Journal of Science & Cycling
Breakthroughs in Cycling & Triathlon Sciences

OPEN ACCESS

Original Article

Effects of Horizontal Saddle Displacement on Energy Expenditure of Mountain Bike Cyclists – A Pilot Study

Pedro Vigario [1,*], Ricardo Maia Ferreira [1,2,3,4], António Rodrigues Sampaio [1,5,6] and Pedro Nunes Martins [1]

[1] Polytechnic Institute of Maia, N2i, Physical Fitness in Sports and Exercise Department, Avenida Carlos de Oliveira Campos, 4475-690, Maia, Porto;
[2] Polytechnic Institute of Coimbra, Coimbra Health School, Physiotherapy Department, Rua 5 de Outubro, 3046-854, São Martinho, Coimbra;
[3] Polytechnic Institute of Castelo Branco, Dr. Lopes Dias Health School, Physiotherapy Department, Avenida do Empresário, 6000-767, Castelo Branco;
[4] Polytechnic Institute of Viana do Castelo, SPRINT, Rua Escola Industrial e Comercial de Nun'Álvares, 4900-347, Viana do Castelo;
[5] Faculty of Sport of the University of Porto, CIFI2D, LABIOMEP, Rua Dr. Plácido da Costa, 4200-450, Porto;
[6] University of Maia, Sports Department, Avenida Carlos de Oliveira Campos, 4475-690, Maia, Porto;

* Correspondence: (PV) pedrovigariogm@gmail.com

Received: 17 August 2024 **Accepted:** 11 November 2024 **Published:** 14 November 2024

Abstract: The process of optimizing the cyclist-bicycle relationship has been referred to as fundamental for optimizing cyclist performance. In the published literature, studies are scarce to understand and make decisions about the consequences of changing the saddle position in mountain bike cyclists. The main objective of this study was to determine the performance implications resulting from changing the position of a mountain bike cyclist's saddle through its horizontal displacement, in relation to the reference position obtained by traditional methods. The experimental design of this study consisted of a cross-sectional, randomized experimental study, where submaximal tests were conducted in laboratory on six high-level mountain bike cyclists. Six saddle positions in flat and uphill simulation were tested and the horizontal displacement of the saddle was related to the variables oxygen consumption, lactate concentration, heart rate and rate of perceived exertion. The results demonstrated that, as the saddle is moved horizontally towards the handlebars, oxygen consumption and blood lactate concentration values decrease. There were no significant differences in the mean values for heart rate and rate of perceived exertion. However, there were significant differences between participants regarding all variables under study in all saddle positions. In conclusion, the results suggest that the horizontal variation of a mountain bike cyclist's saddle has an impact on oxygen consumption, lactate concentration, heart rate and rate of perceived exertion and, consequently, on performance. The results also seem to suggest that horizontal displacement of the saddle position towards forward positions in the direction of the handlebars has benefits for the cyclist by reducing energy consumption and, when determining the ideal position of the saddle, the cyclist's individual characteristics must be considered.

Keywords: Saddle Position, Mountain Bike, Energy Expenditure, Performance.

1. Introduction

The evaluation of biomechanical parameters contributes to the success of the high-performance cyclists, namely in determining their ideal position on the bicycle (Burt, 2014; Di Alencar, de Sousa Matias & de Oliveira, 2010; Ferrer-Roca, 2016). The cyclist's position on the bicycle is related to the bicycle's ergonomics and can be defined as the process of setting its specific parameters to best suit an individual and optimize cyclist positioning. The process of optimizing the cyclist-bicycle relationship is considered one of the key factors for maximizing cyclist performance, improving comfort, and reducing the risk of injury (Atkinson, Davidson, Jeukendrup, Passfield, 2003; Belluye and Cid, 2001; Menard, Domalain, Decatoire & Lacouture, 2016; Peveler & Green, 2011; Swart & Holliday, 2019). In the process of finding the ideal position of the cyclist on the bicycle, several geometric variables intervene such as the position of the saddle, the position of the handlebars, the length of the crank and the position of the foot on the pedal. Thus, the adjustment of the bicycle to the cyclist's body segments is essential for the optimization of the forces exerted by the muscles involved in pedalling (Bini & Carpes, 2014), as well as in the patterns of muscle activation (Chapman et al., 2008), it contributes to the production of mechanical work of the lower limbs´ joints, impacting on pedalling efficiency (Ferrer-Roca, Roig, Galilea & García-López, 2012) and the production of power (Rankin & Neptune, 2010).

To determine the ideal position of the cyclist on his bicycle, saddle height selection seems to be the main adjustment variable for most researchers (Burt, 2022; Garcia-López & del Blanco, 2017). The adjustment of the saddle position can be conducted through dynamic methods, in which the cyclist pedals, or static, in which the cyclist is at rest (Ferrer-Roca et al., 2012). According to the same authors, static methods are traditionally used, especially due to their ease of application and low cost, while dynamic methods, particularly those in which 2D or 3D technology is used, are more advanced and produce more accurate results (Burt, 2014). For Burt (2014), the optimal height of the saddle is the most important adjustment in terms of power production and, consequently, in the cyclist's performance.

The saddle can be adjusted in both vertical and horizontal directions and its position measured relative to bicycle components (e.g., saddle position relative to bottom bracket) or relative to the rider (e.g., saddle height relative to trochanter height) (Bini & Carpes, 2014). According to Ricard, Hills-Meyer, Miller & Michael (2006), depending on the geographical characteristics of the race, cyclists modify their position in the saddle. The same authors report that some cyclists tend to sit further back in the saddle on climbs, opting for positions further forward in the saddle in sprints and time trials. Bini, Hume & Croft (2014) report that triathletes tend to adopt a more advanced position than road cyclists, moving the knee forward of the pedal axis, although the prevalence of knee injuries is similar among athletes of both sports. However, according to Fonda, Panjan, Markovic & Sarabon (2011), during climbs, mountain bike (MTB) cyclists need to make postural adaptations to avoid lifting the front wheel, to stabilize the position on the bike and without losing the necessary traction. This adaptation usually results in the movement of the rider´s body in the direction of the front of the bicycle, accompanied by the flexion of the trunk and elbows. To assist in this position advancement, cyclists move the saddle horizontally towards the handlebars. This change is conducted empirically, without any scientific basis and often without the proper advice of the coaches.

With this displacement of the saddle, cyclists and coaches claim that the cyclist is able to apply more power and be more efficient. However, in a study with road cyclists, Rankin & Neptune (2010) concluded that this claim is false. Although some studies suggest a relationship between the horizontal position of the saddle and anterior knee pain (Asplund & St Pierre, 2004; Callaghan, 2005; Silberman, Webner, Collina & Shiple, 2005), in a study by Menard et al. (2018), the authors concluded that forward saddle displacement is not associated with increased forces on the patellofemoral joint. According to Holliday & Swart (2021), modifying the position of the saddle by moving it backwards or forwards alters the spatial position of the joints and their angles, influencing the production of force in the pedals. However, in a study by Bini, Hume, Lanferdini & Vaz (2013), the authors report that this horizontal modification in saddle position does not affect patellofemoral and tibiofemoral compression forces. Nonetheless, no results were presented regarding the association between these alterations and the cyclist's performance. Thus, the results obtained in these studies are not consensual, differing on the advantages or disadvantages of having a saddle set back or forward in relation to the reference position, making it impossible to make concrete decisions.

