de Barcelona (UAB), Barcelona, Spain

ABSTRACT

Ferrer-Roca, V, Bescós, R, Roig, A, Galilea, P, Valero, O and García-López, J. Acute effects of small changes in bicycle saddle height on gross efficiency and lower limb kinematics. *J Strength Cond Res* 28(3): 784–791, 2014—The aim of the present study was to assess the acute effects of small changes in bicycle saddle height on gross efficiency (GE) and lower-limb kinematics. Well-trained cyclists ($n = 14$) performed a submaximal pedaling test (∼70–75% of the $\dot{V}O_2$max) at constant cadence (90 rpm). It consisted of 3 randomized sets of 6 minutes with the preferred saddle height, 2% higher and 2% lower. Gross efficiency was significantly lower and oxygen consumption ($\dot{V}O_2$) was significantly higher when raising the saddle (GE = 19.9 ± 1.5%; $\dot{V}O_2$max = 43.8 $ml\cdot kg^{-1}\cdot min^{-1}$) than when lowering it (GE = 20.4 ± 1.3%; $\dot{V}O_2$ = 42.8 $ml\cdot kg^{-1}\cdot min^{-1}$). Additionally, a change of 0.8% in GE (20.6 ± 1.6% to 19.8 ± 1.6%, $p < 0.05$) was observed when comparing the positions where the best and worst GE was obtained. A significant effect of the small changes in saddle height on lower limb kinematics was also observed ($p < 0.05$). The differences between lower and higher saddle positions, in hip, knee, and ankle joints were an increase of extension (∼4, 7, and 8°, respectively), a decrease of flexion (∼3, 4, and 4°, respectively) and, consequently, an increase of the range of movement (∼1, 3, and 4°, respectively). The results of the present study indicate that small changes in saddle height affected GE and lower limb kinematics The observed changes in lower limb kinematics could justify, in part, the GE changes. Further research should evaluate long-term effects of these small modifications in the seat height on GE and lower limb kinematics.

KEY WORDS cycling, bike fitting, seat height, pedaling efficiency

INTRODUCTION

Proper bicycle configuration reduces aerodynamic drag (16), improves cycling efficiency (12,25,29–31,33), and may prevent overuse injuries (2). Saddle height is an important factor in correct bike fitting. Based on static evaluations, a 25° knee angle during goniometric assessment with the pedal located at the bottom dead center seems to be an optimal saddle height to improve pedaling efficiency and also prevent injuries (32). Additionally, anthropometric measurements such as ∼109–110% of inseam length (15) or ∼100–102% of trochanteric height (33,34) have been recommended to adjust the saddle height when the modern clipless pedals are used. However, recent studies have considered a dynamic evaluation instead of a static one as a component of the bike fitting process (15,32). These authors suggest the use of video analysis to obtain a knee flexion angle of 30–40° when the crank is parallel to the seat tube and the pedal is located close to the bottom position during active pedaling at optimal saddle height.

To the best of our knowledge, only 2 previous studies have evaluated the effect of changing the seat height on pedaling efficiency and lower limb kinematics during active pedaling (29,33). One of them (n = 10 female students) compared 3 different saddle heights (95, 100, and 105% of trochanteric height) and recommended 100% of trochanteric height as optimum saddle height (29). The other (n = 14 experienced male cyclists) demonstrated that pedaling efficiency was better with seat height at either 96 or 100% of trochanteric height compared with 104% (33). This second study obtained major kinematic changes at the knee and at the ankle when the saddle height was modified. These findings were consistent

---

Address correspondence to Ventura Ferrer-Roca, vferrer@car.edu.

28(3)/784–791

Journal of Strength and Conditioning Research

with those reported in the literature when changing the saddle height 11 (12), 15 (36), and 6% (5).

In a recent review (2), it was claimed that changing the saddle height 4% (e.g., from 96 to 100% of trochanteric height) is a wide range, more than any experienced cyclist would consider. Therefore, it seems necessary to know if smaller variations in saddle height could affect both gross efficiency (GE) and lower limb kinematics. Furthermore, various of the abovementioned studies (12,29,33) have not taken into account the preferred saddle height of the cyclists, where their pedaling technique could be more efficient (8). It has been demonstrated that well-trained cyclists have a stable pedaling pattern (9). Furthermore, they optimize their oxygen consumption at cycle geometries (seat-tube angles) that elicit similar lower-limb kinematics as the preferred geometries from their own bicycles (19).

The aim of this study was to assess the acute effects of small changes in saddle height on gross efficiency and lower-limb kinematics in well-trained cyclists. It was hypothesized that these changes would cause a loss of efficiency and major alterations to lower limb kinematics as an acute response.

METHODS

Experimental Approach to the Problem

The cyclists reported to our laboratory at the same time of day on 2 occasions, separated by 1 week, under similar environmental conditions (21–23° C, 60–65% relative humidity) and after a 24-hour period with no hard training. In the first week, they did an incremental maximal exercise test to establish the intensity of the submaximal sets of pedaling. Furthermore, anthropometric characteristics of the subjects and bicycle dimensions were obtained. In the second week, the cyclists performed a submaximal test with 3 different saddle height positions (preferred, 2% higher and 2% lower) to obtain gross efficiency and lower limb kinematics. During all the tests, mechanical variables of pedaling were strictly controlled by an electronically braked ergometer. Physiological variables were continuously measured by a computerized gas analyzer and biomechanical variables were recorded by a high-speed 2-dimensional video analysis system.

