Analysis of the aerobic-anaerobic transition in elite cyclists during incremental exercise with the use of electromyography

Alejandro Lucia, Oscar Sánchez, Alfredo Carvajal, José L Chicharro

Abstract
Objectives—To investigate the validity and reliability of surface electromyography (EMG) as a new non-invasive determinant of the metabolic response to incremental exercise in elite cyclists. The relation between EMG activity and other more conventional methods for analysing the aerobic-anaerobic transition such as blood lactate measurements (lactate threshold (LT) and onset of blood lactate accumulation (OBLA)) and ventilatory parameters (ventilatory thresholds 1 and 2 (VT1, and VT2)) was studied.

Methods—Twenty eight elite road cyclists (age 24 (4) years; \(\dot{V}O_{MAX}\) 69.9 (6.4) ml/kg/min; values mean (SD)) were selected as subjects. Each of them performed a ramp protocol (starting at 0 W, with increases of 5 W every 12 seconds) on a cycle ergometer (validity study). In addition, 15 of them performed the same test twice (reliability study). During the tests, data on gas exchange and blood lactate levels were collected to determine VT1, VT2, LT, and OBLA. The root mean squares of EMG signals (rms-EMG) were recorded from both the vastus lateralis and the rectus femoris at each intensity using surface electrodes.

Results—A two threshold response was detected in the rms-EMG recordings from both muscles in 90% of subjects, with two detected in the rms-EMG recordings from all the working muscles. The results of the reliability study showed no significant differences \((p>0.05)\) between mean values of EMG\(_{vastus}\) and EMG\(_{rectus}\), obtained in both tests. Furthermore, no significant differences \((p>0.05)\) existed between mean values of EMG\(_{vastus}\), in the vastus lateralis and rectus femoris, and VT1, and LT (62.8 (14.5) and 69.0 (6.2) and 64.6 (6.4) and 68.7 (8.2)% of \(\dot{V}O_{MAX}\) respectively), or between mean values of EMG\(_{rectus}\), in the vastus lateralis and rectus femoris, and VT2 and OBLA (86.9 (9.0) and 88.0 (6.2) and 84.6 (6.5) and 87.7 (6.4)% of \(\dot{V}O_{MAX}\) respectively).

Conclusion—rms-EMG may be a useful complementary non-invasive method for analysing the aerobic-anaerobic transition (ventilatory and lactate thresholds) in elite cyclists.

Keywords: electromyography; muscle; ventilatory threshold; lactate threshold; cycling; metabolic response

Surface electromyography (EMG) is an acceptable method for quantifying the total activity of working muscles and for estimating muscle fatigue non-invasively.1 An increase in EMG activity has been shown to reflect the recruitment of additional motor units and an increase in motor unit rate coding to compensate for the deficit in contractility resulting from impairment of fatigued motor units, as the strength of a muscle contraction increases.1 Along this line of thought, several studies have shown the existence of a non-linear increase in EMG during the aerobic-anaerobic transition phase in ergometer cycling.3–8 Indeed, an EMG threshold (EMGT) has been suggested to occur in the vastus lateralis,9 vastus medialis,10 rectus femoris,11 gastrocnemius,12 biceps femoris,13 and soleus of healthy not highly trained subjects during progressive tests on a cycle ergometer. The EMGT, in turn, would represent the point where an increased contribution from fast twitch motor units occurs to maintain the required energy supply for muscle contraction.14 In other studies, in contrast, a linear relationship has been reported between EMG and exercise intensity in ergometer cycling.3,4

In addition to these controversial findings, some questions still remain unanswered. First, only one study has assessed the test-retest reliability of the EMG response to progressive exercise.5 In this study, the EMG response was reported to be repeatable but linear (not threshold-like) during an incremental treadmill test. As reliability is an integral part of validity,11 no study has accurately determined the validity of the EMG, method for analysing the aerobic-anaerobic transition. Furthermore, little research has been conducted using elite athletes (cyclists) as subjects, and the findings that have been reported seem somewhat controversial.7,14

The aim of this study was to investigate the validity and reliability of EMG as a new non-invasive determinant of the metabolic response to incremental exercise in elite cyclists. We studied the relation between EMG activity and other more conventional methods of analysing the aerobic-anaerobic transition, such as blood lactate measurements (lactate threshold (LT) and onset of blood lactate accumulation (OBLA)) and ventilatory parameters (ventilatory thresholds 1 and 2 (VT, and VT2)).

