Journal of Science and Medicine in Sport (2008) 11, 363—370

ELSEVIER

Journal of Science and Medicine in Sport

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ORIGINAL PAPER

Physiological and electromyographic responses during 40-km cycling time trial: Relationship to muscle coordination and performance

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Received 17 September 2006; received in revised form 12 March 2007; accepted 22 March 2007

KEYWORDS
Muscle activation;
Fatigue;
Power output;
Athletes;
Recruitment strategies;
Oxygen uptake;
Endurance performance

Summary The purpose of this study was to compare the oxygen uptake (VO_2), respiratory exchange ratio (RER), cadence and muscle activity during cycling a 40-km time trial (TT), and to analyse the relationship between muscle activity and power output (PO). Eight triathletes cycled a 40-km TT on their own bicycles, which were mounted on a stationary cycle simulator. The VO_2, RER and muscle activity (electromyography, EMG) from tibialis anterior (TA), gastrocnemius medialis (GA), biceps femoris (BF), rectus femoris (RF) and vastus lateralis (VL) of the lower limb were collected. The PO was recorded from the cycle simulator. The data were collected at the 3rd, 10th, 20th, 30th and 38th km. The root mean square envelope (RMS) of EMG was calculated. The VO_2 and PO presented a significant increase at the 38th km (45.23 ± 8.35 ml kg min^{-1} and 107 ± 7.11% of mean PO of 40-km, respectively) compared to the 3rd km (38.12 ± 5.98 ml kg min^{-1} and 92 ± 8.30% of mean PO of 40-km, respectively). There were no significant changes in cadence and RER throughout the TT. The VL was the only muscle that presented significant increases in the RMS at the 10th km (22.56 ± 3.05% max), 20th km (23.64 ± 2.52% max), 30th km (25.27 ± 3.00% max), and 38th km (26.28 ± 3.57%max) when compared to the 3rd km (21.03 ± 1.88%max). The RMS of VL and RF presented a strong relationship to PO ($r = 0.89$ and 0.86, respectively, $p < 0.05$). The muscular steady state reported for cycling a 30-min TT seems to occur in the 40-km TT, for almost all assessed muscles, probably in attempt to avoid premature muscle fatigue.

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✠ In memoriam.,

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doi:10.1016/j.jsams.2007.03.006

Introduction

The power output (PO) and pedalling cadence has been recently described throughout the cycle stage of a triathlon competition (e.g., 2006 Hawaii Ironman).[1] The measurement of these variables during competition is extremely important because during a laboratory test it is not easy to reproduce a competitive situation, especially in triathlon where swimming and running are involved.[2,3] However, the evaluation of PO and other biomechanical variables in a laboratory test (e.g., time trial) can provide information about cycling movement (kinematics evaluation), pacing strategies and the fatigue process.[4–6] Nevertheless, there is a lack of research regarding biomechanical variables (e.g., PO, force applied on the pedal and pattern of muscle activation) throughout cycling time trials.

The behaviour of PO during cycling races has been described according to the control of exercise intensity.[1,5,7] Based on the strong relationship between PO and effort level, during a time trial, the behaviour of PO may be also influenced by other variables as fatigue mechanisms during competition.[7] The anticipatory adjustments of PO based on previous experience have been proposed as a control mechanism of effort level.[8,9] It is possible to observe that the 'all out' behaviour during a short duration time trial (less than 1 h) can result in the increase of PO in the final minutes of the race.[5–7] Therefore, physiological and biomechanical information should be analysed together during a time trial (TT) to provide a better understanding of the behaviour of PO and its relationship with muscle activation.