Subjects

Fourteen well-trained cyclists volunteered to participate in this study (age, 32.6 ± 5.6 years; range, 20.2–41.5 years; 72.5 ± 9.3 kg; 1.76 ± 0.05 m; body mass index, 23.4 ± 2.0 $kg \cdot m^{-2}$). Participants were members of competitive cycling or triathlon events and none of them reported any medical conditions at the time of the study. They had 8 ± 5 years of experience in competitions, and their average weekly training volume was 15.7 ± 5.0 hours. Other cyclists' characteristics were shown in Table 1. Subjects were informed of the procedures, methods, benefits, and possible risks involved in the study before their written consent was obtained. The study protocol was approved by the Ethics Committee of the Sports Council of Catalonia and met the requirements of the Declaration of Helsinki for research on human beings.

Procedures

Power output, heart rate, and pedal cadence were controlled by an electronically braked ergometer (SRM; Schoberer Rad Messtechnich, Julich, Germany) during the incremental and submaximal pedaling tests (11). The SRM ergometer was adapted to the characteristics of the cyclists' bicycles and was calibrated according to the manufacturer's recommendations (offset of powermeter slope). Oxygen uptake ($\dot{V}O_2$), ventilation (V_E), carbon dioxide production (VCO_2), and respiratory exchange ratio (RER) were continuously measured breath-by-breath by a computerized gas analyzer (Jaeger Oxycon Mobile; CareFusion Corporation, San Diego, CA, USA) (Figure 1). Before each test, ambient conditions were measured and the gas analyzer and respiratory flowmeter were calibrated following the manufacturer's instructions, using high-precision calibration gases (15 ± 0.001% O_2 and 6 ± 0.001% CO_2;

TABLE 1. Anthropometric characteristics of the cyclists and bicycle dimensions at their preferred saddle height position.*

	Mean ± *SD*	Range
Anthropometric and bicycle measurements		
Trochanteric height (m)	0.886 ± 0.031	0.814–0.937
Inseam length (m)	0.830 ± 0.036	0.779–0.896
Saddle height (m)	0.745 ± 0.038	0.681–0.813
Saddle back (m)	0.062 ± 0.017	0.039–0.095
Crank length (m)	0.173 ± 0.002	0.170–0.180
Saddle height (% TH)	103.6 ± 2.3	100.1–108.6
Saddle height (% IL)	110.6 ± 2.6	106.0–117.6
Incremental test		
$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	59.0 ± 6.5	51.9–69.5
Maximal heart rate ($b \cdot min^{-1}$)	180 ± 11	161–196
Maximal aerobic power output (W)	378 ± 29	325–419
Maximal aerobic power output ($W \cdot kg^{-1}$)	5.28 ± 0.73	4.27–6.20
VT–% $\dot{V}O_2max$	64.8 ± 7.8	59.9–80.4
RCT–% $\dot{V}O_2max$	85.3 ± 7.5	80.1–96.3

*Physiological values obtained during the incremental test. % TH = percentage of trochanteric height; % IL = percentage of inseam length; VT = ventilatory threshold; RCT = respiratory compensation threshold.

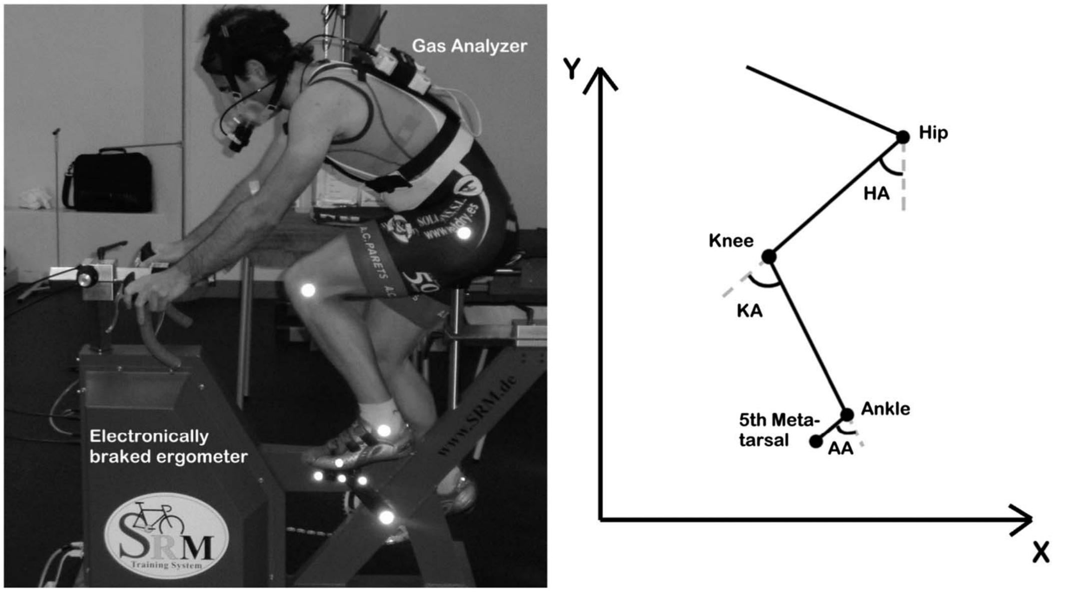

Figure 1. Materials location, cyclist's position and placement of the reflective markers during the experimental procedure (left). Convention used to specify angular displacement of the hip (HA), knee (KA), and ankle joints (AA) (right).

