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A maximal isokinetic pedalling exercise for EMG normalization in cycling

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Abstract

An isometric maximal voluntary contraction (iMVC) is mostly used for the purpose of EMG normalization, a procedure described in the scientific literature in order to compare muscle activity among different muscles and subjects. However, the use of iMVC has certain limitations. The aims of the present study were therefore to propose a new method for the purpose of EMG amplitude normalization in cycling and assess its reliability. Twenty-three cyclists performed 10 trials of a maximal isokinetic protocol (MIP) on a cycle ergometer, then another four sub-maximal trials, whilst the EMG activity of four lower limbs muscles was registered. During the 10 trials power output (CV = 2.19) and EMG activity (CV between 4.46 and 8.70) were quite steady. Furthermore, their maximal values were reached within the 4th trial. In sub-maximal protocol EMG activity exhibited an increase as a function of exercise intensity.

MIP entails a maximal dynamic contraction of the muscles involved in the pedalling action and the normalization session is performed under the same biomechanical conditions as the following test session. Thus, it is highly cycling-specific.

MIP has good logical validity and within-subject reproducibility. Three trials are enough for the purpose of EMG normalization in cycling.

Keywords: Surface electromyography; Maximal dynamic exercise; Sub-maximal dynamic exercise; Reproducibility; SRM ergometer

1. Introduction

Surface electromyography (EMG) is a non-invasive method used to obtain information on muscle activity. Absolute EMG amplitude level is of interest, for instance, in clinical studies, since patients usually can not perform maximum contractions (van Dieën et al., 2003), or to make differences in EMG activity between a pain and a non-pain group come to light (Danoff, 1986). However, absolute EMG values depend on many factors unrelated to the level of muscle activation (e.g. van Dieën et al., 2003). It is widely accepted that a procedure of EMG amplitude normalization is required in order to: (i) make a between- and within-subject comparison of activation level in working muscles (Bolgla and Uhl, 2007; Lehman and McGill, 1999; Mirka, 1991), (ii) facilitate comparison between two different muscles, or right and left side muscles of the same subject (Lehman and McGill, 1999), (iii) allow for comparisons between different joint angles, namely different specific positions throughout the range of motion of a joint (Mirka, 1991), (iv) compare results with similar data from other studies (Soderberg and Knutson, 2000).

Most published studies have used an isometric maximal voluntary contraction (iMVC) for the purpose of EMG normalization (Arokoski et al., 1999; Lobbezoo et al., 1993; Smith et al., 2004). Although this method has been demonstrated to be reliable (Dankaerts et al., 2004; Kollmitzer et al., 1999), it is strongly dependent on the specific joint angles used during the iMVC. In fact, an EMG signal

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collected during an iMVC performed at a reference joint angle should be used only for normalization of muscle activity recorded at the same specific joint angle, otherwise a considerable error can occur (Enoka and Fuglevand, 1993; Mirka, 1991). A second potential limitation is the assumption that subjects can actually perform an effort involving maximal force generation, especially if they are not trained and well motivated.

The use of normalization to sub-maximal isometric contraction is present in studies conducted with the patient population and when assessing low level of muscle activity (Dankaerts et al., 2004; Hunt et al., 2003). This method was found to be even more reliable, compared to iMVC, in between-days repeated measures, although the correct determination of relative sub-maximal loads for every muscle is difficult (Dankaerts et al., 2004). Moreover, the EMG associated with a dynamic activity has also been proposed as reference value (e.g. Prilutsky et al., 1998).

The problem of a correct selection of an EMG normalization procedure is essential. A recent paper (Rouffet and Hautier, 2007) has widely addressed this issue. The authors underlined that while executing a specific task, physiological modifications in the neural drive should be reflected in the EMG signal. Other authors pointed out that when dealing with sports movements the electromyogram should be the expression of the dynamic involvement of specific muscles (Clarys and Cabri, 1993). In cycling, EMG is often performed in order to assess the muscular intervention during the pedalling action. For the normalization purpose it is therefore pivotal to choose a meaningful reference contraction so that its activation is regulated by the same neuromuscular pattern as the pedalling action. This means that the task parameters of the reference contraction (e.g. movement amplitude, joint position, speed, etc.) should reproduce, as much as possible, the pedalling action (Latash, 1998).

