

Surface EMG analysis on normal subjects based on isometric voluntary contraction

P.A. Kaplanis ^{a,d,*}, C.S. Pattichis ^{a,b}, L.J. Hadjileontiadis ^c, V.C. Roberts ^d

^a Cyprus Institute of Neurology and Genetics, Nicosia, Cyprus

^b Department of Computer Science, University of Cyprus, Nicosia, Cyprus

^c Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece

^d Kings College, School of Medicine and Dentistry, University of London, London, UK

Received 7 August 2006; received in revised form 28 March 2007; accepted 28 March 2007

Abstract

The objective of this study was to compute reference SEMG values for normal subjects of 13 parameters extracted in the time, frequency and bispectrum domain, from the Biceps Brachii (BB) muscle generated under isometric voluntary contraction (IVC). SEMG signals were recorded from 94 subjects for 5 s at 10, 30, 50, 70 and 100% of maximum voluntary contraction (MVC). The Wilcoxon signed rank test was applied to detect significant differences or not at $p < 0.05$ between force levels for each of the 13 parameters. The main findings of this study can be summarized as follows: (i) The time domain parameters turns per second and number of zero crossings per second increase significantly with force level. (ii) The power spectrum median frequency parameter decreases significantly with force level, whereas maximum power and total power increase significantly with force level. (iii) The bispectrum parameter, maximum amplitude, increases significantly with force level with the exception the transition from 30% to 50% MVC. Although, the tests for Gaussianity and linearity show no significant difference with force level, the SEMG signal exhibits a more Gaussian distribution with increase of force up to 70% MVC. The SEMG linearity test, which is a measure of how constant the bicoherence index is in the bi-frequency domain, shows that the signal's bicoherence index is less constant (hence, the signal is less linear) at 70% of MVC compared to 10, 30, 50 and 100% MVC. (iv) The time domain parameters have good correlation between them as well as, between each one of them and maximum and total power. The median frequency has a good (negative) correlation with the bispectrum peak amplitude. (v) No significant differences exist between values based on gender or age. The findings of this study can further be used for the assessment of subjects suffering with neuromuscular disorders, or in the rehabilitation laboratory for monitoring the elderly or the disabled, or in the occupational medicine laboratory.

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Keywords: SEMG; Time domain analysis; Power spectrum analysis; Bispectrum analysis

1. Introduction

Surface Electromyography EMG (SEMG), provides a non-invasive way of studying muscular function. The

SEMG signal is very complex, representing a summation of tissue-filtered signals generated by a number of concurrently active motor units. The generated motor unit action potentials (MUAPs) recorded on the skin surface vary in amplitude, duration and frequency content (Basmajian and De Luca, 1985). Although, SEMG has been used effectively for functional electrical stimulation (FES) or for the controlling of artificial limbs, its use in clinical diagnosis has been very limited or non-existent (Haig et al., 1999; Pullman et al., 2000). Grossman and Weiner (1966) have warned physiologists from as early as 1966, that SEMG

* Corresponding author. Present address: Department of Computational Intelligence, The Cyprus Institute of Neurology and Genetics, P.O. Box 23462, Nicosia 1683, Cyprus. Tel.: +357 22603130; fax: +357 22357935.

E-mail addresses: p.a.kaplanis@cytanet.com.cy (P.A. Kaplanis), pattichi@ucy.ac.cy (C.S. Pattichis), leontios@auth.gr (L.J. Hadjileontiadis), colin.roberts@kcl.ac.uk (V.C. Roberts).

Table 1
SEMG Studies and findings in chronological order carried out on the BB muscle on normal subjects

Group	Year	Reference	N (age)	Parameters									Comments
				t/s	zc/s	Pf_{med}	Pfx	P_{max}	P_{total}	PS	MPF	RP	
Chaffin	1968	(Chaffin, 1969)	12 (NP)							✓			PS → LSB*PS → LSB [5 & 30% MVC, 15 s/NP]
Hagberg et al.	1982	(Hagberg and Ericsson, 1982)	4 (21–24)								✓		MPF ↑ FL > 25% MVC [5–80% MVC 3–5 s/1 min]
Muro et al.	1982	(Muro et al., 1982)	5 (32.5 ± 8.2)				✓				✓		Pfx ↓ FL; MPF ↑ FL [0.25, 0.50, 1.0, 2.0 and 3 kg, 10 s/30 min]
Gander et al.	1985	(Gander and Hudgins, 1985)	6 (20–40)			✓	✓			✓		✓	Pf_{med} ↑ FL; Pfx ↓ FL PS → HFB ↑ FL [1–10 Nm randomly selected, 8.2 s/2-several min]
Inbar et al.	1986	(Inbar et al., 1986)	(Gerdle et al., 1990)		✓	✓							zc/s ↓ FL; Pf_{med} ↓ FL zc/s correlated with Pf_{med} & MPF [30, 50, 70 and 90% MVC, 6 s/NP]
Moritani et al.	1987	(Moritani and Muro, 1987)	12 (26.3 ± 2.5)								✓		MPF ↑ FL up to 80% of MVC [0–80% MVC, 5 s/2 min]
Shankar et al.	1989	(Shankar et al., 1989)	10 (25–28)			✓			✓				Pf_{med} affected by torque [4.9 Nm monitored at 8 joint positions, 10 s/5–10 min]
Gerdle et al.	1990	(Gerdle et al., 1990)	9 (30–40)								✓		MPF ↑ up to 60% MVC [20, 40, 60, 80 and 100% MVC, 1–2 s/several min]
Li et al.	1996	(Li and Sakamoto, 1996)	12 (22–25)						✓		✓		P_{total} ↑ FL*MPF ↓ with distance from end plate zone*[20 40 60% MVC, brief contraction/NP]
Krivickas et al.	1998	(Krivickas et al., 1998)	31 (22–37)			✓							Pf_{med} range broad, may limit the clinical use of spectral analysis [50% MVC, 45 s/15 min]
Rainoldi et al.	1999	(Rainoldi et al., 1999)	10 (23–43)								✓		MPF ↓ FL 30–70% MVC [10, 30, 50 and 70% MVC randomly selected, 30 s/5 min]
Farina et al.	2002	(Farina et al., 2002)	10 (22–35)			✓					✓		No relationship between spectral parameters and force may be drawn
This study	2005		94 (5–69)	✓	✓	✓	✓	✓	✓				t/s, zc/s, P_{max} , P_{total} , B_{max} ↑ FL, Pf_{med} ↓ FL Bx , By , Bx_{slope} , By_{slope} , Pfx , sg, sl, ↑ of FL [10, 30, 50, 70 and 100% MVC, 5 s/2 min]