Abelló Linde S.A., Barcelona, Spain) and a 3.0-L syringe (COSMED S.R.L; Rome, Italy).

Anthropometric and Bicycle Measurements. An anthropometric tape (Holtain LTD, Crymych, United Kingdom) and a Harpenden anthropometer (CMS instruments, London, United Kingdom) were used to measure bicycle (saddle height, saddle back, crank length, and handlebars position) and anthropometric (trochanteric height and inseam length) dimensions. All the measurements were performed by the same researcher. Trochanteric height was the length from the most prominent bony surface of the greater trochanter to the floor (2). Inseam length was the barefoot distance between the ground and the pubis (10). Saddle height was the distance between crank center to top of saddle (24). Saddle back was the horizontal distance between the crank center and the saddle tip. Crank length was the distance between both crank and pedal axes (24) and was indicated by the manufacturer. Handlebar position was determined by the vertical distance between the top of the saddle and the middle of the handlebar, and by the horizontal distance between the middle of the saddle and the middle of the handlebar (24). To get the riders' relative saddle height, expressed as a percentage (17,33), the crank arm length and the saddle height were added and divided by both inseam length (15,18,30,31) and trochanteric height (29,33,36).

Incremental Test. First, the preferred bicycle dimensions of each cyclist were reproduced exactly in the SRM ergometer. The cyclists underwent a continuous and progressive maximal test to exhaustion to determine maximal oxygen uptake ($\dot{V}O_2max$), maximal power output, ventilatory threshold, and respiratory compensation point. The test started at 50 W, and power output was increased by 25 W every 1 minute until voluntary exhaustion. Pedal cadence was freely chosen during the whole test (range of 70–100 rpm). Each incremental test was terminated (a) voluntarily by the subject, (b) when pedaling cadence could not be maintained at 70 rpm (at least), or (c) when established criteria of test termination were met (26). $\dot{V}O_2max$ was determined as the mean $\dot{V}O_2$ measured during the final 60 seconds of exercise (1). The maximal power output and the maximal heart rate were obtained at the point of exhaustion during the test. To determine the ventilatory threshold and the respiratory compensation point, data were averaged at 30-second intervals and analyzed by 2 independent reviewers, according to the methods described by Wasserman et al. (40).

Submaximal Test. The test was preceded by a 15-minute warm-up at 50% of $\dot{V}O_2max$ with 5 minutes separating the end of the warm-up from the test. The cyclists performed three 6-minute sets at 65% of maximal power output (~70–75% of the $\dot{V}O_2max$) on the SRM with their preferred saddle height position, 2% higher and 2% lower. The 3 sets were separated by a 6-minute rest. This intensity of pedaling was selected because the RER was lower than 1.00 in all the cyclists studied (35), indicating no significant anaerobic contribution. The order of the 3 positions was randomized (25) to avoid possible effects of fatigue, learning, or drift of energy expenditure. The participants received continuous feedback about their cadence and were asked to keep it at 90 rpm, and they were cooled with a fan throughout the bouts of exercise (26). The recovery period was used to change the seat height. Handlebar height was adjusted, and the hands were placed on the top of the handlebars, near to the stem (Figure 1), to eliminate the metabolic cost impact of modifying the cyclists' trunk position (19).

During the submaximal test, heart rate, oxygen consumption, and RER were monitored during the entire duration and were averaged for the last 2 minutes of each set (11). Gross mechanical efficiency (GE) was calculated as the ratio of work accomplished (expressed in $\text{kcal}\cdot\text{min}^{-1}$) to energy expended ($\text{kcal}\cdot\text{min}^{-1}$), using the formula of Brouwer (7) for the corresponding energy equivalent for each oxygen consumption value based on carbon dioxide production. The saddle height positions where each cyclist obtained the lower and higher GE were also registered. Furthermore, during the last 30 seconds of each trial, capillary blood samples were taken from earlobe (10 μL) for the determination of blood lactate concentration using a Dr. Lange miniphotometer LP2 (Dr. Bruno Lange GmbH, Berlin, Germany). In addition, subjects completed Borg's ratings perceived exertion (RPE) scale (6) immediately at the end of each set. This RPE scale is a 15-point single-item scale ranging from 6 to 20 that assesses levels of perceived exertion.