During cycling events, the surface electromyography (EMG) has been extensively employed looking for quantification of muscle activity and motor units' recruitment, as well as identification of muscle fatigue.[10–12] However, there are few investigations regarding muscle activity during cycling time-trial events,[13,14] and to our knowledge there is no study regarding EMG during a 40-km TT. The measurement of muscle activity during short (20 km) and long duration (100 km) TT[13,15] has been limited to the evaluation of only one muscle (e.g., rectus femoris and vastus lateralis, respectively), which does not allow the comprehension of muscle coordination during TT. St. Clair Gibson et al.[13] indicate that the recruitment strategies of the lower limb were probably altered as the cyclists became fatigued during a TT, formulating the hypothesis that other muscles should be recruited at different levels compared with the changes measured in the rectus femoris muscle. The behaviour of four muscles' activity during a cycling 30-min TT has been reported,[11] indicating no change in muscle activation in the end of the TT. However, the relationship between EMG data, physiological variables and PO were not evaluated in an attempt to understand the cyclists' control of exercise intensity. The relationship between electromyographic, physiological (e.g., oxygen uptake) and biomechanical variables (e.g., PO and cadence) during a cycling TT could provide important information about muscle coordination and the anticipatory control of effort level.

Hence, the aims of the present study were: (1) to evaluate the pattern of five lower limb muscle activity during a laboratory 40 km TT and (2) to analyse their relationship with physiological and biomechanical variables. The choice of TT was to evaluate the effects of anticipatory control of effort level on EMG activity and performance variables.

The primary hypothesis was that the muscle activity would increase in the final stages of the TT, based on the fact that a short duration cycling TT (less than 1 h) elicits an increase of oxygen uptake (VO_2) and PO in the final stage of the race.[5–7]

Methods

Subjects

Eight triathletes volunteered to participate in this study. All subjects had competitive experience. All participants signed an Informed Consent Term in agreement with the Committee of Ethics in Research with Humans of the Institution where this study was conducted. The triathletes were asked to avoid high-intensity or exhaustive exercise at least 24 h before the laboratory trials. Table 1 presents the characteristics of the athletes.

Incremental test to exhaustion

During the first evaluation day, a maximal oxygen uptake (VO_{2max}) test was performed on a cyclo-ergometer CardiO$_2$ (Medical Graphics Corp., St. Louis, EUA) adapted with drop handlebars, clipless pedals and a racing saddle. A ramp protocol was employed where the initial load was set at 50 W with increments of 25 W every minute[16] and pedalling cadence between 70 rpm and 110 rpm. Exhaustion was defined as the moment that the subject was no longer capable of maintaining 70 rpm. VO_{2max} was defined as the highest VO_2 value of the last minute of the progressive cycling test.[11] VO_2 and carbon dioxide produced (VCO_2) were deter-

Table 1 Individual data, and the group mean with standard deviation (S.D.) for age, body mass, height, maximal oxygen uptake (VO_{2max}), VO_2 at the ventilatory threshold (VO_2 at VT) and years of training of the evaluated triathletes

Triathlete	Age (years)	Body mass (kg)	Height (m)	VO_{2max} (ml kg^{-1} min^{-1})	Peak power output (W)	VO_2 at VT (% of VO_{2max})	Years of training (years)
1	37	85.4	1.85	50	339	74	2
2	35	71.4	1.73	68	462	83	8
3	37	83.3	1.81	—	—	—	3
4	22	73.0	1.68	66	432	79	2
5	31	76.3	1.74	65	435	74	7
6	27	82.0	1.76	51	394	70	4
7	31	65.7	1.72	70	412	80	12
8	34	78.2	1.77	57	423	86	6
Mean	31.7	76.9	1.75	61	414	78	6
S.D.	5.2	6.7	0.05	8.2	39	5	3

mined breath-by-breath during the test using an open-circuit indirect gas exchange system (MGC CPX/D, Medical Graphics Corp., St. Louis, EUA). Prior to the VO_{2max} test, the O_2 and CO_2 analysers were calibrated using calibrated medical grade gases that spanned air in the physiological range. All subjects received equal verbal encouragement by the same researcher, to perform their very best during the evaluation. During the incremental test, PO was continually recorded to determine the peak (PO_{peak}).[11] VO_2 at the ventilatory threshold (VT) was determined by the ventilatory equivalent method.[17]