Methods
SUBJECTS
Twenty eight elite male cyclists (age 24 (4) years; height 177.1 (5.2) cm; body mass 67.2 (6.0) kg; all values mean (SD)) participated in
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with that used in our investigation.1–8 13

increase in the EMG response to incremental
exercise; (b) previous research showing a non-linear
relationship during the tests, using the method-
ology previously described by Weltman and co-workers.14 Thus the greatest power output
that was not associated with a rise in lactate
concentration above baseline was designated as
the power output corresponding to LT. This
always occurred just before the curvilinear
increase in blood lactate observed with subse-
quently increasing exercise intensities. A lactate increase of at least 0.2 mM (the error associated with the lactate analyser) was required for LT determi-
nation. OBLA, on the other hand, was defined as
the power output corresponding to a blood
lactate concentration of 4.0 mmol.l15

EMG
Electrode placement
Surface EMG recordings were taken from the
vastus lateralis and rectus femoris (at sites
respectively approximately one third and one
half of the perpendicular distance from the
superior border of the patella to the greater
trochanter). Pairs of surface electrodes (Blue-
sensor Medicotest Ag/AgCl electrodes; Rug-
marken, Denmark) were attached to the skin
with a 4 cm interelectrode distance. The
electrodes were placed longitudinally with
respect to the underlying muscle fibre arrange-
ment. For those subjects who performed the
test twice (reliability study), the skin was
tattoed using ink in order to place the
electrodes on the same site on the two tests.
Two reference electrodes were placed over the
anterior superior spine of the iliac crest. Before
electrode application, the skin was shaved and
abraded using sandpaper and cleaned with
alcohol to minimise the source impedance. A
saline EMG electrode gel was placed between
the electrode and the underlying skin to
enhance signal conductivity. The cables
donnected to the electrodes to measure myoelectri-
cal activity were firmly attached with tape to
minimise artefacts from leg movements.

EMG instrumentation and procedures
Myoelectrical activity was recorded using a
ME3000P analyser (ME3000P; Mega Elec-
tronics Ltd, Kuopio, Finland). The measure-
ment sensitivity of the instrument is ±1 µV
and its range for bipolar EMG signals is ±5000 µV.
The raw EMG signals were band-pass filtered
between 20 and 480 Hz, amplified, and
converted from analogue to digital at a
sampling rate of 1 kHz. An EMG power spec-
tral density was then computed for two second
sampling periods, at fixed intervals throughout
the tests, and the root mean square voltage
(rms-EMG) contained in each two second

this study. Sixteen subjects were professional
road cyclists with a minimum competition
experience of three years, and some of them
had won several professional races. The other
12 were elite road cyclists (competition experi-
ence at least two years in the amateur
category). Written informed consent was given
before participation in the experiments, in
accordance with the institutional human sub-
jects guidelines (Complutense University of
Madrid).

STUDY PROTOCOL
Before each exercise testing session, subjects
were familiarised with the equipment and pro-
cedures used in this investigation. In addition,
they were previously instructed to refrain from
intense training during the day before testing.

Fifteen subjects were randomly selected for
the reliability study. Each of them performed
two exercise tests on a bicycle ergometer
(Ergometrics 900; Ergo-line, Barcelona, Spain)
on different occasions and separated from each
other by a period of no more than five days.
Each of the two tests consisted of a ramp pro-
ocol until exhaustion, starting at 0 W. The
power output was increased by 5 W every 12
seconds and pedalling cadence was kept
constant at 70–80 rpm. The selection of a
ramp-like protocol instead of a graded steady
state test was chosen for two reasons: (a) in
previous research conducted in our
laboratory15 this type of protocol was used to
analyse physiological responses—that is, venti-
latory thresholds and lactate kinetics—in elite/
professional cyclists during incremental exer-
sive; (b) previous research showing a non-linear
increase in the EMG response to incremental
exercise used exercise protocols comparable
with that used in our investigation.16 17 For the
validity study, each of 28 subjects performed a
single bicycle ergometer test following the
above protocol.

