Review

Electromyographic (EMG) activity during pedalling, its usefulness in diagnosing fatigue in cyclists

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Summary

Muscle fatigue has multiple definitions, but with a special mission what is the protective mission, warning the body about weakness or the appearance of a functional disability. In this review, we present the applications of Electromyography (EMG) as a technique to gain insight into the activation patterns during cycling and the onset of fatigue.

A narrative review has been carried out in which analysis of the EMG activity during the different phases of the pedal cycle. The movement of the pedal has been studied exhaustively and has been able to distinguish 4 phases in the pedaling that originate the propulsion and the recovery. By using the EMG it is possible to describe the typical activation patterns in terms of the activity level and activation time of the main muscles of the lower limbs. Muscle activity and coordination can vary between people throughout a single cycle of pedaling and between different cycles of the same person. Moreover, we examine the main factors that can influence these electromyographic patterns during the pedal cycle. We also describe the influence of factors such as output power, cadence or frequency of pedaling, slope and posture, foot pedal interface, training level and muscle fatigue that produce alterations in the time of activation and muscular coordination.

In conclusion, we believe that EMG can detect the occurrence of muscle fatigue, either of central or peripheral origin. The method used to estimate the neuromuscular fatigue threshold from the EMG amplitude during an incremental test on a cycle ergometer is presented. In general there is an increase in amplitude to try to maintain the force and a decrease in the frequency spectrum.

Key words:
EMG. Pedaling. Cyclism. Fatigue.

Actividad electromiográfica (EMG) durante el pedaleo, su utilidad en el diagnóstico de la fatiga en ciclistas

Resumen

La fatiga muscular tiene múltiples definiciones, pero con una misión especial cual es la misión protectora, avisando al organismo sobre la debilidad o la aparición de una incapacidad funcional. En esta revisión se hace un análisis de las aplicaciones de la electromiografía (EMG) como técnica para comprender los patrones de activación musculares durante el pedaleo y la aparición de fatiga muscular.

Se ha realizado una revisión en la cual se analizan las variaciones de la actividad EMG durante las fases del pedaleo. El movimiento del pedaleo ha sido estudiado exhaustivamente y se ha legado a distinguir 4 fases en el pedaleo que originan la propulsión y el recobro. Mediante el uso de la EMG se pueden describir los patrones de activación típicos, en cuanto al nivel de actividad y el tiempo de activación de los principales músculos de las extremidades inferiores. La actividad muscular y la coordinación pueden variar entre personas a lo largo de un solo ciclo de pedaleo y entre diferentes ciclos de la misma persona. También se examinan los principales factores que pueden influir en estos patrones EMG durante las fases del pedaleo. Asimismo, se describe la influencia de factores como la potencia de salida, cadencia o frecuencia de pedaleo, pendiente y postura, interfaz calzado pedal, nivel de entrenamiento y fatiga muscular, que producen alteraciones en el tiempo de activación y coordinación muscular.

En conclusión, la EMG permite detectar la aparición de la fatiga muscular, bien de origen central o periférico. También, estimar el umbral de fatiga de neuromuscular a partir de la amplitud EMG durante un test incremental en un cicloergómetro. Al aumentar de la amplitud para intentar mantener la fuerza y una disminución del espectro de frecuencias.

Palabras clave:
EMG. Pedaleo. Ciclismo. Fatiga.

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Introduction

Muscle fatigue has multiple definitions, though we can assume the following: "the reduction in physical performance associated with a real increase or with the perceived difficulty upon performing a task or exercise"[1-3]. In reality, it has a protective function, warning the body about the weakness in energy reserves, or that functional incapacity is starting to appear[1-3].

This very common sign/syndrome is particularly accentuated among athletes. Within sport it is much clearer and easier to assess and diagnose in individual sports such as cycling. For this reason, the aim of this review is to understand electromyographic behaviour and its usefulness in diagnosing fatigue. We must mention that the electromyography (EMG) is a technique used increasingly in electrophysics as a way of assessing muscle behaviour, and in particular in diagnosing fatigue.