Time-trial test

At least 48 h following the maximal test, the subjects performed a 40-km time trial (TT) on their own bicycles mounted on a stationary wind-trainer (Cateye CS1000, Cateye Co., Osaka, Japan) in the fastest time possible, using the strategy of freely chosen pacing.[5,6,18] During the 40 km TT, the subjects prevented alterations in muscle fibre recruitment patterns which result from changes in posture by adopting the conventional cycling posture with ~75° trunk inclination and grasping the handlebars with elbows slightly bent to remain in a seated position.[11]

The wind-trainer's display provided these data: (1) distance (km), (2) time (min), (3) speed (km h^{-1}) and (4) PO (W) throughout the TT. Because of the dearth of comparative data of PO collected with the wind-trainer employed in the present study and other validated systems (e.g., SRM powermeter), we will not present the results of the absolute value of PO, but instead, PO was normalized by the mean PO achieved in the TT. This was done in an attempt to describe only the behaviour of PO and to compare the intensity of each kilometre with the mean value.

VO_2, cadence, time, speed, PO and muscle activity were monitored at the 3rd, 10th, 20th, 30th, and 38th km of the time trial. The respiratory gases were recorded during the first minute of the aforementioned selected distances and they were used to determine the respiratory exchange ratio (RER).

A reed switch attached to the bicycle frame recorded the pedalling cadence by registering each crank revolution.[10] The electrical pulse produced by the reed switch was used to identify the beginning and the end of each crank cycle. This information was also used to analyse the muscle activity related to crank cycle.[19]

Electromyography

Surface electromyography was employed to measure the activity from the tibialis anterior (TA), the medial head of gastrocnemius (GA), the long head of biceps femoris (BF), rectus femoris (RF) and the vastus lateralis (VL) muscles from the left lower limb during the time trial. Pairs of Ag/AgCl electrodes (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 in order to respect the recommendation of the International Society of Electrophysiology and Kinesiology.[20,21] The electrodes were placed over the belly of the muscles, parallel with the muscle fibres and taped to the skin using micropore tape (3M Company, USA). A bandage was also wrapped around the electrode to minimise sweat interference. The reference electrode was placed over an electrically neutral site (anterior surface of tibia). The electrodes' wires were taped to the skin to reduce movement artifact.

The raw EMG signals were pre-amplified and band-passed filtered at 10—500 Hz through a five-order Butterworth digital filter. One minute of EMG

signal was collected employing an eight channels electromyography system (Bortec Eletronics Inc., Calgary, Canada) when the subjects achieved the 3rd, 10th, 20th, 30th and 38th km, at a sample rate of 2000 Hz per channel. Off-line data analysis was supported by the software WINDAQ® (WINDAQ, DataQ Instruments Inc., USA) and MATLAB® (MathWorks Inc., USA).

The root mean square (RMS) envelope was used as an indicator of total muscle activation.[10] A previous study showed that this computation is highly correlated with the number of active motor units.[22] The RMS was averaged in 40 ms moving windows[23] for the entire raw signal and then cut in 10 consecutive crank revolutions to determine the average and standard deviation of each muscle.

For each muscle, the average RMS envelope was calculated during the entire crank cycle and normalized by each subject's own peak value observed at the 3rd km, which corresponds to the beginning of the test and no effect of fatigue was expected. The peak value of 10 curves of RMS envelope was defined as the normalization factor. It was used to calculate the mean ensemble individual curve and the mean value of RMS envelope of this ensemble curve.[12]

Statistical analysis

The mean and standard deviation (S.D.) for all values was reported. A one-way ANOVA was employed for the comparison of the VO_2, RER, cadence, PO and speed between the 3rd, 10th, 20th, 30th and 38th km. The same procedure was applied to compare the mean value of RMS envelope of the five muscles. Post hoc analysis where the main effects or interactions were significant was subsequently performed using Tukey's HSD post hoc test to determine the significant differences between the kilometres. Further, a correlation analysis (using Pearson's product-moment) was performed to verify the relationship between PO and mean value of RMS envelope and between PO and cadence. The level of statistical significance for all analysis was set at $p < 0.05$ and <0.01. For statistical procedures the SigmaStat 2.03 package (SPSS Inc., USA) was used.

