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Original Article

Are Peak Power Output, Critical Power and Lower Limb Muscle Power Correlated in Recreational Endurance Cyclists?

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Abstract: Although the variables associated with endurance cycling performance, as peak power output (PPO) and critical power (CP) as well with lower limb muscle power have been investigated previously, no studies have verified the association between these variables in endurance cyclists. The aims of this study were to determine and correlate PPO, CP, and lower limb muscle power in recreational endurance cyclists. Nineteen recreational endurance cyclists (31.4 ± 5.6 years) performed the following tests in the laboratory: incremental test to determine the PPO, 3-min all-out test to determine the CP, and vertical jumps (VJ) tests (squat jump [SJ], countermovement jump [CMJ], and countermovement jump with arms swings [CMJA]) to determine lower limb muscle power. The tests for PPO and CP determination were performed on the subjects' own road bike and the VJ tests were performed on an electronic platform. The values of PPO (4.2 ± 0.5 W kg^{-1}) and CP (3.8 ± 0.6 W kg^{-1}) found were similar to those of other studies that evaluated recreational level endurance cyclists; a significant and "very large" correlation was also observed between these two variables (r = 0.751). In contrast, no significant correlations were found between lower limb muscle power with PPO (SJ = 0.027; CMJ = 0.075; CMJA = 0.124) and with CP (SJ = -0.122; CMJ = -0.122; CMJA = -0.093). Therefore, PPO and CP were highly correlated however, these variables obtained in the cycle tests were not associated with the lower limb muscle power determined in the VJ tests. Considering practical applications, PPO and CP represent different intensities and should be used for training prescription, while the VJ tests were not a good measure for monitoring changes in cyclist performance.

Keywords: Athletic performance; Physical endurance; Exercise test; Exercise tolerance.

1. Introduction

Endurance cycling, which incorporates road cycling and mountain biking, is a predominantly aerobic sport, that includes situations in which explosive strength is needed, requiring the development of repeated high-power actions with short duration (Arriel, Souza, Sasaki, & Marocolo, 2022; Faria, Parker, & Faria, 2005; Impellizzeri & Marcora, 2007; Jeukendrup, Craig, & Hawley, 2000; Prinz, Simon, Tschan, & Nimmerichter, 2021). In this sense, there are some physiological and performance variables that are considered predictive and are associated with endurance cycling performance, such as peak power output (PPO) and critical power (CP) (Bartram, Thewlis, Martin, & Norton, 2017; Borszcz, Tramontin, de Souza, Carminatti, & Costa, 2018; Faria et al., 2005; Passfield, Hopker, Jobson, Friel, & Zabala, 2017).

The PPO is characterized as the highest intensity (*i.e.*, power) of effort reached during a maximal incremental cycling test performed until voluntary exhaustion, being correlated with the intensity of occurrence of VO_{2max} (IVO_{2max}) (Balmer et al., 2000; Borszcz et al., 2018; Possamai, de Aguiar, Borszcz, do Nascimento Salvador, de Lucas, & Turnes, 2019). Additionally, PPO is an important variable shown to predict cycling endurance performance and is used to determine intensity zones for aerobic training prescription (Balmer et al., 2000; Borszcz et al., 2018; Caputo & Denadai, 2008). Borszcz et al. (2018) correlated the VO_{2max}, PPO, and lactate and ventilatory thresholds with performance in time trials of 5, 20, and 60 minutes in trained cyclists and found higher correlations with performance in the longer tests. In addition, the PPO demonstrated correlation coefficients of 0.84 and 0.89 with the total power in 20- and 60-minute time trials, respectively (Borszcz et al., 2018).

Another important variable related to endurance cycling performance is the CP, which is defined as the estimated effort intensity that can be sustained for a given period, approximately 30 to 60 minutes, based on the hyperbolic relationship between predetermined effort intensities and the time over which that effort can be sustained (Wrigth, Bruce-Low, & Jobson, 2017). Studies with cyclists have used the 3-min all-out test to determine CP (Vanhatalo, Doust, & Burnley, 2007; Vanhatalo, Doust, & Burnley, 2008; Wright et al., 2017). Karsten et al. (2021) compared and associated the CP with the intensity of the functional threshold power (FTP) and found high correlations between these variables, however the intensities were different, in which the CP was greater than the FTP, indicating that CP and FTP cannot be used interchangeably. Passfield et al. (2016) used combined data from training and competitions of Grand Tour cyclists over a season and demonstrated that CP was predicted based on performances lasting 3, 7, and 12 minutes.