During the muscle contraction process, a series of events occur dominated by brain commands that discharge in the cross-bridge formation of actin-myosin, which is why fatigue can be associated with alterations to the central nervous system (CNS) or to causes associated with contractile activity[1-3]. For this reason, from a practical perspective we can distinguish two types of fatigue that will intervene directly in the muscle contraction process: a) central or regulation fatigue, in which the cause is located above the motor plate, causing a reduction in the voluntary activation of the muscle, which is due to a reduction in the number and rates of discharge of the motor units (MUs), recruited at the start of the generation of muscle strength; b) peripheral or effectuation fatigue, which affects structures below the motor plate, causing a reduction in the muscle contraction strength of the muscle fibres and changes to the mechanisms underlying the transmission of muscle action potentials[1-3].

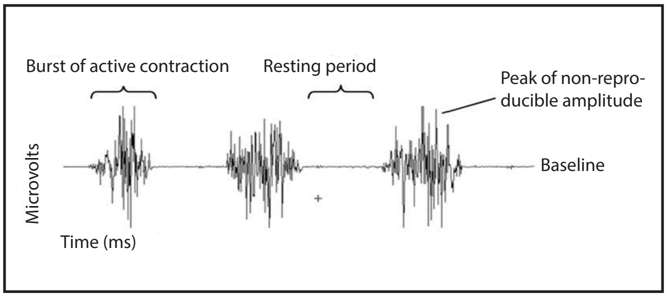
During sustained contractions in maximum efforts, or sub-maximum efforts, central and peripheral fatigue is produced, whilst only central fatigue is produced in intermittent contractions. Fatigue is more evident in maximum efforts; if it is a sub-maximum effort or if there is enough rest between contractions, only peripheral fatigue is produced[2-3].

Some concepts of the electromyography (EMG)

The EMG is an indirect assessment measurement of muscle activity, as it detects the electrical activity that is generated by the passing of the nervous impulse that causes an action potential in the membrane of the muscle cell. This potential comprises three phases: the de-polarisation of the membrane, the re-polarisation and a period of hyper-polarisation, generating an electrical field that is collected by the EMG electrodes[4,5].

In dynamic studies the motor unit recruitments (MURs) detectable in the place where the electrode is positioned superpose electrically, observed as a bipolar signal with a symmetric distribution of negative and positive amplitudes. The signal that is obtained without filtering is the so-called "Raw signal" which is composed of periods of contraction and relaxation. In the relaxation period we observe the baseline EMG, which depends on many factors (quality of the amplifier, environmental noise and the quality of the detection condition given), and if these factors are within suitable margins, the line should not exceed 3-5 microvolts[6] (Figure 1).

Figure 1. Characteristics of the Raw Signal.



There are many factors that can alter the quality of the signal, such as: the characteristics of the tissue; cross talk, i.e. the possibility of registering signals from other muscles near the one being studied, which is mainly produced with the surface electrodes; changes in the geometry between the stomach and the area of electrodes; and external noises[6].

In the signal quantification process it should be considered that many variables can affect it, such as:

- *Frequency variables*. The spectrum of frequencies reveals the frequency of activity of the MURs during the action analysed. In the EMG this frequency oscillates between 10 and 250 Hz[6]. In the frequency analysis we can extract various values: average frequency, which is the average of all the frequencies; and middle frequency (MF), the frequency at which the spectrum is divided into two regions of equal power[4]. There are also other frequency measurements that are not based on the frequency spectrum, such as the "zero cross" (number of times the raw signal crosses the baseline), which is related to the strength of contraction; the "number of turns" (point where the signal direction changes following a power difference of over 100 mV).
- *Amplitude variables.* The "integration of the signal" is studied, which is the total amount of muscle activity in an interval of time. The "envelope curve" is obtained following the rectification of the signals. In order for it to be valid, the recording must be carried out at high sample frequencies[4,6] (Figure 2).

The electrical power of the electromyographic signal is also assessed, i.e. the "root mean square" (RMS), which is the square root of the area between the square of the signal and the time counted in an interval of time divided by that time. Rectification is not required, it is obtained in variable times depending on the activity studied and it provides more information than the integrated signal[4,6].

Finally, a normalisation of the data is required, i.e. to express it regarding an obtained reference value, as the absolute values do not represent the muscle effort.

