

Acute effects of small changes in bicycle saddle height on gross efficiency and lower limb kinematics

## Abstract

The aim of the present study was to assess the acute effects of small changes in bicycle saddle height on gross efficiency and lower-limb kinematics. Well-trained cyclists (n=14) performed a submaximal pedaling test (~70-75% of the  $VO_{2max}$ ) at constant cadence (90 rpm). It consisted on three randomized sets of 6 min with the preferred saddle height, 2% higher and 2% lower. Gross efficiency (GE) was significantly lower and oxygen consumption ( $VO_2$ ) was significantly higher when raising the saddle (GE =  $19.9 \pm 1.5\%$ ;  $VO_2 = 43.8 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) than when lowering it (GE =  $20.4 \pm 1.3\%$ ;  $VO_2 = 42.8 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ). Additionally, a change of 0.8% in GE ( $20.6 \pm 1.6$  to  $19.8 \pm 1.6\%$ ,  $p < 0.05$ ) 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.

**Keywords:** cycling, bike fitting, biomechanics, 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, as well as to 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 in order 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 two 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 three 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) obtained 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 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 and lower limb kinematics. Furthermore, various of the above mentioned 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 two occasions, separated by one week, under similar environmental conditions (21–23°C, 60 to 65% relative humidity) and after a 24 h 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 three 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 two-dimensional video analysis system.

### **Subjects**

Fourteen well-trained cyclists volunteered to participate in this study (age  $32.6 \pm 5.6$  years;  $72.5 \pm 9.3$  kg;  $1.76 \pm 0.05$  m; body mass index  $23.4 \pm 2.0$  kg·m<sup>-2</sup>). 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  $8 \pm 5$  years of experience in competitions, and their average weekly training volume was  $15.7 \pm 5.0$  hours. Other cyclists' characteristics were shown in the 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.

## **Procedures**

Power output, heart rate and pedal cadence were controlled by an electronically braked ergometer (SRM, Schoberer Rad Messtechnik, 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 ( $\dot{V}_E$ ), carbon dioxide production ( $\dot{V}CO_2$ ) and respiratory exchange ratio (RER) were continuously measured breath-by-breath by a computerized gas analyzer (Jaeger Oxycon Mobile, Germany) (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 ( $15\% \pm 0.001\% O_2$  and  $6\% \pm 0.001\% CO_2$ ; Abelló Linde S.A; Barcelona, Spain) and a 3.0-liter syringe (Cosmed srl; Roma, Italia).

*Anthropometric and bicycle measurements.* An anthropometric tape (Holtain LTD; Crymych, UK) and a Harpenden anthropometer (CMS instruments, London, UK) 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. Handlebars position was determined by the vertical distance between the top of the saddle and the middle of the handlebars, and by the horizontal distance between the middle of the saddle and the middle of the handlebars (24). In order 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 ( $VO_{2max}$ ), 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 min until voluntary exhaustion. Pedal cadence was freely chosen during the whole test (range of 70 – 100 rpm). Each incremental test was terminated 1) voluntarily by the subject; 2) when pedaling cadence could not be maintained at 70 rev/min (at least); or 3) when established criteria of test termination were met (26).  $VO_{2max}$  was determined as the mean  $VO_2$  measured over 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 two 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  $VO_{2max}$  with 5 min separating the end of the warm-up from the test. The cyclists performed three 6-min sets at 65% of maximal power output (~70-75% of the  $VO_{2max}$ ) on the SRM with their preferred saddle height position, 2% higher and 2% lower. The three sets were separated by 6 min rest. This intensity of pedaling was selected because the respiratory exchange ratio was lower than 1.00 in all the cyclists studied (35), indicating no significant anaerobic contribution. The order of the three 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  $rev \cdot min^{-1}$ , 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 respiratory exchange ratio were

monitored during the entire duration and were averaged for the last 2 min of each set (11). Gross mechanical efficiency (GE) was calculated as the ratio of work accomplished (expressed in kcal·min<sup>-1</sup>) to energy expended (kcal·min<sup>-1</sup>), using the formula of Brouwer (1957) for the corresponding energy equivalent for each oxygen consumption value based on carbon dioxide production (7). 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 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.