In their daily practice, mountain bikers modify the position of the saddle by advancing it, doing so according to their personal preferences. However, it appears that the literature is scarce regarding the effects of the modification of the horizontal positioning of the saddle in MTB cyclists in relation to the reference position and the possible implications on the metabolism, energy consumption and competition performance of the cyclists caused by this modification. For high-performance athletes, this finding is more critical since slight differences in any of the factors that affect performance can mean failure in competition (Faria, Parker & Faria, 2005a, 2005b). To evaluate the consequences of the variation in the horizontal position of the saddle of a MTB cyclist, it is necessary to understand how the physiological and biomechanical variables involved in the positioning of the cyclist on the bicycle, in the movements generated, in the production and energy consumption, are related.

The main objective of this study is to determine the implications on performance resulting from changing the position of the saddle of a MTB cyclist through its horizontal displacement, in relation to the reference position obtained by traditional methods. As secondary objectives, to determine the implications of this change on the physiological variables oxygen consumption (VO_2), lactate concentration (LAC) and heart rate (HR), as well as on the rate of perceived exertion (RPE) of the participants.

2. Materials and Methods

2.1. Study Design

A cross-sectional, randomized experimental study was conducted, in which the variables VO_2, maximum aerobic power (MAP) and saddle horizontal displacement (SHD) were correlated, with the objective of understanding the effects of horizontal saddle displacement in MTB athletes. This study was conducted according to the guidelines of the CONSORT protocol (Schulz, Altman, & Moher, 2010) for randomized trials. The trials were conducted in the laboratory of the High-Performance Cycling Centre of Anadia, UCI Continental Satellite Centre. Prior to carrying out this study, its design was validated by performing a complete trial with a single participant, thus ensuring that all its procedures were in accordance with the objectives proposed for this study.

2.2. Participants

A total of six male MTB cyclists, aged between 18 and 36 years, international level mountain bikers, from the under-23 and elite competitive categories, participated in this study. Despite the small number of participants, the sample was made up of a group of cyclists with a highly competitive level since five represent or represented the Portuguese national MTB team and regularly compete in major international competitions. As inclusion criterions, participants would have to be male and have a minimum of two years of competitive experience at national and/or international level. Participants were instructed to reduce the volume and intensity of training in the two days prior to the experimental procedure to low levels to avoid fatigue, and to abstain from consuming energy drinks, coffee, or other stimulants in the same period until after the trials. As exclusion criterion, participants could not have had an injury in the two years prior to data collection. The reason for choosing these participants is due to the ease of access to them, the possibility of using athletes of a highly competitive level and the fact that they are experienced athletes in the rigorous application of the techniques and instruments used in this study. The study and its objectives were described to the participants, as well as its risks and benefits.

An informed consent form was distributed and signed by the participants, ensuring the confidentiality of the personal data collected. Each participant was assigned an identification number from 1 to 6, which functioned as a code in the analysis of the data and their personal data will not appear in any document or presentation, nor will it ever be mentioned. This study was approved by the Ethics Committee of the Research Centre of the Polytechnic Institute of Maia N2i, and it was in accordance with the ethical standards of the 1964 Helsinki Declaration.

2.3. Procedures

Each participant performed all their trials in a single visit to the laboratory. The experimental procedure began with the initial recordings: place, date, time of day, temperature, humidity, and personal data of the participant. Next, the following were collected: (a) Anthropometric data of each participant: height, weight, BMI, sum of eight skinfolds; (b) The measurements required to establish the reference position of the saddle: inseam, saddle height, saddle setback and saddle displacement range (SDR). Next, six submaximal trials were performed in which the following variables were evaluated and manipulated: (1) Independent variable: SHD; (2) Dependent variables: VO_2, HR, LAC, RPE; (3) Control variables: pedaling frequency or cadence (CAD), mechanical power (%P), crank length (CL).

In this study, three positions were studied in both flat and uphill simulations: (1) The reference position adopted by the cyclist on his bicycle, which we called the Base position calculated through the adoption of the Pruit (saddle setback) and Ferrer-Roca et al. (2012) (saddle height) methods; (2) Base + 25%. The horizontal distance of the saddle from the reference position of the cyclist's bike by adding 25% of the maximum displacement range of the saddle rails; (3) Base+50%. The horizontal distance of the saddle from the reference position of the cyclist's bicycle by adding 50% of the maximum displacement range of the saddle rails.

$$Base + 25\% = di + ((df - di) \cdot 0.25)$$

Equation (1)

$$Base + 50\% = di + ((df - di) \cdot 0.50)$$

Equation (2)

di = initial distance; df = final distance; df-di = maximum displacement range of the saddle rails (SDR).

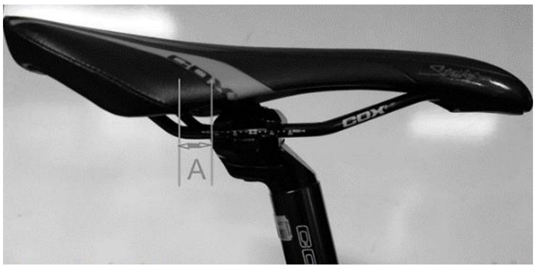

Figure 1. A = SDR (Maximum displacement range allowed by the saddle configuration).

In the uphill situation, a 20% slope was used, thus simulating one of the typical conditions of a MTB Cross-country competition. The 20% slope was guaranteed in all tests by using a support for the front wheel, specially built for this purpose (Figure 2). The order in which each trial was conducted was randomized, non-sequential, anonymous, and determined using the open-source software Randomizer, available online at https://www.randomizer.org/. All participants performed the experimental trials on the same Drag Hardy 9.0 bike (Velomania Ltd, Sofia, Bulgaria) and the same crank size (175mm), thus ensuring that these were not influencing factors in the data collected.

Figure 2. Bicycle setup with 20% slope.

