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Performance indicators and functional adaptive windows in competitive cyclists: effect of one-year strength and conditioning training programme

AUTHORS: Leonardo Cesanelli[1*], Achraf Ammar[2,3*], Jorge Arede[4], Julio Calleja-González[5], Nuno Leite[4,6]

[1] Department of Psychological, Pedagogical and Educational Sciences, Sport and Exercise Sciences Research Unit, University of Palermo, Palermo I-90128, Italy

[2] Institute of Sport Science, Otto-von-Guericke University, 39106, Magdeburg, Germany

[3] Interdisciplinary Laboratory in Neurosciences, Physiology and Psychology: Physical Activity, Health and Learning (LINP2), UFR STAPS, UPL, Paris Nanterre University, Nanterre, France

[4] Research Center in Sports Sciences, Health Sciences and Human Development, CIDESD, CreativeLab Research Community, Vila Real, Portugal

[5] Department of Physical Education and Sport- Faculty of Education-Sport Section. University of Basque Country (UPV/EHU), 01007, Vitoria-Gasteiz, Spain

[6] Dep. of Sports Sciences, Exercise and Health, University of Trás-os-Montes and Alto Douro, Vila Real, Portugal

** These authors contributed equally to this work as first author*

Corresponding author:
Achraf Ammar
Department of Sport
and Technology
Institut III: Philologien,
Philosophie, Sportwissenschaft,
Otto-von-Guericke University
Magdeburg, Zschokkestraße
32,39104 Magdeburg, Germany
Tel.: +49 391 6757395
E-mail: ammar.achraf@ymail.com

ORCID:
Leonardo Cesanelli
0000-0003-2822-1836

Achraf Ammar
0000-0003-0347-8053

Jorge Arede
0000-0003-2267-1182

Julio Calleja-González
0000-0003-2575-7168

Nuno Leite
0000-0001-5181-6390

ABSTRACT: Changes and relationships between cycling performance indicators following a one-year strength and conditioning training have not been totally clarified. The aims of this study are to investigate (i) the effect of a combined one-year strength and conditioning training programme on performance indicators and the possible relationships between these indicators, and (ii) the existence of possible endurance-functional-adaptive windows (EFAWs) linked to changes in muscular strength and body composition markers. Functional and lactate threshold power (FTP and LTP), maximal strength (1RM) and body composition (body mass index [BMI], body cell mass [BCM] and phase angle [PA]) were measured at the beginning and the end of a one-year strength and conditioning training programme of thirty cyclists. Correlations, differences, and predictive analysis were performed among parameters. Significant differences were found between pre- and post-conditioning programme results for FTP, LTP, 1RM ($p < 0.0001$) and BCM ($p = 0.038$). When expressed as power output (W), FTP and LTP were significantly correlated with 1RM ($r = 0.36$, $p = 0.005$ and $r = 0.37$, $p = 0.004$, respectively), body mass ($r = 0.30$ and $p = 0.02$), BCM ($r = 0.68$, $p < 0.001$) and PA ($r = 0.42$ and 0.39, respectively and $p < 0.001$). When expressed as $W \cdot kg^{-1}$, these power thresholds were strongly correlated with body mass ($r = -0.56$ and -0.61, respectively) and BMI ($r = -0.57$ and -0.61 respectively) with $p < 0.001$. Predictive polynomial regressions revealed possible endurance and strength adaptation zones. The present findings indicated beneficial impacts of one-year strength and conditioning training on cycling performance indicators, confirmed the correlation between performance indicators, and suggested the existence of different EFAWs. Strategies aiming to improve performance should consider cyclist characteristics and performance goals to achieve EFAWs and thereby enhance cycling performance.

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INTRODUCTION

In the literature a wide range of determinants of cycling performance have been reported [1] which have been grouped into four main dimensions: mechanical, biomechanical, physiological, and environmental [2]. Features related to these dimensions as well as the interactions between these features were found to influence cycling performance and chances of success [3]. Indeed, cyclists' power output is the result of the equilibrium and interaction among internal factors (e.g., physiological variables) influencing mechanical power production and external factors (e.g., environmental variables) determining power demands [4].

From a physiological perspective, traditional models described endurance performance as a biological formula determined primarily through a combination of measures reflecting (i) the maximal rate of whole-body oxygen consumption (VO_{2max}), (ii) a valid fatigue threshold, and (iii) an index of bioenergetic efficiency during exercise [4–7]. However, recent reports identified functional threshold power (FTP) based on power output, and lactate threshold power (LTP) based on blood lactate concentrations as the most reliable and commonly acquired parameters to test, predict and assess cycling performance [8–10]. The FTP can be defined as the uppermost average power sustainable in a semi-steady state one-hour effort and normally estimated through 20-min protocols at 95% of the test mean power output [8, 10, 11]. Importantly, some authors suggested the FTP as a good indicator of lactate threshold or LTP [10].

Physiological aspects determining athlete's FTP and LTP arise from the joint action of genetic and epigenetics factors, body composition changes, nutrition assessment, psychological status of the athlete and specific training adaptations [1]. In this sense, inducing profound changes and multiple physiological adaptations, endurance training was suggested as major determinant of the athlete's FTP and LTP [9,12]. Indeed, endurance training was previously shown to enhance mitochondrial biogenesis and capillary density (e.g. peroxisome proliferator-activated receptor-gamma coactivator 1-alpha also known as PGC-1α and the tumour suppressor protein p53 regulation), muscle hypertrophy and growth (e.g. mTOR and mTOR-independent mechanisms regulation), acid-base status regulation (e.g. lactate metabolism regulation) and fuel supply metabolism (e.g. nutrient oxidation rate) [6, 13, 14] with main changes observed in quadriceps muscle among cyclists [15]. These molecular adaptations and the entity of muscle hypertrophy and growth were shown to be mainly affected by exercise intensity and volume, training load and level of muscle fibre recruitment [15-17]. Lee et al. [18] found that increased muscle thickness in the predominant muscles involved in cycling was positively correlated with both anaerobic and anaerobic power in cyclists. Similarly, high performance cyclists showed increased body cell mass (BCM) and phase angle (PA) compared to lower-level athletes [19]. Taken together, it seems that (i) the adaptive effects of endurance training on cyclists' performance have been widely investigated and that (ii) the increase in athletes' FTP and LTP can be considered the results of acute and chronic adaptive responses to this conditioning programmes [20].

Although high resistance strength training (HRST) represents a widely applied method to enhance multiple aspects of athletes' performance [14], less is known regarding the medium and long term adaptive effects and the impacts of HRST on cycling performance. Accordingly, one previous study was interested in determining the adaptations phases to HRST and suggested two main phases: an early phase mainly involving neuromuscular pathways and connective tissue adaptations, followed by a second phase in which muscular adaptations occur as a result of a progressive increase in training volume and loads [14]. Regarding the possible impacts of applying strength training strategies on endurance disciplines, previous reports described how endurance designed resistance training can be successfully tolerated by elite cyclists to promote functional adaptations, support endurance training capacity and directly contribute to performance improvements [21–24]. Particularly, these reports suggest that strength training should (i) include heavy load sessions with higher velocity during the concentric phase and increased time under tension during the eccentric one, (ii) involve discipline-specific muscle groups, and (iii) reproduce sport-specific movements [21–24].

However, to the best of the author's knowledge, the beneficial impacts of a conditioning programme combining endurance and HRST and the resulting increase in BCM on cyclists' functional power (FTP and/or LTP) are not yet confirmed. Additionally, the extent and the possible limits to which an increase in BCM and muscular strength can be reflected in functional power are not clear.

