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ORIGINAL ARTICLE

Does changing the bike frame influence pedal force pattern in mountain bike cyclists?

Le type de cadre de vélo influence-t-il le patron d'application des forces des vététistes ?

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KEYWORDS
Pedalling efficiency;
Performance;
Cycling biomechanics;
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Summary

Objectives. — In cycling, the interaction between the athlete and his bike is crucial for the resulting performance with frame geometry and bike-setup being known to affect the biomechanical and physiological outputs. Road and Olympic cross-country (XCO) bike frames are routinely used in training programs, despite having different frame configurations. The present study compared biomechanical indices of the pedalling techniques between road and off-road bike frames.

Equipment and methods. — Ten XCO mountain bikers of national level performed two sessions on their personal bikes. For each frame, the athletes achieved one-minute tests at 65%, 90% and 115% of their maximal aerobic power (MAP) while recording 3D pedal forces. Together with various frame and bike-setup measurements, the peak of effective force, corresponding crank angle, global and instantaneous index of efficiency were compared for Power and Frame statistical effect.

Results. — The frame geometry and bike-setup showed significant differences between the road and XCO frames. The Power factor significantly ($P < 0.05$) influenced the biomechanical indices of pedalling technique, but no effect of the Frame on any variable was reported. We posit that an internal reorganization was adopted by each cyclist to retrieve a specific and individual pedalling pattern regardless of the frame type. Such results can have important implications for training.

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MOTS CLÉS
Efficacité de pédalage ;
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Biomécanique du cyclisme ;
Vélo tout-terrain

Résumé

Objectifs. — En cyclisme, l'interaction entre l'athlète et son vélo est cruciale pour la performance, la géométrie du cadre et la configuration du vélo étant connues pour affecter les données biomécaniques et physiologiques. Les cadres de vélo de route et de cross-country olympique (XCO) sont couramment utilisés dans les programmes d'entraînement, malgré des configurations de cadres différentes. La présente étude a comparé les indices biomécaniques des techniques de pédalage entfre les cadres de vélo de route et de vélo tout-terrain.

Matériels et méthodes. — Dix Vététistes XCO de niveau national ont effectué deux séances sur leur vélos personnels. Pour chaque cadre, les athlètes ont réalisé des tests d'une minute à 65 %, 90 % et 115 % de leur puissance aérobique maximale (PMA) tandis que les forces 3D aux pédales étaient enregistrés. En plus des diverses mesures du cadre et de la configuration du vélo, le pic de force effective, l'angle de manivelle correspondant, l'indice global et instantané d'efficacité ont été comparés en observant les effets statistiques de la puissance et du cadre.

Résultats. — La géométrie du cadre et la configuration du vélo ont montré des différences significatives entre le cadre de route et le cadre XCO. Le facteur de puissance ($n < 0,05$) a influencé de façon significative les indices biomécaniques de la technique de pédalage, mais aucun effet du cadre n'a été rapporté, sur aucune variable. Nous supposons qu'une réorganisation interne a été adoptée par chaque cycliste pour retrouver un modèle de pédalage spécifique et individuel quel que soit le type de cadre. De tels résultats peuvent avoir des implications importantes pour l'entraînement.

