A study on the biomechanical efficiency of different cycling positions

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SUMMARY. This study was designed to determine how modifications in cycle geometry and lower-limb kinematics determine changes in oxygen uptake and lactate accumulation during submaximal cycle ergometry. First a series of tests with ten athletes was carried out with different seat-tube angles (STA test) determining different frame geometries. The tests performed with a rigid protocol show an interesting relationship between the trend of the coefficient of variation of O_2 consumption (respiratory dynamics) and the forces measured on saddle and handlebar. The stabilization of the respiratory dynamics registered for a particular position could be considered as a first step of O_2 consumption physiologic adaptation. For this reason a long term adaptation test (LTA test), in which the subject trained for 8 weeks with a determined STA, was executed to find out how long time spent using a specific frame geometry results in a minimization of the energetic cost of pedalling at a constant power output. The findings obtained suggest that, after a long training period with a bicycle frame geometry that minimizes the force exerted by the subject on saddle and handlebar, a stabilization of O_2 consumption and a decrease of blood lactate accumulation occur. This physiologic adaptation of the human body means a decreasing trend of energy consumption in central (O_2) and peripheral (lactate) level. Moreover this paper proposes an innovative method to determine the optimum cycling position, considering also the contribution of the upper part of the human body. In fact the original method proposed here, takes into consideration the horizontal components of the forces exerted on the handlebar and on the saddle as fundamental parameters for minimizing the ineffective efforts during cycling. This study is part of an extensive research that uses quantitative methods to establish the optimum rider position in order to minimize the muscular efforts performing a specific task, in aerobic phase.

1 INTRODUCTION

It is well known that several are the "biomechanical" parameters (e.g. the pedalling frequency, the crank-arm length, the saddle height, the seat tube angle, etc. only to name a few) that could affect cycling performance. Even if the optimal values and the sensitivity of each parameter would differ whether the efficiency or the power output have to be maximized, the variations in the positioning of the athlete are found to be, in either case, of particular importance. The biomechanical analysis of bicycle pedalling through experimental devices designed to evaluate the muscular efficiency of the lower limbs is an important asset in sport medicine. In this field, one of the main effort is focused to improve athlete's performance through special positions that may influence the muscular coordination and the pedalling technique [1] [2]. For these reasons, in the last decades many researches has been carried out in sport medicine making use of both mechanical and medical techniques. The biomechanical analysis of pedalling requires a theoretical model together with a proper experimental device, suitably equipped to detect the parameters involved by the model in order to obtain a fully determined activity monitoring [3]. Then by a mathematical model of the two human body structures, the skeleton and the muscular apparatus, the kinematics and dynamics of the system of lower limbs and crank can be obtained. The medical techniques mainly consist of estimating the muscular metabolism based on measurements of heart rate, lactate production, oxygen uptake and determination of the ventilatory threshold [4] while mechanical-engineering devices are developed to detect the kinematical and dynamical parameters [5]. Many researchers have attempted to relate specific geometry variables to the optimization of maximal [6] and submaximal [7] oxygen uptake (VO_2) during stationary cycling. This body of literature often makes a distinction between optimal and preferred cycle geometries. An optimal geometry during submaximal cycling is commonly defined as one that coincides with the minimization of a VO_2-based cost function when evaluated over a specific range of the geometry variable. Conversely, a preferred geometry is defined as one which a cyclist would freely choose when given a choice [8].

The present study was designed to determine how changes in frame geometry during submaximal cycle ergometry may influence physiological parameters (i.e. oxygen uptake (VO_2), pulmonary ventilation (VE), heart rate (HR) and carbon dioxide output (VCO_2)) and mechanical parameters (i.e. forces exerted on pedals, saddle and handlebar). In particular the correlation between metabolic and mechanical parameters was analyzed at six different seat-tube angles (70°÷75°) (STA test) using the CPS (Cycling Positioning System) ergometer [3]. Long term adaptation test (LTA test) with a particular cycling position was then carried out to investigate the effect of variation in seat-tube angle in oxygen uptake and lactate accumulation.