In addition to the variables associated with aerobic performance (*e.g.*, PPO and CP), lower limb muscle power is an important physical capacity for endurance cyclists (Kordi, Folland, & Goodall, 2020; Lee, Lee, Takeshi, Lee, & Kim, 2021; Lee, Lee, Lee, & Kim, 2018). In this context, vertical jump (VJ) tests are used to determine lower limb muscle power from the combination of maximum contraction force and speed. It is worth noting that for endurance cyclists, regardless of the aerobic prevalence, explosive actions are required to reach and maintain high intensities (Coetzee & Malan, 2018).

While the variables associated with endurance cycling performance (*e.g.*, PPO and CP), as well with lower limb muscle power, have been investigated previously, were are unaware of prior research verifying the association between these variables in endurance cyclists. The aims of this study were to determine and correlate PPO, CP, and lower limb muscle power in recreational endurance cyclists. We hypothesized that the investigated variables would present high correlations with each other.

2. Materials and Methods

2.1. Participants

The sample size was calculated from a *priori* analysis (correlation bivariate: normal model) according to a correlation p H1 of 0.6, power of 80% and significance level of 5%, using the software Gpower® 3.1 (Düsseldorf, Germany) for the calculation. The priori power analysis revealed a minimal sample of 19 participants. Thus, nineteen male recreational endurance cyclists (31.4 ± 5.6 years; 180.0 ± 10.0 cm; 77.8 ± 8.0 kg; 15.6 ± 4.2% body fat) involved in systematic training for at least two years took place in this study. The cyclists had experience in state-level competitions of road and Mountain Bike cycling, with a training volume of 10.4 ± 2.5 $h \cdot w^{-1}$. Concerning the training level, the athletes were classified as trained at the performance level 3, based on the classification of De Pauw et al. (2013) who defines Cat 1 through 5 for cyclists.

The inclusion criteria were: included answering NO on all seven questions in the physical activity readiness questionnaire (PAR-Q short version), presenting TOP 3 results in events at regional and/or state level in their category; do not use any type of medication and/or supplementation during the data collection; have not any pathology such as: diabetes; hypertension; heart and respiratory problems or any other chronic illness. The exclusion criteria were: voluntary withdrawal, development of pathologies and/or occurrence of injuries during the experimental protocol.

Prior to testing, written informed consent was obtained from all participants and the test protocols were explained individually to each participant. Appropriate standard for human experimentation were followed according to international standards (Harris, MacSween, & Atkinson, 2019). The experimental protocol was approved by the Local Human Research Ethics Committee (#5204494/2022), in the spirit of the Helsinki Declaration.

2.2. Design

The participants undertook two visits to the laboratory for data collection at the same time of the day (in the morning), with an interval of 48 hours between visits.

The cyclists performed the following tests: (a) test to determine the PPO; (b) test to determine CP; (c) VJ tests. The participants completed all testing on their own bike attached to the training roller (Elite Suito T, Fontaniva, Italy). All evaluations were performed under laboratory conditions (temperature = 20-24°C and relative humidity = 50–60%). The order of the PPO and CP tests was randomly defined and the VJ tests were performed on the same day as the CP test. The tests for PPO and CP determination were performed on a road bike, using an interactive training roller (Elite Suito -T®, Fontaniva – Italy); the VJ tests were performed on an electronic platform (Jump System Pro 1.0 Cefise®, Nova Odessa – SP, Brazil).

The participants were instructed to maintain the same diet routine before all testing sessions, and to attend the tests well rested, nourished, and hydrated. Participants were also instructed not to consume ergogenic substances during the experimental protocol period and to avoid eating for 2 h before the maximal tests, to abstain from caffeine and alcohol, and to refrain from strenuous exercise for 24 h before testing (Machado, Kravchychyn, Peserico, da Silva, & Mezzaroba, 2013).

2.3. Peak Power Output (PPO)

The incremental protocol to determine PPO started with an initial power of 105 W and increased by 35 W between each successive 3-min stage until participants reached volitional exhaustion or the protocol was terminated when the participant could not maintain a cadence of > 67 rpm despite verbal encouragement (Caputo & Denadai, 2008).

If the final stage was not completed, the PPO was calculated as the power of the final complete stage added to the completed fraction of the incomplete stage, according to the equation: $PPO = P_{complete} + (Inc \times t/T)$, in which $P_{complete}$ is the power of the final completed stage, Inc is the power increment (*i.e.*, 35 W), t is the number of seconds sustained during the incomplete stage, and T is the number of seconds required to complete a stage (*i.e.*, 180 s) (Kuipers, Rietjens, Verstappen, Schoenmakers, & Hofman, 2003).