*Figure 1 about here*

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 over 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, two reflective markers of 10 mm in diameter were attached to both crank and pedal axes of rotation. A two-dimensional video analysis system (Peak Motus, Version 9.2.0; Vicon Motion System; Centennial, USA) was used for video recording, digitizing, processing and analyzing data. A single high-speed IEEE1394 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 x 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 IEEE1394 device interface cards do not use square pixels. Images were acquired at 200 Hz sampling frequency with a resolution of 428 x 322 pixels for 10 seconds in the last 2 minutes of every trial. Automatic tracking during fourteen pedal cycles was performed to obtain the two-dimensional coordinates of the markers. Raw coordinate data were smoothed using a fourth-order Butterworth digital filter with cut-off frequencies

individually determined (3 to 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 plantarflexion (minimum angle). The range of movement (ROM) of each joint was the difference between the maximum and minimum angles.

## **Statistical analysis**

Main descriptive statistics (mean, standard deviation and range) were calculated for anthropometric and bicycle measurements of the cyclists and their physiological values obtained during the incremental test. The Shapiro-Wilk normality test was used to assess normality. The analysis of bicycle dimensions, physiological and biomechanical variables (registered during the submaximal test at three 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 three positions was considered as a random effect. Post-hoc pairwise comparisons were computed using Tukey's HSD. 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, North Carolina, 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  $110.6 \pm 2.6\%$  of inseam length and  $103.6\% \pm 2.3\%$  of trochanteric height. They reached  $59.0 \pm 6.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  of  $\text{VO}_{2\text{max}}$  and the respiratory compensation threshold was obtained at  $85.3 \pm 7.5\%$  of the  $\text{VO}_{2\text{max}}$ .

*Table 1 about here*



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 range of movement of the three joints (~ 1, 3 and 4°, respectively). Power output, pedaling cadence, heart rate, lactate production and Borg's rating of perceived exertion were not affected ( $p > 0.05$ ).

*Table 2 about here*

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 three saddle heights were found in peak ankle angular velocity. However, no statistical differences were noted in peak hip angular velocities.

*Figure 2 about here*

The mean values for the best and worst GE position were  $20.6 \pm 1.6\%$  and  $19.8 \pm 1.6\%$ , respectively. Statistical differences between these positions were 0.8% (CI 95% 0.4 – 1.1% and  $p < 0.05$ ). In addition, oxygen consumption increased significantly:  $0.8 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  (CI 95% 0.3 – 1.3  $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$   $p < 0.05$ ), while heart rate, lactate production and Borg's rating of perceived exertion did not increase. 85.7% of the riders 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 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  $VO_{2max}$ ) and at constant cadence (~90 rpm) produced significant changes in both GE and lower limb kinematics in well trained cyclists (Table 2). GE 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 due to greater modifications in saddle height, between 4 to 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 three positions were  $0.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  (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  $0.13 \text{ l}\cdot\text{min}^{-1}$ , from 1.74 to 1.61 and  $1.69 \text{ l}\cdot\text{min}^{-1}$  at low work rate (130.6 W or 799 kpm/min) and at constant cadence (60 rpm), when lowering the saddle height 5% and 10% respectively. In the present study (Table 2), oxygen consumption changed  $0.08 \text{ l}\cdot\text{min}^{-1}$  (approximately one half), from 3.14 to 3.10 and  $3.18 \text{ l}\cdot\text{min}^{-1}$ , 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 % ( $20.4 \pm 1.3$  to  $19.9 \pm 1.5\%$ ,  $p < 0.05$ ) 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 (2010) stated that changes in GE of  $\sim 0.6\%$  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 (28). Therefore, our findings may have a certain relevance to the cycling performance, because it is well known that variation in GE explains  $\sim 30\%$  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 in order to solve the limitations of this study, further research should evaluate long-term changes in GE due to 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  $VO_2$  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 utilized 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 (2001) demonstrated that muscle oxygen uptake was elevated at high contraction frequency when the same total power output was performed(14). Therefore, it seems reasonable to expect that an increase in the knee and ankle angular velocities due to 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 range of movement 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), while 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 due to modifications in saddle height.