1. Introduction

Olympic Cross-Country mountain-biking (XCO) is a sporting discipline that requires extensive physical [1] and technical [2,3] qualities in order to perform at the highest level. It is also a sport in which equipment stands as an important factor and where the concept of optimising the man-machine interaction is essential. With the aim of characterising performance parameters, previous research on XCO has focused on the influence that frame geometry and bike-setup may have on pedalling technique parameters [4—6]. For instance, it has been shown that changes of seat position induce a larger discomfort over time for upward and backward positions compared with neutral posture [7]. Compared to other cycling disciplines [8—10], XCO riders have a lower loss of developed power than road cyclists and even less than sprinters (respectively 6.4 W/s vs. 7.9 W/s vs. 13.3 W/s) during a 30 s sprint test, which points to the specific nature of each discipline [11]. Despite a large literature on the study of pedalling, it appears that the physical abilities were studied in comparing different disciplines, but few analyses have been performed regarding the influence of the discipline-specific equipment on the performance. To analyse the cycling performance, some studies have focused on joint kinematics [12] or muscle activation patterns [13,14] as features giving rise to the power output, but most of them have observed the mechanical indices representative of the pedalling technique as these indices represent the actual mechanical output the athlete is producing to achieve its performance. The most commonly used parameter is the pedalling index of efficiency (IE) [15,16]. This index of efficiency illustrates the athlete's capacity to correctly orient the applied force perpendicularly to the crank to optimise effective power generation [17]. In their review on the subject, Bini et al. [18] state that improvement of force effectiveness can increase power output. Many factors can influence the IE, primarily power output and pedalling cadence. The IE increases with the rise in the required relative power [19—21] and decreases with pedalling cadence [22,23]. For example, Sanderson [2] reported that the change from 100 W to 235 W increased IE by approximately 20%. The strong influence of equipment on cycling performance was also highlighted, especially with regard to the forces transferred to the pedals [24]. In particular, it was observed that changes of ±3% of the preferred saddle height (corresponding to ±10° knee flexion), irrespective of direction, could lead to a variation in the IE from 2% to 6% [25]. Bike-setup also affects the upper body position and a recent study demonstrated a loss of efficiency of 9.5% during the rear phase of pedalling whilst in aerodynamic position, compared to a classic position (upper body upright) [26].

In the majority of XCO riders' training programmes, long-lasting road bikes sessions are included in order to focus on the physiological and pedalling techniques aspects without the off-road piloting overload. Given the specific nature of each discipline (road vs. XCO), unexpected effects on the pedalling technique could arise due to the modification of bike-setup, geometry, or mechanical characteristics.

The aim of this study was to compare the influence of bike frame, considering both bike-setup and frame geometry, on biomechanical characteristics of pedalling. More precisely, the present study observed mechanical indices related to pedalling efficiency of XCO athletes during a session comparing a road bike frame and a mountain bike frame. Considering the reported influence of bike-setup and bike features on performance [7,26,27], our hypothesis was that the resulting pedalling pattern would be different between the two bike frame types.

2. Materials and methods

2.1. Subjects

In order to ensure homogenous participant features, we choose to control for the gender, age range, practice level and chainring types (circular). The combination of these criteria (especially the practice level and chainring types) largely restrain the available population of participants. A total of 10 mountain bikers riding at amateur level with performance in national level competitions took part in this study (age: 18.8 ±2.2 years; height: 177.3 ±5.4 cm; weight: 64.9 ±3.9 kg). The participants were predominantly involved in competitive mountain-biking activities and spent at least 80% of their training sessions on a mountain bike. The study protocol complied with the standards established in the Helsinki declaration and all the procedures have been approved by the sport sciences department ethics committee.

2.2. Frames analysis

At first, it was necessary to check if the two frame types selected were indeed different. Ten measurements of frame geometry were registered in order to compare the structures: angles of seat tube and head tube; length of top tube, seat tube, head tube, wheelbase, chainstay, reach, and stack; and bottom bracket drop (Fig. 1). Three measurements reflecting the bike-setup and parameters that may influence pedalling indices were recorded [28,29]: the saddle height from the centre of the seat, above the saddle tube, to the crank-centre; the horizontal length from the centre of the saddle to the handlebars and the vertical drop between the saddle and handlebar (Fig. 1).