Despite the above considerations, several studies examining cycling have improperly implemented EMG normalization using an iMVC as a reference contraction, and then expressing the dynamic EMG activity as a percentage of it (Ericson, 1986; Ericson et al., 1985; Hautier et al., 2000; Marsh and Martin, 1995; Neptune et al., 1997). In 2002, Hunter et al. published a paper comparing four normalization protocols: three of them involved an iMVC, the fourth a dynamic pedalling action against a constant load, which was repeatedly increased until the subject could no longer complete a full revolution of the pedal. The authors found that the iMVC test performed on an isometric leg extension dynamometer yielded the highest iEMG amplitude values and concluded suggesting that, for this reason, the use of iMVC as a normalization procedure for dynamic cycling activity would be better. This assumption, however, has been recently questioned since the reference EMG signals collected during iMVC can hardly represent the maximal neural drive obtained during cycling (Rouffet and Hautier, 2007). Furthermore, other authors compared the EMG amplitude signal during iMVC and maximal dynamic cycling contractions (Hautier et al., 2000; Rouffet and Hautier, 2007) and found that the electrical activity of some of the analysed muscles were not significantly different between the two methods, or even higher when the dynamic contraction was used.

More recently, alternative dynamic methods for the EMG normalization in cycling have been proposed. Takaishi et al. (1998) set the integrated EMG corresponding to the lowest cadence (45 rpm) as reference value, while Hug et al. (2004b) normalized the vastus lateralis EMG activity with a 40 W intensity exercise. However, it could be argued that due to the low intensity chosen, the muscular recruitment pattern could be quite different from a pedalling action at higher intensity; furthermore, the vastus lateralis activity at 40 W intensity is probably not different from baseline.

Neptune and Herzog (2000), assessing the adaptation of muscle coordination when traditional and elliptical chainrings were adopted, used the highest EMG value observed across all trials for normalization purposes. Since the experimental design entailed a variation of pedalling biomechanical conditions (e.g. instantaneous crank angular velocity), the normalization procedure chosen could not represent all the different tests performed.

Hug et al. (2004a) and Laplaud et al. (2006) normalized the EMG of a graded pedalling exercise as a percentage of the highest intensity step. Interestingly, Taylor and Bronks (1995) showed that the reference EMG amplitude value (a maximal “unfatigued” EMG value obtained by rapidly increasing the resistance until the subject could no longer maintain the fixed cadence) was about twice than the one reached during the last step of the graded exercise. It could be maintained therefore that when the EMG reference value is the latter, a normalization to a sub-maximal dynamic contraction is performed and the limit of this procedure, as previously reported, is the determination of equivalent sub-maximal efforts for different muscles (Dankaerts et al., 2004; Marras and Davis, 2001) and subjects.

Several methods have been proposed for the purpose of EMG amplitude normalization in cycling but, based on the above evidence, the best reference contraction to use is still controversial. Methods grounded on iMVC or sub-maximal dynamic contractions have evidenced limitations. Accordingly, the main aim of this paper was to present a maximal isokinetic protocol (MIP) as a new method for the purpose of EMG normalization in cycling. Briefly, this protocol should produce a maximal dynamic contraction of the muscles involved in the pedalling action. Furthermore, the normalization session is performed under the same biomechanical conditions as the following test session, thus making the protocol highly specific. It is therefore hypothesized that the cyclists do not need to learn the required task as it is inherent in their pedalling patterns.

The second aim of this investigation was to detect the intra-individual variability of the method proposed.

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2. Methods

2.1. Subjects

Twenty-three recreational and competitive healthy male cyclists (age 29.3 ± 9.0 yr, height 177.5 ± 7.4 cm, weight 71.6 ± 9.8 kg) volunteered and gave their written informed consent to participate in the study, which was previously approved by the Human Ethics Committee of the University of Urbino (Italy). All the cyclists used to train about 10 h per week with a quite homogeneous training programme. Competitive cyclists, unlike recreational ones, competed during weekends at Masters level. They all had covered an average of 9000 km during the last season. None of them had previous experience in riding an isokinetic cycle ergometer, and they were asked to refrain from exhausting exercise 24 h before testing.

2.2. Exercise protocol

An SRM ergometer (Schoberer Rad Meßtechnik SRM GmbH, Jülich, Germany) was used for all tests, mounted with the two flywheels and in the ninth gear. The SRM crankset, equipped with strain gauges, directly measured the torque produced by the force applied to the pedals perpendicularly to the crank length. The ergometer was customized with subject's own bicycle's measures and clipless pedals. A display was available close to the handlebars of the ergometer to let the cyclists check their pedalling cadence.