2 MATERIALS AND METHODS

2.1 *The prototype*

Both STA and LTA tests were carried out with a special instrumentation device called CPS apparatus which consists of a 7-degrees of freedom device designed to analyze, test and optimize different positions of a bicycle rider. The ergometer is driven by seven hydraulic actuators that allow a complete regulation of the following parameters: 1) elevation of the saddle, 2) slope of the saddle, 3) seat tube angle (STA), 4) elevation of the handlebar, 5) saddle-to-handlebar distance, 6) wheelbase (inter-axles front-to-rear wheel distance) and 7) frame slope. The measurement chain includes two strain gage cells (mod. Vishay 1042) to measure the forces exerted on saddle and handlebar in levelled horizontal position along the longitudinal frame direction and an electric brake system (Elite Realaxiom) to control via computer the power performance.

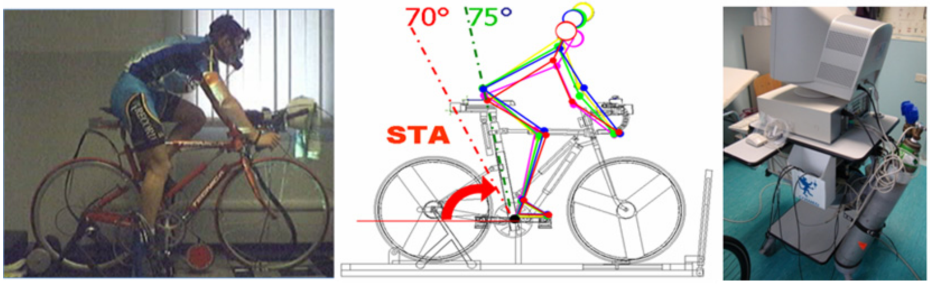
The special apparatus is completed by two instrumented pedals for three-axial force measurement equipped with piezoelectric load cells (Kistler 9047B) and with bi-directional incremental encoder (Baumer BDK) to detect the pedal slope and by a device for the measurement of the crank rotation angle [9]. In this way eight forces and three angles are simultaneously measured during the pedal stroke. The system allows data acquisitions of forces, angles and velocities during cycling performance by means of a LabVIEW-based software and data processing by means of programs written in Matlab code. Moreover the athletes were equipped with a portable system (Cosmed Quark b^2) to measure pulmonary ventilation (VE, [$lmin^{-1}$]), HR [bpm], carbon dioxide output

(VCO_2, [$lmin^{-1}$]) and oxygen uptake (VO_2, [$lmin^{-1}$]) on time basis.

The traditional method adopted to determine the frame geometry assumes the position of the rider according with the KOPS configuration (Knee Over the Pedal Spindle). It consists in positioning the rider's saddle so that the knee (the tibial tuberosity) is over the pedal spindle with the crank in horizontal position. In this way the relation between the positions of torso, arms and head for different physiques is not explicitly taken into account and the importance of the position of the whole body centre of mass of the rider, results completely neglected.

This paper proposes an innovative method to determine the optimum cycling position, considering the contribution of the upper part of the human body. In this way the horizontal components of the forces exerted on the handlebar and on the saddle are taken into account as fundamental parameters for minimizing the ineffective efforts during cycling. In particular the difference between the forces exerted by the subject on the saddle and on the handlebar is considered as the proper index to realize an equilibrated position. The minimization of such difference seems to guarantee the minimum effort for grasping the handlebar and for the push/pull action on the saddle that do not produce any active effect to the propulsion. Further consequence of the method is the concentration of the pushing action of the legs on the pedals in the best effective way, i.e. with the charge as vertical as possible. This way to detect the optimum rider position in some cases resulted in a configuration very close to the KOPS. Anyhow, the authors consider this method more affordable than KOPS, since it takes into consideration the whole body mass and force distribution in a more comprehensive way.

The particular prototype realized with the horizontal dynamometric pick-ups on the saddle and the handlebar was especially realized in order to validate the method proposed here. The experimental tests carried out confirmed the validity of the idea.



a) b) c)

Figure 1: a) Training session with CPS
b) Change in STA angle c) Cosmed Quark b^2 Metabograph.

2.2 *Subjects*

In the first part of the study (STA test) the experiments were performed on ten semi-professional road male cyclists of [Mean (SD)] 29.40 (6.80) years of age, 68.30 (6.00) kg body mass and 174.50 (5.30) cm body height. The LTA test was carried out with a professional road cyclist of 18 years of age, 171 cm body height and 62 kg body mass. Before participating to the tests the subjects were fully informed about the aim of the study and gave their informed consent to the experimental procedure.