During the test, heart rate (HR) was monitored (GARMIN®, Kansas - USA), as well the rating of perceived exertion (RPE), with the 6-20 Borg scale 20 (Borg, 1982). The maximal HR (HR_{max}) and maximal RPE (RPE_{max}) were defined as the highest HR and RPE values, respectively. The maximal effort was deemed to be achieved if the incremental test met the following criteria (Howley et al., 1995): (1) $HR_{max} \geq 100\%$ of endurance-trained age-predicted HR_{max} (APMHR) using the age-based "206 – 0.7 × age" equation (Tanaka, Monahan, & Seals, 2003) and (2) $RPE_{max} \geq 19$ in the 6–20 Borg scale (Borg, 1982).

2.4. Critical Power (CP)

To determine the CP, the protocol proposed by Griffin, Gissane, Bailey, and Patterson (2018) was used. The participants performed a 10-min warm-up at a light intensity (RPE 9 – 11) at a self-selected cadence followed by a 5-min passive rest. After this interval, the participants underwent a 3-min pre-test with moderate intensity (RPE 12 – 14) and self-selected cadence, and the final 10 s of the period were used to increase the intensity and cadence to approximately 110 rpm, thus providing the beginning of the total effort test (Griffin et al., 2018). A countdown was performed to coincide with the start of the 3-min all-out test. At that moment, participants were strongly encouraged verbally to generate maximum effort and then maintain the highest possible cadence. Participants were not informed about the elapsed time, power, or cadence, thus avoiding rhythm strategies. At the end of the test, a return to calm was performed for 10-min with self-selected power (Griffin et al., 2018). The CP was calculated as the average power output in the final 30 s of the 3-min all-out test. During the test, HR and RPE were monitored following the same procedures as previously described.

2.5. Lower limb muscle power

VJ performances were measured using electronic platform equipment (Jump System Pro 1.0 Cefise®, Nova Odessa-SP, Brazil) designed to determine contact time and vertical jump flight time. Participants performed three different vertical jump tests: Squat Jump (SJ), Countermovement Jump (CMJ), and Countermovement Jump with arms swings (CMJA). Before testing, the cyclists performed self-administered submaximal CMJs and SJs as a warm-up.

In the SJ test, the participants started in an isometric crouched with hands on the waist, and at the signal from the evaluator performed the jump. In the CMJ tests, the participants stood on the mat, fully erect, with hands positioned on the waist, and at the signal from the evaluator squatted quickly and performed the jump. Finally, in the CMJA participants followed the same steps as the CMJ test but used the aid of the arms to propel themselves. All tests were performed three times, with an interval of 30 s between repetitions and the highest values obtained for height (cm) and the power were considered as the performance for the analysis (Loturco, Pereira, Kobal, Kitamura, Cal Abad, Marques & et al., 2017; Meylan, Nosaka, Green & Cronin, 2011; Petridis, Utczás, Tróznai, Kalabiska, Pálinkás & et al., 2019).

2.6. Statistical analysis

Data were analyzed using the statistical package Statistical Package for the Social Sciences (SPSS® v.20, Inc, Chicago, IL). Data normality was verified using the Shapiro Wilk test and results are presented as mean ± standard deviation (SD). Correlations between PPO, CP and VJ were performed using the Pearson's correlation coefficient (r). The correlations were classified according to Hopkins, Marshall, Batterham, and Hanin (2009) as trivial (< 0.1), small (< 0.3), moderate (0.3 - 0.5), large (0.5 - 0, 7), very large (0.7 - 0.9), almost perfect (> 0.9), perfect (1.0). The significance level adopted for all analyzes was $p < 0.05$.

3. Results

Table 1 presents the descriptive variables obtained during the tests to determine PPO and CP (3-min all-out). The CP represented 91.7% of PPO.

The relative values of the lower limb muscle power obtained from the performance in the VJ tests are shown in table 2.

Table 1. Variables obtained during the maximal incremental test to determine PPO and during the 3-min all-out test to determine CP.

Variables	PPO	CP
Time to exhaustion (min)	21.9 ± 1.9	-----
Absolute Power (W)	325.7 ± 22.6	297.7 ± 32.7
Relative Power (W·kg-1)	4.2 ± 0.5	3.8 ± 0.6
RPE_{max} (6-20)	19.8 ± 0.7	19.8 ± 0.7
HR_{max} (bpm)	193 ± 14.1	188 ± 12.6
Absolute maximal power (W)	----	1099.0 ± 164.7
Relative maximal power (W·kg-1)	----	14.2 ± 2.2

Note: n = 19; PPO: peak power output; CP: critical power; RPE_{max}: maximal subjective perception; HR_{max}: maximal heart rate; W·kg-1: relative power.

