Linear and non-linear analysis of surface electromyograms in weightlifters

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Abstract The present research was aimed at investigating the peculiarities of surface electromyogram (sEMG) signals in 12 weightlifting athletes (WLA) and 9 control subjects (control group, CG). The sEMG signals were recorded from both vastus lateralis muscles during 20 s isometric contractions made at 30% and 60% of the maximal voluntary contraction (MVC). Ground reaction force (vertical component) was recorded using a force plate. The sEMG was analysed in the frequency domain and the median frequency (MDF) was computed over successive 1 s epochs. A non-linear technique, recurrence quantification analysis was also applied to assess the presence and time course of deterministic structures in sEMG. The percentage of determinism (%DET) was used as a synthetic parameter to quantify the amount of regularly repeating sEMG waves within the signal itself (bursts). In 5 WLA the sEMG displayed a clear burst activity centred at 11 Hz. These bursts were correlated with force output oscillations and were evident both at 30% and 60%MVC. The MDF decay with time was more evident in WLA than in CG subjects. The %DET increased in WLA, this increase being more evident during 60%MVC contractions. Our results seemed to suggest a special disposition among WLA for the development of long-term changes in firing probability during sub-maximal isometric exercise. The MDF and %DET data provided indications of a greater involvement of fast twitch muscle fibres in WLA than in CG.

Key words Weightlifting athletes · Tremor · Surface electromyography · Linear and non linear analysis

Introduction

Why examine weightlifters? The adaptation of the neuromuscular system to heavy resistance exercise is a very complex result of many factors. This implies central and peripheral neural adaptations as well as chemical and morphological modifications of muscle tissue (for a reference see Kraemer et al. 1996). Indeed, a number of studies regarding weightlifting athletes (WLA) has already been made and a good insight into maximal strength performance has been obtained as reviewed by Kraemer et al. (1996). Some research has partially attributed the enhancement in strength of weight-trained subjects to an increase in the recruitment and firing rate of motor units (MU) (Hakkinen et al. 1985, 1988). Furthermore, structural adaptations of muscle fibres can imply a change in the conduction velocity properties of the fibre membrane (Hakkinen et al. 1985, 1988). A greater MU synchronisation in WLA with respect to untrained persons has been noted in the work of Milner-Brown et al. (1975). Besides the enhanced MU synchronisation, common simultaneous fluctuations in MU firing rate have been described (Semmler and Nordstrom 1988).

These results have indicated that the peculiarities of the neuromuscular adjustments in WLA might be recognised in the surface electromyography (sEMG) of the athletes as an enhancement of the common fluctuation
of the activities of many concurrently active powerful MU (De Luca et al. 1982). Grouping the activities of the MU should produce a more regular appearance of sEMG characterised by bursts of activity isolated from background muscle activation. Therefore we decided to analyse the sEMG obtained in WLA during extension effort from the quadriceps muscles (vastus lateralis, VL). This muscle is mainly involved in lifting exercise and may exhibit the most marked adaptation to intense long-lasting training. To analyse ongoing sEMG changes during sustained contractions the median frequency (MDF) of the power sEMG spectrum and recurrence quantification analysis (RQA) were used (Webber et al. 1995). Filligoi and Felici (1999) have shown the capability of RQA, and of one of the variables obtained from it – namely the percentage of determinism (%DET) – in detecting hidden rhythmicity within the sEMG.

Methods

Subjects

After giving written consent, 21 male subjects volunteered for this research. For anthropometric data see Table 1. Of the subjects a group of 12 were WLA belonging to the national team, and a group of 9 were untrained sedentary subjects (CG). The VL muscle of both sides was studied.

Experiment set-up

The experimental device consisted of a rigid frame formed by a force plate (Kistler type 9261A) connected to a barbell by means of two vertical adjustable rigid bars. Following the instruction of an expert trainer, each subject assumed a posture as close as possible to that of the pushing phase of a real weightlifting exercise. In particular, the angles at the ankle, knee and hip in the sagittal plane were fixed at 80, 120, 160°, respectively.

The vertical ground reaction force, which was obtained from the force platform positioned under the feet of the subjects, was assumed to be a measure of the isometric force applied to the barbell. The body mass was subtracted from the ground reaction force. Each subject was asked to push on the barbell for 5 s with maximal force. This test was repeated three times and the maximal value obtained was taken to be the maximal voluntary contraction (MVC). Subjects made a 20 s contraction at 30% MVC and, after 5 min rest, a 20 s contraction at 60% MVC. During the test, the sEMG activity from the VL muscles of both legs was recorded and then amplified using Grass amplifiers (model P511). High-pass and low-pass filters were set at 1 Hz and 1 kHz, respectively. Pairs of disposable adhesive Ag-AgCl circular electrodes (blue sensor, type K-50-VS; diameter 5 mm) with an inter-electrode distance of 20 mm were applied to the muscle belly. Skin impedance was reduced by abrading and cleaning the area (inter-electrode resistance below 10 MΩ). A reference electrode was applied to the patella. Force and sEMG were A-D sampled at 2,048 points a second at 12 bit resolution (DAQCard-AI-16XE-50, National Instruments), and the raw signals were stored on a personal computer.

