

Relationship between physiological and biomechanical variables with aerobic power output in cycling

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Abstract

Performance in cycling may be determined by physiological and biomechanical parameters. The aim of this study was to assess the relationship between biomechanical and physiological variables with aerobic power output in cycling. Twelve cyclists and twelve non-athletes performed an incremental cycling test to exhaustion during their first evaluation session and a constant load cycling test in a second evaluation session. Aerobic power output and oxygen uptake were measured during the first evaluation session, while muscle volume (determined using ultrasound measures in static conditions) and pedal forces were measured at the second session. Pedal forces were used to compute total force applied to the pedal and force effectiveness. Two multivariate stepwise regression analyses were conducted to measure the relationship between power output and oxygen uptake obtained at the second ventilatory threshold (VT_2), muscle volume, total force applied to the pedal, force effectiveness and lower limb muscle activation for cyclists and non-athletes. Only oxygen uptake at the VT_2 was significantly related to power output for non-athletes ($0.640 * VT_2 + 4.152$) ($r = 0.64$, $p = 0.03$), whereas the resultant force was included in the regression model ($0.665 * Resultant Force + 0.685$) for cyclists ($r = 0.66$, $p = 0.02$). Muscle volume, pedal force effectiveness and muscle activation seem to have a minor effect in aerobic power output during cycling.

Keywords: power output, oxygen uptake, pedaling technique

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Introduction

Time trial endurance performance in cycling has been related to the percentage of type I fibers in mono-articular knee extensor muscles (i.e. vastus lateralis), to the percentage of maximal oxygen uptake that can be sustained during a race, and to mid-thigh circumference (Coyle et al. 1991). Empirical knowledge on cycling performance led to the belief that a good pedaling technique (i.e. maximal pedal force effectiveness) is linked to better performance, but this has not been shown true (Coyle et al. 1991). However, recent research showed that improving pedal force effectiveness may lead to higher efficiency (Zameziati et al. 2006; Leirdal and Ettema 2011). Coyle et al. (1991) showed that mid-thigh circumference was strongly related to 1-h laboratory performance ($r^2 = 0.95$), suggesting that cyclists with greater thigh muscle volume might be able to produce more power during endurance cycling trials. More importantly than thigh circumference, muscle volume can be strongly related to performance in cycling. However, the relationship

between muscle volume and power output at the second ventilatory threshold is still undetermined.

Increases in muscle activation may result in greater power output production in cycling. Bijker et al. (2002) found a strong relationship between vastus lateralis activation and power output ($r = 0.92$) and a moderate relationship for biceps femoris and medial gastrocnemius ($r = 0.64$ and 0.55 , respectively) during laboratory cycling tests. These findings suggest that increased selected muscle activation (i.e. hip and knee joint extensors) may be a key factor in lower limb muscle power output during the crank cycle. High percentage of type I fibers in vastus lateralis of trained cyclists presented high correlation with power output (Hansen and Sjogaard, 2007), and activation of this muscle has been linked to power output in cycling time trial (Bini et al. 2008).

To date no evidence was found in the literature on the contribution of muscle volume and muscle activation to power output, when physiological and biomechanical variables are also included in a multiple linear regression model. The analysis of the relationship between physiological and biomechanical variables may help coaches and cyclists to decide whether it is important to allocate time for pedaling technique training looking at improvements in pedal force effectiveness (i.e. biomechanical variables) or whether cyclists should focus on physiological adaptation from regular cycling training.



Therefore the aim of this study was to assess the relationship between physiological (i.e. oxygen uptake and muscle volume) and biomechanical variables (i.e. resultant force, pedal force effectiveness and muscle activation) with aerobic power output. Evidence indicates that cyclists with best performance have greater power output at the anaerobic threshold (Coyle et al. 1991; Amann et al. 2004). The hypothesis of this study was that a strong correlation between oxygen uptake, resultant pedal force and muscle volume with the power output should be observed. In addition, increased pedal force effectiveness should not be related to power output. Rectus femoris and vastus medialis activation should also present a strong correlation to power output due to their potential contribution to power output in cycling (Bini et al. 2008).