2.2.1. Warm up

Cyclists performed a 10 min warm up at a recommended cadence of 80 rpm. The power constantly increased from 75 to 200 W during the first 6 min (25 W min^{-1}), the intensity was then set to 125 W for the next 2 min and increased to 200 and 250 W for the last 2 min. Depending on the performance level of the subjects, the warm up intensity could be increased by no more than 25 W per step.

2.2.2. Maximal isokinetic protocol (MIP)

MIP was performed in the isokinetic mode of the ergometer, at a fixed pedalling frequency of 80 rpm. This mode allows the subject to pedal without resistance up to the fixed cadence, while resistance is automatically and proportionally increased when the subject tries to overcome it. Prior to the maximal effort, cyclists pedalled at 80 rpm and low intensity (50–100 W) and at the signal they started to pedal as forcefully as possible for 6 s, while a vigorous verbal encouragement was given. They were instructed to remain seated and to hold the hands on the low part of the handlebars during the trial. Every cyclist completed a total of ten 6 s all-out sprints. A full recovery was ensured by a 3 min rest period between sprints, in which they were allowed to drink water and pedal at a low intensity.

2.2.3. Sub-maximal protocol (SMP)

After the MIP, cyclists rested for 10 min, pedalling at 50 W at a freely chosen cadence. They were then asked to perform four sub-maximal exercises at 0%, 20%, 40% and 60% of the maximum power output obtained during the MIP. In order to perform the 0% exercise, the brake was turned off. It is however useful to know that, due to the friction of the moving parts, the workload was actually about 30–35 W. Concerning the other sub-maximal exercises, while the subject was pedalling at 50 W, the load was increased and as soon as a steady pedalling cadence of 80 rpm was reached, data were collected for 20 s. Trials were separated by a 2 min active rest period. The 80% intensity was too demanding to be maintained for at least 20 s, hence it was not included in the SMP.

2.3. Recording of EMG and angular crank position

Following the recommendations of the SENIAM project (Freriks et al., 1999), EMG of four muscles of the right leg was recorded during the MIP and the SMP. The selected muscles were vastus lateralis (VL), biceps femoris (BF), tibialis anterior (TA) and gastrocnemius lateralis (GL). Skin was shaved, slightly abraded with sandpaper and cleaned with alcohol. Ag/AgCl bipolar electrodes (Blue Sensor N-00-S, Ambu Medicotest A/S, Ølstykke, Denmark) were placed over the muscle belly of selected muscles at an interelectrode distance of 20 mm. To avoid artefacts from lower limb movements, the wires connecting electrodes were well secured with tape.

Signal was amplified at a gain of 600. Common mode rejection rate and input impedance were respectively 95 dB and 10 GΩ. Raw electromyographic data were band-pass filtered using a fourth order Butterworth filter, with cut-off frequencies of 10 and 350 Hz. Fig. 1 depicts an individual example of the raw EMG signals as a function of time, related to the four analysed muscles.

In order to measure the instantaneous angular position of the crank, a rotational encoder (EL40B, Eltra, Sarego (VI), Italy) with a resolution of 2000 pulses per turn was coupled to the left crank of the ergometer by a chain drive. Since the gear ratio between the gear wheel of the left crank and the sprocket of the encoder was 53/15, the total resolution of the system was 7066.7 pulses per pedal cycle (Picture 1).

The EMG and angular position of the crank signals were synchronized, sampled at 1000 Hz and stored on a PC using a 16 bit A/D converter data acquisition system (APLabDAQ, APLab, Rome, Italy).