Table 3 presents the correlations between the values of PPO, CP, and lower limb muscle power. A significant correlation was found and classified as "very large" between the PPO and CP. In addition, as expected, the power values obtained in the different VJ tests (SJ, CMJ, and CMJA) showed high and significant correlations with each other. Concerning the correlations between PPO and CP with the lower limb muscle power, no significant associations were demonstrated.

Table 2. Relative values of the lower limbs muscle power and height obtained in vertical jump tests.

Variables	Mean ± SD
SJ power (W·kg^{-1})	45.0 ± 4.7
SJ height (cm)	33.4 ± 5.9
CMJ power (W·kg^{-1})	46.7 ± 5.3
CMJ height (cm)	35.5 ± 6.6
CMJA power (W·kg^{-1})	50.3 ± 5.8
CMJA height (cm)	40.1 ± 7.3

Note: n = 19; SJ: squat jump; CMJ: counter movement jump; CMJA: counter movement jump with arm.

Table 3. Correlations between the variables PPO, CP, and lower limb power.

Variables	PPO (W·kg^{-1})	CP (W·kg^{-1})	SJ (W·kg^{-1})	CMJ (W·kg^{-1})	CMJA (W·kg^{-1})
PPO (W·kg^{-1})	--	0.751* Very large	0.027 Trivial	0.075 Trivial	0.124 Small
CP (W·kg^{-1})	--	--	-0.122 Small	-0.122 Small	-0.093 Trivial
SJ (W·kg^{-1})	--	--	--	0.972* Almost perfect	0.888* Very large
CMJ (W·kg^{-1})	--	--	--	--	0.945* Almost perfect

Note: n = 19; * $p < 0.05$; PPO: peak power output; CP: critical power; SJ: squat jump; CMJ: counter movement jump; CMJA: counter movement jump with arm.

4. Discussion

The aims of this study were to determine and correlate PPO, CP, and lower limb muscle power in recreational endurance cyclists. The main findings were that there was a significant correlation, classified as "very large" between PPO and CP, and no associations were found between lower limb muscle power and the variables PPO and CP, partially confirming the initial hypothesis. In addition, the PPO and CP values were similar to those of other studies that evaluated recreational endurance cyclists.

PPO values in the present study were similar to those found in other studies with endurance cyclists (Karsten et al., 2021; Valenzuaela, Alejo, Montalvo-Pérez,Gil-Cabrera, Talavera, Lucia, & Barranco-Gil, 2021). Valenzuela et al. (2021) evaluated 17 recreational cyclists (33.0 ± 5.0 years) with a maximal incremental test started at 150 W and with increments of 25 W every three minutes and found an absolute PPO of 321.0 ± 40.0 W and relative PPO of 4.5 ± 0.7 W·kg^{-1}. Two other studies demonstrated slightly higher PPO values (Griffin et al., 2018; Karsten et al., 2021;) than demonstrated in our study. Karsten et al. (2021) evaluated 17 trained cyclists and triathletes (31.0 ± 9.0 years) and found an absolute PPO of 350.0 ± 56.0 W, while Griffin et al. (2018) evaluated 12 recreational cyclists (30.0 ± 6.0 years) and found and absolute PPO of 344.0 ± 52.0 W. Furthermore, it is important to mention that in our study the time to exhaustion on the PPO was 21.9 ± 1.9 min, reinforcing that PPO reflect an aerobic variable.

Concerning the CP obtained in the present study during the 3-min all-out test (297.7 ± 32.7 W and 3.8 ± 0.6 W·kg^{-1}), this variable was higher than the values found in other studies with different samples (Griffin et al., 2018; Karsten et al., 2021). Griffin et al. (2018) evaluated 12 recreationally active males, who also performed the 3-min all-out, and found a CP of 234.0 ± 67.0 W. Karsten et al. (2021) with 17 trained cyclists and triathletes used a different protocol for determining the CP, consisting of three time-trial tests with different durations (3, 7 and 12 minutes in duration) and with a passive rest of 30 min between them, in which the CP value found was 256.0 ± 50.0 W.