2.3. Protocol

During the days prior to the experiment, each of the participants followed a discontinued incremental test protocol on a bicycle ergometer (Lode Excalibur Sport, Groningen, Netherlands) in order to determine their maximal aerobic power (MAP). In a previous study, it was state than the ventilatory parameters showed similar responses between continuous vs. intermittent protocol on that same bicycle ergometer [30]. The choice of a discontinuous protocol was made to propose an effort as similar as possible to the real XCO practice [1]. After a 5-minute warm-up at 100 Watts, the imposed power was increased by 30 Watts every 2 minutes [9]. Each stage was followed by a 30-second recovery period [31]. The MAP was defined as being the power

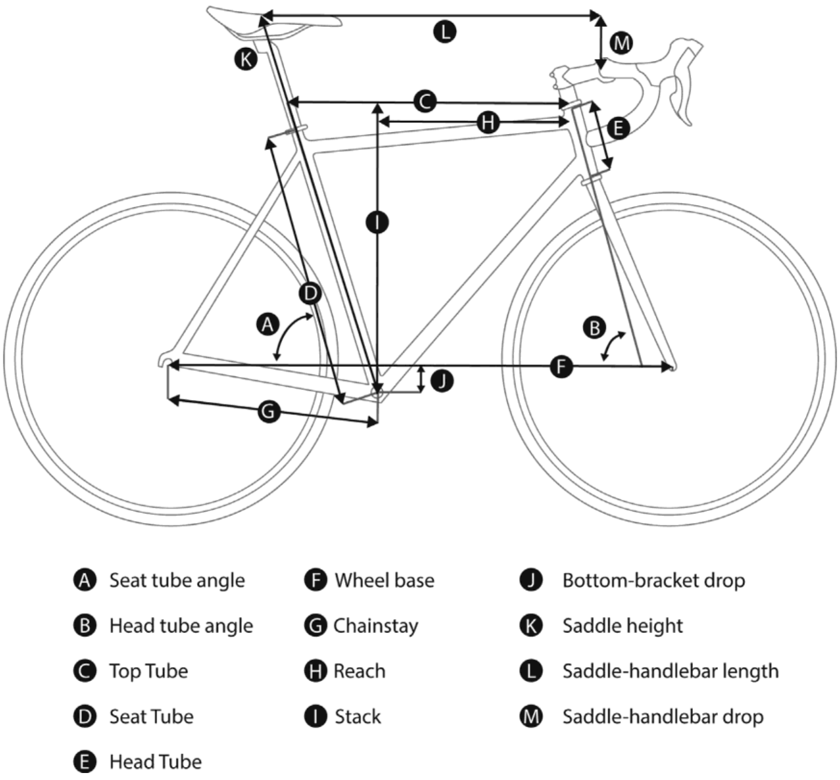

Figure 1 Measurements for comparison of frame geometry and bike-setup.

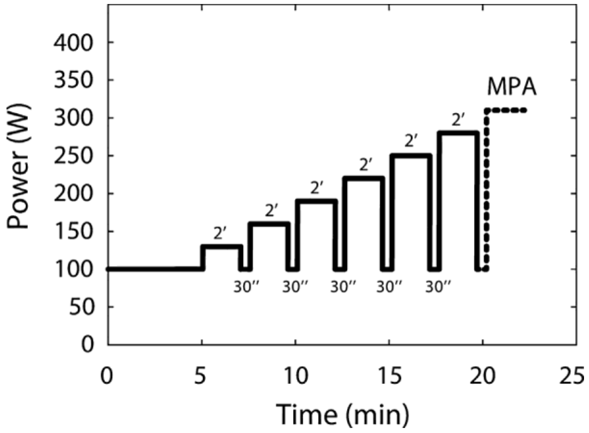

Figure 2 Chronology of the discontinued incremental test for determining the maximal aerobic power (MAP).

maintained for more than one minute during the last stage reached before exhaustion (Fig. 2).