To analyze the lower limb kinematics during submaximal pedaling, the left side of the cyclists was filmed assuming symmetry of motion between left and right sides (19). Four spherical reflective markers of 15 mm in diameter were attached to the skin or clothing at the anatomical reference points of the cyclists' lower limb (Figure 1): greater trochanter, lateral femoral condyle, lateral malleolus, and lateral aspect of the fifth metatarsal-phalangeal joint (15). Additionally, 2 reflective markers of 10 mm in diameter were attached to both crank and pedal axes of rotation. A 2-dimensional video analysis system (Peak Motus, Version 9.2.0; Vicon Motion System, Centennial, CO, USA) was used for video recording, digitizing, processing, and analyzing data. A single high-speed IEEEI1394 digital video camera (Basler A602fc; Basler AG, Ahrensburg, Germany) and a floodlight were positioned 6 m away from the subjects and perpendicular to the sagittal plane. A calibration frame (1 × 1 m) was placed in the plane of motion and was recorded before each subject's data collection. A projective scaling calibration method was used because IEEEI1394 device interface cards do not use square pixels. Images were acquired at 200 Hz sampling frequency with a resolution of 428 × 322 pixels for 10 seconds in the last 2 minutes of every trial. Automatic tracking during 14 pedal cycles was performed to obtain the 2-dimensional coordinates of the markers. Raw coordinate data were smoothed using a fourth-order Butterworth digital filter with cutoff frequencies individually determined (3–6 Hz) for each coordinate of each marker (38). Sagittal hip, knee, and ankle angles (Figure 1) were determined following Nordeen-Snyder's convention (29). Angular position values were expressed as hip and knee flexion and ankle dorsiflexion (maximum angle) and hip and knee extension and ankle platarflexion (minimum angle). The range of movement (ROM) of each joint was the difference between the maximum and minimum angles.

Statistical Analyses

Main descriptive statistics (mean, *SD*, and range) were calculated for anthropometric and bicycle measurements of the cyclists, and their physiological values were obtained during the incremental test. The Shapiro-Wilk normality test was used to assess normality. The analysis of bicycle dimensions and physiological and biomechanical variables (registered during the submaximal test at 3 different saddle height positions) was carried out using linear mixed models with repeated measures (39) to compare saddle height positions (preferred, 2% higher and 2% lower). The order of the 3 positions was considered as a random effect. Post hoc pairwise comparisons

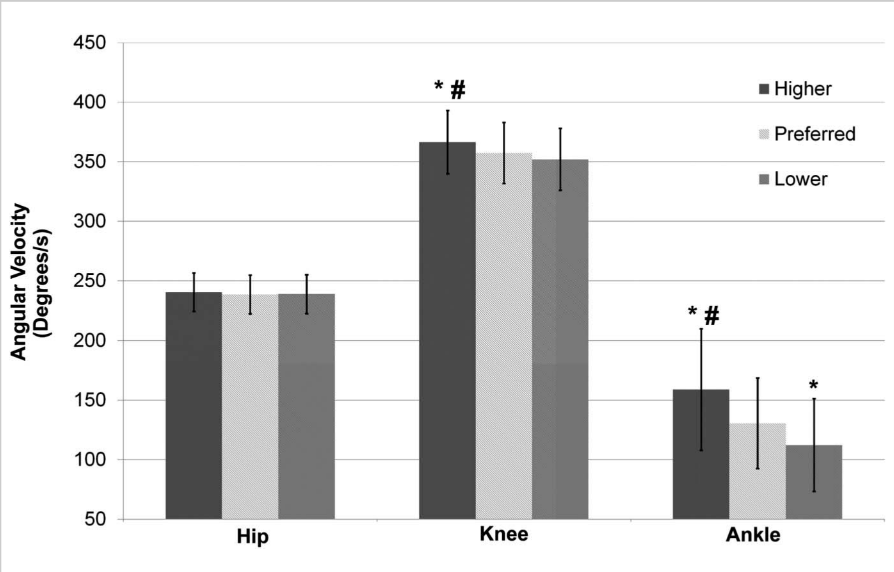

Figure 2. Mean and *SD* of the peak joint angular velocity (hip, knee, and ankle) during the downstroke phase at 3 different saddle heights (preferred, 2% higher and 2% lower). *Significant difference with preferred seat height ($p < 0.05$). #Significant difference between the 2% lower and the 2% higher seat heights.

were computed using Tukey's Honestly Significant Difference. Additionally, a second analysis was performed using also linear mixed models with repeated measures (39) to compare the positions where the best and worst gross mechanical efficiency were obtained. Statistical analyses were performed with the SAS system for Windows version 9.2 (SAS Institute Inc., Cary, NC, USA). Statistical significance level was set at 0.05.

RESULTS

Table 1 illustrates the anthropometric and bicycle measurements of the cyclists and their physiological values obtained during the incremental test. In their preferred bicycle position, the cyclists selected both relative saddle height of 110.6 ± 2.6% of inseam length and 103.6 ± 2.3% of trochanteric height. They reached 59.0 ± 6.5 $\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$ of $\dot{V}O_2$max, and the respiratory compensation threshold was obtained at 85.3 ± 7.5% of the $\dot{V}O_2$max.

Results from the linear mixed models are presented in Table 2. Statistically significant differences between positions were found in GE, oxygen consumption, and lower limb kinematics (at the hip, knee, and ankle joints). The kinematic differences between lower and higher saddle height positions were an increase in the hip and knee joints extension and ankle plantarflexion (~4, 7, and 8°, respectively), a decrease in hip and knee joints flexion and ankle dorsiflexion (~3, 4, and 4°, respectively) and an increase in the ROM of the 3 joints (~1, 3, and 4°, respectively). Power output, pedaling cadence, heart rate, lactate production, and Borg's rating of perceived exertion were not affected ($p > 0.05$).

Figure 2 illustrates the changes in peak angular velocity of the hip, knee, and ankle during the downstroke phase. Peak knee angular velocity increased significantly at higher saddle height compared with the preferred and the lower position of the saddle. Statistical differences between the 3 saddle heights were found in peak ankle angular velocity. However, no statistical differences were noted in peak hip angular velocities.