Subject	**Age [years]**	**Height [cm]**	**Body Mass [kg]**	**Thigh length [cm]**	**Shank length [cm]**	**Experience**
A	25	182	71.0	49	41	Semi professional
B	34	180	72.0	47	42	Semi professional
C	21	178	75.0	41	39	Semi professional
D	31	171	59.0	50	39	Semi professional
E	30	164	68.0	45	36	Semi professional
F	24	177	73.0	48	43	Semi professional
G	32	176	74.5	46	38	Former racer
H	44	175	69.0	48	39	Former racer
I	31	170	60.0	44	39	Semi professional
L	22	172	62.0	46	39	Racer
M (LTA)	18	171	62.0	45	36	Racer

Table 1: Anthropometric data.

2.3 *Protocol*

A systematic series of tests with an accurate protocol were performed in this research. At first the anaerobic threshold with V-slope method was determined for each subject. In particular the test was performed with the CPS ergometer in a configuration reproducing the position of each subject usual bicycle frame and the athletes were monitored passing from a resting state reproducing their natural metabolic rate and gradually increasing the external mechanical power by 50 W every 5 min. The subjects were requested to maintain the 90 rpm pedalling cadence at each load rate. In this way the maximum power output performed by the subject was determined and the power rate for the subsequent STA test was chosen equivalent to 80% of the oxygen uptake (VO_2) at each subject's ventilatory threshold. The STA test was then performed for each athlete one week after the preliminary session at approximately the same hour of the day. The athletes were requested to repeat the test with the fixed power and pedalling rate while the STA was changed from 70° to 75° with an interval of 1 degree every 5 min. The range indicated is the best interval for standard bicycle frame geometry as demonstrated by previous researches [3, 5]. Those results are further confirmed in the following (see for example Figure 6). In order to evaluate the long term adaptation of the human body to a specific frame geometry and the correlation between mechanical and metabolic parameters the LTA test was then performed. In addition to the other parameters, the lactate was involved in the process via a lactate Mader test to determine the Onset of Blood Lactate Accumulation (OBLA), defined as the effort that corresponds to a lactate concentration of 4 mMol/l. A professional road male cyclist carried out the same two previous experimental sessions, with the same accurate protocol, with the STA changing from 67° to 80° and then was requested to train for 8 weeks with a frame bicycle corresponding to a STA of 75° that reproduced the equilibrium force position between the horizontal component of the force on the saddle and on the handlebar registered with the prototype ergometer.

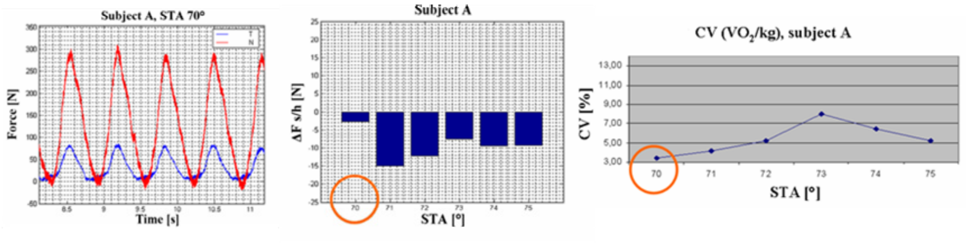
2.4 *Kinematical and dynamical analysis*

The special prototype adopted allows to detect the external mechanical power, the pedalling frequency, the force exerted on each pedal in three main directions, the angle of oscillation of each pedal during revolution and the forces exerted on the saddle and the handlebar. By “link-segment modeling” and considering the kinematical parameters, by means of an inverse dynamic procedure it is possible to calculate the internal actions and in particular the moments acting on each link segment with free-body diagram method. The bidimensional five-bar linkage model has been previously and successfully applied in many researches [10]. Moreover, a session of video sampling was recorded for each test with a sampling rate of 30 Hz and circular reflective markers were placed on relevant joints of the subjects of the right para-sagittal plane of the body to obtain the coordinates and the angles between the body segments: in particular the changes in mean angle of elbow, shoulder, pelvis (hip), knee and ankle were taken into account to relate the change of the mechanical and metabolic parameters to the different STA values, determining particular cycling positions.