Linear analysis of sEMG

To avoid transient phenomena, the sEMG analysis was started from the 2nd s of the contraction. Within the remaining 18 s, subtracting the raw sEMG mean value from the signal itself eliminated the DC component. The sEMG signals were segmented in epochs of 1 s overlapping each other by 0.5 s.

To quantify the strength of the association between the sEMG and force, we evaluated their cross-correlation function (De Luca et al. 1982). For the purpose of cross-correlation only, sEMG was full-wave rectified and then band-passed (0–40 Hz) with a moving average filter (window length 25 ms). The cross correlation r_{xy}(t) of the signals x(t) and y(t) was defined as:

\[ r_{xy}(t) = x(t) \otimes y(t) = \int_{-\infty}^{+\infty} x(\tau)y(t+\tau)d\tau \]

where the symbol \( \otimes \) denotes correlation. A value of 0.4 was adopted to define high correlation in accordance with De Luca et al. (1982). A time window of 100 ms on either side of a given force peak was chosen to test for the presence of an association between force and sEMG (see Fig. 1).

Table 1 Subjects’ data. WLA Weightlifting athletes, CG control group

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (years)</th>
<th>Stature (m)</th>
<th>Body mass (kg)</th>
<th>Maximal force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>WLA (n=12)</td>
<td>21</td>
<td>4.2</td>
<td>1.70</td>
<td>0.06</td>
</tr>
<tr>
<td>CG (n=9)</td>
<td>28</td>
<td>5.2</td>
<td>1.70</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Fig. 1 Typical functions obtained by cross-correlation between force output (60% maximal voluntary contraction) and surface electromyograms (sEMG) (single subject). Negative shift of peaks indicates sEMG signal leads force output. Continuous line early phase of contraction, dotted line late phase of effort. The time shift is indicated by \( \Delta \). The vertical axis denotes the strength of the correlation.
Linear analysis of raw sEMG signals was made in the frequency domain using MDF as a synthetic parameter. This was defined as:

\[ f_{med} = \int_{f_{med}}^{\infty} P(f) df = \frac{1}{2} \int_{f_{med}}^{\infty} P(f) df \]

Non-linear analysis of sEMG (%DET)

Mathematical concepts and theories that produce %DET parameters are very complex. Readers interested in obtaining more details about this analytical tool can refer to the work of Filligoi and Felici (1999). In short the procedure is based upon embedding myoelectric data in a N-dimensional Euclidean space. The following steps must be followed.

1. Lag sEMG data epochs \((n=2,048)\) by a number \(i\) of samples \((i=0,1,2,\ldots,15)\) of the autocorrelation function. According to Filligoi and Felici (1999), embed these data up to \(D=15\) \((D=\text{embedding dimension})\) to build the embedding matrix \(G\).

2. Compute the Euclidean norm between all possible vector pairs according to:

\[ d(i,j) = d(rowG(i), rowG(j)) \]

3. To get the distance matrix DM:

3. Compute the percentage of recurrent points \((\text{Re})\) in the recurrence plot that form upward diagonal line segments. Lines \((L)\) are made by two or more points that are diagonally adjacent with no intervening white space. The %DET is defined as:

\[ \%DET = \frac{L}{\text{Re}} \times 100 \]

All the MDF and %DET were normalised with respect to the value obtained at the beginning of the constant force phase of the contraction; therefore the data presented here are expressed as percentages of that value.

**Results**

In 5 out of 12 subjects the sEMG was characterised by an evident burst activity. An example of this pattern is shown in Fig. 2 in which segments of the sEMG of 1 subject are illustrated. Six segments 0.5 s long are depicted, corresponding to various periods of the effort (60%MVC; sample time: 2, 5, 10, 12, 15 and 19 s after the start of the contraction). On the upper part of each sEMG recording the corresponding force trace is shown.

At the top of each trace the results of the RQA analysis of the corresponding sEMG segment are given. Clearly the burst activity became more and more evident as time progressed, the bursts becoming more regular and more similar to one another in shape. These data indicated that as in each epoch bursts became isolated and easily recognisable, so the %DET increased. Each burst was made up of very brief groups of large waves.