Materials and Methods

Twelve cyclists and twelve non-athletes participated in the study. Non-athletes were assessed to determine maximal aerobic power output in subjects with low cycling skill and experience. Sample size was determined based on an effect size of 1.0, an observed power of $1-\beta > 0.80$ and $\alpha < 0.05$ using a statistical package (G*Power 3.1.3, Fraunhofer Universität Kiel, Germany). Information about age, body dimensions, maximal power (PO_{MAX}), and power output at the second ventilatory threshold ($PO-VT_2$) are presented in Table 1.

Before the start of the evaluation sessions, all procedures were presented to the participants who signed a consent form approved by the Ethics Committee of Human Research under the number 17684, where the study was conducted.

Data Acquisition

First evaluation session

On the first evaluation session, anthropometrics (height and body mass) were measured according to the International Society for Advancement of Kinanthropometry protocols (Marfell-Jones et al. 2006). Participants' femur length was measured from

the greater trochanter to the lateral femoral condyle with participants lying prone. After that, participants warmed up at a power output of 150 W for 10 minutes before the cycling test began. Cyclists were tested using their own bicycles while non-athletes used a standard road cycling bicycle with configuration of handlebars and saddle position set to their anthropometrical characteristics (De Vey Mestdagh 1998; Bini et al. 2011). Bicycles were mounted on a stationary cycling trainer (Computrainer, ProLab 3D, Racermate Inc., Seattle, WA, USA) to determine PO_{MAX} (in W) and $PO-VT_2$. Step increments of 25 W every minute until exhaustion were used (Figure 1). Cadence was maintained close to 90 ± 2 rpm for all participants using visual feedback from the cycling trainer head set. Oxygen uptake (VO_2) was measured by an open-circuit indirect gas exchange system (CPX/D, Medical Graphics Corp., St Louis, USA) and VO_{2MAX} was defined as the greatest value obtained in the last test stage, along with PO_{MAX} (Duc et al. 2005). Gas exchanges data were analysed to define the second ventilatory threshold based on the ventilatory equivalent method (Weston and Gabbett 2001), where the curves of VE/VO_2 and VE/VCO_2 were assessed by two trained raters.

Second evaluation session

On the second evaluation session, femur and tibia length were measured followed by the estimative of lower limb total muscle volume (sum of quadriceps in both limbs and triceps surae in both limbs - see data analysis). Ultrasound images were obtained from the participants lying prone using an ultrasound system. The ultrasound probe (7.5 MHz, Aloka SSD 4000, Tokyo, Japan) was positioned perpendicular to the muscle belly at 50% of thigh length (distance between the greater femoral trochanter and the lateral femoral condyle) to measure quadriceps muscle thickness. After that, the probe was positioned at 30% proximal to the distance between the femoral condyle and the lateral malleolus to measure triceps surae muscle thickness (Miyatani et al. 2004).