Considering previous studies investigating the dynamics of endurance athletes' adaptations, the present study aims to investigate (i) the effect of a combined one year strength and conditioning training programme on performance indicators (FTP, LTP and 1RM), body composition and the possible relationships between these variables, and (ii) the existence of possible endurance-functional-adaptive windows (EFAW) linked to changes in muscular strength and body composition markers (Figure 1).

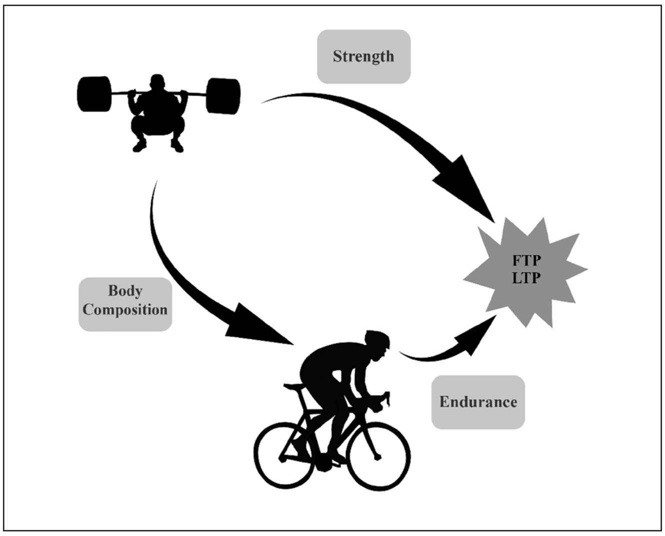


FIG. 1. Graphical representation of the possible interplays among performance determining factors.

MATERIALS AND METHODS

Study design

This is a longitudinal study in which data were acquired at the beginning (pre-measurements in November 2018) and the end (post-measurement in June 2019) of a one-year strength and conditioning training programme of well-trained cyclists. Pre- and post-values of performance indicators (FTP-LTP), body mass composition and strength were compared to assess the impacts of the one-year strength and conditioning training programme. The pooled data (pre- plus post-measurements) were used to search for relationships between the different assessed parameters. The strength and conditioning programmes were structured by athletes' personal staff or teams' staff with the common goals to improve aerobic power, anaerobic power, maximal power, strength, and maximal strength, providing both cycling training and resistance training gym sessions. The investigators supported athletes' and teams' staff with the testing procedures and data collection and analysis.

Participants

Thirty well-trained male (26.33 ± 3.61 years; 176.13 ± 6.01 cm; 70.94 ± 8.15 kg body mass; 6 to 13 years of training experience) competitive cyclists (amateurs and sub-élite categories) voluntarily agreed to participate in this study. All cyclists performed similar team-monitored practice sessions for 4 to 6 days/week (depending on the period of the season and individual training periodization, planned, and prescribed by athletes' or teams' staff). The sessions were 1 or 2/day, including cycling endurance conditioning training, preventive and strength individual training and recovery sessions, plus specific and tapering phases during/in concomitance with competitive periods (10 to 16 official competitions planned). No participants had any diseases, and none of them smoked, drank alcohol, or took medications, which would alter hormone response. All the participants obtained health medical certificate for sport and physical activities as a mandatory step to participate in the competitive season. During the investigation period, dietary behaviours were monitored and assessed by certified nutritionists. All the participants were fully informed of all aspects of the study and signed a statement of informed consent. Informed consent and approval on data sharing was further signed by the team's staff members and by the responsible of the sport centre where all performance tests were carried on. This research was designed in accordance with the Declaration of Helsinki (2008), with the Fortaleza update 2013 [25]. Characteristics of the participants are summarized in Table I, expressed as mean ± standard deviation.

TABLE I. Participants' characteristics (mean ± SD)

	Total (n = 30, males)	
	Pre-	**Post-**
Age	26.33 ± 3.61	
Body mass (kg)	70.76 ± 8.15	71.13 ± 8.30
Height (cm)	176.13 ± 6.01	
FTP (W)	253.37 ± 22.37	267.20 ± 26.60
LTP (W)	254.33 ± 20.81	266.87 ± 25.69
BCM (kg)	35.14 ± 4.17	35.56 ± 4.87
PA°	6.89 ± 0.43	6.97 ± 0.46
1RMtot (kg)	62.85 ± 28.00	105.42 ± 47.38

Values are expressed as mean ± SD

Training programme

According to the characteristics of the competition the main focus was firstly on endurance capacity (e.g. steady state medium intensity long distance training) and progressively shifted to lactate threshold and neuromuscular capacity (e.g. steady state high intensity intervals or maximal effort short intervals). Endurance training was performed 3–4 times per week and one hour of supervised heavy strength training was performed once to twice per week. Strength exercises targeting the muscles involved in cycling exercise (including exercises mimicking pedalling gesture) were performed with explosive concentric phases and slowed eccentric phases. Sets were structured as classic sets and cluster sets. The performed exercises were full back barbell squat, leg press 45°, monopodal horizontal leg press, cable kickbacks, horizontal leg curl, seated leg curl, monopodal cable knee rises, and core stability exercises. Sets per exercise depended on the type of the exercise (from 3 to 5 sets) and repetitions depended on load. Generally, one or two warm up sets were planned in fundamental exercises (e.g. barbell squat). Training intensity (load) referred to 1RM, and was progressively managed according to the period of the season and the relative performance goals. Cyclists were allowed to have assistance if needed during the execution of heavier load sets, with loads progressively adjusted considering strength increases and/or daily sensations. Before starting with the effective training protocol, a first week of familiarization with the exercises was planned.

Cycling performance indicator testing procedures (FTP and LTP)

Power output (W) was measured through athletes' crankset or pedal power meters (Stages Cycling power meter, Boulder, USA; SRM power meter, Schoberer Rad Meßtechnik, Jülich, Germany; Garmin Vector 2 pedals. Garmin International Inc., Olathe, KS, USA). Blood lactate concentration was measured using a blood lactate test meter (Lactate Pro 2 LT-1730; Arkray Inc., Japan) [26]. All the tests were performed on athletes' own bicycles placed on a cycling ergotrainer (Tacx Neo Smart, Wassenaar, The Netherlands) and after a "recovery" (active recovery training session) day.

The FTP test was performed with a 20-minute protocol and warm-up procedure as described by Allen and Coggan [11]. The standardized warm-up consisted of 20 minutes at ~100 W followed by three 1-minute efforts pedalling at 100 rpm with 1-minute recovery between intervals (~100 W) and by a 5-minute all-out effort before a final 10 minutes of light pedalling. After this warmup, participants performed the FTP test, which was a 20-minute time trial in which they were encouraged to achieve the highest mean power being able to finish the test. Cyclists were allowed to change gears and to maintain their preferred cadence during the test. The mean power (P20) was recorded, and FTP determined as 95% of P20 [11].

The LTP test was planned according to the description by Valenzuela et al. [10]. After 10 minute warm-up (~100 W), participants performed a maximal incremental test starting from a power output of 150 W. Workload was increased by 25 W every 3 minutes until reaching exhaustion or cadence reduction falling below 60 rpm. Peak power output (PPO) was determined as the average power during the last 3 minutes [9–11]. Blood lactate samples were recorded at the beginning, at the end, and during the last 30 seconds of each stage, taken from the earlobe of subjects [10]. LTP was determined from the lactate-power curve based on the Dmax method [10, 27].