Results

Subjects' characteristics

As reported in the literature, the triathletes evaluated were in agreement with the physical and performance competitive level.[24,25] Table 1 shows the individual triathletes' characteristics. Due to technical problems with data acquisition, triathlete 3 was not able to perform the incremental test.

Cycling time-trial test

The subjects completed the time trial in 60.16 min (±2.98 min) while increasing the speed at the 38th km ($40.75 \pm 2.72\,km\,h^{-1}$) compared to the 3rd km ($38.36 \pm 3.56\,km\,h^{-1}$). The mean total time spent by the subjects to complete the 40 km was higher than results previously presented.[18]

During the simulated cycling test, PO (Fig. 1) increased throughout the test. PO and cadence are depicted in Fig. 1. There was no significant difference in pedalling cadence throughout the time trial. The 38th km showed a higher PO which was significant ($p < 0.05$) compared to the 3rd km.

Fig. 2 depicts the kinetic of VO_2 and RER during the cycling test. There was no significant difference in RER throughout the time trial. VO_2 at the 38th km was higher than observed in the 3rd km ($p < 0.05$).

EMG related to the pedalling cycle during the 3rd km of triathlete 2 is depicted in Fig. 3. All subjects showed a similar activation pattern.

The qualitative observation of the EMG envelope indicates a similar pattern in agreement with the literature.[10,12] The mean and S.D. of RMS envelope from the evaluated muscles along the kilometres are shown in Table 2.

Statistical analysis of the mean value of RMS envelope indicated significant differences only for the vastus lateralis (VL) when the 10th, 20th, 30th and 38th km were compared to the 3rd km and when comparing the 38th km to 10th km. The relationship

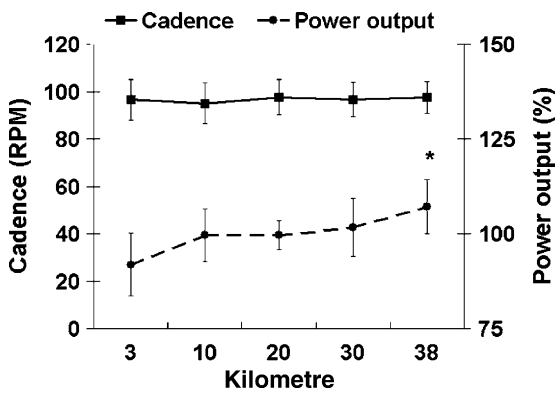

Figure 1 Power output and cadence profiles during the time-trial evaluation. Mean and S.D. of the evaluated triathletes ($N = 8$). The values of PO were normalized by the mean individual value in the time trial. *Significant difference related to 3rd km ($p < 0.05$). $^{\$}$Significant difference related to 3rd km ($p < 0.01$).

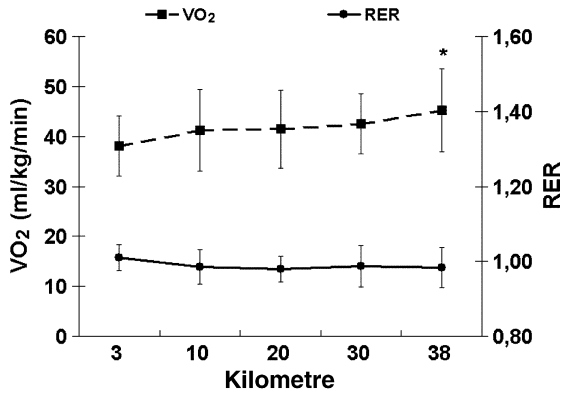

Figure 2 VO_2 and RER profiles during the time trial. Mean and S.D. of the evaluated triathletes ($N = 8$). *Significant difference related to 3rd km ($p < 0.05$). $^{\$}$Significant difference related to 3rd km ($p < 0.01$).

between the RMS and PO, as well as the relationship between PO and cadence, is presented in Table 3.