After ultrasound measurements, participants warmed

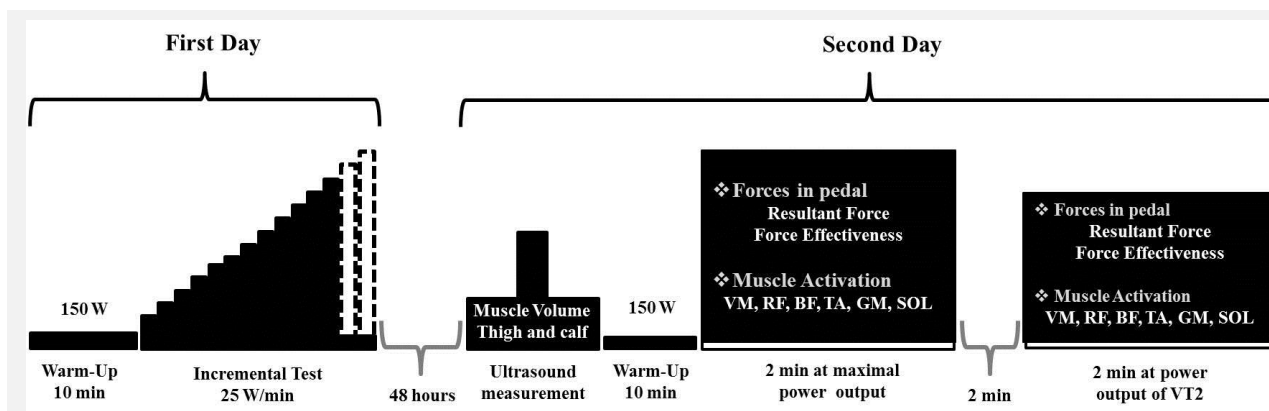


Figure 1. Time line of the experimental setup. In the first evaluation session, oxygen uptake at the second ventilatory threshold (VO_2-VT_2), maximal power output (PO_{MAX}) and power output at the second ventilatory threshold ($PO-VT_2$) were acquired. In the second evaluation session, the following variables were acquired: muscle volume (thigh and calf), pedal forces (resultant force and force effectiveness) and muscle activation [vastus medialis (VM), rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), gastrocnemius medialis (GM) and soleus (SOL)], for two workload levels (PO_{MAX} and $PO-VT_2$) corresponding at first day of tests.

up at 150 W for 10 minutes before the cycling test began. After that, participants performed two minutes of constant workload cycling test at their PO_{MAX} and two minutes at $PO-VT_2$ measured on the first evaluation session. These trials were separated by two minutes of rest. Pedaling cadence was visually controlled by the participants at 90 ± 2 rpm through visual feedback from the cycling trainer headset. During this test, normal and anterior-posterior force applied at the surface of the right pedal were amplified (Entran MSC6, Entran Ltd., England) and collected at 600 Hz using a pedal dynamometer (Nabinger et al. 2002) via an analog-to-digital system with a 16-channel board (DI220, Dataq Instruments Inc., Akron, USA). Pedal angle was measured by an angular potentiometer (Spectrol 1045, Vishay Inc, USA) attached to the pedal spindle and pedal to crank position was defined by a reed-switch trigger attached to the bicycle frame. Muscle activity was measured by surface electromyography from the tibialis anterior, the medial head of gastrocnemius, soleus, the long head of biceps femoris, rectus femoris, and the vastus medialis muscles using a Bortec electromyography system (Octopus AMT-8, Bortec Electronics Inc., Calgary, Canada) via an analog-to-digital system with a 16-channel board (DI720, Dataq Instruments Inc., Akron, USA) at 2400 Hz of sampling rate. Pairs of Ag/AgCl electrodes (Medi-Trace 100, Kendall., Chicoppe, Canada) in bipolar configuration with a diameter of 22 mm were positioned on the skin after carefully shaving and cleaning the area using an abrasive cleaner and alcohol swabs to reduce the skin impedance as recommended by the International Society of Electrophysiology and Kinesiology (De Luca, 1997; Merletti et al. 2009). Electrodes were placed over the distal third of the muscles belly (one third of the muscle length from the midpoint to avoid the myotendinous junction), parallel to the muscle fibers and fixed to the skin with micropore tape (3M Company, USA). The reference electrode was placed over the skin recovering the anterior surface of the tibia. The electrodes' wires

were also taped to the skin to reduce movement artifact. Force and electromyographic signals were offline synchronized using an external source that was triggered to deliver an analog TTL signal (+5V) to both analog-to-digital systems.

Data Analysis

The distance between the rectus femoris superficial aponeurosis and vastus intermedius deep aponeurosis was manually digitized on the ultrasound image to determine quadriceps muscle thickness using ImageJ (National Institute of Health, USA). Similarly, the distance between the gastrocnemius superficial aponeurosis and the tibialis posterior deep aponeurosis was measured to obtain calf muscle thickness (Blazevich et al. 2006). Muscle volume (MV) was estimated from Miyatani et al. (2004) (Equations 1-3):

1. $MV \text{ of thigh} = (\text{quadriceps muscles thickness} * 320.6) + (\text{length of femur} * 110.9) - 4437.9$
2. $MV \text{ of calf} = (\text{calf muscles thickness} * 219.9) + (\text{length of tibia} * 31.3) - 1758$
3. $Total \text{ MV of lower limb} = MV \text{ of thigh} + MV \text{ of calf}$

Force signals were filtered using a third order zero lag low-pass Butterworth digital filter with cut frequency defined to minimize the residuals of the signal, as described elsewhere (Winter 2005). Normal and anterior-posterior force components were converted to the tangential component at the crank (effective force) to calculate the overall force effectiveness (pedal force effectiveness), which was based on the ratio between the angular impulse of the force effectiveness by the linear impulse of total pedal force (resultant force) (Rossato et al. 2008). Force data was divided into ten consecutive revolutions to calculate the mean ensemble results for each participant. Data analyses were conducted offline using custom made scripts written in MATLAB® (MathWorks Inc., Natick, USA).

