The effect of seat-tube angle on biomechanical efficiency in cycling investigated by a new methodology: preliminary results on a new virtual sensor.

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SUMMARY. Recent studies in Biomechanics are focused on postural optimization in cycling: among the numerous mechanical parameters the Seat Tube Angle (STA) is analyzed as the one that may influence the performance of cycling and triathlon athletes. In particular, it was conjectured that the STA may affect the biomechanical efficiency of a cyclist. The diffusion of this conjecture is testified by the frequent use of tuning techniques intending to get the optimal STA angle by professional teams. In order to define a model of the biomechanical efficiency based on mechanical parameters, this paper presents a preliminary study aiming to confirm (or deny) this conjecture which asserts that a realistic biomechanical model has to include the STA as the independent (input) variable. The natural dependent (output) variable is the biomechanical efficiency measured by a new virtual sensor which hinges on both a dynamic and a static physiological model. In particular, those models where used to determine a range of mechanical and physiological values that guarantees a linear relationship between the biomechanical efficiency and the oxygen uptake. A two-phase experiment was designed to determine how changes in frame geometry during submaximal cycle ergometry have effects on the biomechanical efficiency. In particular, different STA positions were tested to argue if the STA is related to the cyclist performances. The methodology adopted was selected in order to keep constant all the major exogenous variables but the STA. The design of experiment results in a rigid protocol implemented on 14 subjects. The preliminary data analysis seems to suggest the existence of a relationship between the STA variation and the cycling efficiency. To prove an explicit relationship for all the athletes involved a more detailed statistical analysis is required. Further studies will investigate this particular aspect.

1 INTRODUCTION

The cycling performance is affected by several biomechanical parameters (e.g. pedalling rate, crank-arm length, saddle height, seat tube angle, etc.) and the variations in the positioning of the athlete are of particular importance whether the efficiency or the power output have to be maximized.

In sport medicine, one of the main efforts is focused to improve athletes performance through special positions that may influence the muscular coordination and the pedalling technique [1], [2]. Many researches have been carried out 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 both 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 measure the kinematical and dynamical parameters. Among those mechanical parameters, the Seat-tube angle (STA) defined as the minor angle between the axis of the seat tube and the horizontal plain, was studied in different riding disciplines (i.e., road cyclists and triathletes). In particular, in [5] the effects of bicycle seat tube angles are compared on power production and muscular activation. The primary finding is that the increasing of the STA value from 72° to 82° enables triathletes to maintain power production, while significantly reduces the muscular activation of the biceps femoris muscle. Many researchers have attempted to relate specific geometry variables to the optimization of maximal [6] and sub-maximal [7], [8] oxygen uptake ($\dot{V}O_2$) during stationary cycling. This body of literature often makes a distinction between optimal and preferred cycle geometries. An optimal geometry during sub-maximal cycling is commonly defined as one that coincides with the minimization of a $\dot{V}O_2$-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 [9].

An important field of research is based on muscular activity and coordination through electromyography to examine different cycling positions [10] and to point out that the patterns of the lower limb muscles activity change as a function of numerous factors such as power output, pedalling rate, body position, shoe-pedal interface, training status and fatigue. The importance of body position in cycling was investigated in [11] through the evaluation of standard and aerodynamic postures (AP) to test the hypothesis that AP would modify the coordination of lower limb muscles. It is now evident from the latest trends in cycling studies that an interdisciplinary approach is needed. On the other hand, the importance of accurate measurements of the pedal forces enhances the use of cycle-ergometer in laboratories for training and testing purposes [12]. Moreover, it can be stated that the apparent simple movement of pedalling actually involves the entire body [13] of the rider and many researches concern the seat design [14], the hand position on the handlebar [15], a method to determine cycling posture via an automatic saddle height-control system [16] or aerodynamic study with Computational Fluid Dynamics (CFD) analysis and wind-tunnel tests [17].

To improve cycling efficiency and performance, investigations have addressed a number of physiological factors related to the rider position [18], [19].