3 RESULTS AND DISCUSSION

3.1 *The STA test*

The tests performed at six different values of the STA (70°÷75°) with ten trained cyclists to relate the change in frame geometry and cycling position to metabolic parameters demonstrate that a minimization of submaximal VO_2 and HR does not occur as a function of a specific seat-tube angle. The analyzed data of the balance force exerted on the saddle and on the handlebar show an increase of the force on the handlebar when increasing STA: the same results does not occur for the saddle. Consequently it is not possible to establish the existence of a STA that produces a balance between saddle/handlebar forces for different subjects as a general result. Besides each subject shows a STA value that minimizes the difference between saddle/handlebar force (ΔFs/h). Considering the biomechanical parameters, no variation of the Normal and Tangential force components on pedals seems to be related to a change in STA. This could be influenced by some limiting factors such as: a) the range of variability of STA parameter is very narrow and probably each of the positions in the interval are very close to the optimum; b) the system adopted to fix the shoe to the bicycle pedal by means of strap probably does not allow to appreciate the difference in force exerted due to the very little rate of change in STA. In Fig.2a) an example of the trend of the two force components (in normal and tangential direction) on the right pedal during the test with STA equal to 70° for subject A is reported.



a) b) c)

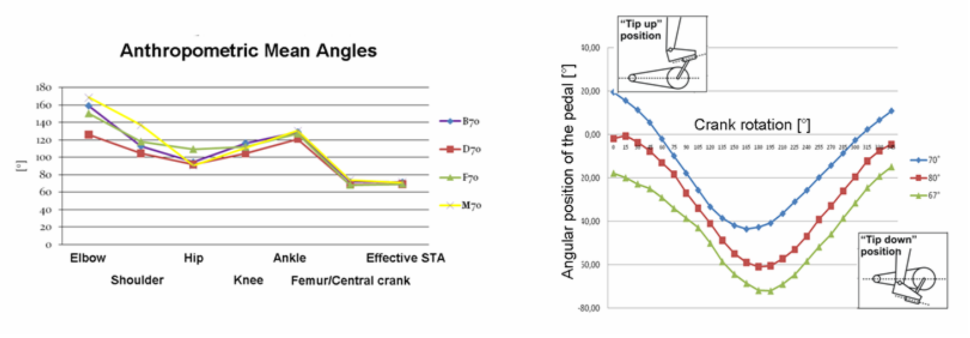
Figure 2: Experimental data for subject A
a) Normal and tangential force components on right pedal for 70° STA
b) Difference between the force exerted on saddle and handlebar in levelled horizontal position along the longitudinal frame direction (ΔFs/h) c) $CV(VO_2/kg)$ trend for different STA.

More interesting results follow by the correlation found between the balance on saddle/handlebar force (ΔFs/h) and the coefficient of variation of the oxygen uptake over the unit of mass subject CV(VO_2/kg). The CV is a normalized measure of dispersion of a probability distribution. It is defined as the ratio of the standard deviation σ to the mean μ: and it is considered as the appropriate index to compare the variability of different parameters. Figures. 2b) and 2c) show the trend of (ΔFs/h) and of CV(VO_2/kg) for subject A. For five subjects out of ten the correlation between these two parameters is evident, for three is probable and for the last two riders there is no correlation at all.

On the other hand it can be observed that a) human body needs a period of physiological adaptation to different positions b) possible different metabolic ways of muscular activation such as lactate recycling process could occur during the exercises and could contribute to the not completely significant data obtained. Besides these results suggest the existence of an interesting relationship between the difference of the forces exerted horizontally on saddle and handlebar by the cyclists and the trend of the coefficient of variation of O_2 consumption showing a stabilization of the respiratory dynamics. This stabilization, registered for a particular position, could be considered as a first step of O_2 consumption physiologic adaptation. For this reason a second test was established to verify the variation in oxygen uptake adopting an equilibrated position with saddle/handlebar force in a long term adaptation exercise (LTA test).

3.2 *The LTA test*

The results obtained from the STA test suggested that the optimization of submaximal VO_2 during stationary ergometer cycling was not directly related to changes in frame geometry variables. Besides a stabilization in respiratory dynamics for a particular position was evident in each subject's test. The relation existing between O_2 consumption and physiologic adaptation of the human body indicated to perform a specific test to investigate the trend of energy consumption in central (O_2) and peripheral (lactate) level. The range in STA was extended from 67° to 80°. The analysis of the changes in lower limb-kinematics with concern to the mean angle of elbow, shoulder, pelvis (hip), knee and ankle shows that: a) an increase in STA determines an adaptation in the rider position: in particular elbow, shoulder and knee angles tend to decrease with an increase in STA; b) the athletes with the same IBM (Index of body mass) tend to adopt the same cycling position (see Figure 3a) referred to subjects B, D, F and M).



a) b)

Figure 3: a) Trend of typical mean angles for subjects with the same IBM at 70° STA b) Change of pedal angle (slope) over a crank rotation in respect to STA change, for subject M.