Note. *not statistically proven; B_{max} , maximum peak of bispectrum; Bx_{slope} , slope of B_{max} in x-direction; By , location of B_{max} in y-axis; By_{slope} , slope of B_{max} in y-axis; MVC, maximum voluntary contraction; P_{max} , maximum power; sl, linearity test; FL, force level [FL used, recording time/resting time]; N, number of subjects; P_{total} , total power; t/s, turns per second; Pf_{med} , median frequency; PS, power spectrum shape; zc/s, zero crossings per second; LSB, lower frequency band; Pfx , frequency at maximum power; RP, relative power; HFB, higher frequency band; →, shifts; ↑, increase; ↓, decrease; ↑, independent; sg, Gaussianity test; MPF, mean power frequency; Bx , location of B_{max} in x-axis.

should not be used as a diagnostic tool due to the phenomenon of crosstalk, signal attenuation and filtering. A number of studies have shown that SEMG generated by either voluntary or electrically elicited muscle activity, contain more significant information than it was originally believed (Merletti and De Luca, 1989). However, only a few studies have been traced in the literature, tabulating normal values of one or maybe two parameters, recorded only though, from a limited number of subjects (see Table 1). The objective of this study was to compute reference SEMG values for normal subjects. Thirteen parameters were extracted in the time, frequency, and bispectrum domains, from SEMG signals recorded from the Biceps Brachii (BB) muscle during isometric voluntary contractions (IVC). The values recorded could then be used as reference values for the assessment of muscle function in the clinical or rehabilitation laboratory.

Table 1 summarizes in chronological order SEMG studies and findings carried out on the BB muscle on normal subjects. The studies shown examined the influence of increase (step or ramp) voluntary contraction, on time domain and/or frequency domain parameters. Step contractions, involve maintaining the force at a constant percentage of MVC for a few seconds, whereas ramp contractions involve a linear increase from 0% to 100% of MVC, without stopping at any percentage. The most frequently examined parameters were the mean power frequency (MPF) (Merletti and De Luca, 1989; Muro et al., 1982; Hagberg and Ericsson, 1982; Moritani and Muro, 1987; Gerdle et al., 1990; Li and Sakamoto, 1996; Rainoldi et al., 1999; Farina et al., 2002), and the median frequency (Pf_{med}) (Farina et al., 2002; Gander and Hudgins, 1985; Shankar et al., 1989; Bilodeau et al., 1994; Krivickas et al., 1998), and to a lesser degree the frequency at max Power (Pfx) (Muro et al., 1982; Gander and Hudgins, 1985), the number of zero crossings per second (zc/s) (Inbar et al., 1986) the Power Spectrum (PS) shape (Gander and Hudgins, 1985; Chaffin, 1969) and the total power (Pt) (Li and Sakamoto, 1996). Hagberg and Ericsson (1982) showed that at levels higher than 25–30% of maximum voluntary contraction (MVC), the MPF became independent of contraction level, whereas Moritani and Muro (1987) showed an increase of MPF up to 80% of MVC. Another study (Muro et al., 1982) however, showed a continuous increase of MPF. On the contrary, Gerdle et al. (1990) showed that the increase in MPF values exists only up to 60% of MVC. A totally different finding was that of Rainoldi et al. (1999), who showed that MPF decreases for force levels (FL) between 30% and 70% of MVC. Farina et al. (2002), investigating the possibilities and limitations of the use of SEMG variables (including MPF), as indicators of Motor Unit recruitment strategies, showed that MPF did not follow a consistent pattern with ramp contractions. Contradictions exist in the findings regarding the PS distribution as well. Although, Chaffin (1969), found that there is a shift of the PS towards the lower frequency band (LSB), with force increment, Gander and

Hudgins (1985), found the opposite. Median frequency (Pf_{med}), illustrates the same contradicting findings (Farina et al., 2002; Gander and Hudgins, 1985; Shankar et al., 1989; Bilodeau et al., 1994; Krivickas et al., 1998) although one may refer to a pilot study (Haig et al., 1999), whose results are in full agreement with this study. It is clearly shown in Table 1 that many discrepancies exist between findings. These could be due to: (i) the limited and different number of subjects examined in most of the cases (4–31), (ii) the difference in recording time (1–45 s), since fatigue may influence results at longer recording times (Siegler et al., 1985; Lariviere et al., 2001), (iii) the method of statistical analysis used, (iv) the force level exhibited, (v) the positioning of electrodes, (vi) to the variations in the experimental conditions (Shankar et al., 1989) and (vii) due to the orientation of the muscle fibres with respect to the recording surface electrodes, their length, and the thickness of the individual subcutaneous layers (Farina et al., 2002).

Besides the above-mentioned parameters, parameters from the bi-frequency domain were recently introduced, although not yet applied on EMG signals. One effort was made by Zazula (1999), who concluded that even a robust approach, based on bicepstral system identification, failed with surface EMG. Still however, by applying bi-frequency techniques one does not have to rely on the assumption that the signal presents a Gaussian (normal) distribution (Hadjileontiadis and Panas, 1997). It is well accepted today that real life physiological signals are highly non-Gaussian and by neglecting this and analyzing bio-signals with inappropriate methods, may lead to false results. For instance, the median frequency is considered more reliable than the mean power frequency and, hence, should be preferred, since: (i) the median frequency estimate is less affected by the noise (Merletti and De Luca, 1989), (ii) the signal does not present the characteristics of a normal distribution, (iii) the median frequency is a zero-order parameter, where all frequency components are weighted equally in contrast to first-order parameters, such as the mean power frequency, where the higher frequency components are weighted more and (iv) in case of a considerable amount of skinfold layer, the mean frequency is influenced more due to the low-pass filtering effect of the skin (Bilodeau et al., 1994). Still however the lack of normal median frequency Pf_{med} values limits the usefulness of spectral analysis in general (Shankar et al., 1989).