**Fig. 2** Surface electromyograms (sEMG) and force signal fragments in different seconds of the constant force phase in one subject (60% maximal voluntary contraction). Each fragment is 0.5 s in length in order to magnify sEMG bursts. Note that data analysis was performed on 1 s time epoch (as detailed in text). At the top of each fragment the corresponding percentage of determinism (%DET) value is given.
Bursts were separated by quasi-silent periods and had a frequency of about 11 s⁻¹. This activity was paralleled in the force tracing by oscillations of the same frequency as those of the sEMG bursts. These oscillations became as large along with the sEMG burst activity. This burst activity was present both at 30% and 60%MVC; in the control group this burst activity was observed only in 1 subject, who was the most active. In the 5 WLA who exhibited the most obvious burst patterns, the cross-correlation function (De Luca et al. 1982) between sEMG (rectified) and force showed that the burst sequences were well correlated with the oscillations in the force tracing. An example of cross-correlation obtained in one of these subjects (60% MVC) is shown in Fig. 1. The cross-correlation function values we obtained in WLA, indicated that sEMG precedes force development by a mean of 41 (SD 3.4) ms at 30% MVC and by 43 (SD 4.2) ms at 60% MVC. The values of the cross-correlation function in CG subjects were below 0.4.

The MDF and %DET data from muscles on the left and right sides failed to show any significant differences, thus we have presented data for the right side only. In the frequency domain WLA (Fig. 3, A) displayed different results from CG subjects. In the former the MDF showed a progressive decay during effort. The regression lines of the data obtained from both groups (WLA and CG), and at both force levels (30% and 60%MVC) are shown. In CG the correlation coefficient r was not significant, while in WLA r was significant at P < 0.01.

A continuous increase in %DET was observed in WLA during both 30% and 60% MVC contractions. This can be seen in Fig. 3, B. The increase in %DET was more evident in the 60%MVC contractions than in the 30% contractions. No significant increase in %DET was observed in the CG.

**Discussion**

The most significant result we obtained in WLA was the evidence of the burst-like sEMG tracing which appeared immediately at the start of the contraction and which was correlated with oscillations in the force tracing. This is not a new finding in resistance-trained athletes. Semmler and Nordstrom (1998) observed that tremor in the first dorsal interosseous muscle was most evident in strength-trained subjects, less evident in the controls and minimal in skilled trained subjects. In the former the MU synchronisation and the common drive of MU (De Luca et al. 1982) were more enhanced than in the others. We did not measure single motor unit potential (MUP) with intramuscular electrodes. Therefore, we did not have direct proof of MU synchronisation or MU common drive as the cause of the burst activity in sEMG. On the other hand, the correlation between the burst and the tremor, as shown in Fig. 1, strongly suggests that the tremor was primarily due to the particular type of muscle activation. Furthermore, the time lag in the correlation (approximately 40 ms) was consistent with the reported timing of electro-mechanical delay as measured in the VL muscle in man (Zhou et al. 1995). Thus, we infer that the burst activity was a manifestation of some grouping of MU activity. During the tremor that followed 1 min of intense effort, Jessop and Lippold (1977) observed very large waves in the sEMG, which attained the amplitude and shape of M-waves obtained by supramaximal nerve stimulation. This effect was attributed to MU synchronisation. Some common modulation of MU activity as the origin of tremor in human beings has been widely reported in the literature (Datta and Stephens 1990; Freund 1983; Halliday et al. 1999; Semmler and Nordstrom 1998). We would like to stress the fact that the more the sEMG activity became structured in wave sequences, similar to one another and separated by quasi-silent periods, the higher was the %DET. This is proof of the effectiveness of this kind of analysis in recognising rhythmical activities in biological signals. Concerning the genesis of this kind of tremor, it has been attributed (Joyce and Rack 1974) to the interference of the central motor programme with the servo-loop effect elicited by peripheral receptors. We can

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**Fig. 3** A Median frequency (MDF) regression lines during sustained contractions in weightlifting athletes (WLA) and control group (CG) at 30% and 60% maximal voluntary contraction (MVC) (right vastus lateralis muscle). B Percentage determinism (%DET) regression lines during sustained contractions in WLA and CG group at 30% and 60%MVC (right vastus lateralis muscle). Continuous lines 60%MVC, dashed lines 30%MVC, thick lines WLA subjects, thin lines CG subjects. All the regressions were significant at P < 0.05.
suppose that an alternate activation of Golgi tendon organs and muscle spindles could maintain a common fluctuation in MU activity. An increasing tremor activity has been described as a correlate of fatigue during long isometric contractions (Allum et al. 1978; Joyce and Rack 1974). Löhser et al. (1994) observed a progressively increasing EMG burst activity, very similar to the one observed by us, in healthy habitually active subjects who made 10 min isometric 30%MVC contractions. The power spectrum of these bursts was characterised by a peak centred at 12 Hz. Furthermore, the frequency analysis revealed a continuous decay of the mean power frequency which the authors attributed to the effect of fatigue (see discussion below). The burst activity was accompanied by an increasing tremor revealed in the force tracing.