The mean values for the best and worst GE position were 20.6 ± 1.6% and 19.8 ± 1.6%, respectively. Statistical differences between these positions were 0.8% (95% confidence interval [CI], 0.4–1.1 and $p < 0.05$). In addition, oxygen consumption increased significantly: 0.8 $\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$ (95% CI, 0.3–1.3 $\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$ and $p < 0.05$), while heart rate, lactate production, and Borg's rating of perceived exertion did not increase. Of the riders, 85.7% obtained their best GE in the lowest saddle position, and the rest of the cyclists in their preferred position.

During the submaximal test, 43% of the cyclists obtained a knee extension value lower than 30° in the preferred saddle position while these percentages were 21 and 57% when both 2% lower and 2% higher seat heights were selected. Furthermore, when comparing the positions where the cyclists obtained their best and worst GE, the percentages of cyclists with a knee extension lower than 30° were 21 and 50%, respectively. On the other hand, in the preferred saddle height position 14.3% of the cyclists obtained their best GE, while this percentage was 85.7% when lowering the seat height. Instead, 21.4, 71.4, and 7.1% of the riders obtained

TABLE 2. Mean and *SD* of the bicycle dimensions, physiological and biomechanical variables registered during the submaximal test at 3 different saddle height positions (preferred, 2% higher and 2% lower).*

	Seat height		
	2% Lower	Preferred	2% Higher
Saddle height (m)	0.730 ± 0.037	0.745 ± 0.038	0.760 ± 0.038
Saddle height (% TH)	101.9 ± 2.3	103.6 ± 2.3	105.3 ± 2.4
Saddle height (% IL)	108.8 ± 2.6	110.6 ± 2.6	112.4 ± 2.7
Power (W)	217.6 ± 19	217.8 ± 18.8	217.5 ± 18.6
Cadence (rpm)	90.2 ± 0.9	90.6 ± 0.9	90.7 ± 0.5
GE (%)	20.4 ± 1.3†	20.3 ± 1.8	19.9 ± 1.5
$\dot{V}O_2$ ($\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$)	42.8 ± 4.9†	43.3 ± 4.9	43.8 ± 4.9
Heart rate ($\mathrm{b \cdot min^{-1}}$)	147 ± 12	147 ± 12	148 ± 11
Lactate ($\mathrm{mmol \cdot L^{-1}}$)	2.2 ± 0.8	2.2 ± 0.8	2.2 ± 0.8
Borg scale (6–20)	12.1 ± 1.4	11.6 ± 0.9	11.8 ± 1.3
Hip (degrees)			
Extension	28.3 ± 4.2†‡	25.8 ± 4.2	23.7 ± 3.6‡
Flexion	74.0 ± 1.9†‡	71.8 ± 2.6	70.5 ± 2.2‡
ROM	45.8 ± 3.1†	46.0 ± 3.2	46.8 ± 2.9
Knee (degrees)			
Extension	36.5 ± 7.5†‡	32.9 ± 7.3	29.7 ± 6.7‡
Flexion	110.5 ± 3.6†‡	108.4 ± 4.3	107.0 ± 3.9‡
ROM	74.1 ± 5.6†‡	75.5 ± 5.1	77.3 ± 4.3‡
Ankle (degrees)			
Plantarflexion	65.8 ± 7.4†‡	62.6 ± 6.2	57.5 ± 5.3‡
DorsiFlexion	76.4 ± 6.9†	74.9 ± 6.3	72.4 ± 8.2
ROM	10.6 ± 4.7†	12.3 ± 4.2	14.8 ± 7.2

*See Figure 1 for the convention used to specify joints' angular displacement; % TH = percentage of trochanteric height; % IL = percentage of inseam length; GE = gross mechanical efficiency; ROM = range of movement.

†Post hoc comparisons: Significant difference between the 2% lower and the 2% higher seat heights.

‡Significant difference with preferred seat height ($p < 0.05$).

their worst GE in the preferred 2% higher and 2% lower saddle height positions, respectively.

Discussion

The main outcome of the present study was that small changes in saddle height at submaximal intensity (~70–75% of the $\dot{V}O_2max$) and at constant cadence (~90 rpm) produced significant changes in both GE and lower limb kinematics in well-trained cyclists (Table 2). Gross efficiency changed significantly when lowering the saddle 4% (3.4% trochanteric height) from the higher to the lower position. In addition, significant differences were found in lower limb kinematics by 2% changes of the preferred saddle height (1.7% trochanteric height). These findings are particularly significant because previous studies showed differences in cycling efficiency and lower limb kinematics because of greater modifications in saddle height, between 4 and 10% of trochanteric height (12,29,33,36) that are too wide to be applied by experienced cyclists (2). In this study, both maximal oxygen consumption and power output (Table 1), besides the GE (Table 2), were comparable to those observed in competitive and experienced cyclists (20,24,25). The mean values of the respiratory compensation point (Table 1) also confirmed the training level of the cyclists, similar to the ~87% showed in previous studies (35).