The objective of this study was to compute reference SEMG values for normal subjects, with the help of a developed simple non-invasive user friendly recording set-up, which could be used with slight modifications on most of the muscle of the extremities. Recordings enabled the development of a large data bank of normal recordings which could be used by other researchers to obtain reference values. The following parameters were estimated: (i) in the time domain: turns per second (t/s) and zero crossings per second (zc/s); (ii) in the frequency domain: median frequency (Pf_{med}), frequency at maximum power (Pfx), maximum power (P_{max}) and total power (P_{total}) and (iii)

in the bi-frequency domain: gaussianity test (sg), linearity test (sl), bispectrum peak amplitude (B_{\max}), its peak location in the x and y directions, B_x and B_y , respectively, and the slope of the peak in the x and y directions $B_{x_{\text{slope}}}$ and $B_{y_{\text{slope}}}$.

2. Materials and methods

2.1. Material

Ninety-four subjects (56 male (M) and 38 female (F)), aged between 5 and 69 years participated in this study. The subjects were divided into 7 age groups (mean (SD)), as follows: <9 years, 12 subjects, [7 M and 5 F] (8.3 (1.4)); 10–19 years, 12 subjects, [8 M and 4 F] (17.3 (2.4)); 20–29 years, 20 subjects, [10 M and 10 F] (23.75 (2.6)); 30–39 years, 15 subjects, [10 M and 5 F] (36.0 (2.6)); 40–49 years, 12 subjects [7 M and 5 F], (44.1 (1.9)); 50–59 years, 13 subjects [7 M and 6 F], (55.0 (2.4)), and 60–69 years 10 subjects, [7 M and 3 F] (65.1 (3.99)). None of the subjects had any previous history of neuromuscular disease. The study was approved by the Ethical Committee of the Cyprus Institute of Neurology and Genetics (CING).

2.2. Recording set-up

Recording took place at a special screened EMG/EEG/EP laboratory, at the Department of Clinical Neurophysiology at the CING. The Nicolet Viking IV, electromyography two-channel amplifier unit was used which was according to manufacturers' specifications, fully electrically isolated to IEC 601-1 and BSS 5724, Part 1 Type BF, and provided a 20–500 Hz bandwidth (12 dB/octave). The input impedance of the system Z_{in} , was stated to be $>1000 \text{ M}\Omega$. The recording system was connected to a printer for hard copies and a specially designed calibrated force measurement system. The force measurement system looked quite similar to a vertical weight lifting device, had a total of 40 kg weights and was placed at the foot end of the couch. Weights could be lifted via a long adjustable strap, placed on the subject's wrist. A force transducer calibrated at 2 kg/V, was installed on the force measurement system, and was connected to an oscilloscope placed 1.5 m above ground for visual feedback, enabling the subject to maintain constant the requested percentage of MVC. A personal computer (PC-Pentium III/660 MHz) was also connected to the electromyography unit for storing the recorded raw signal, digitized by a 12-bit Analogue-to-Digital (A/D) converter (E Series Multifunction I/O – 250 KS/S, from National Instruments). The sampling frequency of 1 kHz and the recording process (start/stop and the recording time of 5 s) were controlled through a program working under LABVIEW 6.0 (National Instruments, Inc.), installed on the PC.

The subject laid on its back, having its arm side by side with the body and bended at 90°. The weight lifting device's strap was placed at the lower part of the forearm, near the wrist. During the experiment, it was ensured that the dominant arm (the right hand), was not lifted from the couch or moved away from the body. With this arrangement, unintentional movements from other parts of the body were eliminated or reduced (Rainoldi et al., 1999).

Signals were detected using four parallel silver bars (10 mm apart, 10 mm long, 1 mm wide), fixed on a plastic block made by Dispositivi Elettronici Medicali of Italy. Although, circular electrodes are generally preferred, than bar electrodes, the correct

diameter choice for circular electrodes is not straight forward, since this influences the low-pass filtering effect of the detected signal. A theoretical approach made by Helal and Bouissou (1992), suggested that the choice of electrode diameter should be a compromise between the desired signal-to-noise ratio and the desired frequency bandwidth. On the other hand parallel bar type electrodes are gaining grounds, based mainly on De Luca's experience (Incorporated and Surface Electromyography, 1996) that a parallel configuration of an equivalent detection area as that of a circular configuration, intersects more fibres and hence provides a higher signal-to noise ratio. Furthermore, an electrode block containing fixed distance parallel bar electrodes, offers practical advantages, and hence was preferred in this study. The buffer amplifier of the electrode block used in this set-up, had a zero-gain, with a phase margin of 50° and an input impedance $Z_{\text{in}} >1000 \text{ M}\Omega$ as per manufactures specifications. Skin preparation of the BB muscle and the dominant arm took place with an alcohol wash. A special conductive paste (Elefix, Model Z-402CE by Nihon Kohden) was placed on the four electrodes. Special care was taken to avoid excessive paste, which could influence results by short-circuiting the electrodes.

The subject was asked to bend his arm and the actual length of the BB muscle was then measured with a measuring tape. The electrode block was then placed in the distal portion of the muscle and secured with a 50 mm Micropore adhesive tape, on the BB in such a way, so that the second electrode towards the dominant arm was always at a distance equal to 1/3 of the BB length. This arrangement ensured that all four electrodes were between the motor point and the tendinous insertion, being the most widely acceptable position (Pattichis et al., 1999). This electrode positioning was as consistent as possible for all subjects. Repeatability of positioning, as well as of the entire recording protocol, was investigated by asking ten arbitrarily subjects to repeat the experiment 30 min after the recording was completed. We asked the subject to stand up, once of course the electrodes were removed from their BB, and walk if needed around the laboratory. During the 30 min interval, they were allowed to drink only water but were restricted from smoking or drinking anything else. Results between the first and second set of experiments showed an excellent repeatability. The positioning of the electrode block was carried out without the necessity of electrically stimulating the BB muscle to find the exact location of the motor point. These criteria were strictly followed to ensure consistent positioning for all recordings. The ground electrode was positioned distantly from the recording electrode, on the subject's left wrist, to ensure a common reference to the amplifier's differential input (Incorporated and Surface Electromyography, 1996). The ground electrode was rather large (3 cm in diameter) ensuring a very good contact with the skin.