For EMG analysis, filtering of the raw EMG signals was conducted using a band-pass Butterworth filter with cut-off frequencies optimized to reduce signal residuals as described elsewhere (Winter, 2005). Signals were cut and averaged for ten consecutive crank revolutions for every muscle of every participant in EMG and also averaged for pedal forces. The root mean square (RMS) envelopes were then normalized by the mean RMS value from the average results of the ten cycles from the PO_{MAX} trial of the second session. EMG data analysis was conducted using custom written scripts in MATLAB® (MathWorks Inc., Natick, USA).

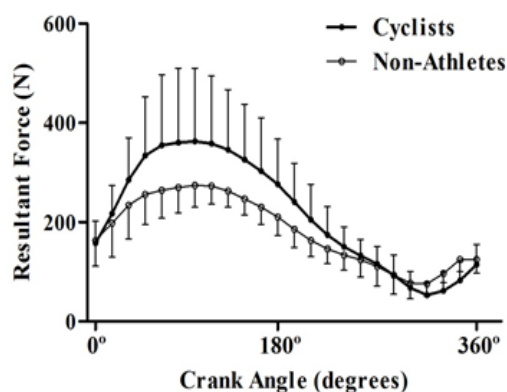


Figure 2. Resultant pedal force during the crank cycle for cyclists and non-athletes.

Statistical Analyses

Data normality and homogeneity were tested with Shapiro-Wilk and Levene tests, respectively. When data was not normally distributed, a logarithm transformation was applied. The between-groups comparison (i.e. cyclists vs. non-athletes) for age, body mass, height, PO_{MAX} , $PO-VT_2$, VT_2 , MV, resultant force and pedal force effectiveness was performed with independent-samples t test. Stepwise multiple linear regressions for cyclists and non-athletes were separately performed to identify correlations between oxygen uptake ($ml \cdot kg^{-1} \cdot min^{-1}$) at the second ventilatory threshold (VT_2), muscle volume (m^3), muscle activation (% of PO_{MAX} trial) for vastus medialis, rectus femoris, biceps femoris, tibialis anterior, gastrocnemius medialis and soleus, resultant force (N) and the pedal force effectiveness (%) with power output at the VT_2 (W) (Dancey and Reidy, 2004). Statistical analyses were performed with SPSS 17.0 for Windows, and the significance level was assumed when $\alpha = 0.05$.

Results

Power output at the VT_2 ($PO-VT_2$), maximal oxygen uptake (VO_{2MAX}) oxygen uptake at the second ventilatory threshold (VT_2) and resultant force were smaller for non-athletes compared to cyclists (Table 2 and Figure 2). The between-groups muscle activation

Table 1. Characteristics of cyclists and non-athletes (mean \pm sd) for age, body mass, height, maximal power output (PO_{MAX}), power output at the second ventilatory threshold ($PO-VT_2$), muscle volume (MV) and maximal oxygen uptake (VO_{2MAX}).

	Age (years)	Body mass (kg)	Height (cm)	PO_{MAX} (W)	MV (cm^3)	VO_{2MAX} ($ml \cdot kg^{-1} \cdot min^{-1}$)
Cyclists (n = 12)	28 \pm 6.6	71 \pm 6.8	177 \pm 9.7	375 \pm 30.2	49.9 \pm 9.9	64.1 \pm 5.0
Non-Athletes (n = 12)	24 \pm 3.0	73 \pm 6.1	175 \pm 5.1	290 \pm 48.2*	45.9 \pm 5.7	49.3 \pm 7.2*

* Significant differences between cyclists and non-athletes ($p < 0.05$).

Table 2. Laboratorial performance markers for cyclists and non-athletes (mean \pm sd) for power output at the VT_2 ($PO-VT_2$), oxygen uptake at the second ventilatory threshold (VO_2-VT_2), resultant pedal force and pedal force effectiveness.

	$PO-VT_2$ (W)	VO_2-VT_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	Resultant Force (N)	Force Effectiveness (%)
Cyclists (n = 12)	308 \pm 51.5	51.9 \pm 6.6	215.3 \pm 50.0	57 \pm 11
Non-Athletes (n = 12)	219 \pm 41.5*	39.8 \pm 6.4*	181.6 \pm 29.0*	51 \pm 9

* Significant differences between cyclists and non-athletes ($p < 0.05$).