Exercise tests were terminated (a) voluntar-
ily by the subjects, (b) when pedalling cadence
could not be kept at least at 70 rpm, or (c) when
established criteria of test termination were
met.14 Each test was performed under similar
conditions (21–24°C and 45–55% relative
humidity).

ANALYSIS OF EXPIRED GAS AND DETERMINATION
OF VENTILATORY THRESHOLD
During the tests, gas exchange data were
collected continuously using an automated
breath by breath system (CPX; Medical
Graphics, St Paul, Minnesota, USA). The
measuring instruments were calibrated before
each test and the necessary environmental
adjustments made. VT, was determined using
the criteria of an increase in the ventilatory
equivalent for oxygen (VE/VO2) with no
increase in the ventilatory equivalent for
carbon dioxide (VE/VC02) and the departure
from linearity of VE, whereas VT, was
determined by using the criteria of an increase
in both VE/VO2 and VE/VC02.15 Two indepen-
dent observers detected VT, and VT, following
the criteria previously described. If they did not
agree, the opinion of a third investigator was
included.

ANALYSIS OF BLOOD LACTATE
Blood samples (25 µl) for the measurement of
blood lactate (YSI 23L; Yellow Springs Instru-
maments, Yellow Springs, Ohio, USA) were taken
from fingertips at rest, every two minutes dur-
ing the test, and immediately after termina-
tion of exercise.

LT was determined by examining the
“lactate concentration-power output (W)” re-
relationship during the tests, using the method-
ology previously described by Weltman and
co-workers.14 Thus the greatest power output
that was not associated with a rise in lactate
concentration above baseline was designated as
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spectrum was calculated (in μV).\textsuperscript{18} The rms-EMG was used as an indication of the “total myoelectric activity” of an exercising muscle, as it has been previously shown that this computation is (a) an accurate measure of EMG amplitude and (b) is highly correlated with the number of active motor units (fibre recruitment).\textsuperscript{18 19}

**Determination of EMG breakpoint**

Previous pilot studies conducted in our laboratory suggested the existence of a two threshold response in elite cyclists, with a second EMG breakpoint occurring at near to maximum intensities, which is easy to detect visually. To establish objective criteria for the determination of one or two breakpoints in the EMG power output response, we used a computer algorithm (Centro de Proceso de Datos, Complutense University of Madrid) that models rms-EMG response to exercise using multisegment linear regression.

With this method, a single linear regression is initially fitted to all data points and is used for later statistical comparisons. A brute force method is then used to fit two lines to the data points. The program calculates regression lines for all possible divisions of the data into two contiguous groups, and the pair of lines yielding the least pooled residual sum of squares is chosen as representing the best fit. The intersection point between these two lines occurred near the end of the test in all the subjects.

Thereafter the program attempts to fit a third line to the data in order to detect another breakpoint in the EMG data. The third middle segment is obtained by methodically adding points on the left side of the two line regression intersection point. The new regression line is then calculated and extended in the direction that yielded the lower sum of squares.

Finally, an analysis of variance determines whether a significant (p<0.05) reduction in the total sum of squares is achieved by the addition of a third line segment. The first (EMG$_{T1}$) and second (EMG$_{T2}$) EMG thresholds are then reported as the first and second intersection points respectively of the computerised model.

**COMPARISONS BETWEEN VT$_1$, VT$_2$, LT, OBLA, AND EMG$_{T1}$ AND EMG$_{T2}$**

Each individual value of VT$_1$, VT$_2$, LT, OBLA, and EMG$_{T1}$ and EMG$_{T2}$ corresponded to a certain time point during the tests, which in turn elicited a certain value of $\dot{V}O_2$ and power output (W). Therefore, in order to compare the exercise intensity at which all thresholds occurred, mean values of VT$_1$, VT$_2$, LT, OBLA, and EMG$_{T1}$ and EMG$_{T2}$ were expressed in both $\dot{V}O_2$ (ml/kg/min) and % of $\dot{V}O_2_{MAX}$, and in power output (W).

**DATA ANALYSIS**

In the group of 15 subjects that performed the test on two different days (reliability study), a paired Student’s $t$ test was used to compare mean values of EMG$_{T1}$ and EMG$_{T2}$ obtained with both tests. Intraclass Pearson’s correlation coefficients were also calculated to determine the degree of correlation between mean values of EMG$_{T1}$ and EMG$_{T2}$, reported with repeated tests.