Before the actual recording took place, the subject was asked to experiment at various Force Levels (FLs), to get accustomed with the process. Then the subject was asked to pull at MVC three times with an interval of two minutes in between. A mark of the maximum MVC was made on the oscilloscope with a red tape. It was stressed out to the subjects that they had to keep the FL each time as constant as possible for the 5 s duration. The subject had 2 min to relax before the actual recording started. The subject was then asked to pull observing the oscilloscope's DC line, which had to reach the bottom part of the red tape. Once this was reached, the signal was recorded for 5 s, and afterwards the subject was asked to relax for a further two minutes. The same procedure was per-

formed again, at the same FL. Then, the tape was placed at positions on the oscilloscope screen corresponding to 70, 50, 30 and 10% of MVC and the process was repeated. For the analysis the pair with the largest single differential output was used.

2.3. Time domain analysis

For each EMG recording of 5 s, at each force level, the following parameters were measured in the time domain:

1. *Turns per second (tls)*: Number of slope reversals per second separated from the previous and the following turn by an amplitude difference greater than 20 μV .
2. *Zero crossings per second (zcls)*: Defined as the number of sign reversals exceeding a threshold of 20 μV per second.

A similar approach was followed for needle EMG by Fuglsang-Frederiksen et al. (1984) and Pattichis et al. (1993). On the other hand Inbar et al. (1986), defined a zero as 0.1 per cent of the maximum voltage which drove the comparator, whereas Preece et al. (1994), defined the zero crossing frequency as excursions of the signal from baseline of greater than 1% of full scale deflection. Hof (1991), defined the zero crossings frequency as half the number of zero crossings per second and without the use of a threshold made a comparison between theoretical and experimental values.

In this study the threshold of 20 μV was selected after experimenting with thresholds at different levels. Initially 50 μV was selected, but this caused many epochs to give zero or very small values for turns per second and zero crossings per second. This was also applicable for threshold values of 40 and 30 μV . On the other hand, 10 μV proved to be too small, since the preamplifier's noise is of the order of a few μV rms.

2.4. Power spectral analysis

For each 512 ms epoch, the average power spectrum (PS) curve was computed by taking the FFT of 512 points, with 25% overlaps segments. The 512 ms epoch satisfies the stationarity criteria (Inbar et al., 1986), under isometric non-fatiguing conditions. The following parameters were computed from the power spectrum curve:

1. *Median frequency (Pf_{med})*: Frequency dividing the area under the PS curve in two equal parts:

$$\sum_{n=0}^{Pf_{p-1}} \text{PS}(n) = \sum_{Pf_p}^{N-1} \text{PS}(n) \quad (1)$$

2. *Frequency at maximum power (Pf_x)*: Frequency corresponding to the peak of the PS curve.
3. *Total power (P_{total})*: Calculated as the total area under the PS curve, and
4. *Maximum power (P_{max})*: Highest value of the PS curve.

2.5. Bispectral analysis

For a real zero-mean, stationary process $\{X(k)\}$, the third-order cumulant (TOC) is defined (Nikias and Petropulu, 1993) as the expected value of the triple product:

$$R(m, n) = E\{X(k)X(k+m)X(k+n)\}, \quad (2)$$

and the bispectrum is defined (Nikias and Petropulu, 1993) as the Fourier transform of the TOC sequence:

$$B(\omega_1, \omega_2) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} R(m, n) e^{-j(\omega_1 m + \omega_2 n)} \quad (3)$$

In addition, the sum of magnitudes of the estimated bispectrum is computed by:

$$D = \sum_{(\omega_1, \omega_2)} |B(\omega_1, \omega_2)| \quad (4)$$

To quantify the non-Gaussianity of a random process, the normalized bispectrum, or bicoherence is estimated as follows:

$$B_n(\omega_1, \omega_2) = \frac{B(\omega_1, \omega_2)}{\sqrt{P(\omega_1)P(\omega_2)P(\omega_1 + \omega_2)}}, \quad (5)$$

where $P(\cdot)$ is the estimated power spectrum, of the three signals with frequencies ω_1 , ω_2 and $\omega_1 + \omega_2$. The test of Gaussianity is based on the mean bicoherence power, defined as follows:

$$S_g = \sum |B_n(\omega_1, \omega_2)|^2 \quad (6)$$

with the summation of P points performed over the non-redundant region (Hinich, 1982).

For each epoch, the average bispectrum curve was computed using a window of 512 points in length with a 25% of overlap. The following tests and parameters were applied and computed, based on the bispectrum curve:

1. *Gaussianity test (sg)* (also known as zero-skewness test): It basically involves deciding whether or not the expected value of the estimated bicoherence index is zero, i.e. $E\{B_n(\omega_1, \omega_2)\} = 0$. When $B(\omega_1, \omega_2) = 0$ the sg statistic in (6) is X^2 distributed, with 2 P degrees of freedom (Hinich, 1982). Consequently, by examining whether the observed sg is consistent or not with a central chi-squared distribution, the assumption of Gaussianity or non-Gaussianity could be adopted, respectively. A measure of this consistency is the probability-of-false alarm value, that is, the probability of being wrong in the adoption of the non-zero bispectrum assumption (Hinich, 1982). In this case, the non-Gaussianity assumption was accepted if the probability-of-false alarm was less than 5%.
2. *Linearity test (sl)*: It involves deciding whether or not the estimated bicoherence is constant in the bi-frequency domain, employing a measure of the absolute difference (dR) between a theoretical inter-quartile range, R' , which corresponds to a $X^2_2(\lambda)$, i.e. a chi-squared distributed random variable with two degrees of freedom and a non-centrality parameter λ , and the estimated inter-quartile range, R , derived from the estimated squared bicoherence (Nikias and Petropulu, 1993). In our case, the non linearity hypothesis was adopted when $\frac{dR}{R} > 2$.
3. *Bispectrum peak (B_{max})*: Calculated as the peak of the bispectrum curve.
4. *Location of the B_{max} in the x-direction (B_x)*: It was calculated as the location of the peak of the bispectrum curve in the x-direction.
5. *Location of B_{max} in the y-direction (B_y)*: It was calculated as the location of the peak of the bispectrum curve in the y-direction.

6. Rate of change of B_{max} in the x -direction (Bx_{slope}), and
7. Rate of change of B_{max} in the y -direction direction (By_{slope}).

The BS analysis was performed with the Hispec toolkit of MATLAB 5.3 (Mathworks Inc).