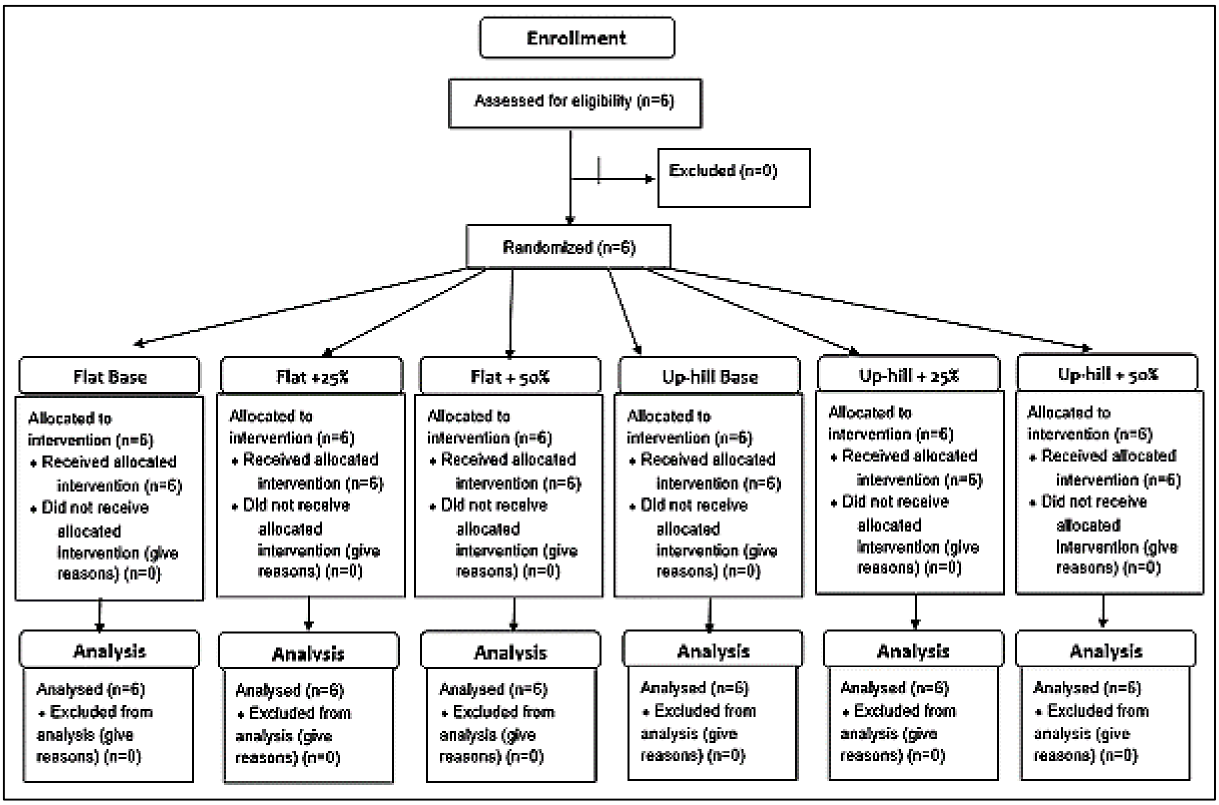

Figure 3. Flow diagram of study procedures and randomization

Table 1. Participants randomization.

Participant 1	Participant 2	Participant 3	Participant 4	Participant 5	Participant 6
Randomization	Randomization	Randomization	Randomization	Randomization	Randomization
Up-hill + 50%	Up-hill + 50%	Up-hill + 25%	Flat base	Up-hill + 50%	Up-hill Base
Up-hill + 25%	Up-hill Base	Flat base	Up-hill + 50%	Up-hill + 25%	Up-hill + 50%
Flat + 50%	Flat + 25%	Flat + 25%	Up-hill + 25%	Flat + 50%	Flat base
Up-hill Base	Flat + 50%	Flat + 50%	Flat + 25%	Flat + 25%	Up-hill + 25%
Flat + 25%	Flat base	Up-hill Base	Up-hill Base	Flat base	Flat + 25%
Flat base	Up-hill + 25%	Up-hill + 50%	Flat + 50%	Up-hill Base	Flat + 50%

2.3.1. Anthropometric assessment

The anthropometric evaluation aimed to briefly characterize the participants. The participant's body composition was also evaluated, and it was at this moment that the participants' inseam measurement was obtained to calculate the saddle height. Weight was measured before the beginning of the experimental procedure, with the participant barefoot and wearing only cycling shorts, using a Seca 818 dr digital scale (Seca, Hammer Steindamm, Germany). Height was measured before the beginning of the experimental procedure, with the participant barefoot, in the reference anatomical position. A Seca 217 stadiometer (Seca, Hammer Steindamm, Germany) was used. Eight subcutaneous folds (triceps, biceps, subscapular, suprailiac, supraspinatus, abdominal, crural and geminal) were recorded using a Harpenden adipometer (Baty International Ltd, Burgess Hill, United Kingdom) and their sum was calculated. The measurement procedure was according to the ISAK method and before the experimental trials. The participant's inseam height was obtained with the participant barefoot, leaning against a smooth wall and placing a square against the maximum allowed height (pubic symphysis), wearing the cycling shorts used in the trials (Figure 4).

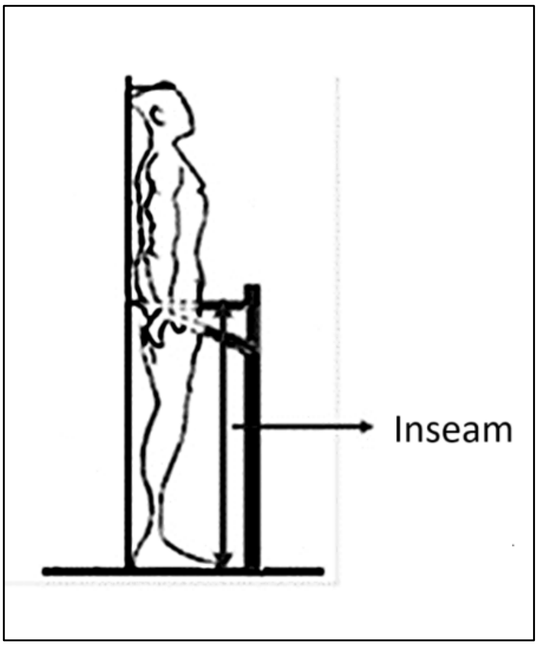

Figure 4. Calculation of the cyclist´s inseam.

2.3.2. Determining the reference base saddle position

For the determination of the reference base saddle position, researchers used the traditional method for saddle setback – Pruitt's method, and the recommendations of Ferrer-Roca et al. (2012) for adjusting the saddle height. In this study, the mean value of 109.5% was used:

$$SH = 109.5\% \cdot Inseam$$

Equation (3)