Kinematic differences observed in the present study (between 4-8°) were not due to the method used to analyze the lower limb kinematics (two-dimensional video analysis). First, the cyclists performed

the submaximal sets in a randomized order. Second, spherical reflective markers were attached over 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 three 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 two-dimensional sagittal plane kinematics during pedaling were similar to the three-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. In order 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 two-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 three-dimensional analysis in the sagittal plane, is easy to use, and free software is available.

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## **Conflict of interest statement**

The authors declare that they have no conflict 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.

## Figure Legends

**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).

**Figure 2.** Mean and standard deviation of the peak joint angular velocity (hip, knee and ankle) during the downstroke phase at three 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.

## Table Legends

Table 1. Anthropometric characteristics of the cyclists and bicycle dimensions at their preferred saddle height position. Physiological values obtained during the incremental test.

Table 2. Mean and standard deviation of the bicycle dimensions, physiological and biomechanical variables registered during the submaximal test at three different saddle heights (preferred, 2% higher and 2% lower). See Figure 1 for the convention used to specify joints' angular displacement.

Table 1. Anthropometric characteristics of the cyclists and bicycle dimensions at their preferred saddle height position. Physiological values obtained during the incremental test.

	<b>Mean <math>\pm</math> SD</b>	<b>Range</b>
<i>Anthropometric and bicycle measurements</i>		
Trochanteric height (m)	0.886 $\pm$ 0.031	0.814 – 0.937
Inseam length (m)	0.830 $\pm$ 0.036	0.779 – 0.896
Saddle height (m)	0.745 $\pm$ 0.038	0.681 $\pm$ 0.813
Saddle back (m)	0.062 $\pm$ 0.017	0.039 – 0.095
Crank length (m)	0.173 $\pm$ 0.002	0.170 – 0.180
Saddle height (%TH)	103.6 $\pm$ 2.3	100.1 – 108.6
Saddle height (%IL)	110.6 $\pm$ 2.6	106.0 – 117.6
<i>Incremental test</i>		
VO <sub>2max</sub> (ml·kg <sup>-1</sup> ·min <sup>-1</sup> )	59.0 $\pm$ 6.5	51.9 – 69.5
Maximal heart rate (bpm)	180 $\pm$ 11	161 - 196
Maximal aerobic power output (W)	378 $\pm$ 29	325 - 419
Maximal aerobic power output (W·kg <sup>-1</sup> )	5.28 $\pm$ 0.73	4.27 – 6.20
VT – %VO <sub>2max</sub>	64.8 $\pm$ 7.8	59.9 – 80.4
RCT – %VO <sub>2max</sub>	85.3 $\pm$ 7.5	80.1 – 96.3