Numerous factors influence the signal received in the muscle, such as the variability of neural recruitment, the thickness of the adipose tissue, the length of the resting muscle, the cross-sectional muscle

Figure 2. Amplitude variables. Register of the rectified signal (mV), the enveloping curve (mV) and the integrated signal (mV/s).

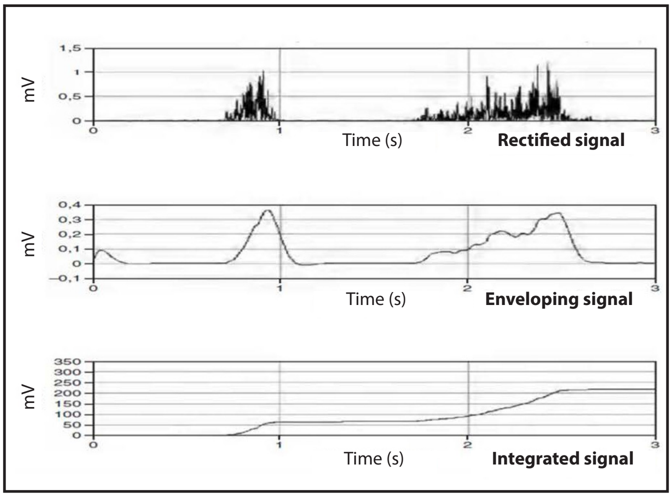
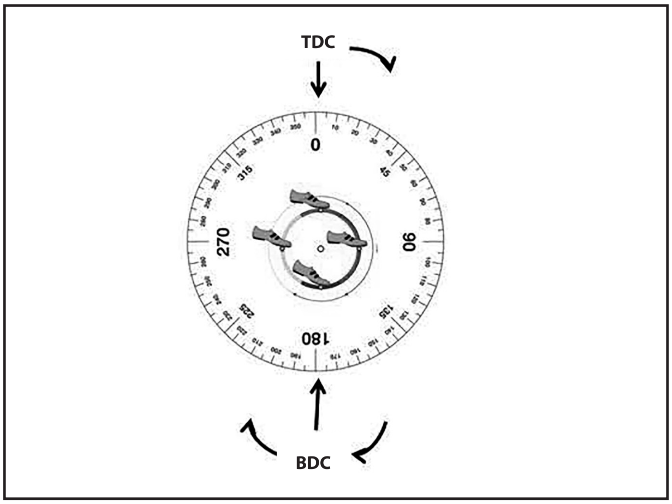


Figure 3. Phases during the pedalling cycle.



TDC: top dead centre; BDC: bottom dead centre.

area, the contraction speed, fibre types, distance between electrodes, positioning of electrodes, impedance of the skin, etc.[4,6].

Muscle activation in pedalling and EMG normalisation

The pedalling movement has been studied exhaustively and 4 phases of pedalling have been classified7, (Figure 3), which generate propulsion and retrieval:

- *Phase I:* This goes from 20º to 145º in relation to the vertical line that passes through the axis of the pedal. During this phase the foot is extended 30º over the leg, the leg is stretched 70º, the muscle is stretched at an extent of 44º. The thigh extension is due to the action of the gluteus maximus muscles, to the tensor of the fascia lata, and to the hamstrings. The extension of the leg is due to the muscle action of the quadriceps by means of the vastus externus and the crural. The foot extension is performed using the sural triceps and also with the collaboration of the internal and external retromalleolar muscle groups. The intrinsic foot muscles do not have an apparent effect;
- *Phase II:* It goes from 145º to 215º. It is an inverse phase in which the lower limb moves from completing the extension to starting its bend. From 180º to 215º, the orientation of the foot remains similar to the previous phase (from 145 to 180º). A bending of the lower limb can be observed: the foot bends from 150º to 135º over the foot, the knee from 150º to 125º over the thigh, and this approaches 5º of the horizontal position;
- *Phase III:* This is the opposite phase to phase I. It goes from 215º to 325º; and
- *Phase IV:* From 325º to 20º, which would begin phase I again. The movements in this phase are complex. At the start of this phase, the foot is extended to 140º, flexing quickly again to 105º, however the extension changes of the knee and hip are minimal[7,8] (Figure 3).