3. Results

A total of 94 subjects were analyzed for the five force levels. The mean parameters, per age decade with the corresponding standard deviation and the mean values of the subject's height and weight, again with the corresponding standard deviations are shown in Table 2 and 3, respectively. Fig. 1a and b, show a time domain plot, the corresponding power Fig. 1c and d and bi-frequency plots Fig. 1e and f of signals recorded at 10% and 70% MVC from a male subject. Table 4, summarizes the mean and standard deviation values as well as the median and quartile values for all parameters analyzed at each force level. Table 5 tabulates the descriptive statistics for the median frequency one of the parameters which is influenced significantly with

Table 3

Mean values of the subject's height and weight, with the corresponding standard deviation

Age group	Height in cm	Weight in kg
< 10	134.9 ± 13.1	32.3 ± 6.2
10–19	167.8 ± 11.6	62.0 ± 15.5
20–29	172.5 ± 7.0	69.0 ± 12.4
30–39	170.8 ± 7.3	75.6 ± 12.9
40–49	173.4 ± 9.5	70.8 ± 14.4
50–59	166.2 ± 7.3	71.2 ± 8.3
60–69	168.6 ± 10.7	75.3 ± 12.4

force level. Table 6 presents the Wilcoxon signed rank test used to classify the transition between any two-force levels as significant (S), or non-significant (NS), based on a confidence level of 95% ($p < 0.05$). The Wilcoxon signed rank test has been preferred than the usually used t -test, which relies on the assumption that the data is taken from a normally distributed set (Gerdle et al., 1990). Fig. 2 illustrates box plots for the six parameters influenced significantly with FL. Also, histogram distributions for (t/s), (Pf_{med}) and

Table 2

Mean and ± standard deviation (mean ± SD), together with median and first and third quartile range values median ($P_{25\%}$ – $P_{75\%}$) of the parameters analysed

%MVC	10	30	50	70	100
<i>Time domain parameters</i>					
t/s	6 ± 7.5 3 (0–8)	12 ± 10.5 10 (2–19)	17 ± 12.4 17 (6–26)	22 ± 13 23 (13–30)	28 ± 12.8 22 (20–36)
zc/s	3–6 0 (0–2)	7–8.8 4 (0–10)	12–11.2 10 (1–21)	16–11.7 17 (6–25)	22–11.8 23 (16–30)
<i>Frequency domain parameters</i>					
Pf_{med} (Hz)	109 ± 26.8 104 (90–125)	104 ± 23 101 (88–116)	102 ± 21.4 99 (86–115)	100 ± 21.1 95 (84–112)	96 ± 19.7 93 (83–110)
Pfx (Hz)	80 ± 23 76 (64–96)	76 ± 19 74 (63–83)	80 ± 20 77 (67–93)	78 ± 19.3 75 (65–91)	77 ± 20 72 (64–88)
P_{max} (nV $^2\text{Hz}^{-1}$)	−0.5 ± 0.84 −0.6 (−1.1–0.08)	0.06 ± 0.91 −0.04 (−0.6–0.6)	0.5 ± 0.98 0.5 (−0.2–1.17)	0.85 ± 1.03 0.7 (0.16–1.5)	1.3 ± 1.03 1.3 (0.57–2.04)
P_{total} (nV $^2\text{Hz}^{-1}$)	0.5 ± 0.8 0.4 (0–1.0)	1.1 ± 0.9 1 (0.43–1.6)	1.5 ± 0.9 1.5 (0.85–2.1)	1.8 ± 0.92 1.8 (1.14–2.4)	2.2 ± 0.94 2.2 (1.6–2.8)
<i>Bispectrum domain parameters</i>					
sg	239 ± 121 198 (166–292)	237 ± 116 213 (169–253)	225 ± 84 202 (171–250)	220 ± 84 199 (173–247)	236 ± 118 205 (158–255)
sl	1.6 ± 1.6 1.1 (0.7–1.6)	1.7 ± 1.4 1.3 (0.7–2.6)	1.6 ± 1.5 1.2 (0.6–2.0)	1.4 ± 1.5 1.14 (0.64–1.6)	2 ± 4.2 1.2 (0.8–2.1)
B_{max} (nV $^3\text{Hz}^{-2}$)	2 ± 0.77 1.9 (1.6–2.3)	2.2 ± 0.95 2.1 (1.6–2.50)	2.3 ± 0.88 2.1 (1.70–2.58)	2.4 ± 0.9 2.2 (1.8–2.8)	2.5 ± 0.9 2.4 (2.0–2.9)
Bx (Hz)	54 ± 26 52 (45–59)	57 ± 30 52 (46–60)	53 ± 11 53 (46–59)	55 ± 13 53 (48–60)	55 ± 13 53 (48–60)
By (Hz)	37 ± 24 47 (22–57)	40 ± 24 48 (21–57)	39 ± 24 47 (24–57)	40 ± 26 49 (22–58)	39 ± 24 47 (22–57)
Bx_{slope} (nV $^3\text{Hz}^{-3}$)	60 ± 25 57 (40–71)	58 ± 24 56 (41–71)	56 ± 23 54 (42–73)	54 ± 22 53 (37–71)	51 ± 20 49 (37–63)
By_{slope} (nV $^3\text{Hz}^{-3}$)	13 ± 5.4 12 (10–16)	14 ± 5.4 14 (10–16)	13 ± 4.7 13 (10–16)	14 ± 5.3 13 (11–16)	14 ± 5.3 13 (10–16)

Log values are used for, P_{max} , P_{total} and B_{max} .