Strength performance assessment

The one repetition maximum test (1RM) was performed in order to quantify strength [28]. Tests were performed on barbell squat and leg press. Before the 1RM test day, each individual performed a familiarization session to ensure habituation with the exercises and to evaluate experience level with the chosen exercises. The familiarization session included the same protocol followed during the strength assessment sessions. Tests started with a specific warm-up of 3–4 sets starting with light loads (± 45–50% 1RM) and after that progressively increasing the load until reaching approximately the 1RM (maximum amount of weight that a person can lift for a given exercise) [28]. Upon reaching the approximate 1RM each subject had 3 attempts to determine the definitive 1RM.

Body composition analysis and body composition indicators

Anthropometric data were collected following standardized international procedures and guidelines described in the NHANES manual [29]. Additionally, the same internationally certified anthropometrist (ISAK level 2) took measurements for all participants. Body mass, height, body circumferences and skinfolds were collected for each participant. Body mass was measured using a mechanical balance scale (Seca 874) with a precision of 0.01 kg [30]. Heights were measured shoeless using a stadiometer (Seca 213) with a precision of 0.1 cm [30]. The measures were taken checking the correct position of the head in the standard position of the reference Frankfurt plane. Body circumferences were taken using a non-stretchable fiberglass insertion tape with a precision of 0.1 mm at different sites: abdominal, chest, left and right arms (both relaxed and contracted), left and right tight (proximal, mid and distal) and left and right calf. Skinfold thicknesses were measured using a GIMA Skinfold Calliper with a precision of 0.2 mm, at different sites on the right site of the body: triceps, biceps, mid-axillary, chest, subscapular, abdominal, suprailiac, thigh, calf. Percentages of fat mass were estimated using Jackson & Pollock equations (both 3 and 7 sites) [31]. The bioelectrical impendence test (BIA) was performed to evaluate tri-compartmental body composition using a BIA AKERN 101 device (AKERN, Florence, Italy) [32]. Both conventional and vector analyses were performed. Resistance (Rz) and reactance (Xc) were measured through the tetrapolar impedance method applying a constant, low level alternating current (50 kHz). The BIA measure was taken with participants in supine position using two current-introducing electrodes in the middle of the dorsal surfaces of the right hand and foot [33]. Conventional analysis was performed evaluating the value of resistance and reactance and using BodyGram Plus software. PA, BCM and body cell mass index (BCMI) were considered. BCM is defined as the total mass of "oxygen-exchanging, potassium-rich, glucose oxidizing, work-performing" cells of the body and can be considered a fairly new approach for assessing body composition [34]. The BIA vectoral analysis was performed using BodyGram Plus software [35].

Statistical analysis

All data in the text, tables and figures are presented as mean ± standard deviation (SD). All data analyses were carried out using SPSS version 21.0 (IBM Corporation, Armond, NY) and GraphPad Prism version 7.0 (GraphPad Software, San Diego, CA, USA). Tests of normal distribution and homogeneity, determined by the Shapiro-Wilk and Levene's test, respectively, were conducted on all data before analysis. Differences between pre- and post- measures were determined with Student's paired *t*-test. Intraclass correlation coefficient (ICC), Pearson's correlation analysis or Spearman correlation analysis was calculated between performance, body composition and strength parameters based on parametric or non-parametric data and the standard error estimation (Sy.x) was used to examine the accuracy of the prediction. Cohen's d effect size was established according to the following criteria: 0 to 0.19, trivial; 0.20 to 0.59, small; 0.60 to 1.19, moderate; 1.20 to 1.99, large; 2.00 to 3.99, very large; > 4.0; nearly perfect [36]. The following criteria were adopted to interpret the magnitude of correlations between measurement variables: < 0.09, trivial; 0.10 to 0.29, small; 0.30 to 0.49, moderate; 0.50–0.69, large; 0.70–0.89 very large; and > 0.90, nearly perfect [36]. Linear (first-order polynomials) regression models were used to analyse the correlation trends. In addition, polynomial (second-order polynomials) predictive models were used to descriptively evaluate further data insights [37]. An alpha level of $p \leq 0.05$ was set to assess the statistical significance.

RESULTS

Participants' data are summarized in Table 1. Mean ± SD of physical performance and body composition acquired parameters are summarized in Table I.

Differences between pre- and post-evaluations and relationships between FTP and LTP are presented in Figure 1 and Figure 2, respectively. Student's paired t-test revealed significant differences between pre- and post-conditioning programme results for both FTP ($p < 0.0001$, Cohen's d = 1.68) and LTP ($p < 0.0001$, Cohen's d = 1.26) with higher values at post-measures (i.e., +13.83 W with 95%CI: 10.75; 16.92 W for FTP and +12.53 W with 95%CI: 8.82; 16.24 W for LTP). Similarly, significantly higher values were registered for barbell squat 1RM test (+26.85 kg with 95%CI: 23.78; 29.91 kg) and leg press 1RM test (+58.31 W with 95%CI: 49.51; 67.11 kg) in post- compared to pre-conditioning programme results with $p < 0.0001$ and Cohen's d = 3.56 and 2.676, respectively. Regarding the body composition, statistical analysis showed a significant difference in BCM between pre- and post-conditioning programme

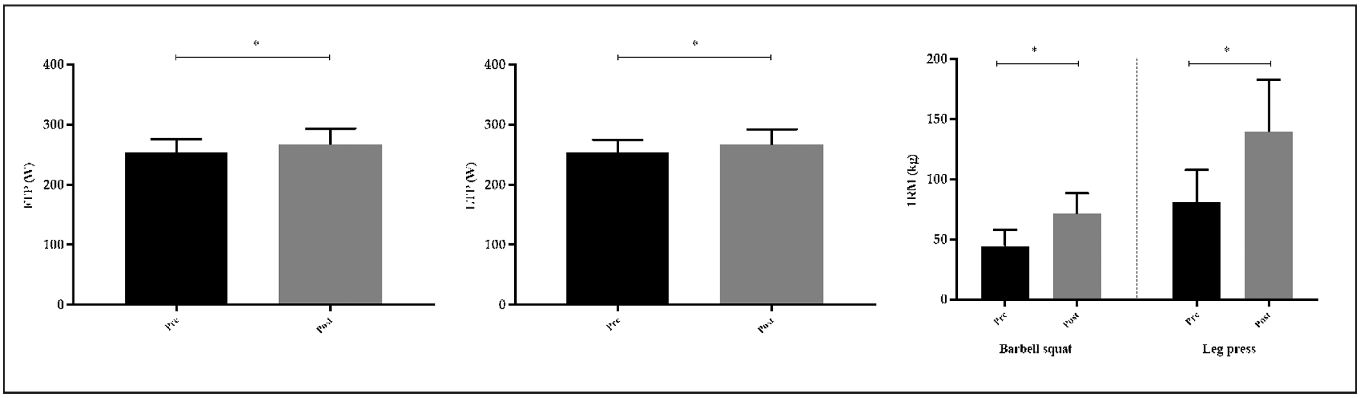
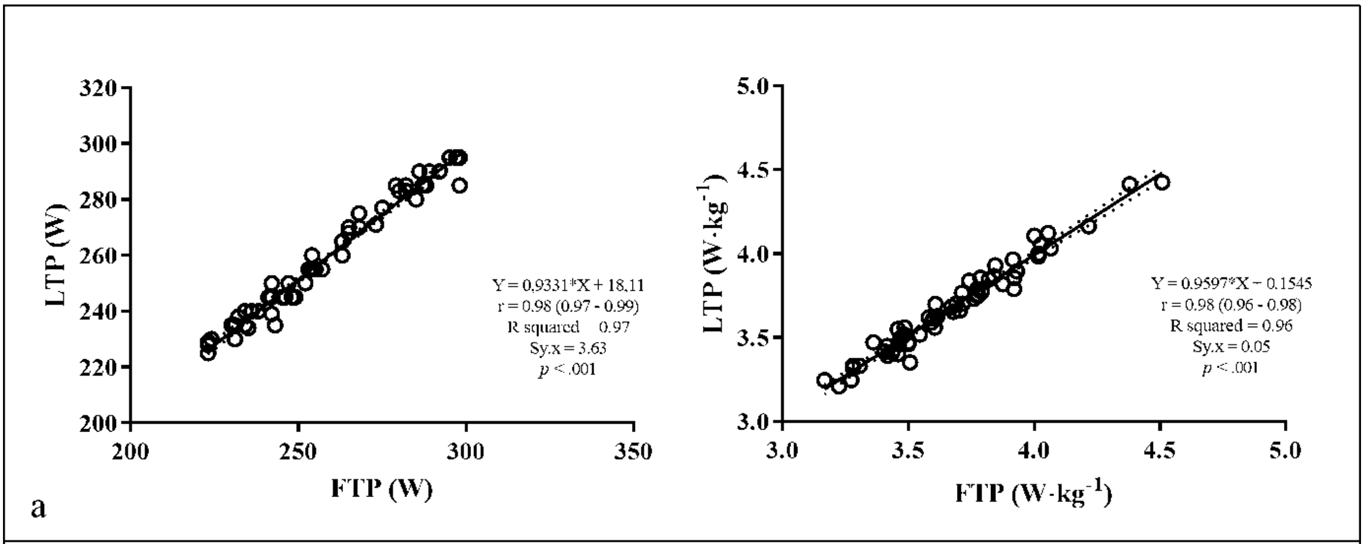