The authors suggested that an input synchronisation (Freund 1983), due to stretch reflex activity and/or Renshaw cell activity, could have been the cause of the group firing of MU and the enhancement of tremor as fatigue progressed. Discussing the genesis of the tremor Löhser et al. (1994) gave great relevance to the fact that this phenomenon was elicited in the absence of vascular occlusion which, conversely, is complete at higher percentages of the MVC. In our subjects the burst activity and the tremor did not show any difference between 30% and 60% MVC. Another interesting difference between our findings and those of Löhser et al. (1994) is that our subjects developed tremor immediately at the start of the contraction, even at 30% MVC, in the absence of any sign of fatigue. This result would seem to suggest a special disposition of WLA to develop input synchronisation (Freund 1983), which could underlie the slow rhythmic force oscillations presented by these subjects. The MU synchronisation has been described by Sale (1987) as a special feature of people trained for brief maximal effort. This author speculated about the usefulness of any sort of synchronisation in improving the force output; in his opinion it does not seem convincing that synchronisation or common drive can increase the force. Conversely, he suggested that the grouping of firing could be effective in increasing the rate of force developing during brief maximal contractions. A weight can be lifted only if it is maximally accelerated when body leverages are in an efficient position as at the start of lifting (Cerquiglini et al. 1973). Although 5 out of 12 subjects are very few to be able to generalise, and we cannot exclude the possibility that a similar burst-like activity could be observed in athletes of other specialities and even in sedentary people, it is interesting that WLA, who are the athletes who can benefit most from activating their muscles as swiftly as possible, are those who are best endowed with this modality of MU recruitment.

It must be noted that we measured the overall force produced by all of the muscles involved (not only those of the lower limb but also of trunk extensor muscles, shoulder and upper limb muscles). In WLA who did not show a clear sEMG burst activity of VL muscle, force oscillations (tremor) were indeed present. Thus, we cannot exclude the possibility, in these subjects, that grouping of myoelectric activity was manifest in muscles other than VL.

The RQA analysis has been used to detect sEMG changes that are attributable to ongoing changes in muscle activation (Webber et al. 1995). In particular, during continuous heavy isometric contractions, an increase of %DET has been taken as an index of myoelectric fatigue. This location is used to indicate the neuro-muscular modification that precedes the task failure when the required force cannot be further maintained, i.e. before fatigue is manifest (Merletti et al. 1991). Even in the cases where burst activity was not observed, an increase in %DET in all WLA was noted; conversely, in the controls this change in %DET was not seen. This result was paralleled by a decay in MDF, i.e. a shifting to the left of the power spectrum of the sEMG. Again, this effect was observed in the WLA and not in the controls. Webber et al. (1995) demonstrated that the two forms of analysis give symmetrical results as indices of developing fatigue, the %DET being a more precocious marker than MDF. We recently obtained a similar result by adopting the first Lyapunov exponent as an index of fatigue (Sbriccoli et al., in press). A left shifting in the sEMG frequency power spectrum, as noted before, was observed by Löhser et al. (1994) during the development of fatigue tremor. The MDF decay during sustained contractions has been attributed to a progressive reduction in the conduction velocity of the MUP along the muscle fibres (De Luca and Knafflitz 1992). This can be attributed to the fact that some 2B fibres, which fatigue more quickly, are exhausted. Therefore, they no longer contribute with their high conduction velocities to the genesis of the sEMG. An alternative hypothesis has maintained that a modification of the membrane conductivity can occur (Merletti et al. 1991). In both cases, it is the most powerful and more rapidly conducting fibres which are compromised. Power and weightlifters usually have bigger fast twitch than slow twitch fibres (Komi 1984). Therefore, it is tempting to consider that it was the subjects with a prominent participation of fast twitch fibres in the sEMG who were those who manifested the most precocious signs of myoelectric fatigue.

The present results prompt us to make more systematic investigations of other muscles activated during weightlifting exercise to acquire a more complete picture. In any case, it would seem that in WLA (as an effect of training) there is a peculiar adaptation of the strategy for motor control, which consists of an enhancement of the common behaviour of MU (MU activity grouping and/or synchronisation) which should be responsible for the presence of bursts in the sEMG.

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References

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