2.3.3. Submaximal Trials

Prior to all trials, the operating and calibration procedures indicated by the manufacturers of the instruments and materials used were followed. The participant´s physical activation was performed at a constant power corresponding to 40% of the MAP of each participant with a duration of 10 min. Each participant's MAP was obtained in an incremental laboratory test and corresponds to the mean power in the last complete level according to the protocol described by Granier et al. (2018). A 5-min passive recovery interval was observed between warm-up and the beginning of the experimental procedure. Each submaximal trial lasted 8 min followed by 5-min active recovery and 15-min passive recovery. The time of 20 min between trials is justified by the need for recovery of the cyclists avoiding fatigue effects and also with the need to adjust the position of the bicycle saddle for the next trial. To avoid possible fatigue or learning effects, the three saddle positions (base, +25% and +50% of amplitude), and the two flat and uphill situations, were randomized, totalling six different combinations randomly determined and distributed to the participants (Leirdal & Ettema, 2011). The experimental protocol used was adapted from the studies by Menard et al. (2018) and Fonda et al. (2011). The bike was placed on an Elite Fluid fixed roller (Elite, Fontaniva, Italy) and equipped with an SRM sensor plate (SRM GmbH, Julich, Germany). The intensity of the load (power) used by the participants should consider the individual response of each cyclist to the applied load. At the same time, it should cause an internal load that corresponds to the predominant metabolism of MTB Cross-country Olympic events reported in the literature, which is essentially aerobic with a large anaerobic contribution (Arriel, Souza, Sasaki, & Marocolo, 2022; Macdermid, & Stannard, 2012). The target power to be developed by the cyclist during the submaximal trial was normalized to the power value corresponding to 70% of the participant's MAP obtained in a laboratory evaluation. This target power was considered an estimated load with relevance in terms of energy consumption, but which does not compromise in terms of fatigue the performance of the various trials. Thus, the load at the first minute of the trial was 25% of the target power, the power was increased by 25% every minute until it reached 100% of the load corresponding to the target power, which occurred at the end of the 3rd min of the trial. The first 3 min aim to promote the adaptation of the cyclist in cardiovascular, muscular and joint terms, as well as to the position adopted. Once the target power was reached, the participant pedaled continuously and at a constant intensity for 5 min. The participants were instructed to maintain constant a cadence close to 85 rpm throughout each trial. The VO_2 value in each trial was obtained by calculating the average of the consumption recorded in the last 2 min at target power and expressed in ml/kg/min, using a K5 Cosmed gas analyser (Cosmed, Albano Laziale, Italy). Capillary blood samples were collected for LAC analysis in the last 30 sec at target power using a lactate analyser Lactate Photometer plus DP 110 (Diaglobal GmbH, Berlin, Germany). Prior to the beginning of the first trial, the participants were informed of the application of the RPE scale and instructed on its interpretation. At the 7th minute of each trial, the participant was asked about the value of their RPE using the Borg Scale 6-20 (Borg, 1990). At the end of each trial, the participant completed a 5-min active recovery period corresponding to 25% of the trial target power, followed by a 15-min passive recovery period. The experimental procedure is shown in Figure 5.

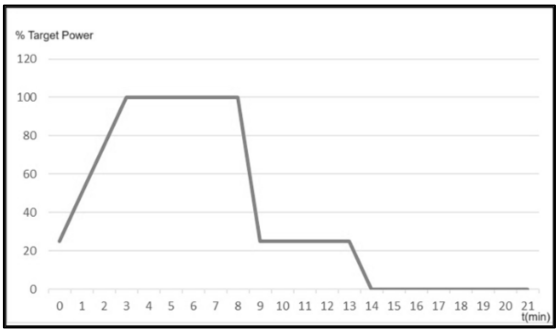

Figure 5. Experimental procedure

2.4. Statistical analysis

The SPSS/PC software (Windows version 29, Statistical Package for the Social Sciences, USA) was used for all statistical analyses. The results were presented as mean and standard deviation.

Regarding the analyses of VO_2, LAC, HR and RPE obtained in the submaximal trial, the Standard Mean Differences (SMD) were calculated and the results were interpreted according to the recommendations of Cohen (2013) and Faraone (2018): equivalent, SMD = 0; low, SMD = 0.2; medium, SMD = 0.5; high, SMD = 0.8. According to Faraone's (2018) recommendations for the interpretation of the results, an SMD equal to zero means that the groups have equivalent effects. If improvement is associated with lower scores on the outcome measure, SMD below zero indicate the degree to which the intervention group is more effective than the baseline group and SMD greater than zero indicate the degree to which the intervention group is less effective than the baseline group. In the case of the present study, an improvement in the results of the variables studied implies a reduction in their values with the modification of the saddle position. Tables were constructed for the presentation and evaluation of the results.

3. Results

3.1. Characterization of the participants

Table 2 presents the data related to the characterization and competitive experience of the participants. Table 3 presents the calculation of saddle height and horizontal displacements.

Table 2. Characterization of the participants

Participant	Age (years)	Years of competition	Nº Weekly training hours	Weight (kg)	Height (cm)	BMI (kg/m²)	Σ skinfolds (mm)	VO_2max (ml/kg/min)	MAP (W)	70% MAP (W)
1	36.2	21	18	52.2	165	19.17	46.7	85	310	217
2	25.2	10	14	76.4	181.5	23.19	65.6	78	315	221
3	18.4	12	16	71.7	170.5	24.66	65.2	72	270	189
4	24.4	12	15	56.1	167.3	20.04	41.6	77	300	210
5	31.9	18	10	76.7	182.5	23.03	59	76	352	246
6	22.2	7	10	66.5	173	22.22	68.8	74	300	210
Mean	26.4	13.3	13.8	66.6	173.3	22.05	57.82	77	308	215
SD	5.97	5.2	3.25	9.5	6.64	1.89	10.2	4.1	24.4	18.7

BMI, Body mass index; VO_2max, Maximum oxygen uptake; MAP, Maximum aerobic power.

Table 3. Calculation of saddle height and horizontal displacements

Participant	Inseam (cm)	SH (cm)	SDR (mm)	25% (mm)	50% (mm)
1	76.0	83.2	30	7.50	15.00
2	74.5	81.6	40	10.00	20.00
3	81.0	88.7	35	8.75	17.50
4	77.0	84.3	45	11.25	22.50
5	86.1	94.3	47	11.75	23.50
6	81.3	89.0	33	8.25	16.50
Mean	79.3	86.9	38.3	9.58	19.17
SD	4.30	4.71	6.80	1.552	3.105

SD, Standard deviation; SH, Saddle height; SDR, Saddle displacement range; 25% = SDR*0.25; 50% = SDR*0.50.

3.2. Oxygen consumption

Table 4 shows the VO_2 values collected in the six determined positions. The data presented relate to each participant and correspond to the mean values taken in the last two minutes of each trial, thus corresponding to 40% of the time that each participant pedaled at the target power. The values shown are the weight-normalized values, expressed in mL/kg/min. The mean for each saddle position and their standard deviations were calculated and displayed. Analysing and comparing the mean VO_2 obtained in each saddle position, significant differences were observed between them, confirming that the variation in the saddle position had effects on VO_2. Regarding the mean values of the trials in flat, there was a direct relationship between the horizontal displacement of the saddle and the decrease in VO_2 meaning that, as the saddle was moved horizontally towards the handlebars, oxygen consumption decreased. The VO_2 in the Flat+25% position was reduced by 2.39% compared to the Flat Base position. The largest reduction was in the Flat+50% position, whose oxygen consumption was reduced by 6.96% compared to the Flat Base position and by 4.69% compared to the Flat+25% position. In the evaluation of the SMD values, the effects were of low magnitude, as can be seen in Table 5. In the uphill simulation trials, the trend was maintained, but with less expression, confirmed by the low SMD values resulting in an effect of equivalent magnitude. The largest reduction in oxygen consumption also occurred in the Uphill+50% position compared to the Uphill Base position of 2.28%, and there was also a reduction of 2.14% in oxygen consumption in the Uphill+50% position compared to the Uphill+25% position. Interestingly, this pattern of VO_2 reduction with SHD in the direction of the handlebars was not observed in all participants. In fact, participant 1 presents an inverse variation to the mean of the group, increasing VO_2 with SHD in both flat and uphill situations. In this case, the most significant increase in VO_2 was observed in the Flat+50% position of 16.1% more compared to the Flat Base position. There was also registered an increase of 5.2% in the Uphill+50% compared to Uphill Base position. Participants 4 and 6 recorded increases in VO_2 in the uphill simulation, also more significant in the Uphill+50% position compared to the Uphill Base position, of 6.1% and 5.1% respectively. However, participant 6 had a higher VO_2 value in the Uphill+25% position, thus originating a non-linear pattern.