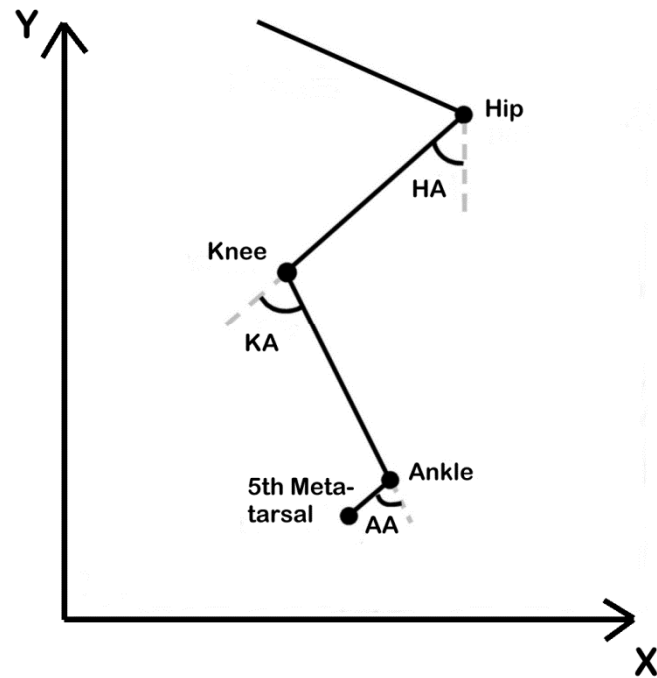
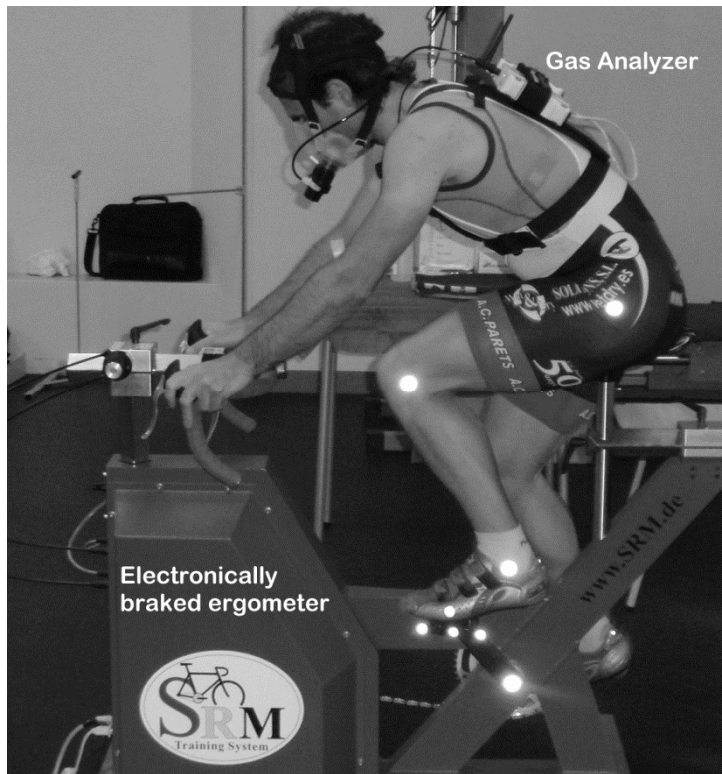
%TH, percentage of trochanteric height. %IL, percentage of inseam length. VT, ventilatory threshold. RCT, respiratory compensation threshold.

Table 2. Mean and standard deviation of the bicycle dimensions, physiological and biomechanical variables registered during the submaximal test at three different saddle height positions (preferred, 2% higher and 2% lower). See Figure 1 for the convention used to specify joints' angular displacement.

		<b>Seat Height</b>		
		<b>2% lower</b>	<b>Preferred</b>	<b>2% higher</b>
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
VO <sub>2</sub> (ml·kg <sup>-1</sup> ·min <sup>-1</sup> )		42.8 ± 4.9 #	43.3 ± 4.9	43.8 ± 4.9
Heart rate (bpm)		147 ± 12	147 ± 12	148 ± 11
Lactate (mmol·l <sup>-1</sup> )		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	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	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	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

%TH, percentage of trochanteric height. %IL, percentage of inseam length. GE, gross mechanical efficiency. Post-hoc comparisons: \* Significant difference with preferred seat height (p < 0.05). # Significant difference between the 2% lower and the 2% higher seat heights.

**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).



**FIGURE 2.** Mean and standard deviation of the peak joint angular velocity (hip, knee and ankle) during the downstroke phase at three 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.