The experimental phase involved carrying out a pedalling session on a bicycle ergometer equipped with power control (Cyclus2, RBM Elektronics, Leipzig, Germany). The workload measurements between the two different ergocycles (Lode and Cyclus) were studied by Reiser et al. [32] who reported very minor differences. In addition, we have used a specific model of Cyclus engine (Sprint) which has been developed to be more reliable than the classic one at high power combined with low cadences. Each rider was instructed to bring his own frames, a road bicycle (with rigid frame) and a mountain bike (with semi-rigid frame) in order to use personal equipment suitably adapted with regard to bike-setup. The suspension systems on the mountain bikes were blocked and it was requested to adopt the same type of grip on the two handlebars.

A standardised warm-up was carried out before the start of the session and also after the change of frame. This warm-up consisted of 6 minutes pedalling at 60% MAP then 3 blocks of 30 seconds at 100% MAP with a one-minute of recovery at 100 W between each block. For the test phase, the participants carried out pedalling sessions that lasted one minute in three different power conditions, for each frame. The three power levels chosen were 65%, 90% and 115% of MAP as reflecting the distribution of effort intensity during XCO mountain bike races [33]. For each condition, two consecutive trials were carried out and only the second one was retained for analysis. All data were recorded during that second period. A recovery phase of one minute was conducted at the end of the $65\%_{MAP}$ and $90\%_{MAP}$ tests; and 3 minutes after the tests at $115\%_{MAP}$. For all the tests, the pedalling frequency was freely selected by the participants, but they were instructed to maintain the frequency at an identical level throughout all the tests. The order of presentation of the different experimental conditions was randomised for both the frames (XCO or road) and power levels (65%, 90% or 115% of MAP), rendering a total of 6 experimental conditions.

During each test, the 3D forces applied to the pedals were recorded at 250 Hz by an instrumented pedal system coupled with optical coders that measure the orientation of the pedal relative to the crank (I-Crankset, Sensix, Poitiers, France). The spatial 3D position of the right pedal axle was also measured (at 200 Hz) by a camera system with active markers (Codamotion, Charnwood Dynamics Ltd, Leicestershire, England) to further break down the pedalling cycles. The starting point of the cycle is defined by the highest position of the pedal. The synchronisation of these two acquisition tools was performed by the Codamotion system that triggered the force recording through an analog TTL signal, because of the separated data storage and sampling rate, an off-line processing consisting in a numerical interpolation was then performed. Due to the cyclical and highly reproducible nature of the kinematics data of the pedal axle trajectory, this variable was oversampled from 200 to 250 Hz using MATLAB custom scripts (MATLAB Release 2015b, The MathWorks Inc., Natick, Massachusetts, United States).

2.4. Data analysis

The forces recorded at the pedals were recomputed within the reference frame of the cranks using the data from the coders. Each cycle was then broken down, using the highest position of the pedal marker as a starting point and time-normalised over 360 points. For each revolution, the angles of the crank corresponding to the maximal effective force were evaluated as well as the related peak of effective force, normalized to the weight of the subjects. The mechanical pedalling efficiency was computed using the instantaneous index of efficiency (IIE, eq. 1). To get an overall efficiency index during a pedalling cycle, we also defined the pedalling index of efficiency (IE, eq. 2). The indices IIE and IE were originally described by Sanderson et al. [2] and Lafortune and Cavanagh [15], respectively.

$$IIE\,(\theta) = \frac{F_{eff}\,(\theta)}{F_{tot}\,(\theta)} \times 100 \qquad (1)$$

$$IE = \frac{\int_0^{2\pi} F_{eff}\,(\theta)}{\int_0^{2\pi} F_{tot}\,(\theta)} \times 100 \qquad (2)$$

In which θ is the crank angle, F_{eff} is the effective force (force perpendicular to the crank) and F_{tot} is the resulting 3D force.

2.5. Statistical analysis

Student's *t*-test were performed in order to test the influence of frame types on bike geometry and bike-setup variables. Two-factor analysis of variance (Anova) with repeated measures were conducted to test the influence of frame types and power levels on the following variables: peak of effective force, crank angle of peak of effective force and IE. These statistics were conducted using the R software (R Core Team, 2013). The significance level was set at $P = 0.05$ for all the statistical tests. HSD-Tukey post-hoc tests were conducted whenever necessary.