It is possible to verify a pattern of variation of the mean oxygen consumption of the three positions of the saddle in the two situations, flat and uphill. However, the mean VO_2 value recorded is similar in both Flat+50% and Uphill+50% positions.

3.3. Blood lactate concentration

The mean LAC values are shown in Table 6, the values are expressed in mmol/L. It is possible to verify, as reported in the case of VO_2, the existence of a tendency for the LAC values to decrease as the saddle is moved horizontally to more advanced positions and closer to the handlebars. This variation is of higher magnitude than that observed in the case of VO_2 and more evident in the case of flat trials, but it can also be observed in the case of uphill trials, although with less expression. Regarding the flat trials, the most significant difference was observed in the reduction of the LAC between the Flat+50% position and the Flat Base position, with a difference of 39.3% less. Between the Flat+25% position and the Flat Base position, there was also a clear reduction in LAC of about 27.4%. Still, between the two most advanced positions, the difference is quite significant, the Flat+50% position presented a LAC value 16.4% lower than that observed in the Flat+25% position. These differences were confirmed by the results of the SMD analysis presented in Table 7. There were high magnitude effects (-0.8784 and -0.871) in the cases in the ratio between the Flat Base – Flat+25% and Flat Base – Flat+50% positions, and medium magnitude in the relationship between the Flat+25% - Flat+50% positions. In the uphill simulation, although the mean values recorded in the Uphill Base and Uphill+25% positions were similar, in the Uphill+50% position there was a reduction of 2.8% in LAC compared to the Uphill Base position. The flat and uphill LAC values show a similar pattern of variation, although the mean LAC in the Flat Base position is higher than that recorded in the Uphill Base position by 31.3%. At the other end of the evaluated positions, the mean LAC in the Flat+50% position was considerably lower compared to the Uphill+50%: -0.74 mmol/L and 18% lower. Despite the trend evidenced by the data collected, significant differences in LAC were observed among athletes and the patterns cannot be considered linear. The greatest difference was observed in the Flat Base position of 3.51 mmol/L between the maximum and minimum value. The Flat+50% position was the one that registered the smallest difference between the participants of 1.2 mmol/L.

3.4. Heart rate

The HR values obtained are presented in beats per minute (bpm) in Table 8. The observed HR values are quite stable throughout the trials, showing a similar pattern in both flat and uphill situations. No significant differences were found between the mean values of the trials, the values obtained in uphill are higher in only one bpm comparing to the same flat saddle positions. These data can be confirmed through the analysis of Table 9, in which it is possible to verify that all calculations related to SMD resulted in effects of equivalent magnitude, i.e., without significant differences between the groups. However, more significant differences were observed between participants. On average, the difference between the maximum and minimum value recorded in the six saddle positions was 26 bpm. It was in the Uphill+50% position that the highest amplitude of results was recorded, of 31 bpm. The smallest difference was recorded at Flat+50% of 22 bpm.

3.5. Rate of perceived exertion

The Borg scale (6-20) was applied to assess the RPE of the participants. The results are shown in Table 10. Regarding the RPE, in the analysis of the mean of each position, there were no significant differences between the various positions under study. However, as observed for HR, there were important differences between participants. From the analysis of the results of the SMD, expressed in table 11, it is possible to verify that most of the effects were classified as having an equivalent magnitude and only in the two groups (Uphill Base – Uphill+25% and Uphill Base – Uphill+50%), low magnitude relationships were found. Participant 3 was the one who presented the highest RPE values in all trials, also presenting values close to the maximum of the scale in the three uphill trials. There was a mean difference of 6.3 between the maximum and minimum values of each saddle position, the highest values were recorded in the Uphill+25% and Uphill+50% positions. The smallest differences were recorded in the Flat Base and Flat+25% positions.

Table 4. Oxygen consumption in flat and uphill situation

	Flat			Uphill		
	VO_2 (Base)	VO_2 (25%)	VO_2 (50%)	VO_2 (Base)	VO_2 (25%)	VO_2 (50%)
1	52.93	53.13	61.48	56.88	55.99	59.83
2	43.75	41.39	41.25	40.31	39.69	34.59
3	40.39	39.00	39.90	41.33	40.55	41.00
4	51.35	50.11	40.41	44.76	46.45	47.51
5	44.05	41.42	33.94	37.21	27.23	29.34
6	48.33	49.05	44.27	43.68	53.89	45.89
Mean	46.80	45.68	43.54	44.03	43.97	43.03
SD	4.445	5.286	8.591	6.237	9.655	9.775

VO_2, Oxygen consumption (mL/kg/min); SD, Standard deviation.

Table 5. SMD related to VO_2

	SMD - VO_2				
	d	Mean	SD	V	Magnitude
Flat Base – Flat+25%	-0.2293	-1.3636	0.906	0.3354	Low
Flat Base – Flat+50%	-0.4766	-1.16242	0.6709	0.3428	Low
Flat+25% - Flat+50%	-0.3	-1.438	0.8379	0.3371	Low
Uphill Base – Uphill+25%	-0.0074	-1.139	1.1242	0.3333	Equivalent
Uphill Base – Uphill+50%	-0.122	-1.2546	1.0107	0.334	Equivalent
Uphill+25% - Uphill+50%	-0.0968	-1.229	1.0355	0.3337	Equivalent

VO_2, Oxygen consumption (mL/kg/min); d, Effect size value; V, Variance; SD, Standard deviation.

Table 6. Blood lactate concentration in flat and uphill simulation

	Flat			Uphill		
	LAC (Base)	LAC (25%)	LAC (50%)	LAC (Base)	LAC (25%)	LAC (50%)
1	3.05	1.98	2.43	2.21	2.31	2.24
2	1.93	1.70	1.76	1.66	1.70	1.29
3	4.82	2.48	1.23	2.42	3.24	2.07
4	3.53	1.70	1.31	1.83	1.87	2.32
5	1.31	1.53	1.50	1.68	1.69	1.80
6	2.45	3.05	2.14	3.24	2.25	2.94
Mean	2.85	2.07	1.73	2.17	2.18	2.11
SD	1.137	0.533	0.436	0.551	0.534	0.503

LAC, Blood lactate concentration; SD, Standard deviation.