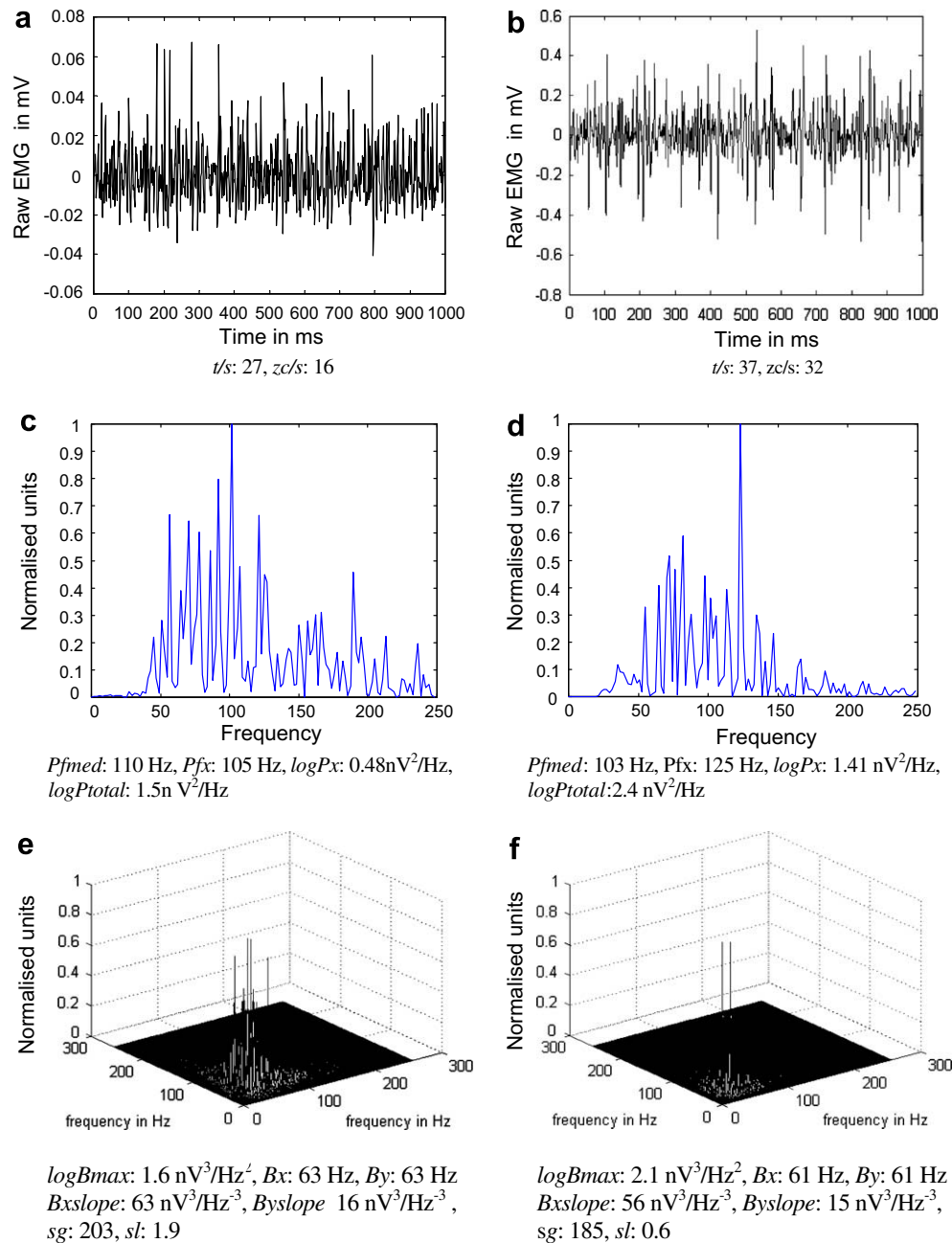


Fig. 1. Time, power and bispectrum plots and features of a male subject aged 54 at 10 (1st column) and 70% (2nd column) of MVC.

(B_{\max}) are presented in Fig. 3, for the five corresponding FLs. Table 7 gives the Spearman correlation coefficient and was used to identify possible correlation results for selected parameter pairs. This coefficient has been preferred instead the corresponding parametric test of Pearson (Wagner, 1992), used by other researchers (Krivickas et al., 1998), for the same reasons listed above.

3.1. Time domain analysis

As given in Table 4, the median values of t/s were, 3, 10, 17, 23 and 22, for FL at 10, 30, 50, 70 and 100% of MVC, respectively. The number of turns per second, as indicated by their mean values, increases significantly with force as

given in Table 6 and illustrated in Fig. 2a. The histogram distribution of t/s is given in Fig. 3a. The number of zero crossings per second (zc/s), exhibited a similar pattern, i.e. the number of zc/s increases significantly with FL, as given in Table 6 and illustrated in Fig. 2b. The median values of zc/s at the corresponding force level were 0, 4, 10, 17 and 23, as tabulated in Table 4. From Fig. 3a, and with reference to turns per second, it is obvious that at low force levels (10 and 30% MVC), the distribution is significantly ($p < 0.05$) non-normally distributed with +ve skew (more observations in the left-tail than normal) and +ve kurtosis (more observations are clustered around the mean value). At MVC however, the distribution does not present a significant –ve skew nor a significant –ve kurtosis. Table 7

Table 4

Mean and \pm standard deviation (mean \pm SD), together with median and first and third quartile range values median ($P_{25\%}$ – $P_{75\%}$) of the parameters analysed