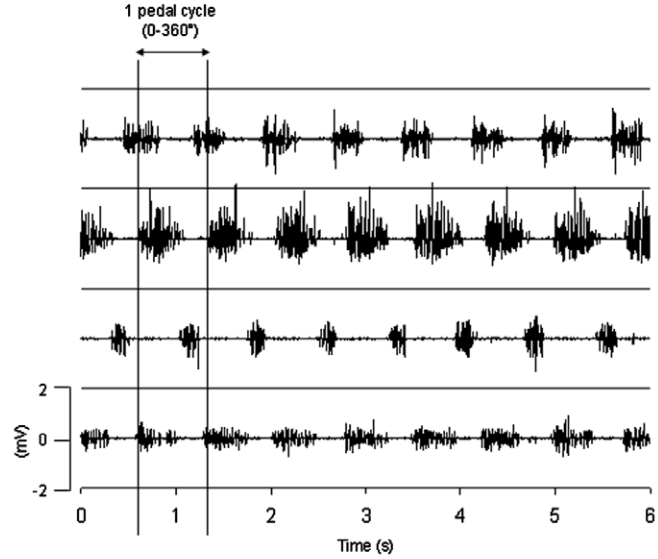

Fig. 1. Raw EMG signals from a single, representative trial recorded during the maximal isokinetic protocol. The window corresponding to a pedal cycle is also shown. VL = vastus lateralis; BF = biceps femoris; TA = tibalis anterior; GL = gastrocnemius lateralis.

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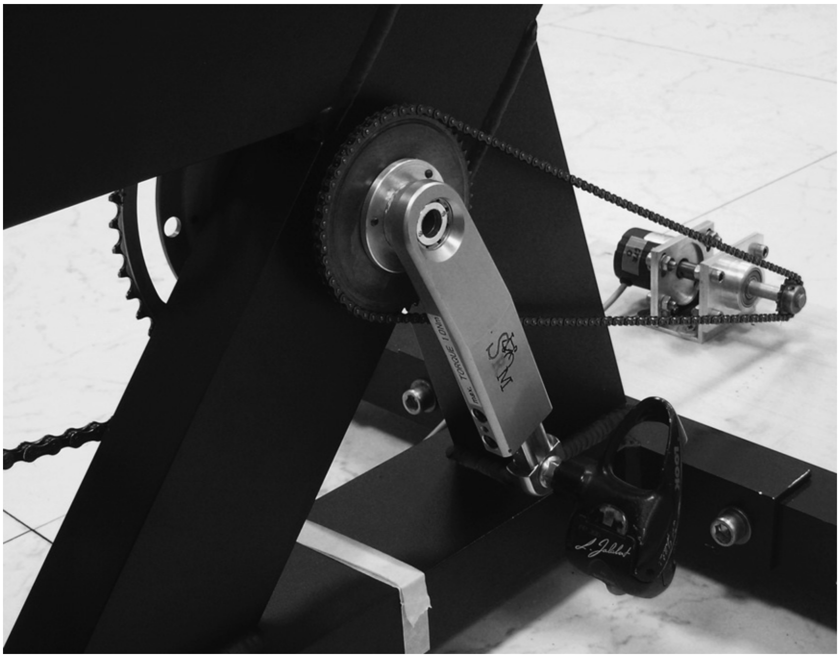

Picture 1. A rotational encoder was coupled to the left crank of the SRM ergometer in order to measure the instantaneous angular position of the crank and synchronize it with the EMG activity.

2.4. Data processing

Torque applied to the crankset during the MIP was recorded at 200 Hz for power output calculation purposes. Average power output of each maximal trial (PO) was calculated as the product of the average torque over the 6 s (in Nm) and the actual average cadence (in rad/s). For each subject, the best PO (PO_B) was set to represent 100% and the other trials were calculated as a percentage of PO_B.

Raw EMG data were processed by root mean square (RMS) determination for each complete cycle, defined as a full revolution of the right crank from top dead center (TDC at 0°) to the next TDC. The mean RMS was calculated averaging the RMS values of the eight pedal cycles completed in every MIP trial, and averaging the complete pedal cycles of the last 10 s (about 13 pedal cycles) in every SMP trial.

For MIP assessment, the highest EMG activity achieved for each muscle was set to 100% and the other trials were calculated as a percentage of the highest. In contrast, for SMP assessment, the EMG activity of all muscles corresponding to PO_B was set to 100% and the values obtained during the submaximal exercises (0%, 20%, 40% and 60% of PO_B) were expressed as a percentage