Table 7. SMD related to LAC

	SMD – LAC				
	d	Mean	SD	V	Magnitude
Flat Base – Flat+25%	-0.8784	-2.0633	0.3065	0.3665	High
Flat Base – Flat+50%	-0.871	-2.065	0.313	0.3649	High
Flat+25% - Flat+50%	-0.6983	-1.8638	0.4673	0.3536	Medium
Uphill Base – Uphill+25%	0.0184	-1.1132	1.15	0.3333	Equivalent
Uphill Base – Uphill+50%	-0.1132	-1.2457	1.0193	0.3339	Equivalent
Uphill+25% - Uphill+50%	-0.1343	-1.2672	0.9985	0.3341	Equivalent

LAC, Blood lactate concentration; SD, Standard deviation; d, Effect size value; V, Variance.

Table 8. Flat and uphill heart rate

	Flat			Uphill		
	HR (Base)	**HR (25%)**	**HR (50%)**	**HR (Base)**	**HR (25%)**	**HR (50%)**
1	154	160	160	163	164	166
2	131	134	139	145	140	141
3	156	150	144	147	146	143
4	144	142	140	145	147	146
5	138	141	138	142	136	135
6	151	154	154	139	153	149
Mean	146	147	146	147	148	147
SD	9.0	8.7	8.3	7.7	9.1	9.7

HR, Heart rate (bpm); SD, Standard deviation

.

Table 9. SMD related to HR

	SMD - HR				
	d	**Mean**	**SD**	**V**	**Magnitude**
Flat Base – Flat+25%	0.113	-1.0195	1.2455	0.3339	Equivalent
Flat Base – Flat+50%	0	-1.1316	1.1316	0.3333	Equivalent
Flat+25% - Flat+50%	-0.1176	-1.2502	1.0149	0.3339	Equivalent
Uphill Base – Uphill+25%	0.1136	-1.0139	1.2512	0.3339	Equivalent
Uphill Base – Uphill+50%	0	-1.1316	1.1316	0.3333	Equivalent
Uphill+25% - Uphill+50%	-0.1063	-1.2387	1.0261	0.3338	Equivalent

FC, Heart rate (bpm); SD, Standard deviation; d, Effect size value; V, Variance.

Table 10. Rate of perceived exertion in flat and uphill

	Flat			Uphill		
	RPE (Base)	**RPE (25%)**	**RPE (50%)**	**RPE (Base)**	**RPE (25%)**	**RPE (50%)**
1	14	14	14	14	13	15
2	11	11	11	14	13	12
3	16	16	17	18	19	19
4	12	11	12	13	11	11
5	11	12	12	12	11	12
6	13	14	15	12	13	12
Mean	13	13	13	14	13	13
SD	1.8	1.8	2.0	2.0	2.5	2.8

RPE, Rate of perceived exertion; SD, Standard deviation.

Table 11. SMD related to RPE

	SMD - RPE				
	d	**Mean**	**SD**	**V**	**Magnitude**
Flat Base – Flat+25%	0	-1.1316	1.1316	0.3333	Equivalent
Flat Base – Flat+50%	0	-1.1316	1.1316	0.3333	Equivalent
Flat+25% - Flat+50%	0	-1.1316	1.1316	0.3333	Equivalent
Uphill Base – Uphill+25%	-0.4417	-1.587	0.7036	0.3415	Low
Uphill Base – Uphill+50%	-0.411	-1.5545	0.7325	0.3404	Low
Uphill+25% - Uphill+50%	0	-1.1316	1.1316	0.3333	Equivalent

RPE, Rate of perceived exertion; SD, Standard deviation; d, Effect size value; V, Variance.

4. Discussion

4.1. Oxygen consumption

SHD had effects on the participants' VO_2. In the data collected, it was possible to observe that, as the saddle was moved horizontally towards the handlebars, the mean VO_2 values decreased, both in flat and uphill trials. However, the magnitude of the VO_2 reduction was not the same in the two test situations, flat and uphill. The largest decrease in VO_2 was recorded in the Flat+50% position where oxygen consumption had a reduction of 6.96%. The same trend was observed in the uphill simulation trials. However, despite the clearly descending pattern of the mean VO_2 values of each position tested, when the participants were observed individually, it was found that the pattern of variation was not uniform within the sample. In fact, for example, participant 1 showed an inverse pattern, with an increase in VO_2 with SHD, while participant 6 had a higher VO_2 value in the Uphill+25% position, also contrary to the global pattern. These data seem to suggest that, despite the trend of reduction of VO_2 with SHD towards the handlebars when considering the mean values of each position tested, when determining the ideal horizontal position of the saddle, attention should be paid to the individual characteristics of each cyclist. The difference between groups was assessed according to the Standard Mean Difference (SMD). As can be seen through the analysis of Table 5, the magnitude of the relationships between the positions tested was classified as low or equivalent respectively in flat and uphill, suggesting few differences between the groups, confirming the greater difference between groups in the flat trials. The highest value of SMD was found in the Flat Base – Flat+50% relationship, as expected by the 6.96% reduction in VO_2 observed. In the uphill simulation trials, the reduction in VO_2 was in the order of 2%, the magnitude of the SMD evaluated as equivalent. However, and given that the sample is made up of athletes with a highly competitive level, a gain of 2% should not be disregarded, in a context where any gain, no matter how small, can have a great impact on success in competition (Hall, James & Marsden, 2012). Despite the scarce published literature, authors state that there is moderate evidence that VO_2 is not affected by changes of leg heights of less than 4% in saddle position (Bini & Priego-Quesada, 2022; Connick & Li, 2012). However, the results of the present study seem to suggest that even small changes in the horizontal position of the saddle such as those applied in this experimental procedure, impact oxygen consumption and, consequently, according to the literature (Cheung & Zabala, 2017; Impellizzeri, Marcora, Rampinini, Mognomi & Sassi, 2005; Vandewalle, 2004), in the energy cost and performance of the MTB cyclist. These results seem to be in line with the findings of Ferrer-Roca et al. (2014), who reported an increase in VO_2 when they changed the position of the saddle in height. In this sense, and although current knowledge remains scarce and not very consensual, the results of this study seem to reinforce that the modification of the saddle position has an impact on the cyclist's energy consumption, even with small variations of the saddle position.

4.2. Lactate concentration

Similar to what was observed in the case of VO_2 in this study, there was also a tendency to reduce LAC values as the saddle moves horizontally to more advanced positions and closer to the handlebars, clearly more evident in flat trials, but also present in uphill trials. These results seem to be in line with the literature, since, like VO_2 or HR, LAC is a measure of the impact of the load imposed on the cyclist (Halson, 2014; Mujika, 2017) and is expected to follow the downward pattern due to SHD, found in the assessment of VO_2. The LAC recorded in the Flat+50% position was 39.3% lower than that recorded in the Flat Base position, and in the Flat+25% position it was 27.4% lower than that recorded in the Flat Base position. This significant difference was confirmed by SMD, with a high magnitude classification for both assays. Similarly, the SMD for Flat+25% - Flat+50%, classified as medium magnitude, also confirms the trend towards a reduction in the LAC value with SHD. It is a substantial difference and confirms, once again, that SHD in the direction of the handlebars seems to be more advantageous for MTB cyclists on flat terrain since, according to the literature (Faria et al., 2005b), high LAC values are limiting for cycling performance. As in the case of VO_2, significant differences in LAC were also observed between participants, with no linear pattern and referring, once again, to the need to consider the individual characteristics of each cyclist. Recent literature reports that about 43% of the total racing time of an XCO race is spent at high intensity, above the second lactate threshold (Arriel et al., 2022). The literature relating the MTB rider's saddle position and performance is scarce. In this sense, the reduction of lactate production by optimizing the saddle position would be highly advantageous for the cyclist, as the results of this study seem to suggest.