From the literature review, one can see that generally the scientific papers are focused on mechanical or on physiological aspects. To avoid such bias, the present research deals with models and variables taken from both the disciplines. In fact, to determine the main variables of a model of the biomechanical efficiency in cycling it considers how changes in frame geometry (mechanical aspect) during sub-maximal cycle ergometry (physiological aspect) may influence biomechanical efficiency. In particular, the STA could be effective as a synthetic description of the frame geometry and rider position. Moreover, the choice of the STA as main factor (independent variable) is justified by the use of tuning techniques aiming to get the "optimal" STA and work rate by professional teams and by scientific literature [5], [20], [21].

To validate this assumption, different STA positions have been experimentally investigated to argue the following conjecture

the cyclist performances are directly related to the STA.
The validation of the conjecture by experimental data is the main focus of the paper.

2 MATERIAL AND METHODS

To collect a data set useful to confirm or deny the conjecture in hand, several methodological aspects were considered. In particular, the paper is focused on the design of an experimental protocol allowing a correct measurement of the biomechanical efficiency.

2.1 Addressing Performance

The state of the art presented in the introduction suggests the STA to be reliably as the main input variable for a biomechanical model of efficiency in cycling. From a physiological point of view, the efficiency is usually evaluated through many parameters such as pulmonary ventilation ($\dot{V}E$), heart rate ($HR$), carbon dioxide output ($\dot{V}CO_2$) and oxygen uptake ($\dot{VO}_2$). The work aims to create a virtual sensor to measure the performances of an athlete. Thus, a mathematical model describing the work efficiency as a function of one (or more) of those parameters is needed.

The work efficiency ($\eta$) can be considered as a measure of the metabolic cost of performing external work [22]. In particular $\eta$ can be calculated as the ratio between the external work performed, expressed by the power output $P$, and the metabolic cost of the work in terms of the caloric value of the oxygen uptake $\dot{VO}_2$:

$$\eta = K \cdot \frac{P}{\dot{VO}_2}$$

where $K$ is a function of the ratio $\dot{VO}_2 / \dot{V}CO_2$ [23], [24], [25], [26].

It is well known that during the performance of most types of exercise the oxygen uptake is tightly coupled to the power output. This relation was described by a dynamic model [27]. Figure 1 shows some dynamic responses (see left plot).

The shape of the curve $\dot{VO}_2 - P$ (see Figure 1) suggests to keep constant the power during the data collection. This choice will increase the robustness of the virtual sensor. In fact, if both the power output $P$ and the STA (the input variable) should change, the subsequent oxygen uptake variation could be due either to (1) or to the correlation under investigation ($STA - \eta$). Hence, a
proper way to monitor the efficiency of an athlete is to observe the oxygen uptake while performing an exercise with a constant load: the lower is the oxygen uptake the higher is the efficiency.

Even if the model (1) is related to the human variability by means of coefficient $K$, it gives other two important issues:

1. the $\dot{VO}_2$ needs a not negligible time to reach a stable point;
2. the relationship between $\dot{VO}_2$ and $P$ demonstrates linearity and remarkable consistency only in a well defined range of $P$, as one can see in the right plot of Figure 1.

The former issue (1) requires to discard the early measurement whenever a not-negligible power variation is expected. The latter issue (2) suggests that the $\dot{VO}_2$ can be used as a virtual sensor for $P$ if and only if the power produced belongs to the interval $[0 \div P^\ast]$, where $P^\ast$ represents the upper limit of the power observed when the athlete reaches the ventilatory threshold. Besides, it is well known that in the same range above defined the ratio $\dot{VO}_2 / \dot{VCO}_2$ can be considered to be constant, so that the same variable $K$ of equation (1) can be considered constant.