The Statistical Parametric Mapping (SPM) procedure [34] was used to determine the potential statistical differences between bike frames and power levels on crank force

Table 1 Summary of *t*-tests comparison for mountain bike (MTB) and road frames.

	#	Variables	MTB	Road
Frame Geometry	A	Seat tube angle (°)	73.3 ± 0.3	73.8 ± 0.9
	B	Head tube angle (°)[a]	70.4 ± 0.8	72.9 ± 0.4
	C	Top tube (cm)[a]	59.9 ± 0.9	54.5 ± 0.9
	D	Seat tube (cm)[a]	44.1 ± 1.4	50.6 ± 2.2
	E	Head tube (cm)[a]	10.3 ± 0.4	14.3 ± 1.5
	F	Wheel base (cm)[a]	108.9 ± 1.4	97.9 ± 0.8
	G	Chainstay (cm)[a]	43.2 ± 0.6	40.5 ± 0.2
	H	Reach (cm)[a]	41.5 ± 1.0	38.7 ± 0.9
	I	Stack (cm)[a]	61.3 ± 0.8	54.2 ± 1.6
	J	Bottom bracket drop (cm)[a]	6.2 ± 0.3	6.9 ± 0.2
Bike-Setup	K	Saddle height (cm)	75.3 ± 3.7	76.4 ± 5.6
	L	Saddle-handlebar length (cm)	69.4 ± 3.0	68.9 ± 3.5
	M	Saddle-handlebar drop (cm)[b]	5.8 ± 4.4	9.7 ± 3.7

Average ± SD over all the participants; MTB ≠ Road.
[a] $p < 0.01$.
[b] $p < 0.05$.

outputs. The use of SPM is appropriate if the hypothesis is ''non-directed'', if an effect of power or bike frame over the whole cycle and not at specific time instant is expected. When the test statistic field exceeded the critical test statistic threshold, a significant effect was observed at the corresponding time period. The greater the test statistic field exceeds the critical test statistic threshold, the more the effect was significant. The SPM was performed from the MATLAB open-source spm1d code (M.0.4.3, www.spm1d.org) where two-way Anova repeated measures evaluated (α=0.05) the main effects of the ''bike frame'' and ''power level'' factors and the interaction between these factors on the IIE waveforms.

3. Results

In terms of geometry, all the investigated parameters were significantly different (all $P < 0.05$), besides the seat tube angle. Taken as a whole, the MTB frame induced higher handlebars relative to the ground than the Road one. The results of the bike-setup values did not display a difference neither for the distance between the saddle and the crank-center, nor for the saddle to the handlebars distance. A significant difference ($P < 0.05$) was found between the frames regarding the vertical drop between the saddle and the handlebars (Variable M on the Fig. 1) (Table 1).

The averaged maximal aerobic power of the participants was 373.0 ±38.6 Watts and the cadence (stable throughout the tests) was 93.8 ±3.2 rpm.

Significant differences ($P < 0.01$) existed between all the power conditions for the peak force and IE parameters, but no difference appeared concerning the crank angle of peak of effective force (Table 2). Conversely, the Anova analysis did not show any significant effect of the bike frame factor on all the investigated parameters. No interaction was highlighted between the type of frame and the power levels (Fig. 3).

The SPM analysis showed no frame type effect on IIE. However, a significant difference located in the second part of the cycle appeared due to the power levels (Fig. 4).

4. Discussion

In this study, we sought to determine whether the biomechanical characteristics of pedalling (mechanical indices related to the force exerted at the pedal and crank levels) were similar or not depending on the type of bicycle frame used (road or mountain bike). We reported differences in the bike geometries, bike-setup as well as a significant influence of the power factor for all the parameters (except for the crank angle of peak of effective force) but did not observe

Table 2 Summary of analysis of variance (Anova) comparisons for mountain bike (MTB) and road frames and for the different intensity (%MPA) conditions.