FIG. 2. Mean and SD of FTP, LTP and 1RM test measurements in pre- and post-conditioning conditions. Note: * indicates significant differences between pre- and post-measurements, p < 0.05.



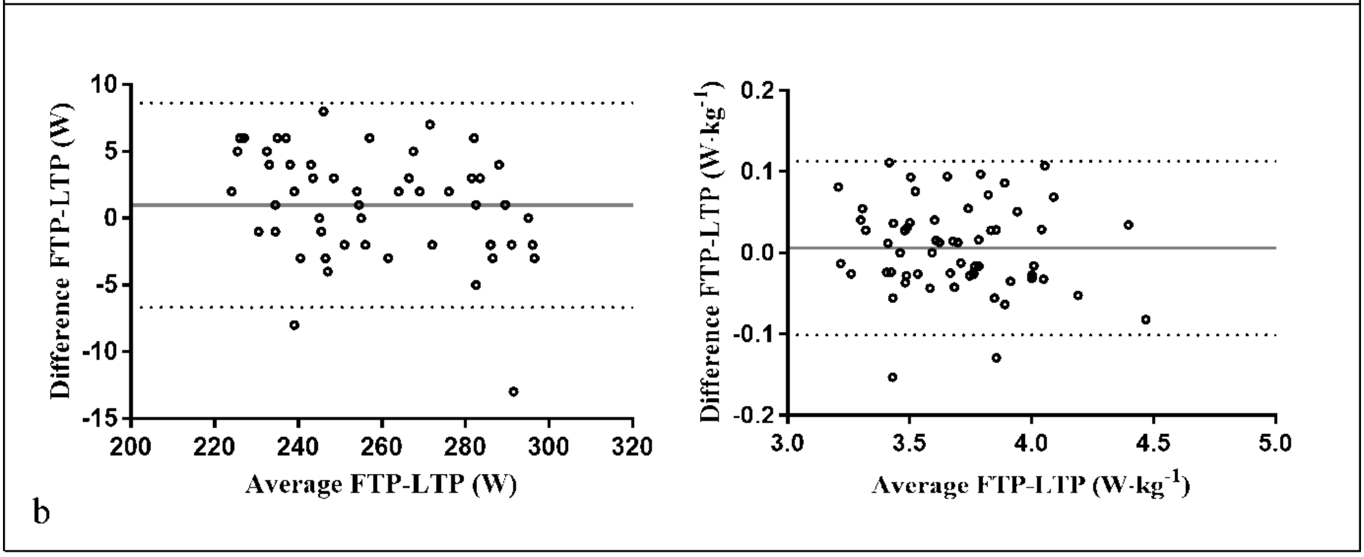


FIG. 3a. Relationship between functional threshold power (FTP) and the lactate threshold power (LTP). Solid and dashed lines represent the regression line and the 95% confidence intervals, respectively.

FIG 3b. Bland-Altman plot displaying the agreement between FTP and LTP. Solid and dashed horizontal lines represent the bias and the limits of agreement, respectively.

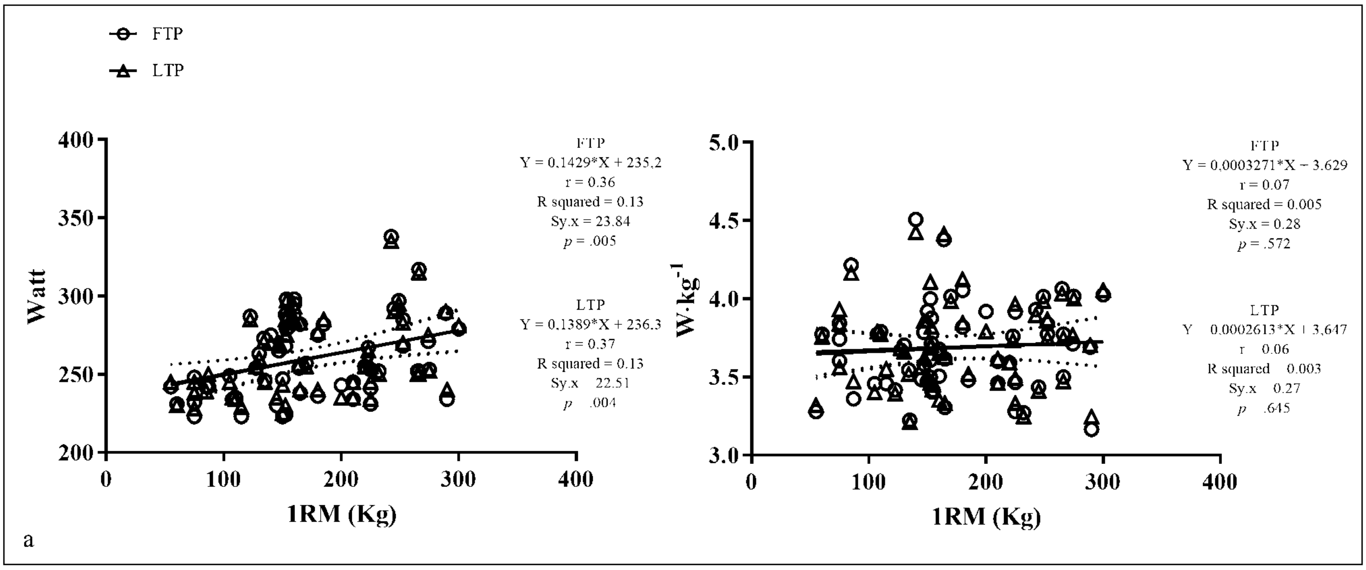


FIG. 4. Relationship between functional threshold power (FTP), lactate threshold power (LTP) and maximal strength (1RM). Solid and dashed lines represent the regression line and the 95% confidence intervals, respectively.

results (p = 0.038) with higher values at post-measure (+0.47 kg with 95%CI: +0.02; +0.91 kg). However, there was no significant effect of conditioning training on PA (p > 0.05).