The model of muscle activation can be analysed in terms of level of activity and/or muscle activation time. The level of muscle activity is identified through the simple motor response (SMR) during a complete cycle (0º-360º) or during the muscle activity period in the EMG bursts. An average is made of various consecutive pedalling cycles to obtain the enveloping curve[9-12].

EMG activity is expressed in relation to the record of a short isometric maximum voluntary contraction (IMVC) (<5 seconds)[13,14]. This method has been widely criticised as it cannot be used to represent the maximum neuronal conduction in pedalling[15]. Hautier *et al.*[16] observed an activity level over 100% of the IMVC. They have proposed new normalisation methods that may help improve the interpretation of the signals in future studies, but in general, and to date, there is no agreement regarding the best method to adopt[17]. De Luca[18] and Yang and Winter[19] indicate that it is more appropriate to take sub-maximum contractions rather than maximum ones as a reference, as above 80% of the MVC the signal is unstable and the reference is not reliable.

Characterisation of the activation of the muscle models of the lower limb during pedalling

Cycling is a repetitive activity that uses coordinated combinations of the leg muscles to apply strength to the pedals. Muscle activity and coordination can vary between people during a single pedal cycle and between different cycles by the same person[20, 21]. On the other hand, coordination or the muscular activation of the leg affects the direction, magnitude and duration of the strength applied to the pedal, which is reflected in the mechanical work and power of the cyclist[22,23].

For the study of the muscle activation model, variables such as the "onset of muscle activity" and "offset of muscle activity" are important in the EMG register in terms of the angles of the bracket or the angle of the bicycle crankset[12].

Blake *et al*[24] indicate that global mechanic efficiency in cycling depends on the levels of activation, synchronisation and coordination in all of the active muscles of the leg, and not of any specific muscle. The time and coordination of muscle activation play an important role in the muscle activity used during the pedalling cycle. Various authors[10,12,13,24-26] have performed an EMG analysis of pedalling. Houtz and Fischer[26] performed it by testing the majority of the superficial musculature of the lower limb (except for the soleus) and affirm that they are activated in an ordered and coordinated way. Ericson[13] revealed that a workload of 120 W (approximately 54% of the maximum aerobic power in their work) induces an EMG activity at 45%, 44% and 43% of the IMVC for vastus medialis (VM) and soleus (SOL) respectively. Whilst for the biarticular muscles, such as the rectus femoris (RF) and gastrocnemius lateralis (GL), it was less, 22% and 18% respectively[13].

During the pedalling phase, the gluteus maximus (GMax) is activated from the top dead centre (TDC) up to approximately 130º, being within the region of the strike of power (25-160º) (Figure 3)[13,25,26]. The vastus lateralis and medialis (VL and VM) are activated from just before the TDC, up to just after 90º. The start of the rectus femoris (RF) activity is previous to that of the vastus (some 270º) and ends at almost 90º. The region of activity of the tibialis anterior (TA) is produced in the second half of the ascending phase (from the bottom dead centre (BDC) to the TDC) of almost 270º. The gastrocneumius (GAS) lateralis and medialis (GL and/or GM), depending on the study, start just after the activation of the TA ends (some 30º) and finish just before the start of the TA activity (approximately 270º). The soleus is activated during the descending phase (from 0º to 180º), specifically from 45º to 135º[13,25,26].

On the other hand, there is much controversy regarding the hamstring muscles, i.e. the femoral biceps (FB), semimembranosus (SM) and semitendinosus (ST). Dorel *et al.*[12] indicate a region of lesser activation, from just after the TDC to the BDC, compared to that shown by Jorge and Hull[25] of around the TDC at almost 270º. In fact, Ryan and Gregor[27] observed these two different models for the FB during pedalling. Dorel *et al.*[12] also observed two different activation models for TA, GL and SOL.