%MVC	10	30	50	70	100
<i>Time domain parameters</i>					
t/s	6 \pm 7.5 3 (0–8)	12 \pm 10.5 10 (2–19)	17 \pm 12.4 17 (6–26)	22 \pm 13 23 (13–30)	28 \pm 12.8 22 (20–36)
zc/s	3 \pm 6 0 (0–2)	7 \pm 8.8 4 (0–10)	12 \pm 11.2 10 (1–21)	16 \pm 11.7 17 (6–25)	22 \pm 11.8 23 (16–30)
<i>Frequency domain parameters</i>					
Pf_{med} (Hz)	109 \pm 26.8 104 (90–125)	104 \pm 23 101 (88–116)	102 \pm 21.4 99 (86–115)	100 \pm 21.1 95 (84–112)	96 \pm 19.7 93 (83–110)
Pfx (Hz)	80 \pm 23 76 (64–96)	76 \pm 19 74 (63–83)	80 \pm 20 77 (67–93)	78 \pm 19.3 75 (65–91)	77 \pm 20 72 (64–88)
P_{max} ($\text{nV}^2\text{Hz}^{-1}$)	−0.5 \pm 0.84 −0.6 (−1.1 to 0.08)	0.06 \pm 0.91 −0.04 (−0.6 to 0.6)	0.5 \pm 0.98 0.5 (−0.2 to 1.17)	0.85 \pm 1.03 0.7 (0.16–1.5)	1.3 \pm 1.03 1.3 (0.57–2.04)
P_{total} ($\text{nV}^2\text{Hz}^{-1}$)	0.5 \pm 0.8 0.4 (0–1.0)	1.1 \pm 0.9 1 (0.43–1.6)	1.5 \pm 0.9 1.5 (0.85–2.1)	1.8 \pm 0.92 1.8 (1.14–2.4)	2.2 \pm 0.94 2.2 (1.6–2.8)
<i>Bispectrum domain parameters</i>					
Sg	239 \pm 121 198 (166–292)	237 \pm 116 213 (169–253)	225 \pm 84 202 (171–250)	220 \pm 84 199 (173–247)	236 \pm 118 205 (158–255)
Sl	1.6 \pm 1.6 1.1 (0.7–1.6)	1.7 \pm 1.4 1.3 (0.7–2.6)	1.6 \pm 1.5 1.2 (0.6–2.0)	1.4 \pm 1.5 1.14 (0.64–1.6)	2 \pm 4.2 1.2 (0.8–2.1)
B_{max} ($\text{nV}^3\text{Hz}^{-2}$)	2 \pm 0.77 1.9 (1.6–2.3)	2.2 \pm 0.95 2.1 (1.6–2.50)	2.3 \pm 0.88 2.1 (1.70–2.58)	2.4 \pm 0.9 2.2 (1.8–2.8)	2.5 \pm 0.9 2.4 (2.0–2.9)
Bx (Hz)	54 \pm 26 52 (45–59)	57 \pm 30 52 (46–60)	53 \pm 11 53 (46–59)	55 \pm 13 53 (48–60)	55 \pm 13 53 (48–60)
By (Hz)	37 \pm 24 47 (22–57)	40 \pm 24 48 (21–57)	39 \pm 24 47 (24–57)	40 \pm 26 49 (22–58)	39 \pm 24 47 (22–57)
Bx_{slope} ($\text{nV}^3\text{Hz}^{-3}$)	60 \pm 25 57 (40–71)	58 \pm 24 56 (41–71)	56 \pm 23 54 (42–73)	54 \pm 22 53 (37–71)	51 \pm 20 49 (37–63)
By_{slope} ($\text{nV}^3\text{Hz}^{-3}$)	13 \pm 5.4 12 (10–16)	14 \pm 5.4 14 (10–16)	13 \pm 4.7 13 (10–16)	14 \pm 5.3 13 (11–16)	14 \pm 5.3 13 (10–16)

Log values are used for P_{max} , P_{total} and B_{max} .

shows that there is a good correlation (0.65) between t/s and zc/s, whereas both t/s and zc/s exhibit also a good correlation with Maximum Power (P_{max} , and total power, P_{total} .

3.2. Frequency domain analysis

Median frequency. The median values of (Pf_{med}) were 104 Hz, 101 Hz, 99 Hz, 95 Hz, 93 Hz for the corresponding five force levels (see Tables 4 and 5). The median frequency decreases significantly with FL, as given in Table 6 and illustrated in Fig. 2c. Median frequency is of particular interest for the reasons outlined in the introduction of this paper, with its descriptive statistics given in detail in Table 5. The corresponding box-plots and histogram distributions are given in Figs. 2c and 3b, respectively. With reference to Fig. 3b, the distribution of values for the median frequency are significantly non-normally distributed at low force levels, with the distribution approximating a nor-

mal distribution at mid force levels, and once again a significant non-normal distribution at MVC.

Frequency at maximum power. The median values for all 94 subjects for the frequency at maximum power for the five force levels investigated are, 76 Hz, 74 Hz, 77 Hz, 75 Hz and 72 Hz, respectively (see Table 4). As given in Table 6, this parameter is not affected with force level neither does it exhibit any correlation with other parameters.

Maximum and total power. The median values for the 94 subjects, for the logarithm of the maximum power for the five FLs are, −0.6 $\text{nV}^2\text{Hz}^{-1}$, −0.04 $\text{nV}^2\text{Hz}^{-1}$, 0.5 $\text{nV}^2\text{Hz}^{-1}$, 0.7 $\text{nV}^2\text{Hz}^{-1}$ and 1.3 $\text{nV}^2\text{Hz}^{-1}$ and those of the total power are 0.4 $\text{nV}^2\text{Hz}^{-1}$, 1 $\text{nV}^2\text{Hz}^{-1}$ and 1.5 $\text{nV}^2\text{Hz}^{-1}$, 1.8 $\text{nV}^2\text{Hz}^{-1}$ and 2.2 $\text{nV}^2\text{Hz}^{-1}$. Both of these parameters showed a significant increase with force level as given in Table 6 and illustrated in Fig. 2d and e, respectively. An excellent correlation between the maximum power and total power and a good correlation between the power and time domain parameters were found.

Table 5
Descriptive statistics for the median frequency, Pf_{med} , for % MVC for 94 normal subjects

%MVC	10%	30%	50%	70%	100%
Mean	109	104	101.7	99.6	96.3
95% CI	103–115	99.3–108.9	97 to 106	95–104	92.16–100.4
Variance	722	532.9	456.8	445.8	388.57
SD	26.9	23	21.4	21.1	19.7
SE	2.8	2.42	2.24	2.21	2.07
CV (%)	25	22	21	21	20
Median	104	101	99	95	93
96.5% CI	95–113	95–105	93–105	91–103	89–98
Range	135	125	115	114	123
IQR	37.5	28.5	28.5	28	27
2.5th Percentile	65.9	66.9	59.9	64.3	58.9
25th Percentile	90	88	87	84.5	83.5
50th Percentile	104	101	99	95	93
75th Percentile	127.5	116	115	112.5	110.5
97.5th Percentile	165.8	159.2	152.9	145.1	132.1
Near outliers (value) (coefficient, p)	1 (187)	2 (164, 190)	1 (168)	1 (177)	1 (170)
Shapiro–Wilk	0.97, 0.034	0.95, 0.0026	0.982, 0.227	0.96, 0.006	0.975–0.081
Skewness	0.54, 0.0349	0.91, 0.001	0.468, 0.065	0.79, 0.003	0.54, 0.035
Kurtosis	−0.176, 0.835	1.29, 0.042	0.39, 0.36	0.90, 0.107	1.23, 0.05

CI confidence interval;
SD standard deviation;
SE standard error of the mean;
CV coefficient of variation;
IQR interquartile range.