4.3. Heart rate

Analyzing the data from the trials performed, HR appears not to have been affected by the change in the saddle position. The mean values of each trial are stable and with minor differences. This is confirmed by the data on SMD described in Table 9, where it is possible to verify that the differences between groups were residual and of equivalent magnitude. However, once again substantial differences were found between participants in the various trials conducted. On the other hand, in the assessment of HR, it should be considered that the normal values of each individual can vary substantially for the same intensity of effort and that HR, which can be affected by environmental, physiological, psychological factors, way of life, among others, has an individual response to the load (Schneider et al., 2018). This can be evidenced by the difference between HR values recorded between the participants of the same trial. For example, in the case of the Uphill+50% trial, HR values reached an amplitude of 31 bpm between participants. Therefore, the collected data suggest that it is not possible to conclude about the influence of SHD on HR.

4.4. Rate of perceived exertion

The Borg scale (6-20) was applied to the participants at the 7th minute of each trial. In the analysis of the mean values of each position, no significant differences were observed between the various positions under study. This data seems to be in agreement with the evaluation of SMD, in which the relationships found were classified as equivalent or low. The greatest differences seem to exist between the groups Uphill Base – Uphill+25% and Uphill Base – Uphill+50%, in which values of respectively -0.4417 and -0.411 were recorded, close to the medium value of magnitude classification. RPE is a subjective analysis of the sensation of exertion that the athlete experiences during the activity. In the overall analysis of the sample, it is possible to verify that most of the reported values suggest that the load imposed on the participants was perceived as being of moderate intensity, according to the scale (Borg, 1990). This finding is in line with the objective of the target load defined for this study, of 70% of the MAP. In the particular analysis of each participant, it is possible to verify that participant 3 reported RPE values significantly higher than the others in both situations, flat and uphill, higher in the latter case. This fact can be explained by the participant's inexperience in applying the scale, having reported that it was the first time he applied it, being still the youngest and least experienced participant in the group. However, Baino (2011) reported that comfort on the bicycle is highly subjective and highly related to the cyclist's personal preferences, which may also explain the differences found between the RPE of participant 3 compared to the others. Therefore, as in the case of HR, the stability of the mean values of each position tested does not allow us to draw conclusions from the data collected on the influence of SHD on the RPE.

5. Practical Applications and Study Limitations

The results of this study are important for the daily practical work of coaches and cyclists and bring new knowledge regarding the determination of the ideal saddle position for MTB cyclists. Changing the position of the saddle must be carried out carefully and considering the individual characteristics of each cyclist, as the change can have an impact on performance, that can be either positive or negative.

To the best of our knowledge, this was the first study carried out on this topic, bringing new data, which attests to its relevance. The major limitation of this study is the fact that it was carried out with a small sample of only 6 participants, and for this reason it is not possible to establish definitive correlations between the physiological variables analysed, thus some caution should be exercised in extrapolating the results obtained. This low number of participants also limited the statistical analysis of the study results. Nevertheless, the fact that the participants are athletes of a highly competitive level is a differentiating factor that enhances the reliability of the data collected. Another important limitation is the fact that the trials were carried out in a laboratory context, in which the researchers sought to reproduce the real conditions of practice. Further studies should be carried out with a larger number of participants, and the research should also be extended to female athletes. It would also be beneficial to increase knowledge in this area, by combining the evaluation of physiological variables, biomechanical variables such as torque, joint angulations and activation of the main muscle groups involved.

6. Conclusions

The results confirmed that the horizontal variation of a MTB rider's saddle impacts on VO_2, LAC, HR and RPE. The results also seem to suggest that the horizontal displacement of the saddle position to forward positions in the direction of the handlebars has benefits for the rider by reducing energy consumption and, consequently, enhancing performance. The Base+50% position seems to be the most advantageous from the point of view of the MTB rider's energy consumption. Further studies should be conducted to confirm. When determining the ideal saddle position, the individual characteristics of the rider must be considered. In high-level competitive athletes, with a focus on performance, individual evaluation should be supported by physiological and biomechanical measurements and choice of materials.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

Arriel, R. A., Souza, H. L., Sasaki, J. E., & Marocolo, M. (2022). Current perspectives of cross-country mountain biking: physiological and mechanical aspects, evolution of bikes, accidents and injuries. *International journal of environmental research and public health*, 19(19), 12552. doi: 10.3390/ijerph191912552

Asplund, C., & St Pierre, P. (2004). Knee pain and bicycling. *The Physician and Sports Medicine*, 32(4), 23–30. doi: 10.3810/psm.2004.04.201

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. doi: 10.1080/0264041031000102097

Baino, F. (2011). Evaluation of the relationship between the body positioning and the postural comfort of non-professional cyclists: a new approach. *The Journal of sports medicine and physical fitness*, 51(1), 59-65.

Belluye, N., & Cid, M. (2001). Approche biomécanique du cyclisme moderne, données de la littérature. *Science & sports*, 16(2), 71-87. doi: 10.1016/S0765-1597(01)00049-1

Bini, R. R., & Carpes, F. P. (2014). *Biomechanics of cycling*. Springer.

Bini, R. R., Hume, P. A., & Croft, J. (2014). Cyclists and triathletes have different body positions on the bicycle. *European Journal of Sport Science*, 14(sup1), S109-S115. doi: 10.1080/17461391.2011.654269

Bini, R. R., Hume, P. A., Lanferdini, F. J., & Vaz, M. A. (2013). Effects of moving forward or backward on the saddle on knee joint forces during cycling. *Physical Therapy in Sport*, 14(1), 23-27. doi: 10.1016/j.ptsp.2012.02.003

Bini, R., & Priego-Quesada, J. (2022). Methods to determine saddle height in cycling and implications of changes in saddle height in performance and injury risk: A systematic review. *Journal of sports sciences*, 40(4), 386-400. doi: 10.1080/02640414.2021.1994727

Borg, G. (1990). Psychophysical scaling with applications in physical work and the perception of exertion. *Scandinavian journal of work, environment & health*, 55-58.

Burt, P. (2014). *Bike Fit*. Bloomsbury: London.

Burt, P. (2022). *Bike Fit 2nd Edition*: Optimise Your Bike Position for High Performance and Injury Avoidance. Bloomsbury Publishing.