Factors that may have an influence on the EMG models during pedalling

- *The output power* (in watts) can be modified by the rhythm of pedalling, the mechanical load (i.e. the resistance imposed by the cycle-ergometer) or both[9]. Ericson[13] observed an increase in the EMG activity of the main muscles of the lower extremities (GMax, VL, RF, VM, FB, ST and GM), in exercises of constant loads performed at different intensities. The output power increased from 120 to 240 W (at a rhythm of 60 rpm) and they proposed that the GMax activity is influenced by the level of workload. These results were confirmed by Sarre *et al*[28] on three knee extensor muscles (VM, VL and RF), at three different output powers, expressed as a percentage of the maximum aerobic power (60%, 80% and 100%). However, another study[25] revealed that at low intensities and with less difference between output powers (from 83 to 125 W), the EMG activity of the GAS does not appear to change. This was confirmed during a progressive pedalling exercise, in which the EMG activity of the GM did not vary until approximately 70% of the maximum aerobic power.

  Farina *et al.*[29], using a new method (eight electrodes in a linear arrangement) on two muscles of the lower extremities (VM and VL), demonstrated that the conduction speed of the muscle fibre increases in accordance with the load, producing a greater and progressive recruitment of the motor units with the conduction speed raised with the increase of strength.
- *Pedalling rhythm or frequency.* Various authors have quantified the level of EMG activity in the muscles of the lower extremity during different pedalling rhythms, accepting that it is an important factor that affects performance in cycling[13,14,29-32].

  In turn, Baum and Li[33] investigated the effects of the frequency and inertia of EMG activity on the muscles of the lower limb during different pedalling rhythms (60, 80 and 100 rpm) at a single output power of 250 W. All the muscles, except for the GAS, displayed significant differences at the onset of the activity in terms of the chain-set axis, and all apart from the SOL revealed a significant linear trend, as the start of the activity occurs earlier with the increase of rhythm. In terms of the offset of activity, GMax, RF, FB and VL displayed significant differences and there were differences in TA, GAS and SOL. With regards to the duration of the FB activity, this reduced, whilst that of the TA and RF increased. Furthermore, on an articular level, changes were observed at the start of the activity (29º GMax, 19º TA, 4º SOL) and at the end (20º GMax, 23º VL, 9º TA and 5º SOL), in that the change of speed of movement and the alteration of the inertia affect the activity and coordination of the lower limb muscles during the pedalling cycle[33,34].
- *The gradient and posture.* Pedalling on a gradient is also important in road cycling, as it will produce changes in the gravitational strengths and it is also accompanied by an alternate sitting and standing posture[9]. Li and Caldwell[30] were the first to study the EMG activity model in the muscles of the lower extremities in terms of gradient (0% to 8%), with no significant changes observed in the activation model. The result was later confirmed by Duc *et al.*[10] on gradients of 4%, 7% and 10%.

  Contrary to the gradient, the change in pedalling posture, from sitting to standing, affects the intensity and time of EMG activity of the main muscles involved[10,30]. Li and Caldwell[30] observed a major activation of the GMax, RF and TA, and a longer duration of GMax, RF and VL. These authors suggest that the greater and more sustained activation of the GMax was due to the fact that the position of the foot forces the pelvis to be stabilised as there is no support from the seat.

  Furthermore, Duc *et al.*[10] observed a greater activation and duration of EMG activity of the lower extremity muscles, with the exception of those that cross the ankle joint (GAS, SOL and TA). The duration of the EMG activity of the GMax of the foot was greater and they supposed that this could be due to the lateral rolls. This data had already been observed by Li and Caldwell[30] with the exception of three muscles (GMax, RF and FB), which did not occur in the previous study.

In the study by Duc *et al.*[10] the RF revealed a significant increase in EMG activity in the second impulse phase (between 90º and 180º), whilst in the study by Li and Caldwell[30] this increase was less. They put this down to the need to increase the extensor moment in the foot position, in which the weaker single-joint knee extensors (VM and VL) may need the help of the RF to extend the knee with strength. Also, that the RF may act in synergy with the GMax to stabilise the pelvis.

In terms of the greater EMG activity of the FB observed by Duc *et al.*[10] regarding the study by Li and Cadwell[30], it could be due to the muscle coordination used by cyclists in pedalling standing up, associated with a specific pedalling technique. In some cases of FB, it is activated by the extension of the hip and the knee (during the descending phase 0º-180º) and in other cases the activity is associated with the bending of the hip and knee, starting much before 0º and stopping at approximately 130º. It could also be associated with the need to generate greater pushing force during the ascending phase of the pedal[35] or to help the GMax and RF to stabilise the pelvis[10].