Figure 3a and Figure 3b represent the relationship between FTP and LTP. Both variables were strongly correlated when expressed as watts (W) or W × kg-^{1} with r = 0.98 and $p < 0.001$.

Figure 4 represents the relationship between maximal strength measures (1RM test) and FTP, and 1 RM and LTP. Statistical analysis showed that 1RM was moderately correlated with FTP (r = 0.36 and $p = 0.005$) and LTP (r = 0.37 and $p = 0.004$) expressed as power output (W). However, there was no significant correlation between 1RM and FTP or LTP when expressed as W × kg-^{1} ($p > 0.05$).

Table II shows the relationships between performance indicators (FTP, LTP, 1RM) and body composition parameters (body mass, BMI, BCM and PA). Moderate to large positive correlations were found between athletes' threshold power (FTP and LTP) expressed as W and body mass (r = 0.29 and p = 0.020), BCM (r = 0.68 and 0.67, respectively; p < 0.001) and PA (r = 0.42 and 0.39, respectively; p < 0.001), while no significant correlation was found with BMI (p > 0.05). Large negative correlations were found between athletes' threshold power expressed as W·kg-^{1} and body mass (with FTP: r = -0.56, with LTP: r = -0.61; p < 0.001) and BMI (with FTP: r = -0.57, with LTP: r = -0.61; p < 0.001), while no significant correlations were found with BCM and PA (p > 0.05). 1RM was only moderately correlated with BCM (r = 0.37, p = 0.004).

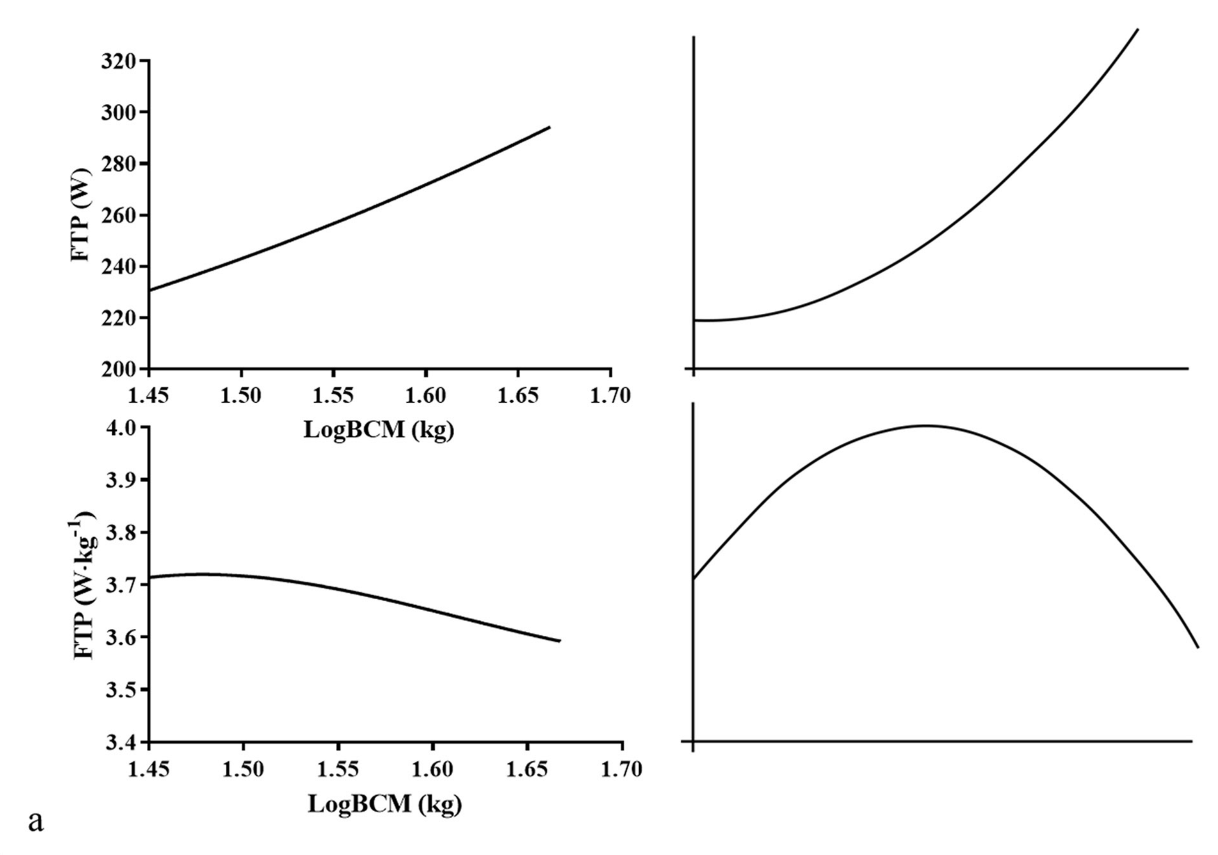
Graphical representations of the relationships between body composition parameters and performance indicators are reported in Figure S1 (supplementary file).

Figure 5a represents the polynomial regressions and the predictive polynomial regressions between the FTP data expressed as watts (W) and expressed as W × kg-^{1} and logBCM (kg). Figure 5b describes a graphical overlay of the two plotted curves to underline the FTP trend to BCM according to the way it is expressed. From the graphical representation three potential adaptation zones emerged: a functional-gain adaptation zone, a functional-loss adaptation zone and a non-functional zone divided by an equality spot where the two curves intersect.

Figure 6a represents the polynomial regressions and the predictive polynomial regressions between the FTP data expressed as watts (W) and expressed as W × kg-^{1} and maximal strength (log1RM (kg). Figure 6b represents a graphical overlay of the two plotted curves to underline the FTP trend to maximal strength according to the way it is expressed. From the graphical representation three potential strength adaptation zones emerged: a 1st functional strength adaptation zone in which both power output expressed as watts (W) and as W × kg-^{1} increase with the increase of strength; a 2nd functional strength adaptation zone in which the W × kg-^{1} curve starts to become flat; and a 3rd functional strength zone where the W × kg-^{1} curve reaches a plateau but the W curve continues to grow.

DISCUSSION

The primary purpose of the present study was to identify the effect of a one-year strength and conditioning training programme on performance indicators (FTP, LTP and 1RM), and body mass composition. The main findings showed an improvement of cycling performance both in terms of threshold power and strength. The improvements in cycling performance were accompanied by an increase in athletes' BCM. The present results are in line with previous