It is important to notice that the $\dot{VO}_2$ can be adopted as a performance index only if the used load $P$ is lower than $P^\ast$ which is variable for every subject $a$. Consequently to avoid fake reading, it is mandatory to fix the correct power range before collecting the experimental data. In the present work, this issue is addressed by creating a two-phase experiment:

**Parameter Tuning (PT):** this phase estimates $P^\ast$ which is the main parameter of the virtual sensor.

**Data Collection (DC):** this phase is devoted to the data collection.

2.2 Experiment Design

The Design of the Experiment (DoE) is an important component in every research project and it becomes critical when high-dimensional processes are in hand. In fact, complex processes may have many connected variables to be considered. In particular, the design of an experiment aiming to verify whether a variable $x$ is connected to a variable $y$, should keep constant all exogenous variables of the process but $x$ (i.e. the independent variable) and observe the variation of the only dependent variable $y$ [28].

The present research considers as the independent variable the bicycle frame parameter known as $STA$ (Seat Tube Angle). Thus, the authors designed a rigid protocol that keeps constant, as much as possible, the parameters of the experimental setup during the test, varying the $STA$ only. In the following the choice of the dependent variables (that address the performance of the cyclist), will be investigated.

The tests were carried out with a special instrumentation device called $CPS$ (Cycling Positioning System) apparatus [3]. It consists of a 7-degrees of freedom (dof) device designed to analyze, test and optimize different positions of a bicycle rider. Each dof corresponds to a parameter regulated by an hydraulic actuator. Moreover, the $CPS$ was instrumented in order to monitor several mechanical and metabolic measures [3], [29]. The monitored variables and the parameters are listed in Table 1.

Each experiment has 10 main parameters: the $CPS$ geometry, the working load applied during the test $P$, the pedalling cadence $PC$ and the duration of the experiment. According to the proposed DoE, only the supposed independent variable ($STA$) may be forced to change in the experiment. Then, the other variables have to be tuned to a constant value.

It was decided to use the same frame geometry in both the experiment phases. In particular, the $CPS$ was tuned in order to reproduce the rider’s own bicycle geometry, with the exception of the
Table 1: Tunable parameters (P) and observable measures (M) provided by the experimental set-up.

<table>
<thead>
<tr>
<th>Group</th>
<th># P/M</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>7 P</td>
<td>saddle elevation and slope; STA; handlebar elevation; frame slope; wheelbase; saddle-to-handlebar distance</td>
</tr>
<tr>
<td>Dynamics</td>
<td>1 P</td>
<td>work load</td>
</tr>
<tr>
<td></td>
<td>8 M</td>
<td>force exerted on: saddle, handlebar and pedals (6 values)</td>
</tr>
<tr>
<td>Kinematics</td>
<td>7 M</td>
<td>pedals slope, velocity (4 values); crank rotation angle, velocity and acceleration (3 values)</td>
</tr>
<tr>
<td>Metabolic</td>
<td>4 M</td>
<td>carbon dioxide output; pulmonary ventilation; heart rate; oxygen uptake</td>
</tr>
</tbody>
</table>

STA which will be varied in the DC phase of the experiment. The other three parameters will have different tuning in the two phases of the experiment.

The PT phase follows the V-slope method [22] which requires a specific tuning that will be motivated in the following.

During the DC phase, the load $P(a)$, tuned for the athlete $a$, was chosen equivalent to the 80% of the power he produced at the ventilatory threshold ($P_a^\text{v}$). This tuning has the major effect to guarantee a linear correlation between the oxygen uptake and the produced power, see Figure 1. The pedalling cadence ($PC$) was fixed at 90 rpm for every subject. According to [30] such setting ($PC(a) = 90$ and $P(a) = 0.8P_a^\text{v}$) allows a cyclist to perform long trials with low energy expenditure. For the athlete $a$, the length of the experiment is related to the number of different STA values tested ($J_a$). This choice will be motivated in the description of the DC phase.