In all 28 subjects (validity study), mean values of VT$_1$, LT (criterion methods), and EMG$_{T1}$ on one hand, and those of VT$_2$, OBLA (criterion methods), and EMG$_{T2}$ on the other, were compared by using a one way repeated measures analysis of variance. In addition, total errors (\(\sum(Y-Y')^2/n\)) where $Y$ is the criterion value and $Y’$ the predicted value) and Pearson’s correlation coefficients (criterion $v$ predicted) were calculated to examine the error inherent in the EMG prediction technique. Further analysis of validity of the EMG method was accomplished by applying the procedures suggested by Bland and Altman.\textsuperscript{20} For this analysis, the mean differences (bias) and standard deviation (SD) of the differences between the mean values (in W) obtained with the two methods (EMG $v$ criterion methods) were calculated. The data are presented graphically comparing the difference between the methods against their average value in W. The mean difference (bias) plus and minus two standard deviations is indicated on the graph. In this way, the bias and precision of the EMG technique could be calculated.

Significance was set at $p<0.05$ for all statistical analyses.

**Results**

**MAXIMAL VALUES**

Maximal values of $\dot{V}O_2$ and power output averaged 69.9 (6.4) ml/kg/min (range 60.0–82.3) and 432.8 (49.1) W (range 364–518) at the end of exercise.

**PATTERN OF EMG RESPONSE**

A two threshold response was detected in 90% of subjects in both vastus lateralis and rectus femoris, and the two breakpoints EMG$_{T1}$ and EMG$_{T2}$ occurred around 60–70% and 80–90% of $\dot{V}O_2_{MAX}$. In 10% of the cases, EMG$_{T1}$ could not be detected in either of the two muscles studied, whereas EMG$_{T2}$ was found in all 28 subjects.

Figure 1 shows an example of an EMG response in one subject.

**RELIABILITY**

No significant differences existed between mean values of either EMG$_{T1}$ or EMG$_{T2}$ obtained in both tests ($p<0.05$) (table 1).

Intraclass correlation coefficients ($r$) between repeated measurements were significant ($p<0.05$) and high (table 1).

**VALIDITY**

**Comparison between VT$_1$, LT, and EMG$_{T1}$**

Using the methodologies described above, VT$_1$ and LT could be detected in 100% of subjects.

Average values of LT occurred at a blood lactate concentration of 1.9 (0.5) mM. Table 2 presents mean values of VT$_1$, LT, and EMG$_{T1}$, expressed in $\dot{V}O_2$ (ml/kg/min), % of $\dot{V}O_2_{MAX}$, and W. No significant differences ($p>0.05$) were found between means.
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Table 1 Reliability of measurements of the electromyographic thresholds EMG<sub>T1</sub> and EMG<sub>T2</sub>

<table>
<thead>
<tr>
<th></th>
<th>EMG&lt;sub&gt;T1&lt;/sub&gt;</th>
<th>EMG&lt;sub&gt;T2&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First test</td>
<td>Second test</td>
</tr>
<tr>
<td></td>
<td>V&lt;sub&gt;0&lt;/sub&gt; (ml/kg/min)</td>
<td>V&lt;sub&gt;0&lt;/sub&gt; (ml/kg/min)</td>
</tr>
<tr>
<td></td>
<td>45.5 (2.5)</td>
<td>43.9 (3.0)</td>
</tr>
<tr>
<td></td>
<td>68.8 (4.0)</td>
<td>63.3 (4.2)</td>
</tr>
<tr>
<td></td>
<td>252.7 (17.6)</td>
<td>238.2 (17.9)</td>
</tr>
<tr>
<td></td>
<td>EMG&lt;sub&gt;T2&lt;/sub&gt;</td>
<td>EMG&lt;sub&gt;T2&lt;/sub&gt;</td>
</tr>
<tr>
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<td>V&lt;sub&gt;0&lt;/sub&gt; (ml/kg/min)</td>
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<tr>
<td></td>
<td>59.7 (1.4)</td>
<td>62.6 (1.4)</td>
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<tr>
<td></td>
<td>90.2 (1.3)</td>
<td>90.2 (2.3)</td>
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<tr>
<td></td>
<td>367.6 (15.4)</td>
<td>372.6 (14.7)</td>
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<tr>
<td>Ratius lateralis</td>
<td>EMG&lt;sub&gt;T1&lt;/sub&gt;</td>
<td>EMG&lt;sub&gt;T2&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>V&lt;sub&gt;0&lt;/sub&gt; (ml/kg/min)</td>
<td>V&lt;sub&gt;MAX&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>48.7 (2.5)</td>
<td>47.3 (1.7)</td>
</tr>
<tr>
<td></td>
<td>70.4 (3.0)</td>
<td>68.4 (2.9)</td>
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<tr>
<td></td>
<td>280.2 (22.4)</td>
<td>268.2 (20.8)</td>
</tr>
<tr>
<td></td>
<td>EMG&lt;sub&gt;T2&lt;/sub&gt;</td>
<td>EMG&lt;sub&gt;T2&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>V&lt;sub&gt;0&lt;/sub&gt; (ml/kg/min)</td>
<td>V&lt;sub&gt;MAX&lt;/sub&gt;</td>
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<tr>
<td></td>
<td>59.8 (2.1)</td>
<td>59.8 (1.5)</td>
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<tr>
<td></td>
<td>89.9 (2.0)</td>
<td>86.2 (1.8)</td>
</tr>
<tr>
<td></td>
<td>374.2 (20.7)</td>
<td>360.8 (20.0)</td>
</tr>
</tbody>
</table>