Variable	MTB 65%	Road 65%	MTB 90%	Road 90%	MTB 115%	Road 115%
Relative peak force (N/kg)[a,b,c]	4.6 ± 0.5	4.6 ± 0.5	5.7 ± 0.5	5.7 ± 0.5	6.7 ± 0.6	6.7 ± 0.6
Max push angle (°)	89.1 ± 9.4	87.9 ± 6.4	88.1 ± 7.3	88.0 ± 8.9	86.9 ± 8.3	85.7 ± 5.7
Index of efficiency[a,b,c]	50.7 ± 13.2	49.5 ± 9.1	60.0 ± 13.0	60.6 ± 13.2	65.9 ± 11.9	66.3 ± 11.5

[a] Significant difference between 65% and 90%.
[b] Significant difference between 65% and 115%.
[c] Significant difference between 90% and 115%.

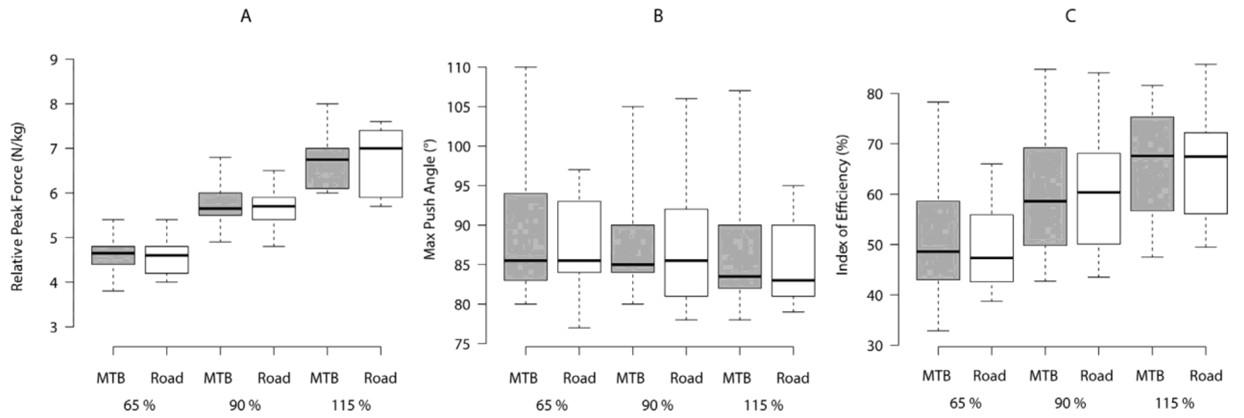

Figure 3 Boxplot diagrams depicting (A) the normalized peak force, (B) the crank angle of peak of effective force and (C) the index of efficiency (IE) under the different conditions (average ± SD over all the subjects).