The differences in oxygen consumption observed between the 3 positions were 0.5 $ml\cdot kg^{-1}\cdot min^{-1}$ (Table 2) and were comparable to those reported in previous studies (12,25,30,31,33). Another study (29) observed changes in oxygen consumption of 0.13 $L\cdot min^{-1}$, from 1.74 to 1.61 and 1.69 $L\cdot min^{-1}$ at low work rate (130.6 W or 799 $kpm\cdot min^{-1}$) and at constant cadence (60 rpm), when lowering the saddle height 5 and 10%, respectively. In the present study (Table 2), oxygen consumption changed 0.08 $L\cdot min^{-1}$ (~1 half), from 3.14 to 3.10 and 3.18 $L\cdot min^{-1}$, when lowering and raising the riders' saddle height, respectively. However, Nordeen-Snyder's study should be interpreted with caution because GE could be particularly affected by both low pedaling cadence and power output (13). In the present study, changes in GE were 0.5% (20.4 ± 1.3 to 19.9 ± 1.5%, $p < 0.05$) when randomly lowering and raising the seat height (Table 2) and 0.8% when comparing the positions where the cyclists obtained their best and worst GE. Noordhof et al. (28) stated that changes in GE of ~0.6% can be reliably detected during submaximal pedaling (RER $\leq$ 1). In addition, they did not find within-day variations in GE in physically active males. Therefore, our findings may have a certain relevance to the cycling performance because it is well known that variation in GE explains ~30% of the variation in power output during cycling time-trials (23). For a trained rider, a 1% improvement in GE will give a 63-s improvement in a 40-km time-trial time (22). Equally, the GE increased by 1% during a competitive season in trained cyclists (20), and the difference in GE between trained and recreational cyclists was 1.4% (21). Taking into account the relevance of these changes in GE and to solve the limitations of this study, further research should evaluate long-term changes in GE because of small changes in saddle height.

The cyclists decreased their oxygen consumption and improved GE by lowering the seat height (Table 2). In fact, 85.7% of the riders obtained their best GE in the lowest saddle position, which was 108.8% of the inseam length or 101.9% of the trochanteric height (Table 2). Probably, GE improved because this position coincided with the recommended saddle height in previous studies: 100–102% of the trochanteric height (29,33,34) and 109–110% of the inseam length (15,18). In this position, only 21% of the cyclists pedaled out of the recommended range of the dynamic method: 30–40° of the knee extension angle (15). Surprisingly, only 14.3% of the riders obtained the best GE at their preferred saddle height. These results are inconsistent with the suggestion that trained cyclists minimize the energetic cost of pedaling at the geometries that elicited similar lower-limb kinematics as the preferred geometries from their own bicycles (19). However, it should be considered that several subjects were triathletes. They possibly configured their bicycles to ride with a higher seat height and more extension of the lower limb joints, similar to those observed during running, to improve the cycle-run transition (37). One mechanism which could explain the changes observed in $\dot{V}O_2$, and GE is the alteration to the joint angular velocities. In the present study, the angular velocity of knee and ankle joints increased when raising the seat height (Figure 2). An increase of joint angular velocity involves a higher number of contractions performed for a shorter duration. It has been suggested that a significant part (20–50%) of the total ATP used during a contraction may be used for muscle fiber activation and relaxation, independent of the ATP necessary for force generation (14). Previous research determined that an increase in pedal speed, a marker for muscle shortening velocity, contributed to an increase in metabolic cost (27). Ferguson et al. (14) demonstrated that muscle oxygen uptake was elevated at high contraction frequency when the same total power output was performed. Therefore, it seems reasonable to expect that an increase in the knee and ankle angular velocities because of a higher saddle height contributed to a decrease of the GE. Nevertheless, further studies are required to confirm this hypothesis.

The present results add to a growing body of literature that shows that changes in saddle height have acute effects on GE and on lower limb kinematics during pedaling (2,3,5,36). Table 2 shows that raising the saddle height increased hip and knee joints extension and ankle plantarflexion more than the decrease in hip and knee joints flexion and ankle dorsiflexion. Consequently, the ROM also increased. These results agree with those obtained in previous studies and could justify the higher GE in the lowest positions (3,4,29,33,36), as explained above. Qualitatively, Table 2 shows that the major adaptations to seat height changes occurred at the knee and ankle joints. These results were similar to those observed when clip-less pedals were used (3,4,29,33,36), but different to those observed when flat pedals were used (29), where major adaptations occurred at the knee and hip joints. It could be possible that the type of pedal (flat vs. clip-less) affects the changes in lower limb kinematics when the saddle height is altered. Further studies should examine this hypothesis. Quantitatively, previous studies (3,4,29,33,36) showed higher changes in the extension of the hip, knee, and ankle joints (~5, 20, and 14°, respectively) with respect to the present study (~4, 7, and 8°, respectively). This could be because the abovementioned studies performed a major change of 6% in the saddle height (with respect to the trochanteric height of the cyclists), whereas the present study only changed it by 2 and 4% (1.7 and 3.4% trochanteric height). In consonance with previous studies, the present results provide some evidence in support of dynamic analysis as an important part of the bike fitting process (15,32). A follow-up of the present study should confirm long-term changes in lower limb kinematics because of modifications in saddle height.