All values are expressed as mean (SEM).
No significant differences existed between means (p>0.05). All correlation coefficients were significant (p<0.05).

Table 2 Comparison between mean values of the first ventilatory threshold (VT<sub>1</sub>) and the lactate threshold (LT)

<table>
<thead>
<tr>
<th></th>
<th>EMG&lt;sub&gt;T1&lt;/sub&gt;</th>
<th>VT&lt;sub&gt;1&lt;/sub&gt;</th>
<th>LT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratius lateralis</td>
<td>EMG&lt;sub&gt;T1&lt;/sub&gt;</td>
<td>EMG&lt;sub&gt;T1&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V&lt;sub&gt;0&lt;/sub&gt; (ml/kg/min)</td>
<td>V&lt;sub&gt;0&lt;/sub&gt; (ml/kg/min)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>43.9 (1.7)</td>
<td>47.0 (1.5)</td>
<td>45.1 (1.2)</td>
</tr>
<tr>
<td></td>
<td>62.8 (2.8)</td>
<td>69.0 (2.1)</td>
<td>64.6 (1.1)</td>
</tr>
<tr>
<td></td>
<td>240.3 (9.8)</td>
<td>270.8 (13.8)</td>
<td>257.8 (10.0)</td>
</tr>
</tbody>
</table>

All values are expressed as mean (SEM).
No significant differences existed between means (p>0.05).

Table 3 Comparison between mean values of the second ventilatory threshold (VT<sub>2</sub>) and the onset of blood lactate accumulation (OBLA)

<table>
<thead>
<tr>
<th></th>
<th>EMG&lt;sub&gt;T1&lt;/sub&gt;</th>
<th>VT&lt;sub&gt;2&lt;/sub&gt;</th>
<th>OBLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratius lateralis</td>
<td>EMG&lt;sub&gt;T1&lt;/sub&gt;</td>
<td>EMG&lt;sub&gt;T1&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V&lt;sub&gt;0&lt;/sub&gt; (ml/kg/min)</td>
<td>V&lt;sub&gt;0&lt;/sub&gt; (ml/kg/min)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>61.5 (1.1)</td>
<td>59.7 (1.3)</td>
<td>59.0 (1.1)</td>
</tr>
<tr>
<td></td>
<td>86.9 (1.5)</td>
<td>88.0 (1.4)</td>
<td>84.6 (6.5)</td>
</tr>
<tr>
<td></td>
<td>371.1 (9.2)</td>
<td>367.5 (14.1)</td>
<td>352.8 (11.4)</td>
</tr>
</tbody>
</table>

All values are expressed as mean (SEM).
No significant differences existed between means (p>0.05).