Callaghan, M. (2005). Lower body problems and injury in cycling. *Journal of Bodywork and Movement Therapies*, 9, 226–236. doi: 10.1016/j.jbmt.2005.01.007

Chapman, A. R., Vicenzino, B., Blanch, P., Knox, J. J., Dowlan, S., & Hodges, P. W. (2008). The influence of body position on leg kinematics and muscle recruitment during cycling. *Journal of Science and Medicine in Sport*, 11(6), 519-526. doi: 10.1016/j.jsams.2007.04.010

Cheung, S. S., & Zabala, M. (Eds.). (2017). *Cycling science*. Human Kinetics.

Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*. Academic press.

Connick, M. J., & Li, F. X. (2013). The impact of altered task mechanics on timing and duration of eccentric bi-articular muscle contractions during cycling. *Journal of Electromyography and Kinesiology*, 23(1), 223–229. doi: 10.1016/j.jelekin.2012.08.012

Di Alencar, T. A. M., de Sousa Matias, K. F., & de Oliveira, F. B. (2010). Cinesiologia e biomecânica do ciclismo: Uma revisão. *Revista Movimenta*; Vol, 3(1).

Faraone, S. V. (2008). Interpreting estimates of treatment effects: implications for managed care. *Pharmacy and Therapeutics*, 33(12), 700.

Faria, E. W., Parker, D. L., & Faria, I. E. (2005a). The science of cycling. Factors affecting performance – Part 2. *Sports medicine*, 35, 313–337. doi: 10.2165/00007256-200535040-00003

Faria, E. W., Parker, D. L., & Faria, I. E. (2005b). The science of cycling. Physiology and training – Part 1. *Sports medicine*, 35, 285–312. doi: 10.2165/00007256-200535040-00002

Ferrer-Roca, B. (2016). *Comparación de diferentes métodos de ajuste de la bicicleta en ciclistas entrenados: influencia de factores biomecánicos y energéticos*. (Doctoral dissertation, Universidad de León).

Ferrer-Roca, V., Bescos, R., Roig, A., Galilea, P., Valero, O., & Garcia-Lopez, J. (2014). Acute effects of small changes in bicycle saddle height on gross efficiency and lower limb kinematics. *Journal Of Strength And Conditioning Research / National Strength & Conditioning Association*, 28 (3), 784–791. doi: 10.1519/JSC.0b013e3182a1f1a9

Ferrer-Roca, V., Roig, A., Galilea, P., & García-López, J. (2012). Influence of saddle height on lower limb kinematics in well-trained cyclists: static vs. dynamic evaluation in bike fitting. *The Journal of Strength & Conditioning Research*, 26(11), 3025-3029. doi: 10.1519/JSC.0b013e318245c09d

Fonda, B., Panjan, A., Markovic, G., & Sarabon, N. (2011). Adjusted saddle position counteracts the modified muscle activation patterns during uphill cycling [Article]. *Journal of Electromyography & Kinesiology*, 21(5), 854-860. doi: 10.1016/j.jelekin.2011.05.010

García-López, J., & del Blanco, P. A. (2017). Kinematic analysis of bicycle pedalling using 2d and 3d motion capture systems. *ISBS Proceedings Archive*, 35(1), 125.

Granier, C., Abbiss, C. R., Aubry, A., Vauchez, Y., Dorel, S., Hausswirth, C., & Le Meur, Y. (2018). Power output and pacing during international cross-country mountain bike cycling. *International journal of sports physiology and performance*, 13(9), 1243-1249.

Hall, D., James, D., & Marsden, N. (2012). Marginal gains: Olympic lessons in high performance for organisations. *HR Bulletin: Research and Practice*, 7(2), 9-13.

Halson S. L. (2014). Monitoring training load to understand fatigue in athletes. *Sports medicine* (Auckland, N.Z.), 44 Suppl 2(Suppl 2), S139–S147. doi: 10.1007/s40279-014-0253-z

Holliday, W., & Swart, J. (2021). Anthropometrics, flexibility, and training history as determinants for bicycle configuration. *Sports Medicine and Health Science*, 3(2), 93–100. doi: 10.1016/j.smhs.2021.02.007

Impellizzeri, F. M., Marcora, S. M., Rampinini, E., Mognoni, P., & Sassi, A. (2005). Correlations between physiological variables and performance in high level cross-country off road cyclists. *British journal of sports medicine*, 39(10), 747-751. doi: 10.1136/bjsm.2004.017236

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. doi: 10.1007/s00421-011-1914-3

Macdermid, P. & Stannard, S. (2012). Mechanical work and physiological responses to simulated cross country mountain bike racing. *Journal of Sports Sciences*, 30:14, 1491-1501. doi: 10.1080/02640414.2012.711487

Menard, M., Domalain, M., Decatoire, A., & Lacouture, P. (2018). Influence of saddle setback on knee joint forces in cycling. *Sports Biomechanics*. doi: 10.1080/14763141.2018.1466906

Mujika, I. (2017). Quantification of Training and Competition Loads in Endurance Sports: Methods and Applications. *International Journal of Sports Physiology and Performance*, 12(s2), S2-9-S2-17. doi: 10.1123/ijspp.2016-0403

Peveler, W.W. & Green, J.M. (2011). Effects of saddle height on economy and anaerobic power in well-trained cyclists. *The Journal of Strength & Conditioning Research*, 25: 629–633. doi: 10.1519/JSC.0b013e3181d09e60

Rankin, J. W., & Neptune, R. R. (2010). The influence of seat configuration on maximal average crank power during pedaling: a simulation study. *Journal of Applied Biomechanics*, 26(4), 493-500. doi: 10.1123/jab.26.4.493

Ricard, M. D., Hills-Meyer, P., Miller, M. G., & Michael, T. J. (2006). The effects of bicycle frame geometry on muscle activation and power during a Wingate anaerobic test. *Journal of sports science & medicine*, 5(1), 25.

Silberman, M., Webner, D., Collina, S., & Shiple, B. (2005). Road bicycle fit. *Clinical Journal of Sport Medicine*, 15, 271–276. doi: 10.1097/01.jsm.0000171255.70156.da

Schulz, K. F., Altman, D. G., & Moher, D. (2010). CONSORT 2010 statement: updated guidelines for reporting parallel group randomised trials. *Journal of Pharmacology and pharmacotherapeutics*, 1(2), 100-107. doi: 10.4103/0976-500X.72352

Schneider, C., Hanakam, F., Wiewelhove, T., Döweling, A., Kellmann, M., Meyer, T., ... & Ferrauti, A. (2018). Heart rate monitoring in team sports—a conceptual framework for contextualizing heart rate measures for training and recovery prescription. *Frontiers in physiology*, 639. doi: 10.3389/fphys.2018.00639

Swart, J., & Holliday, W. (2019). Cycling biomechanics optimization—the (R) evolution of bicycle fitting. *Current sports medicine reports*, 18(12), 490-496. doi: 10.1249/JSR.0000000000000665

Vandewalle, H. (2004). Oxygen uptake and maximal oxygen uptake: interests and limits of their measurements. *Annales de réadaptation et de médecine physique* 47, 243-257. doi: 10.1016/j.annrmp.2004.05