In figure 3b) the trend of pedal angle during a complete crank rotation for three different STA positions is reported. In general it can be stated that the pedal tends to naturally oscillate during the crank rotation passing from a 'tip up' position when the foot is pushing (active phase) to a 'tip down' position in the recovery phase of the pedalling. Besides this common aspect may differ from subject to subject and some particularly trained and skilful athletes may have a range of oscillation of the pedal extremely limited. The analysis of the angular position of the pedal, for subject M, shows that in the extreme configurations of STA at 67° and 80° a 'tip down' position of the pedal is adopted while for the intermediate 75° STA an oscillation of the pedal from 'tip up' to tip down' occurs. This aspect denotes a more equilibrated kinematics of the lower limb during cycling and in particular a more natural trend of change in ankle mean angle. The range of angular position of the pedal is very similar for all the configurations adopted.

Considering the force exerted on the pedal by the subject during the test, it can be noted that the effective force on pedal (which is the vectorial sum of the measured normal N and tangential T force components) rotates with STA change: in particular the variation is noteworthy (15°) in the range 67°÷75° STA whilst stable in the range 75°÷80° (see Figure 4). Increasing STA the subject tends to settle in the different position by putting forward to the handlebar and consequently tends to shift forward the beginning of the active phase during the crank rotation. Moreover the range of the active phase is almost identical and equal to approximately 200° in each STA configuration.

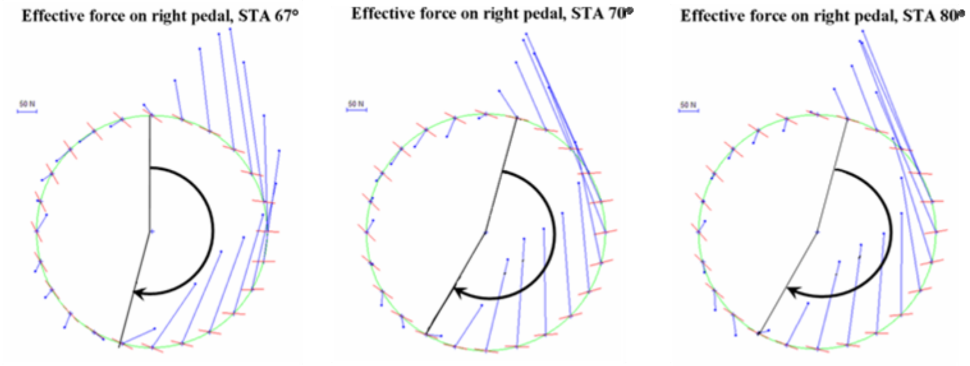
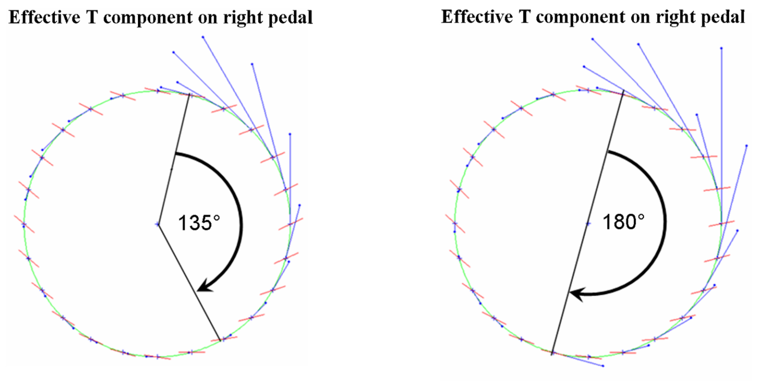


Figure 4: Effective force on pedal during a complete crank rotation for different STA values.