Comparison between VT<sub>2</sub>, OBLA, and EMG<sub>T2</sub>

Using the methodologies described above, VT<sub>2</sub>, and OBLA could be detected in 100% of subjects. Table 3 presents mean values of VT<sub>2</sub> and OBLA in ml/kg/min, and in all of them peak power output <360 W) than those selected for our investigation (V<sub>0</sub> <65 ml/kg/min; peak power output 432.8 (39.1) W). To date, no conclusion could be inferred from previous research.
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on the EMG response of elite cyclists reaching high power outputs during exercise testing. In addition, no previous study has assessed the reliability of the EMG method during a ramp protocol. As reliability is an integral part of validity,11 no previous report has assessed the validity of such a method for analysing the aerobic-anaerobic transition.

A novel finding of our study was that in elite cyclists the EMG activity of the muscles primarily involved in pedalling (vastus lateralis, rectus femoris) show a two threshold response with two distinct breakpoints, EMG1 and EMG2, occurring at an exercise intensity of 60–70% and 80–90% of VO2\text{MAX} respectively. A second finding of our investigation was that the EMG method is both valid and reliable for analysing the aerobic-anaerobic transition during exercise. Finally, in elite cyclists it appears that muscle fatigability is not significantly affected by muscle fibre type distribution, as EMG1 and EMG2 occurred at similar intensities in the vastus lateralis and rectus femoris.

METHODOLOGICAL LIMITATIONS

Our study is not without potential limitations. Firstly, the literature on the usefulness of EMG in the determination of ventilatory or lactate thresholds is somewhat controversial. The differences in results could be attributed to difficulties in reliably following the myoelectrical activities in working muscles.4 In addition, during exertion the skin blood flow and temperature increase.21 This phenomenon could induce alterations in the electrical properties of the skin and affect the records of surface EMG. In this regard, previous research has shown no correlation between skin temperature and EMG measurements, excluding the possibility that EMG breakpoints are related to changes in electrical properties of the skin.4

On the other hand, although we measured the myoelectrical activity of the muscles (vastus lateralis and rectus femoris) involved during the work (descending) period of pedalling only, no records were obtained for other muscles—for example, gastrocnemius, tibialis anterior—that are also involved during the rest (ascending) period of pedalling exercise. However, previous research has shown that a non-linear increase in EMG also occurs in the gastrocnemius muscle.4 In addition, previous EMG22 and biopsy studies23 suggest that the muscle most heavily involved during cycling is the vastus lateralis.

Furthermore, a single ramp increment (5 W every 12 seconds) was chosen in our protocol, whereas the results of a previous study using different ramp slopes (10, 20, 30 and 40 W/min) suggest that the metabolic state at which the EMG occurs in untrained subjects may differ during the different ramp exercises.22 Further research should be conducted with elite cyclists to determine the influence of varying ramp protocols on the EMG response.

Finally, the results obtained during a progressive test in a cycle ergometer using a fixed cadence (70–80 rpm), as was used in this investigation, cannot be easily extrapolated to
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real sports situations (in contrast with more specific field tests). A similar study should be conducted under field conditions with unixed cadence, to corroborate the implications of our findings. In this regard, it could be hypothesised that the pattern of muscle fibre recruitment may differ in laboratory to outpatient conditions. Indeed, in laboratory tests using a fixed cadence the exercise intensity is augmented solely by increasing the force applied to each pedal stroke, whereas, during physical activity (cycling, running, swimming, etc) under real conditions, both the cadence and the force applied during each movement are involved in the increase in exercise intensity. Therefore, with increasing work intensity, the muscular power required in tests performed at a fixed cadence is considerably higher than that required by tests at increasing cadence—that is, field tests—and under actual cycling conditions.

COMPARISON WITH PREVIOUS STUDIES

Previous studies with healthy non-elite subjects have shown the occurrence of a single point (the "EMG₃") at which the increase in EMG of quadriceps muscles becomes non-linear during exercise protocols comparable with that used in our investigation. Furthermore, a similar response has been reported in cardiac transplant patients in a study conducted in our laboratory. This EMG₃, in turn, has been shown to occur during the transition from aerobic to anaerobic metabolism, at about 65–70% of VO₂MAX in healthy subjects and about 60% of VO₂MAX in cardiac transplant patients. In these studies, the aerobic-anaerobic transition was expressed using ventilatory parameters (VT₁, VT₂), or lactate measurements based on a first or second abrupt increase in blood lactate (corresponding to blood lactate concentrations of about 2 and 4 mM respectively). Indeed, the EMG₃ may occur as a result of a change in the pattern of motor unit recruitment from predominantly slow twitch motor units to fast twitch motor units, which could contribute to the accumulation of circulating lactate during exercise. The EMG₃ has therefore been suggested as an alternative non-invasive method for determination of ventilatory and/or lactate thresholds.