Table 3 The relationship (Pearson's r) between the mean value of the 10 cycles of cadence, RMS of the five muscles and mean PO of the eight subjects

Variables	r
Cadence and PO	0.36
Tibialis anterior and PO	0.65
Gastrocnemius medialis and PO	−0.77
Biceps femoris and PO	0.67
Rectus femoris and PO	0.94*
Vastus lateralis and PO	0.95*

*Pearson's r values significant for $p < 0.05$. $^{\$}$Pearson's r values significant for $p < 0.01$.

Discussion

To our knowledge, this study is the first to examine the relationship between EMG and performance variables during a cycling 40 km TT in a laboratory. The novelty of the present study was the investigation of EMG responses of the muscles of the lower limb to elucidate the selective activation of vastus lateralis during a cycling TT. The relationship of EMG data with physiological and biomechanical variables by means of statistical correlation analysis is another innovative approach in cycling TT studies. The duration of the TT (40-km) and stochastic PO (self-selected) were chosen in attempt to evaluate the effects of the anticipatory control of effort level on muscle coordination and performance variables. The innovation of the present study in relation to others with EMG and PO evaluation[13,15] was the assessment of EMG from five lower limb muscles and the analysis of their relationship with performance variables in a cycling TT. St. Clair Gibson et al.[13] did not compare the relationship of EMG data and PO throughout statistical correlation analysis, which limits their conclusions.

Our primary hypothesis was that the muscle activity, PO and VO_2 would increase at the end of the time trial. This hypothesis was partially supported by the results of PO and VO_2, which increased at the 38th km compared to the 3rd km. It is possible to observe that at the start of the TT the subjects were cycling approximately at 92% of their mean PO and in the end they increased it to 107%. A variation of 5% in PO has been suggested to improve the performance of 1-h cycling time trial,[26–28] which indicates a 'down regulation' of effort level in the beginning of the exercise, and the 'all out' behaviour of PO at the end of the time trial.[5–7,29] This pattern of PO may be related to the attempt to avoid premature fatigue and improve performance.[7]

No significant changes in lower limb muscle activity have been observed in the 30-min TT[11] and for 1 h at critical power.[30] However, after prolonged cycling exercise at sub-maximal PO, a reduction in evocated muscle activation has been observed, which suggests a decrease in peripheral contractile properties.[31] In dynamic tasks, RMS has presented an increase related to muscle fatigue,[32,33] which does not seem to be observed in the present study. During cycling at the same PO, if fatigue had occurred, an increase of VO_2

Table 2 Mean ± S.D. results of the mean value of RMS envelope of the evaluated muscles

Muscle	3rd km	10th km	20th km	30th km	38th km
Tibialis anterior	19.53 ± 6.15	20.06 ± 4.15	22.08 ± 6.14	22.67 ± 5.00	21.69 ± 5.50
Gastrocnemius medialis	20.44 ± 3.10	20.04 ± 3.45	18.98 ± 3.52	20.13 ± 3.54	18.20 ± 3.64
Biceps femoris	26.11 ± 6.52	23.66 ± 4.68	25.94 ± 7.34	28.43 ± 8.92	30.24 ± 11.58
Rectus femoris	25.00 ± 10.24	27.18 ± 14.97	28.43 ± 11.76	31.98 ± 18.18	33.50 ± 17.69
Vastus lateralis	21.03 ± 1.88	22.56 ± 3.05*	23.64 ± 2.52*,$	25.27 ± 3.00*,$	26.28 ± 3.57*,#,$

The mean values of RMS envelope are presented in percentage of maximal peak activation observed in the 3rd km. *Significant difference related to 3rd km ($p < 0.05$). #Significant difference related to 10th km ($p < 0.05$). $^{\$}$Significant difference related to 3rd km ($p < 0.01$).