Regarding the activity of the SM muscle, a reduction in the EMG activity was observed, whilst being the agonist of the FB, similar results would be expected. The hypothesis would be that this muscle would act more in the bending of the knee than in the extension of the hip[10]. The greater plantar flexor momentum in both studies during standing pedalling led to the hypothesis that by removing the support of the saddle, the gravitational forces on the pedal increase, with more weight falling on the pedal during the descending phase. The use of gravity along with fixing the ankle in a horizontal position enables this greater plantar flexor momentum without producing a change in the EMG activity of the flexors and extensors of the ankle[10].

- *Pedal-footwear interface*. Bicycle pedals have become a study focus, as this is the main energy transfer point between the cyclist and the bicycle. Today, the majority of professional and amateur cyclists use automatic pedals. Standard pedals enable the application of positive effective strength during the descending phase (TDC to the BDC), whilst automatic pedals also enable the application of positive effective strength from the BDC to the TDC[9].

  However, very few studies have focused on the study of the effects of the pedal-shoe interface and the muscle activation models of the lower limbs. Hug and Dorel[9] compared the level of EMG activity of the lower extremity muscles when automatic pedals were used, finding a greater level of activity in RF, FB and TA, and less in VM, VL and SOL. Other muscles were not affected (hamstring and gastrocnemius muscles, GMax)[13].

- *Level of training*. Professional cyclists reach distances of approximately 35,000 km/year, between competitions and training sessions, equivalent to 25 hours a week[31,32]. This has led to the considerations that muscle behaviour could be different in amateur and professional cyclists. In this respect, Hug and Dorel[9] have suggested that there are differences in the muscle recruitment models between professional and amateur cyclists. However, Marsh and Martin[14] did not discover significant differences in the electromyographic models of five muscles from the lower extremities (VL, RF, SOL and GM) between cyclists and non-cyclists with similar aerobic capacities.
- *Muscle fatigue*. The EMG studies carried out to date indicate that muscle fatigue can be studied and diagnosed based on the changes in the frequency spectrum[4,36]. In general, when the muscle is fatigued there is an increase in the low frequency components and a reduction of those of high frequency. The reduction of frequency may be due to a reduction in conduction speed, but also possibly to an increase of the synchronisation of motor units[4,36].

  During fatigue, increases in the width of the signal (RMS) are described, arguing that this is due to the increase of the recruitment of more motor units or to the increase in synchronisation of the already active motor units[4], in an effort to maintain the strength. This increase in width has been observed in the muscles of the lower limbs during strenuous pedalling exercises with a constant load[34].

  When it is not possible to hold the contraction for more time, the force reduces and a reduction can be seen in the extent[36], probably caused by a reduction of the excitement of the motor units. If a truly reliable discrimination of fatigue were achieved, it could be used as a diagnostic method.

Determination of the threshold of neuromuscular fatigue via EMG techniques

Over the past few decades, significant research efforts have been made in identifying the workload thresholds that enable the start of critical fatigue to be distinguished during incremental tests performed on a cycle-ergometer. Depending on the measurement variable used, there are different recognised fatigue thresholds, such as metabolic thresholds (point of accumulation of blood lactate) and ventilatory thresholds (aerobic ventilatory thresholds and point of respiratory compensation)[37,38]. However, as the exercise intensity increases, fatigue is not just related to the cardio-respiratory system, but also to the neuro-muscular system. Neuro-muscular fatigue can be identified based on the superficial electromyography measurement (sEMG) and its variations in time[39-41].

In previously performed research studies, deVries *et al.*[38,39] proposed a neuro-muscular fatigue threshold based on EMG activity defined as the "Physical Working Capacity and Fatigue Threshold" (PWCFT), via a specific test on a cyclo-ergometer. In their original version, the establishment of the PWCFT threshold was performed by examining the EMG-time curves obtained from 4 series of work carried out at 4 different power levels. The authors of this method identified the PWCFT threshold by determining