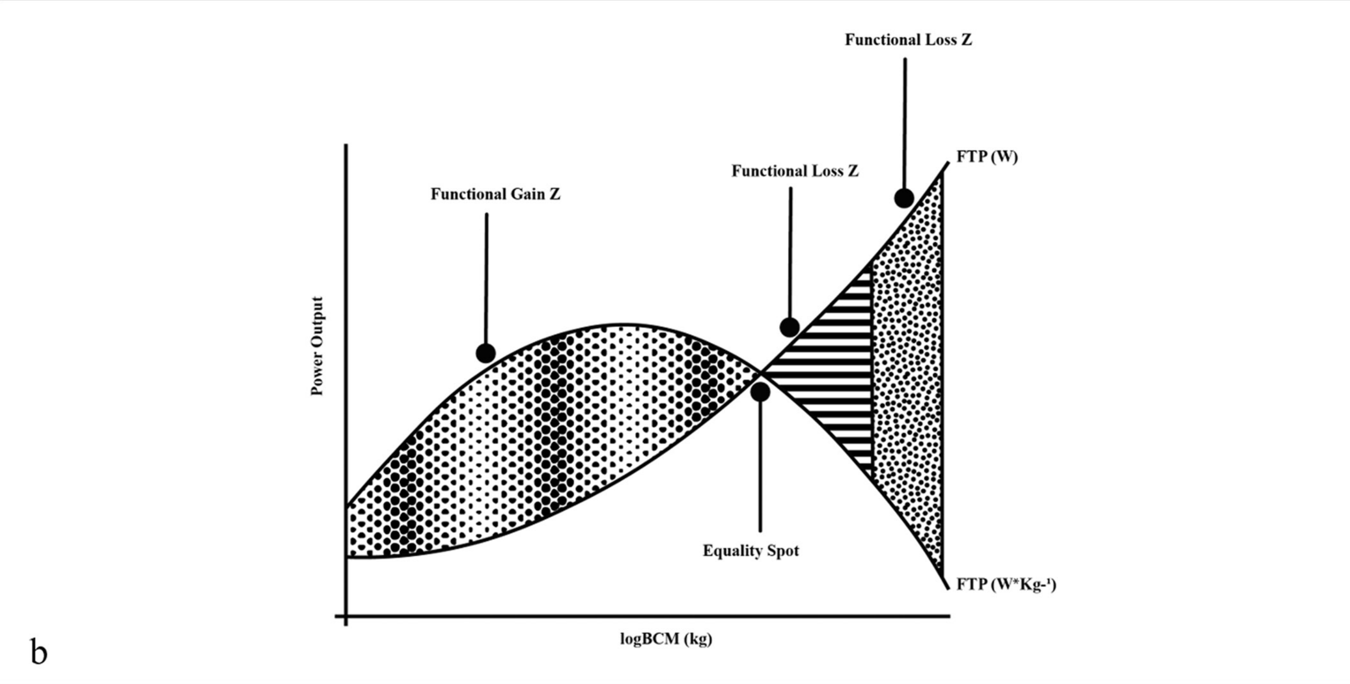
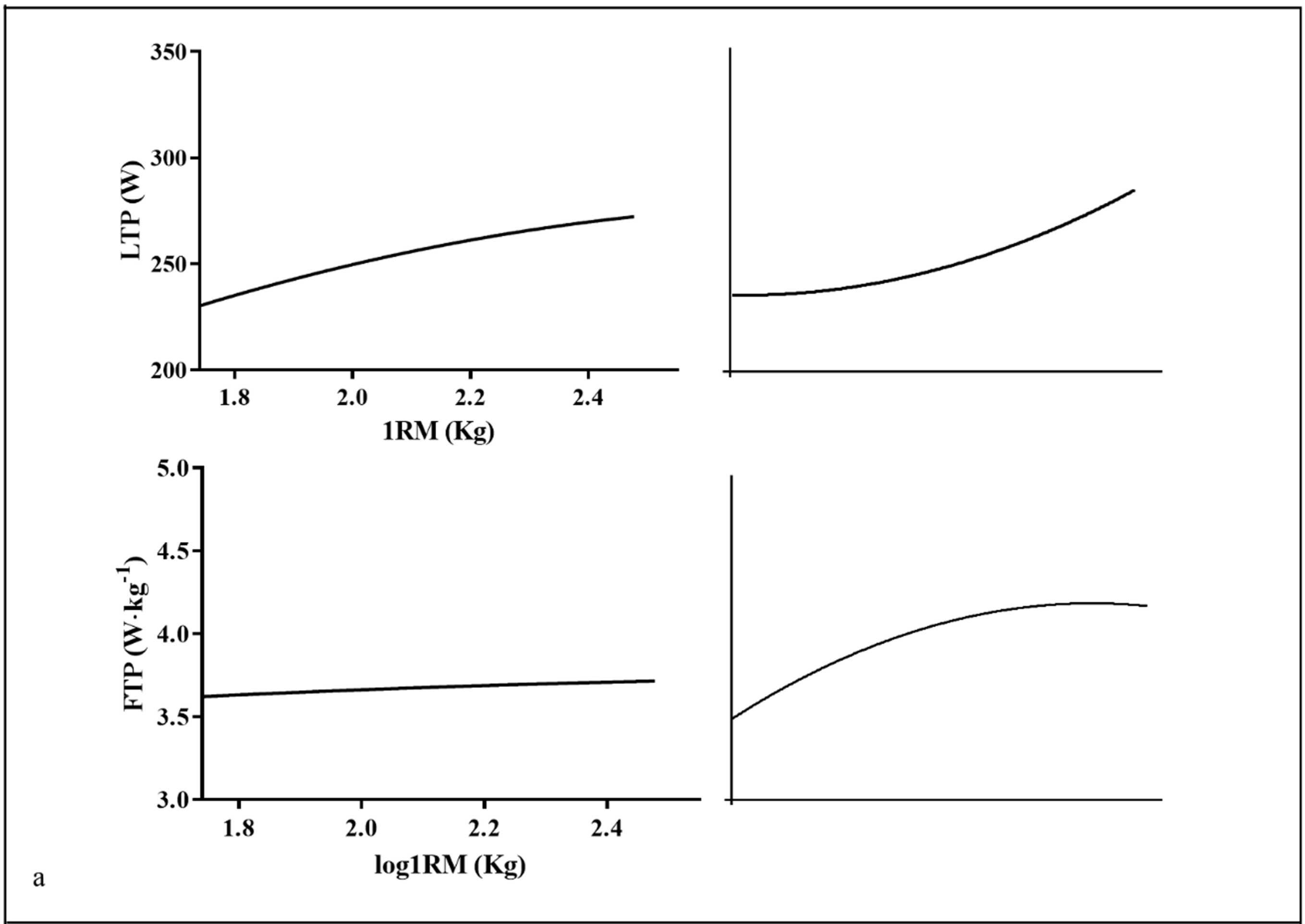


FIG. 5a. Polynomial regression and predictive polynomial regression between functional threshold power (FTP) and logBCM.

FIG. 5b. Functional adaptation zones representation.