PT phase: Anaerobic threshold determination This phase aims to determine the work load $P_a^\text{a}$ correspondent to the anaerobic threshold (AT) of the athlete $a$. The V-slope is a well known method to determine the AT [22]. This method is based on the analysis of the relationship between oxygen uptake ($\dot{V}O_2$) and carbon dioxide output ($\dot{V}CO_2$). Both $\dot{V}O_2$ and $\dot{V}CO_2$ increase with work load. In particular, during aerobic metabolism, they increase proportionally with an approximately 1:1 slope and, as anaerobic metabolism begins, the $\dot{V}CO_2$ starts to increase at a faster rate. The AT detection is accomplished by fitting a linear regression from the maximal values backwards to the intersection with the 1:1 slope achieved during early sub-maximal exercise.

DC phase: data collection This phase collects the oxygen uptake values $v_i(j, a)$ at different STA values $S_j(a)$ for a given athlete $a$.

If the conjecture holds, a variation of the STA during a run implies a variation of $\eta$. Recalling (1) and considered that $P$ is constant, it is clear that a small variation of the oxygen uptake should occur. Such variation requires approximately 100 seconds to get a value close to the stable value (see left plot curves in Figure 1). Conversely, if the conjecture is false, no significant variation in $\eta$ should occur, then after 3 minutes the oxygen uptake should be stable whatever load is in hand. Hence, to get data useful in both cases, it is preferable a) to perform a single run and varying the STA without stopping the athlete in order to try to keep as constant as possible his metabolism; b) to discard the first 3 minutes of measurement (required if the conjecture is false); c) to discard the first 100 seconds of data whenever a new STA value is applied (required if the conjecture is true). Table 2 reports the protocol set up specifically to collect experimental data from the athlete $a$. 

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1. Tuning CPS according to subject usual bicycle geometry

2. Warm-up: the athlete performs a warm-up exercise for 10 min using a work load of 150 W and a pedalling cadence equal to 90 rpm (PC = 90).

3. Start test: subject \( a \) performs a workload equal to \( 0.8P_a^* \) at PC pedalling cadence.

4. Wait 3 minutes.

5. For each STA value \( s_j \):
   (a) Pose \( STA = s_j \).
   (b) Wait 100 seconds.
   (c) Collect the oxygen uptake values \( v_i(j,a) \) for 60 seconds.
   (d) Wait 20 seconds while keeping a constant PC.

6. End test

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Table 2: DC phase protocol to collect experimental data from athlete \( a \).

3 EXPERIMENTAL RESULT

The riding position experiments were performed on 14 semi-professional road male cyclists. 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. Table 3 reports the anthropometric data of the athletes and the power \( P_a^* \) identified from the PT phase of the experiment.

The DC phase was performed for each athlete one week after the PT session at approximately the same hour of the day. The second phase of the experiment was conducted using different STA values set. It is important to notice that the range used for subjects \( A \div L \) is indicated as the best interval for standard bicycle frame geometry by previous researches [9], [5], [3]. Nevertheless, to achieve a more general result, the range was enlarged to \([73^\circ \div 80^\circ]\) for 3 subjects \((N = P)\). Moreover, to randomize the data entry, the order of STA values was changed among subjects \( A \div L \). Finally subject \( M \) performed the test with only 3 STA values.

To verify if the STA variation affects the efficiency, a simple performance index was computed. For cycler \( a \) and for each STA \( s_i \), the oxygen uptake mean \( \bar{V}(i,a) \) was computed. Then for each subject the influence of the STA was evaluated by computing the maximum relative distance

\[
D_a\% = \frac{\max_i \bar{V}_{i,a} - \min_i \bar{V}(i,a)}{\min_i \bar{V}(i,a)} \cdot 100
\]

4 DISCUSSION

The preliminary analysis performed has shown a clear relationship only in approximately half of the subjects. This percentage and the number of tests (14 subjects) do not allow to fully confirm the proposed conjecture. Nevertheless, a relationship between the STA and the cycling efficiency arguably exists but besides this other variables are probably involved too.

This assertion matches with the findings of several experimental studies. Many variables may
Table 3: Anthropometric data, experience ('Sp': semi-professional, 'Er': ex-racer, 'A': amateur, 'R': racer), workloads identified after the PT phase of the proposed protocol and experimental result.