Our results are in overall agreement with those of previous studies, as no significant differences were observed between the exercise intensity corresponding to the EMG₃ and that corresponding to VT, or LT. It follows that rms-EMG may represent a complementary non-invasive indicator of the aerobic-anaerobic transition during gradual exercise tests. A second breakpoint (EMG₄), however, also occurred in our subjects, which needs further discussion.

COINCIDENCE OF EMG AND BLOOD LACTATE RESPONSES

The reason for an abrupt increase in EMG activity above a certain exercise intensity is not fully understood, and could be at both a local (muscle fatigue) and a generalised level. With respect to the first phenomenon, it can be assumed that after LT is reached, ATP supply from slow twitch oxidative (type I) fibres through oxidative phosphorylation becomes inadequate and therefore must be supplemented by using energy reserves available through anaerobic glycolysis, leading to metabolic acidosis. Accumulation of hydrogen ions, in turn, has been shown to impair excitation-contraction coupling through impairment of the function of (a) the sodium/potassium ATPase of the sarcolemma, (b) the calcium ATPase of the sarcoplasmic reticulum, or (c) the myosin ATPase involved in actin-myosin interaction. Moreover, high lactate levels preferentially disrupt excitation-contraction coupling. Thus, under these physiological conditions, in order to compensate for the deficit in contractility resulting from impairment of fatigue-damaged motor units, muscle force output must be increased during an incremental exercise test through recruitment of additional motor units, particularly those made of fast twitch oxidative glycolytic (type IIa) and fast twitch glycolytic (type IIb) muscle fibres. The observed non-linear increases in rms-EMG (EMG₃, and EMG₄) could therefore be explained by a progressive recruitment of motor units with possible participation of type Ia and IIb fibres (at the EMG₃, and EMG₄, respectively) producing larger action potentials, followed by some degree of synchronisation of motor unit potentials as these fibres may undergo progressive fatigue. In fact, our findings are in agreement with previous research with muscle biopsy samples, which has shown a 1:1 relation between the fraction of active fibres in the vastus lateralis and the intensity (determined as a percentage of VO₂MAX) of cycle ergometer exercise following this pattern: at about 40% of VO₂MAX, almost only type I fibres are recruited, whereas at about 60% of VO₂MAX (EMG₃) both type I and IIa are activated, and during severe exercise (about 90% of VO₂MAX or EMG₄) fibres of type I, IIa, and IIb are recruited.

However, the underlying mechanism may not be limited to a local level (muscle fatigue induced by metabolic acidosis). Such an hypothesis is supported by previous research showing that changes in EMG activity consistent with motor unit recruitment and muscle fatigue can also be recorded from patients with McArdle’s syndrome or from normal subjects under conditions of changing muscle pH. Therefore, other ions—for example, potassium, ammonia, adenosine monophosphate, and magnesium—may be responsible for altering muscle function during exercise. In addition, Airaksinen and co-workers showed that both working (vastus lateralis and gastrocnemius) and non-working (frontalis) muscles showed a shift in EMG at the same load, suggesting that the breakpoint(s) observed in muscle electrical activity may not only be attributed to peripheral fatigue. Thus the explanation could also be a change in the basic activation of muscles in general. Such a generalised response could be due to a change in the membrane function initiated not only by an
increase in lactate levels but also by other factors such as an increase in neural or hormonal activity.4

COINCIDENCE OF EMG AND VENTILATORY RESPONSES

The correlation encountered between VT1 and EMGT1, on the one hand, and VT2 and EMGT2, on the other, could be due to a muscle derived signal to ventilation. Indeed, previous studies provide evidence for the existence of ergoreceptors or mechanoreceptors which respond to increases in the work performed per unit muscle.20 Moreover, Morikawa and co-workers31 found that a ventilatory response occurred in normal subjects with both active and passive leg exercise, but was absent with passive exercise in patients with thoracic spine transection. It could then be hypothesised that ventilation shows a first deflection point (VT1) when muscle work is increased (at an exercise intensity corresponding to EMGT1) and a further increase (VT2) when additional motor units are recruited to maintain power output—that is, recruitment of type IIb fibres at the EMGT2.