Table 3. Correlation between oxygen uptake at the second ventilatory threshold (VO_2-VT_2), muscle volume, resultant force, force effectiveness and muscle activation (vastus medialis, rectus femoris, biceps femoris, tibialis anterior, gastrocnemius medialis and soleus) with the dependent variable power output ($PO-VT_2$).

Correlations from Multiple Regression (Stepwise)	Cyclists $PO-VT_2$ (W)	Non-Athletes $PO-VT_2$ (W)
VO_2-VT_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	$r = 0.261$	$r = 0.640^*$
Muscle Volume (m^3)	$r = 0.542$	$r = 0.170$
Resultant Force (N)	$r = 0.665^*$	$r = 0.030$
Force Effectiveness (%)	$r = -0.005$	$r = 0.255$
Vastus Medialis (% of PO_{MAX} trial)	$r = -0.025$	$r = 0.454$
Rectus Femoris (% of PO_{MAX} trial)	$r = 0.176$	$r = -0.202$
Biceps Femoris (% of PO_{MAX} trial)	$r = 0.253$	$r = 0.243$
Tibialis Anterior (% of PO_{MAX} trial)	$r = -0.487$	$r = -0.450$
Gastrocnemius Medialis (% of PO_{MAX} trial)	$r = -0.004$	$r = -0.129$
Soleus (% of PO_{MAX} trial)	$r = -0.153$	$r = 0.248$

*Significant correlation coefficients between variables included in model of multiple linear regression ($p < 0.05$).

comparison did not present significant differences ($p > 0.05$) for any of the evaluated muscles (vastus medialis, rectus femoris, biceps femoris, tibialis anterior, gastrocnemius medialis and soleus). No differences between-groups were observed for muscle volume or pedal force effectiveness.

The multiple linear regression indicated that only the resultant force had a significant relationship to $PO-VT_2$ for cyclists ($p = 0.02$), whilst for non-athletes, VO_2-VT_2 was the only variable included that presented significant relationship with $PO-VT_2$ ($p = 0.03$). Equations 4 and 5 are shown for cyclists and non-athletes, respectively.

$$4. PO - VT_2 = 0.665 * Resultant Force + 0.685$$

$$5. PO - VT_2 = 0.640 * VO_2 - VT_2 + 4.152$$

Where:

PO-VT₂ = power output at the second ventilatory threshold

VO₂-VT₂ = Oxygen uptake at the second ventilatory threshold

Discussion

To address the question of whether biomechanical variables (i.e. pedal force effectiveness) and morphological characteristics of cyclists' vastus lateralis (i.e. muscle volume) could dictate aerobic performance, we assessed the relationship between physiological, biomechanical and morphological parameters of cyclists. The resultant force applied to the pedal was the only variable related to aerobic power output at the VT₂ for cyclists in our study. However, power output at the VT₂ was not related to oxygen uptake, muscle volume, muscle activation or force effectiveness. This result is partially in agreement to previous findings (Coyle et al. 1991) that suggested a minor influence from pedal force effectiveness in cycling endurance performance. In other words, cyclists seem to apply large forces on the pedals without concern on the percentage of the force that drives the cranks. Patterson and Moreno (1990) and Rossato et al. (2008) found that to sustain larger workload levels, cyclists increase resultant pedal force application. These results help to explain our findings for cyclists. However, non-athletes did not follow the same path by showing greater dependence on oxygen uptake to optimize power output. A potential explanation is that non-athletes may have lower percentage of type I fibres in their driving muscles (i.e. knee and hip joint extensors) which reduces their potential to apply force on the pedals for sustained aerobic exercise. In addition, non-athletes may be limited to a larger recruitment of less efficient fibres from less efficient muscles when exercising close to their ventilatory threshold, making the oxygen uptake the limiting factor for aerobic power production. In other words, cyclists may adapt to push the pedals maximally using minimum possible energy compared to non-athletes.