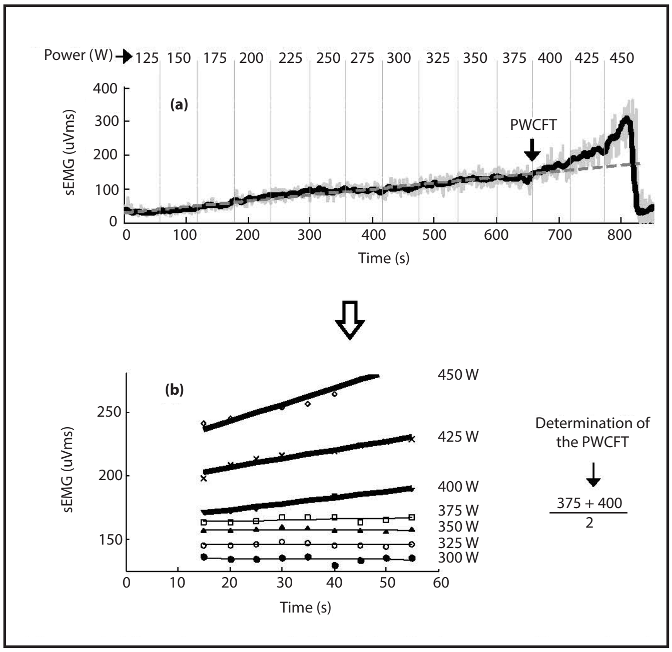


Figure 4. Representative model of the method to stimulate the neuro-muscular fatigue threshold based on EMG (PWCFT) during an incremental test on an ergometer. (a) Time record of the sEMG obtained during the incremental test. The solid black line represents the averaged sEMG width for each 15 pedals. (b) Regression lines corresponding to the sEMG width vs time relationship for each power. The highest power with a non-significant gradient is of 375 W (P >0.05), whilst the lowest power with a significant gradient was 400 W (P<0,05). The PWCFT (387.5 W) is calculated as the average of these two powers.

the greatest power level (load) that the cyclist could maintain over a 2-minute period without the EMG signal increasing significantly. In their original version, the deVries method had the major shortcoming of being a discontinued test that required the cyclist to pay various visits to the laboratory. Later, this group[41] refined its method, which enabled the researchers to extract the PWC threshold by performing a single incremental test.

The EMG signals are obtained using electrodes positioned on the dominant leg over the VL muscle at 1/3 of the distance between the lateral extreme of the kneecap and the projection of the hip bone[42].

During each phase (25w/min) of the incremental test, various consecutive segments of EMG are registered (each segment coinciding with the interval in which the muscle is active in a single pedal cycle). Normally the first 10-15 seconds of each stage of 1 minute are ruled out for analysis, as during this initial period the cyclist performs changes in posture to adapt to the new power. For each power level of the test, the sEMG width of each of the segments is calculated and represented depending on the time. Likewise, the lowest workload is identified (power), which generates a significant positive curve in the sEMG width/time relationship and also the highest workload (power), which generates an insignificant positive curve in the sEMG width/time relationship[37,41]. The PWCFT is established by getting the average of the two aforementioned powers (Figure 4).

However, despite the large amount of information that the EMG provides, we[42] have recently observed heterogeneous and irregular behaviour in the register of the superficial sEMG signal, fundamentally due to the effect that depends on the distance of the conductor of the muscle volume, the diaphony, the cancellation, the length of the muscle, the temperature and the lack of distinction of the fibre diameter via motor units with different recruitment thresholds. We have seen that the sEMG indications did not reduce significantly in the final periods of fatigue in the incremental test, as recently suggested.

Conclusions

We think that EMG allows the level of muscle activation in any muscle to be detected, apart from deep muscle, where wired electrodes are needed (intra-muscular), and can be used as a diagnostic method to assess muscle fatigue. The clinical applications of EMG as a diagnostic tool can include not only fatigue, but also neuromuscular illnesses, assessment of lumbar pain, kinesiology and motor control disorders. The activation time of the lower limb muscles during pedalling can be discovered, and the influence that specific factors - such as the output power, pedalling rate, posture, pedal-footwear interface, and the level of training - may have on the activation time and muscle coordination of the main muscles in the lower limbs can be seen.

We consider that the EMG enables the detection of the appearance of muscle fatigue, whether of central or peripheral origin. In general an increase occurs in the amplitude to try and maintain strength and a reduction of the frequency spectrum.

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