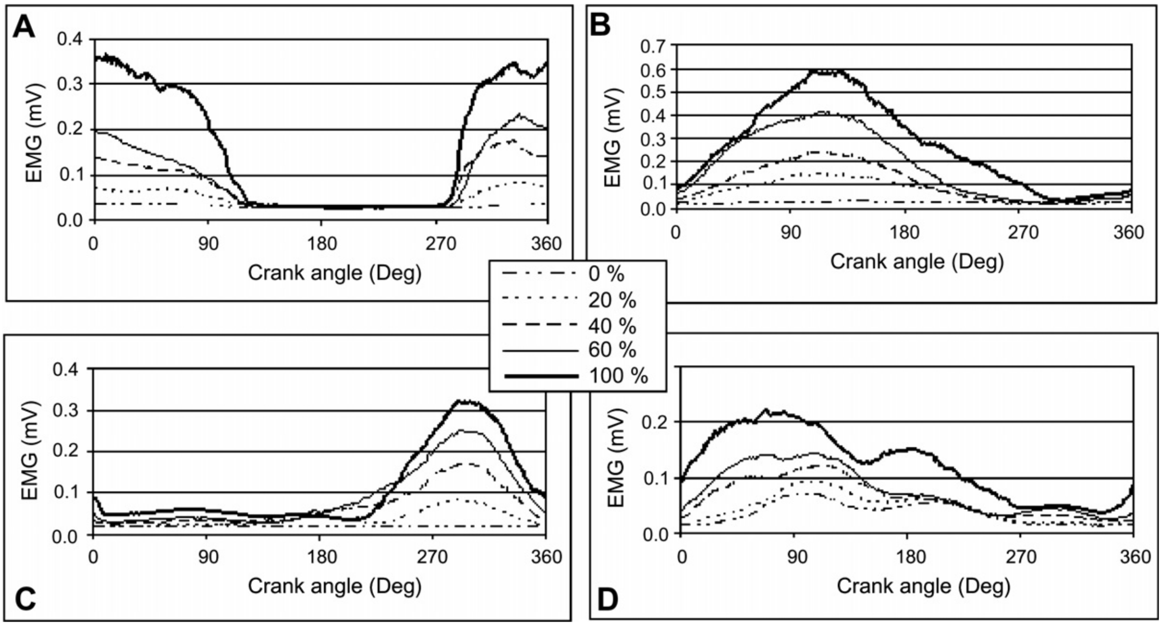

Fig. 2. Example of individual muscle activity, as a function of crank angle, obtained at five different intensities for the vastus lateralis (A), biceps femoris (B), tibialis anterior (C) and gastrocnemius lateralis (D).

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of the former. An example of individual EMG patterns obtained for the four analysed muscles is represented in Fig. 2. The raw data were root mean squared with a moving window length of 100 ms.

2.5. Statistical analysis

In order to evaluate the within-subject reproducibility of PO and EMG for the four muscles analysed, the variables were checked for normality and homoscedasticity and were log-transformed when these assumptions were violated. Thereafter the intra-subject standard error of measurement (SEM), the coefficient of variation (CV) and the intra-class correlation coefficient (ICC) were calculated as proposed by Hopkins (2000) with the assistance of a reliability spreadsheet (Hopkins, 2007). The CV is defined as $100 \cdot (e^{SD/\sqrt{2}} - 1)$, where SD is the standard deviation of the change scores of natural log of the measure. The ICC is defined as $(V - v)/V$, where V is the between-subject variance averaged over the two trials analysed, and v is the square of the standard error of measurement.

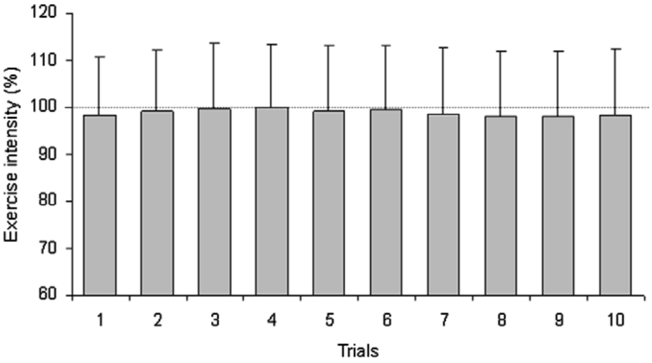

Fig. 3. Power output (mean ± SD) reached during the 10 trials of the maximal isokinetic protocol. The best power output was set equal to 100 and the other trials' were calculated as a percentage of the best one.

3. Results

Fig. 3 shows PO (mean ± SD) reached during the 10 trials. The PO_B (100%) was achieved during the 4th trial. The PO values were, however, very close to each other, ranging from 98.0 to 100.0, thus indicating a quite high reproducibility of the variable, with no observable learning or fatigue effect. The PO_B obtained ranged from 664.6 to 1013.9 W (data not shown).