It is worth mentioning that we found that the CP represented 91.7% of the PPO, a percentage that is higher than that already reported in previous studies (Griffin et al., 2018; Karsten et al., 2021; Valenzuela et al., 2021), in which the %CP/ PPO ratio was between 68% and 78.3%. Two factors could have influenced this difference: the different protocols used in the studies, especially for the determination of PPO and CP, and the high absolute CP value in the athletes of the present study in relation to the values found in the literature. For practical applications, considering that the PPO and CP do not represent the same intensity, one of these variables should be chosen for the training prescription.

The correlation between PPO and CP was classified as “very large” (r = 0.751), indicating that the higher the CP, the higher the PPO. It is important to note that the PPO and CP in our study was not strongly associated when compared to the correlation’s values between CP and lactate thresholds markers demonstrated by Valenzuela et al. (2021) (r = 0.81–0.98) with 17 male recreational cyclists. However, concerning the association with endurance performance, several studies have revealed that lactate threshold and PPO predict different time trial performances in cyclists (Balmer et al., 2000; Bentley et al., 2001; Borszcz et al., 2018).

Although no previous studies with recreational endurance cyclists have demonstrated the association between PPO and CP, one study (Figueiredo, Figueiredo, Manoel, & Machado, 2021) with recreational runners evaluated the peak velocity (V_{peak}), which represents the maximal intensity attained during an incremental test, similarly to the PPO in our study. Figueiredo et al. (2021) with 25 recreational runners (28.6 ± 4.7 years) examined the correlation between V_{peak} and critical velocity (CV) to verify which variable could best predict performance in a 5-km race. The determination of CV was carried out from three time-trials (2600, 1800, and 1000 m) with a rest period of 30 minutes between them. V_{peak} was obtained from a maximal incremental test with velocity increments of 1 $km \cdot h^{-1}$ every three minutes. The authors found that both V_{peak} and CV were predictors of 5-km performance, with high correlations ranging from 0.80 to 0.95; however, no correlation was demonstrated between V_{peak} and CV.

In addition to PPO and CP, there are other variables that are determinants of cycling performance, such as muscle size and architecture, knee extension strength, and distribution of muscle fiber types, all of which are related to lower limb muscle power (Lee et al., 2021), that can be well characterized by VJ performance.

Only one previous study performed VJ tests with a sample of cyclists. Coetzee and Malan (2018) determined the VJ performance in 45 well-trained, male, amateur road cyclists (21.3 ± 3.1 years) who performed several physical tests to determine physiological and performance variables, including the CMJA test. The value reported by Coetzee and Malan (2018) for the CMJA height (45.7 ± 6.7 cm) was different to that of the present study for the same VJ (40.1 ± 7.3 cm). It is important to mention that only the CMJA was performed, which is different to our study that evaluated three VJ types.

Specifically, regarding associations with VJ, no significant correlation was demonstrated between aerobic variables (*i.e.*, PPO and CP) and lower limb muscle power. This non-correlation can be explained because the vertical jump movement is not common for cyclists and not reflect the power used during cycling performance. In addition, the lack of correlation between these variables in our study suggest that the aerobic performance of endurance cyclists is not explained by the lower limb peak instantaneous muscle power.

Dal Pupo, Ache-Dias, Kons, and Detanico (2021) analyzed the relationship between VJ parameters (SJ and CMJ) with specific physical performance in different sports. The sample consisted of 52 male athletes (21 judokas, 18 futsal players and 13 sprinter runners who performed the SJ and CMJ in addition to a specific physical test for each modality (Special Judo Fitness Test, Running Anaerobic Sprint Test and 20- and 200-meter sprints). The authors verified that the height and relative power of the VJ presented significant correlations with the physical performance evaluated in the specific tests performed by the athletes, a result that differs from that found in our study with recreational endurance cyclists. These differences for the correlations between our study and Dal Pupo et al. (2021) can be explained because the different sample of athletes and performance tests used in each study. However, similarly to the present study, Lanferdini, Silva, Machado, Fischer, and Peyré-Tartaruga (2020) demonstrated no association between VJ performance and peak running performance in recreational endurance runners.

5. Practical Applications

Considering practical applications, PPO and CP represent different intensities and should be used for coaches and athletes for training prescription, but not interchangeably. We suggest caution for training prescription when choosing between PPO and CP. Furthermore, the VJ tests were not a good measure for monitoring changes in cyclist performance.

Despite the important results presented, the current study has some limitations, such as the lack of dietary control based on a dietary recall and the lack of a time trial test to determine the cyclist's endurance performance. Future studies should associate the variables PPO, CP, and lower limb muscle power with performance in cycling endurance events.

6. Conclusions

Based on the data presented, PPO and CP values were highly correlated but neither of these variables obtained in the cycle tests were associated with the lower limb muscle power determined in the VJ tests.

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