Kinematic differences observed in the present study (between 4 and 8°) were not due to the method used to analyze the lower limb kinematics (2-dimensional video analysis). First, the cyclists performed the submaximal sets in a randomized order. Second, spherical reflective markers were attached at bony points, such as lateral femoral condyle or lateral malleolus, avoiding movements of muscles and fat tissue. In addition, steps were taken to ensure that the cyclists' clothing was completely attached to the body. Third, reflective markers were not removed until the end of the submaximal test, and they remained in the same place throughout the 3 sets. Fourth, images were acquired at a higher sampling frequency (200 Hz) than previous studies (5,12,15,29,32), recording 14 pedal cycles for every set and subject. Fifth, a projective scaling calibration method was used, and it was accepted that the results of the 2-dimensional sagittal plane kinematics during pedaling were similar to the 3-dimensional ones (38).

In conclusion, the results of the present study indicate that small changes in saddle height affected GE and lower limb kinematics in well-trained cyclists. GE significantly increased by 0.5% (from 19.9 to 20.4%) when lowering the saddle height by 4% (3.4% of the trochanteric height), which may have a certain relevance to cycling performance. Probably, the GE improved because the lower saddle position of most cyclists coincided with the recommended saddle heights in previous studies, such as 100–102% of the trochanteric height, 109–110% of the inseam length, or 30–40° of the knee extension angle during active pedaling. Furthermore, by raising the saddle height, angular velocity of both knee and ankle joints increased. This could also justify the abovementioned GE changes. Further research should evaluate long-term effects of small changes in saddle height on GE and lower limb kinematics.

PRACTICAL APPLICATIONS

The present study demonstrates that small changes in saddle height produced significant changes in GE during submaximal pedaling. These results suggest that the bike fitting process should be considered in cycling efficiency research studies. To maintain the internal validity, sport scientists should ensure that every subject is using the same saddle height throughout a particular study. Modifications in bike setting could change the cyclist's position and joint motion during pedaling. Using a 2-dimensional video analysis system, we demonstrated that lower-leg kinematics is sensitive to small changes in saddle height (2%), which could be even applied by high-level cyclists. Sports coaches should introduce a dynamic evaluation in the bike fitting process in addition to the static one. Two-dimensional video analysis should be considered a useful tool to determine the kinematics of the cyclists because it has a high correspondence with the 3-dimensional analysis in the sagittal plane, is easy to use, and free software is available.

ACKNOWLEDGMENTS

This study was funded by the Performance and Health Research Group for High-Level Sports (GIRSANE), High Performance Sport Center of Sant Cugat, the Professional Sports Medicine School (University of Barcelona), and the Faculty of Physical Activity and Sports Sciences, Institute of Biomedicine (IBIOMED), University of Leon (Spain). We are indebted to Dr. Francek Drobnic, Dr. Joan Riera, and Mr. Carles Turró for their technical support during the study. The authors declare that they have no conflicts of interest with any financial organization regarding the material discussed in the manuscript. The authors declare that the experiments comply with the current laws of the country in which they were performed.

REFERENCES

1. Balmer, J, Bird, S, Davison, R, and Lucia, A. Effect of age on 16.1-km time-trial performance. *J Sports Sci* 26: 197–206, 2008.
2. Bini, R, Hume, PA, and Croft, JL. Effects of bicycle saddle height on knee injury risk and cycling performance. *Sports Med* 41: 463–476, 2011.
3. Bini, RR. Patellofemoral and tibiofemoral forces in cyclists and triathletes: Effects of saddle height. *J Sci Cycling* 1: 9–14, 2012.
4. Bini, RR, Rossato, M, Diefenthaeler, F, Carpes, FP, dos Reis, DC, and Moro. Pedaling cadence effects on joint mechanical work during cycling. *Isokinet Exerc Sci* 18: 7–13, 2010.
5. Bini, RR, Tamborindeguy, AC, and Mota, CB. Effects of saddle height, pedaling cadence, and workload on joint kinetics and kinematics during cycling. *J Sport Rehabil* 19: 301–314, 2010.
6. Borg, GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 14: 377–381, 1982.
7. Brouwer, E. On simple formulae for calculating the heat expenditure and the quantities of carbohydrate and fat oxidized in metabolism of men and animals, from gaseous exchange (oxygen and carbonic acid output) and urine-N. *Acta Physiol Pharmacol Neerl* 6: 795–802, 1957.
8. Cavanagh, PR and Williams, KR. The effect of stride length variation on oxygen uptake during distance running. *Med Sci Sports Exerc* 14: 30–35, 1982.