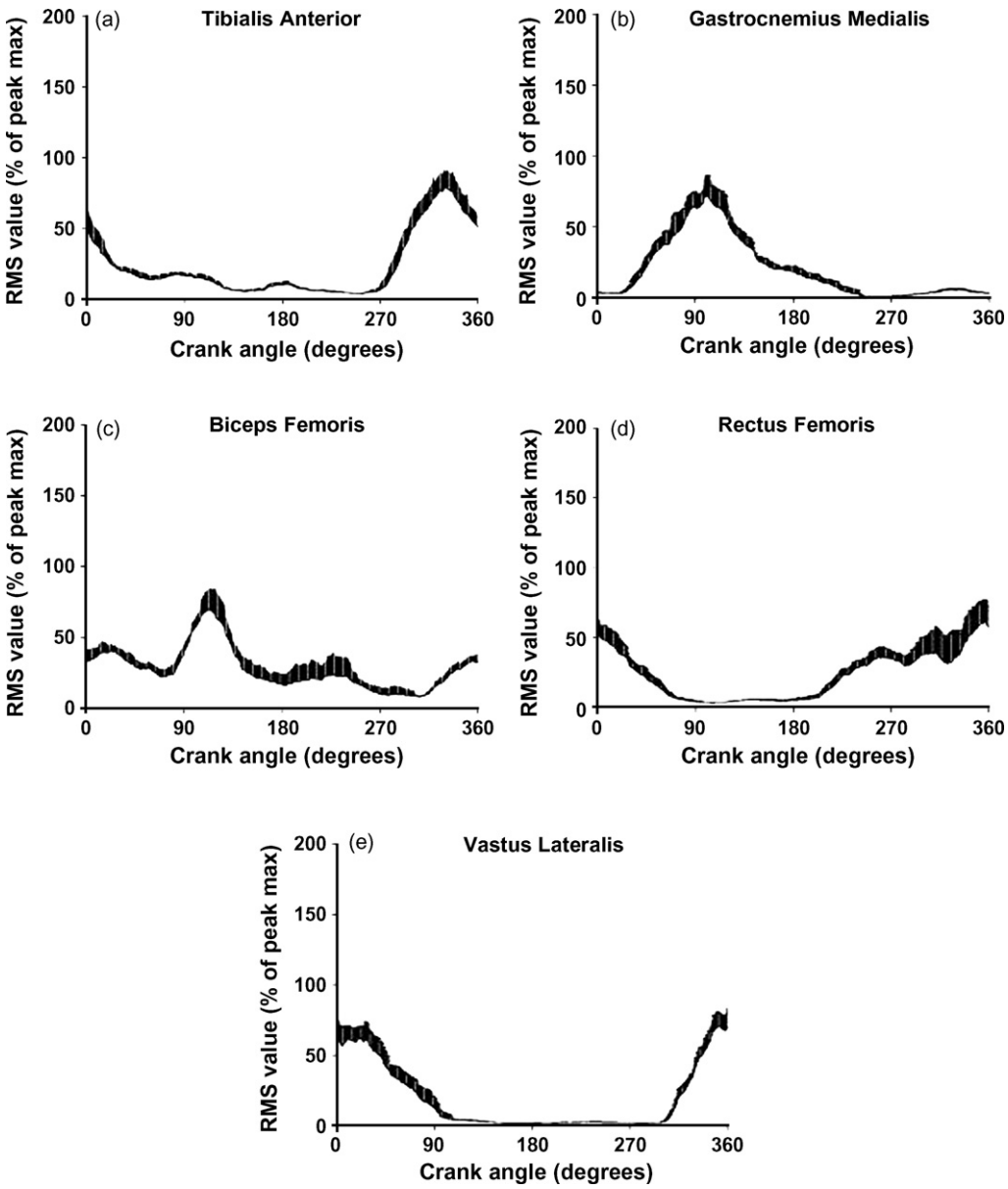

Figure 3 EMG activity processed employing RMS windows along the crank cycle: (a) tibialis anterior, (b) gastrocnemius medialis, (c) biceps femoris, (d) rectus femoris and (e) vastus lateralis muscles. The values were normalized by the maximal value of RMS envelope obtained on the 10 cycles of triathlete 2 at the 3rd km.