For the subsequent session a STA of 75° was detected as the optimum between the balance on saddle/handlebar force (ΔFs/h) and the minimum CV(VO_2/kg). Then the professional road cyclist (subject M) trained for 8 weeks with a frame bicycle corresponding to a STA of 75°. All biomechanical parameters were registered before and after the training period. In particular the comparison, before and after the training, between the tangential component of the effective force in respect of the pedal trajectory, which is the real active force for the propulsion, shows the presence of the same previous rotation and moreover highlights an increase of the downstroke angular phase (see Figure 5). In fact, after the training the active phase starts in the same point at approximately 285° but the range of action extends from 135° to 180°. This fact demonstrates the influence of adaptation during long training.



a) b)

Figure 5: Effective tangential force during a complete crank rotation a) Before the training b) After 8 weeks of training with 75° STA.

In addition to the other biomechanical and physiologic parameters, the lactate concentration was even monitored for subject M. By blood samples during STA test protocol and after the long training session it was possible to compare the lactate concentration that is directly related to the amount of effort to perform a specific task. The analysis of the trend in lactate accumulation, before the training, highlights the presence of high values for the positions corresponding to STA 67° and 80°, showing a marked saddle point for the intermediate position. After the training the same shape is maintained but all the lactate accumulation values are significantly lower. Moreover the presence of a minimum in correspondence of the position adopted for the training suggests the existence of a physiologic adaptation of the human body consisting in a decreasing trend of energy consumption in central (O_2) and peripheral (lactate) level.

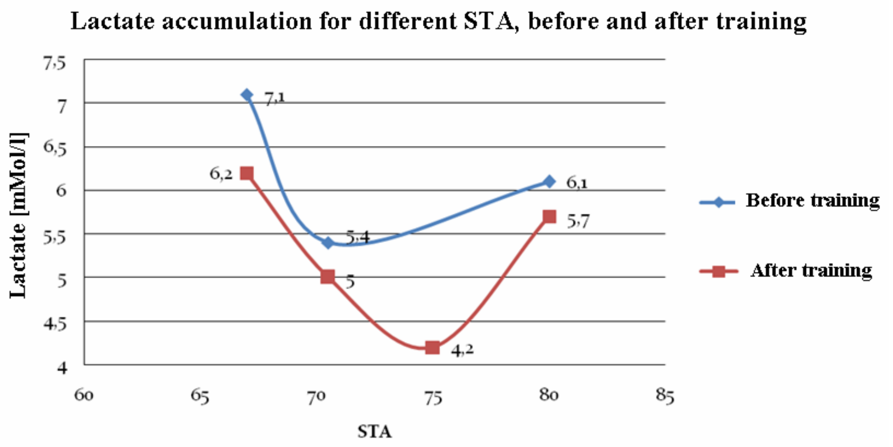


Figure 6: Trend of lactate accumulation before and after LTA test for different STA values.

4 CONCLUSIONS

This study was designed to determine how changes in cycle geometry and lower-limb kinematics determine changes in oxygen uptake and lactate accumulation during submaximal cycle ergometry. A rigid protocol by means of a special apparatus was carried out to analyze quantitative data from many biomechanical parameters. In particular two series of tests were carried out to investigate how changes in seat-tube angle may influence the energetic cost of cardiovascular and ventilatory functions and the importance of adaptation in the active musculature during a specific task. First a series of tests with ten athletes was carried out with different seat-tube angles (STA test) determining different frame geometries.

Remark 1. The STA tests demonstrate that a minimization of submaximal VO_2 and HR does not occur as a function of a specific seat-tube angle. Besides the tests show an interesting relationship between the trend of the coefficient of variation of O_2 consumption (respiratory dynamics) and the forces measured on saddle and handlebar. The stabilization of the respiratory dynamics registered for a particular position could be considered as a first step of O_2 consumption physiologic adaptation.

For this reason a long term adaptation test (LTA test), in which the subject trained for 8 weeks with a determined STA, was executed to find out how long time spent using a specific frame geometry results in a minimization of the energetic cost of pedalling at a constant power output.

Remark 2. It can be stated that after a long training period with a bicycle frame that minimizes the force on saddle and handlebar (ΔFs/h), a stabilization of O_2 consumption and a decrease of blood lactate accumulation occur. This physiologic adaptation of the human body suggests a decreasing trend of energy consumption in central (O_2) and peripheral (lactate) level.

Remark 3. The rider position obtained, detected with an innovative method, guaranties to minimize the effort for grasping the handlebar and for the push/pull action on the saddle that do not seem to produce any active effect to the propulsion.

This study is part of an extensive research that uses quantitative methods to establish the optimum rider position in order to minimize the muscular efforts performing a specific task, in aerobic phase.

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