EMG activity (mean ± SD) is shown for VL (Fig. 4A), BF (Fig. 4B), TA (Fig. 4C) and GL (Fig. 4D), registered during the 10 trials. For each of the muscles included in the analysis, the 100% activity was achieved within the 3rd trial, although BF (Fig. 4B) and GL (Fig. 4D) tend to decrease thereafter.

Reliability measures from consecutive pairs of trials are summarized in Table 1. SEM and CV are presented as a mean value, whilst for ICC maximal and minimal values are shown. PO has the lowest CV (2.19), indicating very good consistency between repeated measures. Among the EMG activities, VL and TA show, respectively, the lowest (CV = 4.46) and the highest variability (CV = 8.70). ICCs in all the variables analysed, ranging from 0.922 to 0.994, are considerably high.

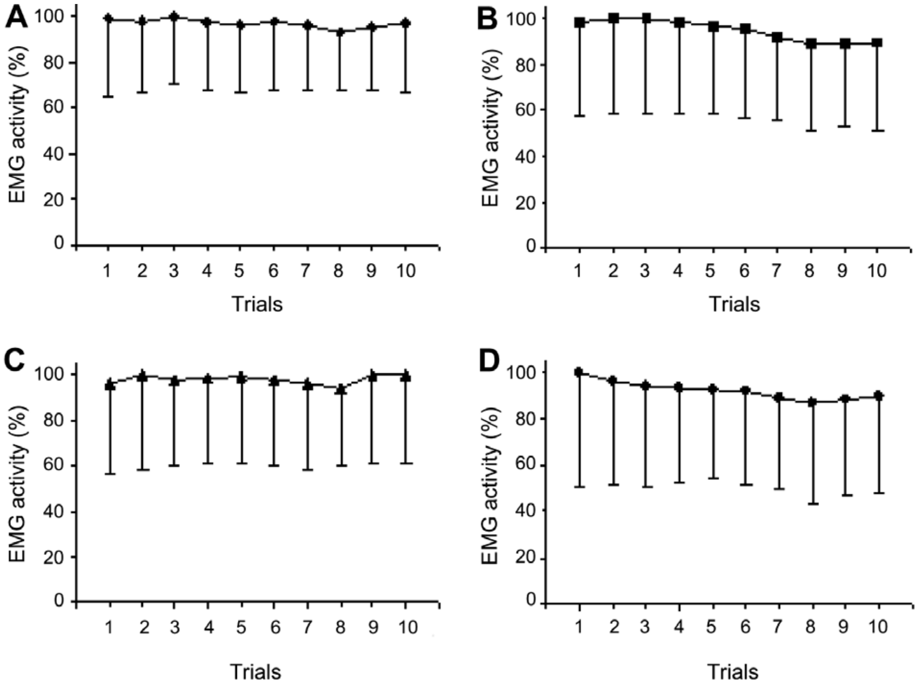

Fig. 4. EMG activity (mean ± SD) for vastus lateralis (A), biceps femoris (B), tibialis anterior (C) and gastrocnemius lateralis (D) registered during the 10 trials of the maximal isokinetic protocol. The highest EMG activity was set equal to 100 and the other trials' were calculated as a percentage of the best one.

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Table 1
Statistical measures of reliability from consecutive pairs of trials

	SEM (mean)	CV (mean)	ICC (range)
Power output (PO, Watt)	17.11	2.19	0.962–0.986
VL EMG activity	0.34	4.46	0.969–0.987
BF EMG activity	0.47	7.32	0.934–0.983
GL EMG activity	0.37	6.85	0.922–0.985
TA EMG activity	0.43	8.70	0.948–0.994

SEM and CV are expressed as a mean, whilst ICC as a range value.
VL = vastus lateralis; BF = biceps femoris; TA = tibialis anterior; GL = gastrocnemius lateralis.
The EMG activity (AU) is the root mean square of the raw EMG data for each complete pedalling cycle.
SEM = standard error of measurement; CV = coefficient of variation; ICC = intraclass coefficient of correlation.

The EMG activity (mean ± SD) corresponding to 0%, 20%, 40% and 60% intensities of PO_B is presented for VL (Fig. 5A), BF (Fig. 5B), TA (Fig. 5C), GL (Fig. 5D). A visual inspection showed a linear EMG activity increase when moving from 0% to 100% of exercise intensity, for VL (Fig. 5A), BF (Fig. 5B) and TA (Fig. 5C). GL (Fig. 5D) instead exhibited a curvilinear trend.