and muscle activity would be expected.[34] This 'slow component' of VO_2 was probably not observed in the present study due to the lack of significant change in almost all muscles activity (except for VL), suggesting no additional motor unit recruitment.

The 'muscular steady state' observed in the TT is probably related to the attempt to prevent premature muscle fatigue.[7–9,35] The increase in VL activity in the present study should be related to the increase in PO due to the importance of this muscle as a 'force producer',[36] and probably with no relation to muscle fatigue. The strong relationship between VL and RF with PO ($r = 0.95$, and 0.94, respectively) reinforces the importance of these muscles in the application of force on the pedals.[10]

No significant changes in pedalling cadence during the 40-km TT suggests that the increase of PO occurred due to the increase of the force applied to the pedals, which corroborates with the increase of VL activation. The weak relationship between cadence and PO ($r = 0.36$) suggest that pedal forces may be the determinant variable of PO during a

cycling TT. If the force applied to the pedals is the only variable that was not controlled in the present study and cadence did not change throughout the TT, the control of force production should be the principal variable related to PO. Previous results[5] have indicated that athletes try to reduce the resistive forces during the recovery phase (180—360°) in an attempt to increase mean torque and, consequently, mean PO,[37] which may explain the high variability in BF and RF during the time trial. Another study described this effect and related it to cyclists' pedalling technique, which may be different among subjects with similar performance.[11] Hence, BF and RF were defined as 'force transfer muscles' to the pedal, and have been related to pedalling technique.[11,38]

A strong inverse relationship was observed between GA and PO, which should be explained by the training effects of cycling on the antagonist muscles in attempt to reduce their activation and prevent fatigue.[39] These authors have suggested that the cyclists learn to use their antagonist muscles to transfer force efficiently to the pedals and to reduce the co-activation between the agonist and antagonist muscles. The lack of significant changes in GA and BF agrees with this result, indicating that these muscles were probably not affected by fatigue.[39] However, GA performs a role of biarticular muscle, and it has been described to work as a 'force transfer' in cycling,[36,38] which contradicts the aforementioned inverse relationship of this muscle with PO. Other variables such as median frequency and muscle fibre conduction velocity (MFCV) should give a better insight into the fatigue effects on EMG of the evaluated muscles.[32,33,40] Analysis of co-contraction should also indicate the occurrence of the reflex compensation observed in cycling movement in the attempt to avoid fatigue of the agonist muscles, as previously described.[39] The relationship between cycling experience, pedalling technique and the co-contraction in TT must be evaluated to better understand the fatigue process during cycling.

Conclusion

The attempt to increase speed and PO at the end of the time trial seems to explain the increase of VL activation, VO_2 and PO. The strong relationship between this muscle and RF activation with PO indicates their importance in the control of workload and effort during a cycling time trial. The 'muscular steady state' suggested in the literature seems to occur in the present study, except for VL, as an attempt to avoid premature fatigue.

Practical implications

- There is a selective activation of VL in relation to other lower limb muscles in the 40 km TT, which indicates suggests a control of effort by the control of muscle activation.
- The strong relationship between VL and RF with the PO indicates the control of workload mainly by the activation of these muscles.
- The down regulation of the PO in the beginning of the TT seems to be an attempt of controling effort level and to improve the performance in TT.

Acknowledgements

Thanks to Capes-Brazil and CNPq-Brazil for financial support. Special thanks to our master, professor and friend Antônio Carlos Guimarães who passed away at the end of this project. The authors thank Benjamin Jason Mathis for correcting the grammar in the manuscript.

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