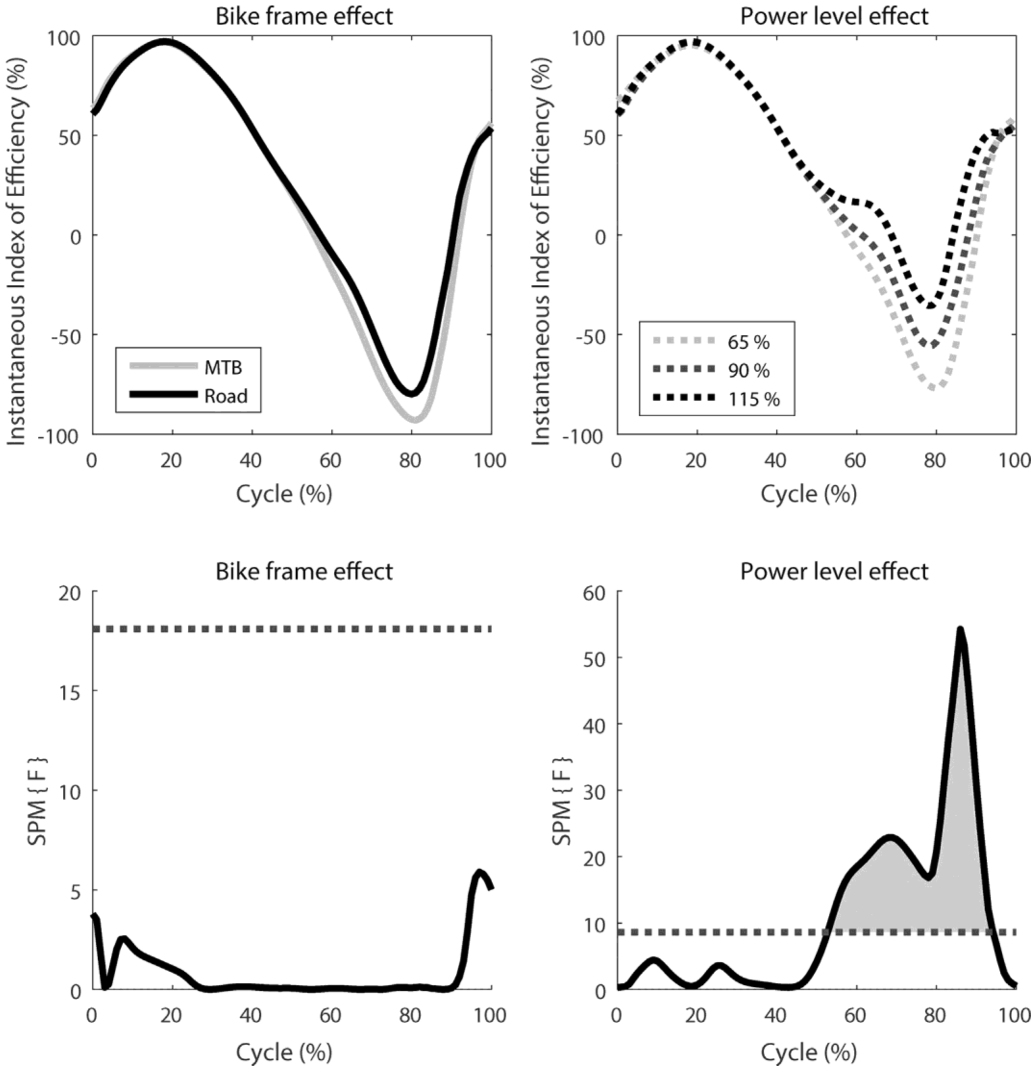

Figure 4 Results of statistical parametric mapping (SPM) analysing bike frame and power effects. No significant interaction was reported. The absence of a significant effect of the frame on the instantaneous index of efficiency (IIE) can be noted as well as a strong effect of relative power, particularly on the lift up phase of the cycle (shaded grey area between 55% and 95% of the crank cycle).

significant difference concerning the influence of the frame type on the mechanical outputs.

Kautz et al. [20] demonstrated, for example, that with an increase in power, the subjects applied greater normal force to the pedal during the push phase. Our results showed a modification in the peak force (Fig. 3A), which changed in a similar upward manner as the requested power output (4.6 ± 0.4 N/kg at 65%$_{MAP}$ vs. 5.7 ± 0.5 N/kg at 90%$_{MAP}$ vs. 6.7 ± 0.6 N/kg at 115%$_{MAP}$). Bini and Diefenthaeler [12] also showed that for an identical pedalling pattern the power output can be improved by an increase in the force applied on the pedal. However, our results showed that although a variation in peak force depending on the power levels do exist, the crank angle at which the peak appears is not affected (Fig. 3B). We therefore confirmed that an adaptation of the pedalling action occurred, but within a pattern that remains identical. Greater force is applied in order to produce the extra crank torque required for the higher power conditions as well as less resistive torque during the backstroke phase (Fig. 4 and [26]), but within a general pattern that is similar for the propulsive torque part.