4. Discussion

The aim of this study was to propose a new method for EMG amplitude normalization in cycling and assess its reliability. Different investigations suggesting isometric or sub-maximal dynamic contractions for EMG normalization in cycling have been gone over, and the limitations were highlighted.

A MIP was introduced as a reference contraction for the EMG normalization procedure. The task required, a maximal 6-s pedalling action, and the submaximal cycling are comparable for at least three reasons: (a) the contribution of the muscles of the lower limb is similar for maximal sprint and submaximal bicycling conditions, as discussed by Rouffet and Hautier (2007); (b) mechanical conditions of the MIP and the following test session match completely: pedalling frequency, posture and joint angle ranges of the cyclist (hip, knee, ankle), and type of muscular contraction; (c) the muscles are activated at the same part of the pedalling cycle, as shown in the EMG profiles (Fig. 2).

The EMG activity registered during SMP supports the validity of the method proposed. Pedalling at 0%, 20%, 40% and 60% intensities of PO_B resulted in a coherent level of muscular activity, which altogether exhibited an increase as a function of exercise intensity.

Three of the muscles analysed (VL, BF and TA) showed a linear trend, whilst the GL had a curvilinear shape. This latter result was deemed to be due to the somehow unusual pedalling pattern when cycling at very low intensities. In fact, it seems that when riding at 0 W the cyclist has to avoid pushing down the pedal during the downstroke in order to maintain the predetermined cadence and a relatively smooth pedal stroke, thus making the knee extensor muscles to remain inactive. GL instead is often overactive to counterbalance the knee extensor muscle inactivity and produce the little amount of power needed for keeping the flywheel rotation. Eight of the 23 subjects showed a similar or even higher GL activity at 0% compared to 20%. These data suggest therefore that due to the high

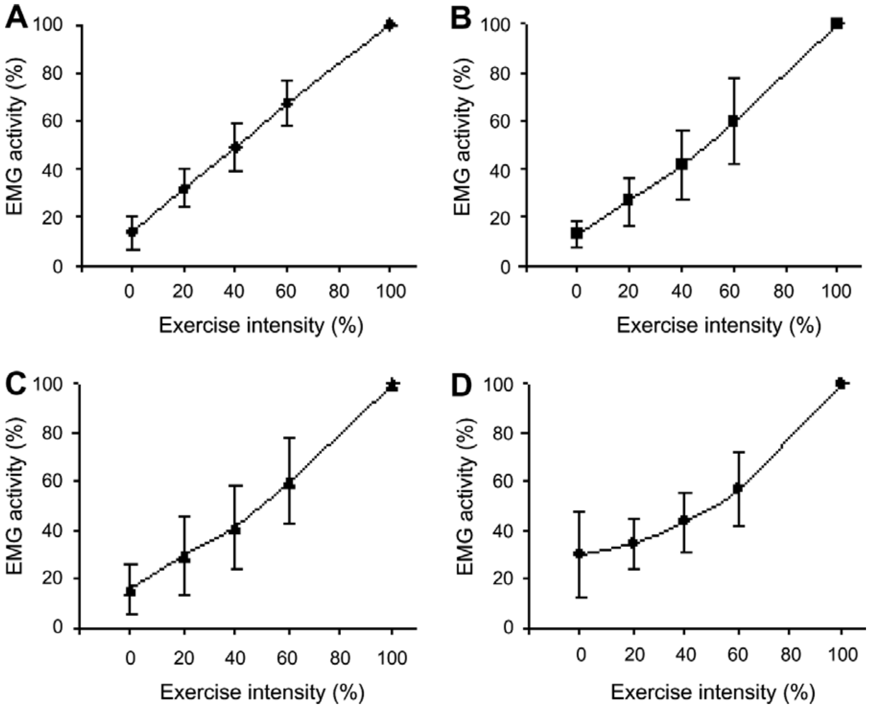

Fig. 5. EMG activity (mean ± SD) corresponding to 0%, 20%, 40% and 60% intensities of the best power output for vastus lateralis (A), biceps femoris (B), tibialis anterior (C) and gastrocnemius lateralis (D).

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inter-subject variability in recruitment pattern of some muscles (e.g. GL) normalization methods based on low intensity reference contractions in cycling are questionable.

The activity of each muscle during submaximal contractions is calibrated in reference to its maximal activity, the two enabling similar neuromuscular responses. On the other hand, it was evidenced that iMVC and pedalling movement differ significantly in biomechanical function and regulation of the lower limb muscles activation (Rouffet and Hautier, 2007).