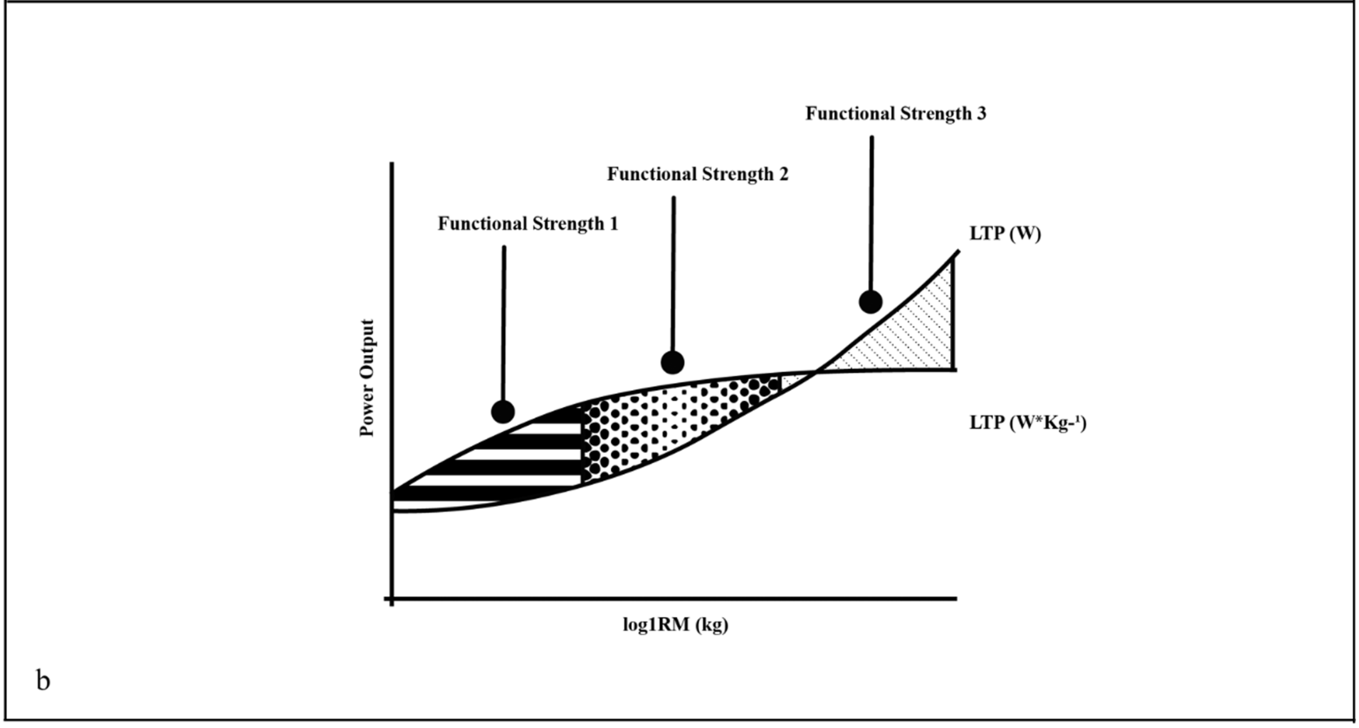


FIG. 6a. Polynomial regression and predictive polynomial regression between functional threshold power (FTP) and log1RM.
FIG. 6b. Functional strength adaptation zones representation.

TABLE 2. Relationships between body composition parameters (body mass, BMI, BCM, PA) and performance indicators (FTP, LTP, 1RM).

Performance	**FTP**						**LTP**						**1RM**		
Body comp.	**W**			**W × kg^{-1}**			**W**			**W × kg^{-1}**					
	r	**ICC**	**p**	**r**	**ICC**	**p**	**r**	**ICC**	**p**	**r**	**ICC**	**p**	**r**	**ICC**	**p**
Body mass	0.29	0.06	*	-0.56	-0.001	***	0.29	0.006	*	-0.61	-0.001	***	0.24	0.033	ns
BMI	0.22	0.001	ns	-0.57	-0.003	***	0.24	0.001	ns	-0.61	-0.003	***	0.25	0.004	ns
BCM	0.68	0.006	***	-0.12	-0.001	ns	0.67	0.005	***	-0.13	-0.001	ns	0.37	0.018	**
PA	0.42	0.000	***	-0.04	-0.003	ns	0.39	0.000	***	-0.05	-0.003	ns	0.16	0.001	ns

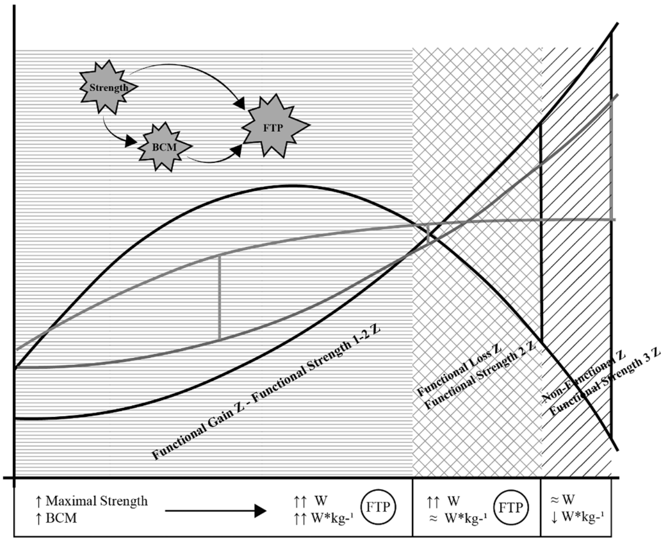


FIG. 7. Discussion graphical summary: increasing maximal strength from low strength levels could produce adaptations also in terms of functional endurance power for some cyclists. Further increase in strength, mainly related to body composition changes (e.g., increase in muscle mass) may be more advantageous for athletes requiring high absolute power and less for athletes who take advantage of a high power to body mass ratio.

studies showing that endurance [18–20] or strength [21–24] training programmes induce enough functional adaptations to promote cycling performance. Particularly, the present findings confirm these beneficial impacts following a combined strength and conditioning training programme. Underlying mechanisms by which the adopted training programme in the present studies may contribute to the observed improvement in cyclists' FTP, LTP and 1RM may possibly be related to (i) increased maximum strength of type I fibres and consequent postponed time to exhaustion and delayed activation of type II fibres, (ii) increased proportion of type IIA fibres and reduced proportion of type IIX fibres, (iii) increased maximum force and/or rate of force development facilitating better blood flow to exercising muscles, and (iv) reduction of activated muscle mass to generate the same absolute submaximal power [21, 22]. Indeed, the provided training protocol has combined cycling training reproducing sport-specific movements and resistance training gym sessions involving discipline-specific muscle groups and including heavy load sessions with higher velocity during the concentric phase and increased time under tension during the eccentric phase. Such a combination was previously suggested to improve cyclists' aerobic, anaerobic, and maximal power, while enhancing strength and maximal strength [21–24].

This study was also conducted to analyse the potential correlations between endurance performance indicators and to investigate the existence of possible endurance-functional-adaptive windows linked to strength and body composition marker changes. The present results showed a strong correlation between the two widely applied tests for cycling performance analysis (FTP and LTP) and therefore confirmed the strength of the relationship between the FTP, an in-field based performance marker, and LTP [10]. LTP is considered, and widely accepted, as one of the most reliable predictors of endurance performance [1, 4, 10]. The results of this study confirm that FTP can be used as an easy test to describe endurance cycling performance [10]. Indeed, FTP can be considered more as a surrogate of LTP when there is no possibility to perform laboratory tests as well as an easy and reliable additional test that can be planned multiple times during the season and replace invasiveness evaluations (e.g., blood lactate samplings) [8–10]. However, additional data are necessary to demonstrate the possible interchangeability of these two performance tests, especially in high level cyclists, where a personalized approach is needed.

On the other hand, changes in body composition and strength led to the hypothesis of the possible existence of different adaptation zones. Particularly, the present results showed that increased maximal strength was moderately correlated with functional power expressed as absolute power but trivially when expressed as power to weight ratio. The polynomial regression suggests the existence of three different strength adaptive zones emerging from the intersection of the two power curves: absolute power and power to weight ratio curve (Figure 6b and Figure 7). Increasing maximal strength from low strength levels could produce adaptations also in terms of functional endurance power for some cyclists (functional strength 1 and 2). Differently, more consistent increases in maximal strength may impact athletes' functional power adaptations in a different way, as shown by the plateau reached by the power to body mass ratio curve and the parallel exponential increase in absolute power curve: functional strength 2–3 (Figure 6b and Figure 7).

One potential explanation could be related to the dynamics of strength increase in athletes described by Hughes, and by the influence of body composition changes necessary to induce large strength increases [14, 21]. Adaptations to HRST in the initial phases involve mainly the neuronal system with a slower progression of muscular adaptations that will proceed in late phases (e.g. increase in muscular CSA and connective tissue) [14]. Thus, based on our results, cyclists aiming to increase peak power output and average power (e.g. sprinters) should incorporate HRST sessions for long term periods, accurately periodized though the season. Differently, when power to body weight ratio represents the key performance aspect rather than absolute power, HRST training sessions should be strategically planned through the season considering both continuous and/or intermittent periods of time (e.g., pre-season and strength-increase-oriented training phases).