On the other hand, the ventilatory thresholds observed during an incremental test could be elicited by enhancement of the neural activity that originates directly from the subthalamic motor region or indirectly via α-γ coactivation of motoneurons innervating the muscle fibres of exercising limbs.32 This increase in neural activity may occur during incremental exercise in response to the need to progressively recruit additional motor units comprised of type IIa (possibly at the EMGT1) and IIb fibres (possibly at the EMGT2) respectively as the work rate is increased and individual fibres begin to fatigue.33 Indeed, numerous investigations have shown simultaneous increases in ventilation and EMG activity during incremental exercise.3 4 13 32

The results of a recent study, however, do not support a link between motor unit recruitment and ventilation, as evidenced by the disassociation between the EMG of the rectus femoris and the ventilatory threshold that existed in trained cyclists after glycogen depletion.3 A similar study should be conducted with professional cyclists in order to assess the effects of glycogen depletion on the rms-EMG response.

ABSENCE OF EMG T2 IN PREVIOUS RESEARCH

The question remains to be answered of why a second EMG threshold (EMG T2) was found only in this study, in contrast with previous research. In this regard, a possible explanation could be that the significant increases in neural activity to the exercising muscles that occur at EMGT2 were not detected in previous studies because EMG activity was mainly recorded from a single muscle—that is, the vastus lateralis. This hypothesis is supported by the findings of Green and Patla,19 which showed that many different muscle groups contribute to the completion of an incremental exercise task and that the average level of activation increases differentially among the muscle groups. It may be possible that only highly trained cyclists (such as those selected for our study) are able to effectively recruit a sufficient number of motor units (especially those with fast fibres) within individual muscles (vastus lateralis or rectus femoris) at near to maximum intensities during an incremental test such as to induce a second breakpoint in the EMG response to exercise. Indeed, EMGT2 occurred at a power output as high as 370 W, which in turn elicited a VO2 of about 60 ml/kg/min. Both values are well above the maximal levels of power output and VO2 reported in most previous EMG studies (<350 W and <55 ml/kg/min respectively). Although two studies have been conducted in this area using highly trained cyclists with similar values of VO2 max to those of our subjects (about 70 ml/kg/min), they attained considerably lower peak power outputs (<360 W) during incremental tests.

SIMILAR RESPONSES IN VASTUS LATERALIS AND RECTUS FEMORIS

Based on the results of previous research with non-elite athletes,15 35 a disparity in the EMG/exercise intensity relation would be expected to exist between the vastus lateralis and the rectus femoris. In effect, previous research has shown distinct responses in the two muscles, such as the occurrence of the EMG fatigue threshold at lower intensities in the rectus femoris.34 This disparity could be partly attributed to kinesiological differences, as the rectus femoris (unlike the vastii muscles) is a biarticular muscle involved in both leg extension and thigh flexion.34 On the other hand, possible differences in muscle fibre composition cannot be excluded, the rectus femoris being comprised of a greater percentage of fatigable fast twitch fibres.34 In this regard, few data are available on the muscle fibre composition of leg muscles in professional cyclists. In our investigation, however, EMGT1 and EMGT2 occurred at similar intensities in both muscles, suggesting a similar pattern of muscle fibre recruitment in the different leg muscles of top level cyclists as an adaptation to training and competition.

CONCLUSION

In elite cyclists the EMG activities of two leg muscles (vastus lateralis and rectus femoris) show similar patterns, with two distinct breakpoints, EMG T1 and EMG T2, occurring at an exercise intensity of 60–70% and 80–90% of VO2 max respectively. The rms-EMG method seems to be both valid and reliable for analysing the aerobic-anaerobic transition during cycle ergometer exercise.
Electromyographic analysis in elite cyclists


Take home message

During incremental cycle ergometer tests performed by top level cyclists, the relation between EMG activity (rms-EMG) of exercising muscles (vastus lateralis and rectus femoris) and exercise intensity exhibits two breakpoints, at around 60–70% and 80–90% of VO2MAX respectively. rms-EMG may be used as a complementary indicator of the aerobic-anaerobic transition in physiological evaluations of cyclists.
Analysis of the aerobic-anaerobic transition in elite cyclists during incremental exercise with the use of electromyography.

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