Another interesting similarity between MIP and the cycling action is the angular velocity profile of the crank. It has been previously demonstrated that the instantaneous crank angular velocity is not constant throughout the pedalling action, rather, it is dependent on the angles of the lower limb relative to the crank position. In fact, the highest and lowest angular velocities occur when the cranks are near vertical and horizontal, respectively (Moussay et al., 2003). This pattern was evident during MIP, despite the isokinetic modality. This is due to the fact that the accommodating braking power exerted by the ergometer is reduced to near zero when the cranks are in vertical position and increased when the cranks are in horizontal position, in order to maintain the desired rotational speed (Wooles, 2006). Actually, this mechanism does not seem to be able to keep completely steady the instantaneous angular velocity of the crank, at least when the cyclist is asked to pedal at 80 rpm and maximal intensity.

From the issues above discussed it could be maintained that the procedure employed in the current setting is highly specific to the cycling gesture. Furthermore, using the current procedures, each muscle may be assessed at the same time, this being a time- and energy-saving process. In contrast, an isometric contraction would entail a more complicated procedure, especially when several muscles require to be analysed, namely an iMVC has to be produced separately for every single muscle involved in the action (Hsu et al., 2006; Rouffet and Hautier, 2007).

A common problem of iMVC is that a certain degree of familiarization is required during the normalization session. A useful implication from the data presented is that cyclists do not need to get skilled with the MIP, since no learning effect was demonstrated during the trials (Fig. 3). Indeed, both PO and EMG activity reached their maximal values respectively, on average, on the 4th and within the 3rd trial. Although the PO and EMG maximal values are not attained at the same trial, it is important to underline that the variability among trials is negligible. Indeed, the average difference between the best and the worst value in the first five trials is 2% for PO and from 3% (BF) to 7% (GL) for the EMG of the four analysed muscles. As a result, based on the data collected, three trials of the MIP proposed appear to be sufficient for the purpose of EMG normalization in cycling. Thus, the important goal of time efficiency during testing sessions is also achieved.

As recently pointed out, the repeatability of EMG recorded during dynamic exercise, especially the muscles involved in a cycling action, has not been fully established (Laplaud et al., 2006). A strong point of the method proposed is the high degree of reliability. EMG signal of the VL, compared to the other muscles analysed, showed the lowest variability and this is in agreement with previous studies which found the EMG activity of VL during cycling to have a high reproducibility (Ryan and Gregor, 1992; Taylor and Bronks, 1995). When comparing the activity of the same muscles, the CVs are considerably lower than those presented by Rouffet and Hautier (2007) who used a maximal torque–velocity test, although it is important to mention that the subjects of their study were not cyclists.

4.1. Limitations

The protocols proposed were performed at 80 rpm. This cadence is widely used in cycling related researches (Baum and Li, 2003; Hull and Jorge, 1985); furthermore, previous studies found that freely chosen cadence in cyclists ranges between 78 and 91 rpm (Foss and Hallén, 2005; Hagberg et al., 1981; Nielsen et al., 2004). Notwithstanding, a cadence of 100–115 rpm, rather than 80 rpm, makes the cyclist attain the maximal power output (Baron, 2001; Baron et al., 1999; Sargeant et al., 1981). Consequently, the pedalling frequency chosen in the present study is situated in the ascending part of the power–cadence curve. Takaishi et al. (1998) demonstrated that the EMG/cadence curve at constant power and pedalling frequency ranging from 45 to 105 rpm showed a quadratic trend. The minimum EMG value was registered at 60 rpm, afterward it exhibited an increase as a function of cadence. It is therefore expected that maximal isokinetic pedalling at higher cadences would lead to higher EMG values, although this issue needs to be investigated further on.

As a consequence, the reference contraction here proposed at 80 rpm should be used only for submaximal bicycling exercises performed at the same cadence. In general terms it could be argued that, whatever the pedalling rate chosen for SMP, the MIP should be performed at the same cadence.

5. Conclusion

The new protocol proposed for the purpose of EMG normalization in cycling, which consists of three 6-s maximal isokinentic pedalling sprints, has very good logical validity and within-subject reproducibility. Further, the test is also highly specific to the actions associated with cycling. The chosen cadence of the normalization protocol should be the same as the sub-maximal exercises.

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