As described by Mujika et al., increased maximal strength is related to better body composition and increased maximal power [21]. However, as suggested by the predictive polynomial regressions between power and BCM, the increase in BCM (consequent to an increase in body mass induced by personalized nutrition [38] and HRST/endurance training [22]) may also have a non-functional impact on the power to body mass ratio: increased BCM may not translate totally to functional power (Figure 5b and Figure 7). In this case (Figure 4b and Figure 6), where the absolute power curve (W) may follow a different path than the power to body mass ratio curve (W × kg-^{1}), the following zones can be identified: (i) a functional gain zone in which the increase in BCM is related to a parallel functional increase in threshold power (a zone in which all cyclists may take advantage from improved body composition and increases in BCM), (ii) a functional loss zone in which the absolute power (W) continues to increase but not the power to body mass ratio (W × kg-^{1}) zone, in which mainly sprinters and time triallists may take advantages from further increases in BCM, and (iii), a non-functional zone in which the adaptations seem no longer to be advantageous for the athlete [39–41]. These frames of interrelationships among performance variables confirm the importance of athletes' personalized and periodized training (Figure 7) [38, 42, 43]. Each athlete has different and unique characteristics [44]. Therefore, strategies to improve cyclists' performance should take into account to what extent and in which period of the season/career a personalised training programme can be provided to achieve targeted functional adaptations and thereby produce performance gains [45]. Nevertheless, long-term data acquisition and additional data on elite and sub-elite cyclists are necessary to provide more insightful analysis and confirm or refute these observations. Therefore, further studies, in larger samples including both elite and sub-elite athletes, are necessary to improve our understanding of the dynamics of long-term adaptations in cyclists.

CONCLUSIONS

The results of this study indicate beneficial impacts of one-year combined strength and conditioning training on cycling performance indicators (i.e., FTP, LTP, 1RM) and confirmed the existent correlation between FTP and LTP, two widely applied tests and descriptors for cycling performance analysis. Additionally, the presently demonstrated correlation between the studied performance indicators (athletes' threshold power, body composition and strength) suggest the possible existence of different adaptation zones. Therefore, strategies aiming to improve performance should consider athlete characteristics and performance goals to achieve functional performance adaptations and thereby enhance cycling performance.

PRACTICAL APPLICATIONS

Monitoring athletes' adaptations (maximal strength, body composition and functional power) may provide consistent feedback to personalize and periodize inputs and stimuli to achieve determined performance goals.

Data integration among athletes' performance assessment staff (e.g. coaches, nutritionists, team physician doctors, directors, psychologists, physiotherapists, etc.) may result in deep insights in analysis of athletes' condition and lead to fundamental decisions to improve athletes' success as well as health preservation.

Practitioners working with cyclists may collaborate through a team approach, sharing data acquired through different methods and relying on the support of performance analysts.

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Conflict of interest

The authors have decleated no conflict of interest.

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SUPPLEMENTARY MATERIAL

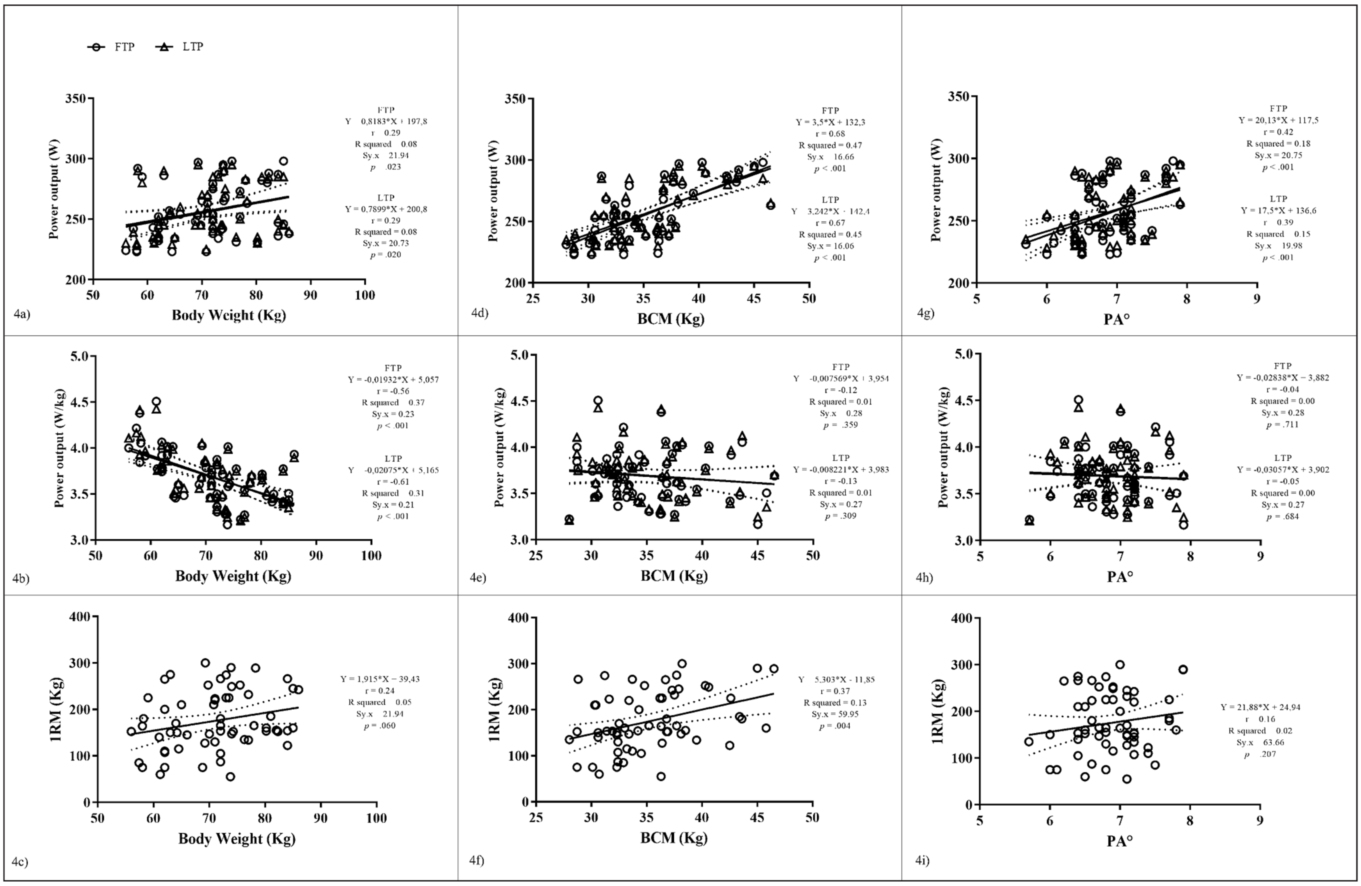

FIG. S1. Left column: relationship between functional threshold power (FTP) (4a), lactate threshold power (LTP) (4b) and body mass and maximal strength (1RM) and body mass (kg) (4c). Middle column: relationship between functional threshold power (FTP) (4d), lactate threshold power (LTP) (4e) and body cell mass (BCM) and maximal strength (1RM) and body cell mass (BCM) (4f). Right column: relationship between functional threshold power (FTP) (4g), lactate threshold power (LTP) (4h) and phase angle (PA) and maximal strength (1RM) and phase angle (PA) (4i). Solid and dashed lines represent the regression line and the 95% confidence intervals, respectively.