Influence the seat configuration such as seat heights, seat tube angle and pelvic orientation but also cyclists’ upper body orientation influences the control of their leg muscles when cycling [13] and moreover all these features can vary greatly between individuals and riding disciplines. Many studies have investigated the influences of seat configuration on performance parameters as metabolic costs [31], muscle activity ([32], [33]) and power output [34]. Testing the influence of different seat configurations on power output faces the difficulty in isolating the effects of specific variables from each other as well as from the effect of rider adaptation during the test as shown in [34]. Seat height [35] and pelvic orientation [9] influence lower extremity kinematics and can alter muscle power generation, and ultimately cycling performance [36] even if the differences between studies seem to be most likely due to different parameters sensitivity. An alternative approach is to use theoretical modelling where the influence of specific variables can be carefully isolated to investigate the minimization of a joint moment-based cost function during sub-maximal pedaling [37] or to identify the overall optimal seat configuration that produces maximal average crank power [21]. In all these studies important discussions on the different aspects involved were introduced. However how STA influences overall efficiency is not clear. Besides, the influence of STA on rider performance is of particular interest as STA varies across different riding disciplines. Differently from [5], in which the effects of muscle activation and power production during anaerobic test were investigated, the aim of the present study was to compare the effects of variations in STA on the biomechanical efficiency of the rider during a long training session with aerobic metabolism. While in [5] it is stated that variations in STA had no effect upon power production in a wingate anaerobic test despite lower levels of muscular activation, a similar conclusive result cannot be asserted in our aerobic test. It would be of interest to repeat the experiment [5] adopting the proposed virtual sensor. Another important feature of the test is the narrow range in STA values which are closely centered around each athlete’s preferred value considering that the typical range for a road bike is between 70 and 76. Besides the test protocol performed a sufficiently wide range of values to prevent adaptation in preferred geometries by the rider according to [9] and [35]. However, it is challenging to understand
the exact influence of single parameter manipulation on the overall efficiency. In fact it is well known that changing in seat configuration contributes to alter the bicycle-rider geometry which influences muscle force and power generation.

Comparing the work with the literature review presented in the introduction two main methodological novelty arise: the use of a virtual sensor to estimate the efficiency and the use of bias free statistical analysis. Beside the analysis of the experimental data gives an important suggestion to improve the data collection protocol in further work.

4.1 Use of a virtual sensor

The use of the $\dot{V}O_2$ is already present in literature (see inter alia [4], [6], [7], [8], [9], [27]), nevertheless the work introduces an original contribution in considering both dynamic and static physiological models to create a proper virtual sensor. The use of such virtual sensor drove the DoE and the data collection protocol. In fact, this protocol was designed taking in hand both static (the anaerobic threshold of every athlete) and dynamic (the period of breath adjustment after the STA modification) parameter of the subject. This aspect represents a new methodological contribution.

4.2 Inclusion of endogenous variables in the model

The test protocol has no constraint on some of the endogenous variables (e.g. the force applied on the saddle and on the handlebar, the trunk inclination, the peripheral muscle perfusion) which can be related to the oxygen uptake variation. To get a solid data set for model identification, these variables should be monitored. This important aspect was investigated also by previous studies. For instance, the results presented in [7] indicate that body posture can affect energy dissipation during uphill bicycling through factors unrelated to air resistance. Beside, the work [35] investigates the relation between the STA, the saddle height and the oxygen uptake. Those two works are not fully comparable with the present one because hinge on a different experimental set-up but suggest which variable should be included in a model of biometrical efficiency in further studies.

5 CONCLUSION

The paper presents a study intending to verify whether the STA is related to the performance of a cyclist. The intuitive conjecture was formalized by figuring a relation among the STA and the oxygen uptake as output. The conjecture was validated by means of a series of non parametric tests conducted on 14 trained subjects. The data analysis most likely indicates that the STA plays an important role in determining the efficiency in cycling, but other variables are involved too.

Further work will investigate both the following aspects to complete the model: the identification of other input variables besides the STA and the kind of relationship existing among the selected variables and the oxygen uptake.

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References