The percentage of type I fibers in a muscle can help to understand the aerobic power output. Coyle et al. (1991) reported that high power output and pedal force application (i.e. greatest peak crank torque) may be related to greater percentage of type I fibers and enhanced cycling efficiency. Furthermore, Coyle et al. (1991) also found a strong correlation ($r = 0.75$) between the percentage of type I fibers and the number of years of cycling training. It appears that elite cyclists have the ability to generate greater power output than lower performance cyclists and this adaptation can be enhanced by endurance training experience. Therefore, trained cyclists may need to focus on improving physiological adaptation during aerobic training (e.g. single leg cycling training – Abiss et al. 2011) rather

than using pedal technique skills (i.e. pulling action during pedaling – Mornieux et al. 2010) to enhance cycling performance.

Greater muscle volume was expected to lead to higher power output, which was not confirmed by our results. This finding is conflicting to the results of Coyle et al. (1991) who showed a strong relationship between thigh circumference and power output during 1-h laboratory test ($r^2 = 0.95$). However, it is important to highlight that errors are expected when linking thigh volume to muscle volume, given cyclists would vary in terms of volume of adipose tissue. Using cross-section images from ultrasound is a better option to compute the volume of muscle tissue in a given limb, excluding adipose tissue and skin (Miyatani et al. 2002). In our study, we used PO-VT₂ rather than the average power output taken during a performance test. This option was based on the strong relationship between PO-VT₂ and performance in 40-km cycling time trials (Amann et al. 2004). Therefore, it is unclear if large quadriceps muscle volume may lead to greater capability to generate aerobic power output. Greater pedal force application may depend on hip muscle power production along with knee extensor power production (Elmer et al. 2011), which limits the combined contribution from quadriceps and calf muscles used in our study.

Conflicting relationship between pedal force effectiveness and cycling efficiency has been previously shown, with most studies suggesting that better technique do not lead to better efficiency (Korff et al. 2007; Bohm et al. 2008; Mornieux et al. 2008). This result may explain the non-significant relationship between the index of effectiveness and power output. Moreover, cyclists may also change joint kinetics and kinematics in order to improve pedaling technique without changes in the index of effectiveness (Bini and Diefenthaler 2010). This may suggest that pedaling technique may not be completely tracked only by assessing pedal force measurements. Zameziati et al. (2006) found increased force effectiveness for non-cyclists pedaling at their maximal workload level, suggesting that non-cyclists may need to improve pedal force effectiveness due to lower oxidative capability at the knee and hip extensor muscles. However, this finding was not supported by our results which suggest that further studies should be conducted to assess adaptation of pedaling technique through training in novice cyclists.

Another factor that may influence power output is activation of lower limb driving muscles (i.e. knee and hip joint extensors). Bini et al. (2008) reported strong correlations between power output and rectus femoris ($r = 0.94$) and vastus lateralis ($r = 0.95$) activations during a 40-km cycling time trial event. On the other hand, tibialis anterior ($r = 0.65$), gastrocnemius medialis ($r = 0.77$) and biceps femoris ($r = 0.67$) activation did not follow the same path. Testing condition (i.e. constant load vs. 40-km time trial) may help to explain differences in our findings. Another conflicting characteristic may be the use of various

bivariate regressions (in the study of Bini et al. 2008) to the use of the stepwise regression in our study. This method takes into account the contribution of all variables used in the model which would be more appropriate to reduce type I errors in multiple analyses. The interaction between physiological and biomechanical variables with aerobic power output in cycling still needs further assessment. Future studies may focus on monitoring physiological and biomechanical variables when cyclists are subjected to training programs. Along with that, the contribution from physiological and biomechanical variables to anaerobic performance may be assessed in future research.

Among the limitations from our study was the measurement of activation and muscle volume from knee and ankle joint muscles, with no mono-articular hip joint muscles involved (e.g. Gluteus Maximus). The use of right lower limb measurements (rather than bilateral) could have affected our results due to potential asymmetries in cycling motion. The addition of joint kinetics and kinematics as measures of pedaling technique could have improved our model. The assessment of ultrasound images from the posterior thigh could have added to our muscle volume analyses given cyclists (and non-cyclists) with large volume for hamstrings could produce large power outputs.

Conclusions

Resultant pedal force application was significantly related to power output for cyclists. Endurance performance in cycling laboratorial tests does not seem to depend on quadriceps muscle volume, pedal force effectiveness or lower limb muscle activation. However oxygen uptake explained endurance performance of cycling in non-athletes.

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