9. Chapman, AR, Vicenzino, B, Blanch, P, and Hodges, PW. Patterns of leg muscle recruitment vary between novice and highly trained cyclists. *J Electromyogr Kinesiol* 18: 359–371, 2008.
10. de Vey Mestdagh, K. Personal perspective: In search of an optimum cycling posture. *Appl Ergon* 29: 325–334, 1998.
11. Edwards, LM, Jobson, SA, George, SR, Day, SH, and Nevill, AM. Whole-body efficiency is negatively correlated with minimum torque per duty cycle in trained cyclists. *J Sports Sci* 27: 319–325, 2009.
12. Ericson, MO, Nisell, R, and Nemeth, G. Joint motions of the lower limb during ergometer cycling. *J Orthop Sport Phys* 9: 273–278, 1988.
13. Ettema, G and Loras, HW. Efficiency in cycling: A review. *Eur J Appl Physiol* 106: 1–14, 2009.
14. Ferguson, RA, Ball, D, Krustrup, P, Aagaard, P, Kjaer, M, Sargeant, AJ, Hellsten, Y, and Bangsbo, J. Muscle oxygen uptake and energy turnover during dynamic exercise at different contraction frequencies in humans. *J Physiol* 536: 261–271, 2001.
15. Ferrer-Roca, V, Roig, A, Galilea, P, and Garcia-Lopez, J. Influence of saddle height on lower limb kinematics in well-trained cyclists: Static vs. dynamic evaluation in bike fitting. *J Strength Cond Res* 26: 3025–3029, 2012.
16. Garcia-Lopez, J, Rodriguez-Marroyo, JA, Juneau, CE, Peleteiro, J, Martinez, AC, and Villa, JG. Reference values and improvement of aerodynamic drag in professional cyclists. *J Sports Sci* 26: 277–286, 2008.
17. Gregor, RJ, Broker, JP, and Ryan, MM. The biomechanics of cycling. *Exerc Sport Sci Rev* 19: 127–169, 1991.
18. Hamley, EJ and Thomas, V. Physiological and postural factors in the calibration of the bicycle ergometer. *J Physiol* 191: 55P–56P, 1967.
19. Heil, DP, Derrick, TR, and Whittlesey, S. The relationship between preferred and optimal positioning during submaximal cycle ergometry. *Eur J Appl Physiol Occup Physiol* 75: 160–165, 1997.
20. Hopker, J, Coleman, D, and Passfield, L. Changes in cycling efficiency during a competitive season. *Med Sci Sports Exerc* 41: 912–919, 2009.
21. Hopker, JG, Coleman, DA, and Wiles, JD. Differences in efficiency between trained and recreational cyclists. *Appl Physiol Nutr Metab* 32: 1036–1042, 2007.
22. Jeukendrup, AE, Craig, NP, and Hawley, JA. The bioenergetics of world class cycling. *J Sci Med Sport* 3: 414–433, 2000.
23. Jobson, SA, Hopker, JG, Korff, T, and Passfield, L. Gross efficiency and cycling performance: A brief review. *J Sci Cycling* 1: 3–8, 2012.
24. Korff, T, Fletcher, G, Brown, D, and Romer, LM. Effect of "Pose" cycling on efficiency and pedaling mechanics. *Eur J Appl Physiol* 111: 1177–1186, 2011.
25. Leirdal, S and Ettema, G. The relationship between cadence, pedalling technique and gross efficiency in cycling. *Eur J Appl Physiol* 111: 2885–2893, 2011.
26. Lucia, A, Hoyos, J, and Chicharro, JL. The slow component of VO2 in professional cyclists. *Br J Sports Med* 34: 367–374, 2000.
27. McDaniel, J, Durstine, JL, Hand, GA, and Martin, JC. Determinants of metabolic cost during submaximal cycling. *J Appl Physiol* 93: 823–828, 2002.
28. Noordhof, DA, de Koning, JJ, van Erp, T, van Keimpema, B, de Ridder, D, Otter, R, and Foster, C. The between and within day variation in gross efficiency. *Eur J Appl Physiol* 109: 1209–1218, 2010.
29. Nordeen-Snyder, KS. The effect of bicycle seat height variation upon oxygen consumption and lower limb kinematics. *Med Sci Sports* 9: 113–117, 1977.
30. Peveler, WW. Effects of saddle height on economy in cycling. *J Strength Cond Res* 22: 1355–1359, 2008.
31. Peveler, WW and Green, JM. Effects of saddle height on economy and anaerobic power in well-trained cyclists. *J Strength Cond Res* 25: 629–633, 2011.
32. Peveler, WW, Shew, B, Johnson, S, and Palmer, TG. A kinematic comparison of alterations to knee and ankle angles from resting measures to active pedaling during a graded exercise protocol. *J Strength Cond Res* 26: 3004–3009, 2012.
33. Price, D and Donne, B. Effect of variation in seat tube angle at different seat heights on submaximal cycling performance in man. *J Sports Sci* 15: 395–402, 1997.
34. Rankin, JW and Neptune, RR. The influence of seat configuration on maximal average crank power during pedaling: A simulation study. *J Appl Biomech* 26: 493–500, 2010.
35. Rodriguez-Marroyo, JA, Garcia-Lopez, J, Chamari, K, Cordova, A, Hue, O, and Villa, JG. The rotor pedaling system improves anaerobic but not aerobic cycling performance in professional cyclists. *Eur J Appl Physiol* 106: 87–94, 2009.
36. Sanderson, DJ and Amoroso, AT. The influence of seat height on the mechanical function of the triceps surae muscles during steady-rate cycling. *J Electromyogr Kinesiol* 19: e465–e471, 2009.
37. Silder, A, Gleason, K, and Thelen, DG. Influence of bicycle seat tube angle and hand position on lower extremity kinematics and neuromuscular control: Implications for triathlon running performance. *J Appl Biomech* 27: 297–305, 2011.
38. Umberger, BR and Martin, PE. Testing the planar assumption during ergometer cycling *J Appl Biomech* 17: 55–62, 2001.
39. Verbeke, G and Molenberghs, G. *Linear Mixed Models in Practice. A SAS-Oriented Approach.* New York, NY: Springer, 1997.
40. Wasserman, K, Hansen, J, Sue, D, Stringer, W, and Whipp, B. *Principles of Exercise Testing and Interpretation.* Philadelphia, PA: Lippincott Williams & Wilkins, 2004.