It has been shown that the efficiency of force application on the pedal is improved at higher power levels [18]. Our results reinforce this point, whether for IE (Fig. 3C) or for IIE. Of interest is the analysis of the pedalling efficiency at each crank angle of the cycle. Indeed, our results on the IIE showed an improvement of the mechanical efficiency during the backstroke phase of the cycle (53 to 94%$_{Cycle}$) for high power levels (Fig. 4), which is consistent with the observations of Sanderson [2] but extends the sharpness of the analysis thanks to the SPM use.

Unlike studies in current literature, the use of the athlete's personal frames allowed to assert that we analyse an effect obtained after a long period of habituation and not an acute effect due to a sudden change of equipment. Within the scope of our analysis on the influence of the bicycle frame used, no statistical effect was observed for any of the variables investigated (Table 2). This seems to indicate that the athletes specialised in the XCO discipline have a pattern of force application exerted on the cranks identical irrespective of the (usual) equipment they use. The comparison of the saddle height and saddle-handlebar distances reinforces this point as there is no difference depending on the frame chosen (Table 1). However, the vertical drop between saddle and handlebars is significantly more pronounced on road bicycles, which implies a more upright posture with MTB frame. This posture variation is reinforced by the difference of geometry parameters between frames (Table 1) and particularly the fact that the stack height (variable I in Fig. 1) is higher with MTB frames. In all likelihood, all these elements lead to a modification on the orientation of the torso and consequently on the angle of the hip joint that may directly impact the pedalling technique [26]. Furthermore, we restricted the position of the hands on the top of the handlebars, but gripping the lower part of the curved handlebars on road bicycles can further reinforce the influence of an inclined torso, creating a more aerodynamic position, yet modifying pedalling characteristics [26].

Surprisingly, despite the difference in the position of the upper body between the frames as well as the influence mentioned in literature of bike-setup and bike features (i.e., wheel size) on pedalling technique and forces exerted on the pedals [6,7,27,28,35,36], the application templates for forces exerted at crank level were identical when changing bike frame. Contrary to our initial hypothesis, the athletes have a different posture but a same force application template which implies an amount of internal reorganisation in order to maintain an identical mechanical output at the crank level. A parallel can be drawn with current research in the field of running which has shown that the use of different running shoes does not necessarily affect an athlete's running pattern [37]. These authors posit the concept of a new paradigm called preferred movement path (PMP), a pattern established through practice and which tends to be naturally retained, regardless of equipment used. Our results support this notion in extending it to the field of cycling.

Our research focused on the link between the bike frame used and the force production pattern that constitutes the mechanical expression of pedalling. Although the pedalling efficiency is a (gold) standard variable describing the quality of the pedalling pattern, it is not sufficient to describe the complete pedalling technique [18]. Movement kinematics and muscle activation strategies are other descriptors of the pedalling technique that would be interesting to explore in order to further assess the location of the reorganisation, the comfort or the injury risks, but these points are beyond the scope of this study.

5. Conclusion

The present study focused on the mechanical characteristics of XCO athletes' pedalling technique. The biomechanical characteristics of pedalling are affected by the required output power but are comparable between the frames tested (XCO or Road). Despite a known influence of the equipment on performance and the difference in bike-setup and bike geometries reported between the participants' mountain bike and road frames, the use of one or the other did not lead to a change in the template of the forces exerted on the crank. The athletes seem to retain the same pedalling technique when using equipment that is not specific to their discipline. With young riders or people undergoing recovery treatment, the internal variability provided by an alternation of frame types could be beneficial. For athletes close to the competition, such change in the bike frame could prove detrimental to the performance.

Disclosure of interest

The authors declare that they have no competing interest.

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