3.3. Bispectrum domain analysis

Gaussianity and linearity tests. The median values for the test of Gaussianity (sg), indicate that the signal is non-Gaussian distributed, with higher values at 30% of MVC (see Table 4). Increase of force level does not cause significant change in sg (see Table 6). The linearity test median values indicate that the signal presents a higher linearity pattern at 30% of MVC (see Table 4). Increase of force level, does not cause a significant change in the linearity test.

Bispectrum peak amplitude. The median values of the logarithm of the bispectrum peak amplitude were 1.9, 2.1, 2.1, 2.2 and 2.4 $\text{nV}^3 \text{Hz}^{-2}$, see Table 4. The bispectrum amplitude increases significantly with force level, as given in Table 6. Fig. 2f illustrates the effect of force level on this parameter. Fig. 3c shows the significant non-normal distribution occurring at 10% MVC, as well as the significant +ve skew and +ve kurtosis. Similar conclusions may be drawn for 30%, 50%, 70% and 100% of MVC.

Bispectrum peak amplitude in the x and y -directions. The position of the bispectrum peak in the x and y directions Bx and By , respectively, remains fairly constant (non-significant difference), with median values in the region of 52–53 Hz and 47–49 Hz, respectively for the five FLs. A good correlation was found between Bx and By (0.71), see Table 7.

Slope of the maximum amplitude of the bispectrum in the x and y -directions. The median values of the slope of the bispectrum peak in the x - and y -axis, $Bxslope$ and $Byslope$,

were in the region of 49–57 $\text{nV}^3 \text{Hz}^{-3}$ and 12–14 $\text{nV}^3 \text{Hz}^{-3}$, respectively. An excellent correlation was found between the two parameters whereas a good correlation was found between the slope of the bispectrum peak in the x and y direction with the position of the bispectrum peak, see Table 7.

3.4. Other findings

In this study no significant differences on all 13 parameters examined with age, using the Wilcoxon test ($p < 0.05$), were found. However, an increase of Pf_{med} and MPF, when voluntary contraction level was increased from 20% to 80%, was found to be smaller (Merletti et al., 1992) in elderly subjects than in younger subjects. However, a previous study (Schulte et al., 2004), has shown that shortening of the muscle fibre, which occurs with age, produced a variation in the estimation of mean power spectral frequencies of the order of 0.7% and 5.1% for superficial and deeper muscles, respectively.

This study did not detect any significant differences with gender either. Gender division was performed for two gender groups, i.e. one for the age group from 20 to 29 years of age, where the gender is evenly distributed (10 male and 10 female subjects), and one for the entire group (56 male and 38 female subjects).

Repeatability measurements on eleven subjects were also performed, with two objectives: (i) to investigate whether similar results were recorded after a period of time had elapsed, and (ii) if analysis depends on whether recording begins from maximum to minimum % MVC or vice

Table 6
Transition classification from one force level to another, using the wilcoxon signed rank test at ($P < 0.05$)

	Turns per second (t/s)	Zero crossings per second (zc/s)	Med freq (Pf_{med})	Frequency at max power (Pf/x)	Max power (P_{max})	Total power (P_{total})	Gaussianity (sg)	Linearity (sl)	B_{max} ampl (B_{max})	Bispectrum peak in x- direction (Bx)	Bispectrum peak in y- direction (By)	Bispectrum slope in x-direction (Bx_{slope})	Bispectrum slope in y-direction (By_{slope})
10–30%	S	S	S	S	S	S	NS	NS	S	NS	NS	S	S
10–50%	S	S	S	S	S	S	NS	NS	S	NS	NS	S	S
10–70%	S	S	S	S	S	S	NS	NS	S	NS	NS	NS	NS
10–100%	S	S	S	S	S	S	NS	NS	S	NS	NS	S	S
30–50%	S	S	S	S	S	S	NS	NS	NS	NS	NS	NS	NS
30–70%	S	S	S	S	S	S	NS	NS	S	NS	NS	S	NS
30–100%	S	S	S	S	S	S	NS	NS	S	NS	NS	S	NS
50–70%	S	S	S	S	S	S	NS	NS	S	NS	NS	S	NS
50–100%	S	S	S	S	S	S	NS	NS	S	NS	NS	S	S
70–100%	S	S	S	S	S	S	NS	S	S	NS	NS	S	NS

S and NS indicate significant and non-significant difference, respectively.

versa. No significant differences ($p > 0.05$) were found in either case.

4. Discussion

In the present study, SEMG reference values extracted in the time domain, frequency domain and bispectrum domain are investigated during isometric voluntary contraction. The mean and standard deviation, median values, the first and third quartile ranges of the parameters were calculated and their influence with force was examined. Transition from one FL to another was classified as significant or non-significant, using the Wilcoxon signed rank test ($p < 0.05$). Correlation between any two parameters was also examined. The findings of these parameters are discussed in this section, as well, as compared to the findings of other studies.

4.1. Time domain analysis

Turns per second and zero crossings per second. Preece and co-workers (Preece et al., 1994) compared the usefulness of these two parameters for surface and needle recordings. They concluded that surface recordings might provide at least equal information for quantitative analysis for some muscles like the tibialis anterior, and even more reliable findings for other muscles such as the rectus femoris.

Needle electrodes have also been used to examine the behaviour of zero crossings. Fuglsang-Frederiksen and co-workers (Fuglsang-Frederiksen et al., 1984) examined the influence of this parameter with force increase, via signals recorded from the Biceps Brachii muscle. They concluded that the number of zero crossings increases only up to mid force levels and then levels off. This remark is in opposition with the findings of this study, where the number of zero crossings per second, was found to increase continuously and significantly at all force levels from 10% to 100% of MVC.

4.2. Frequency domain analysis

Median frequency. One of the earliest studies conducted on normal subjects regarding the influence of voluntary contraction on the shape of the PS (Chaffin, 1969), noted a shift of the spectrum towards the lower frequency region with force increase. Although, not stated by the author (Chaffin, 1969), this would result in a decrease in the median frequency (Pf_{med}), as shown in this study. Other studies have shown an increase in the median frequency (although insignificant), with force level (Gander and Hudgins, 1985) others have found Pf_{med} to be independent of FL (Inbar et al., 1986), whereas others have simply stated that this parameter is somehow affected by IVC without specifying how (Shankar et al., 1989). On the other hand Farina et al. (2002), does not support a relationship between spectral variables and force espe-

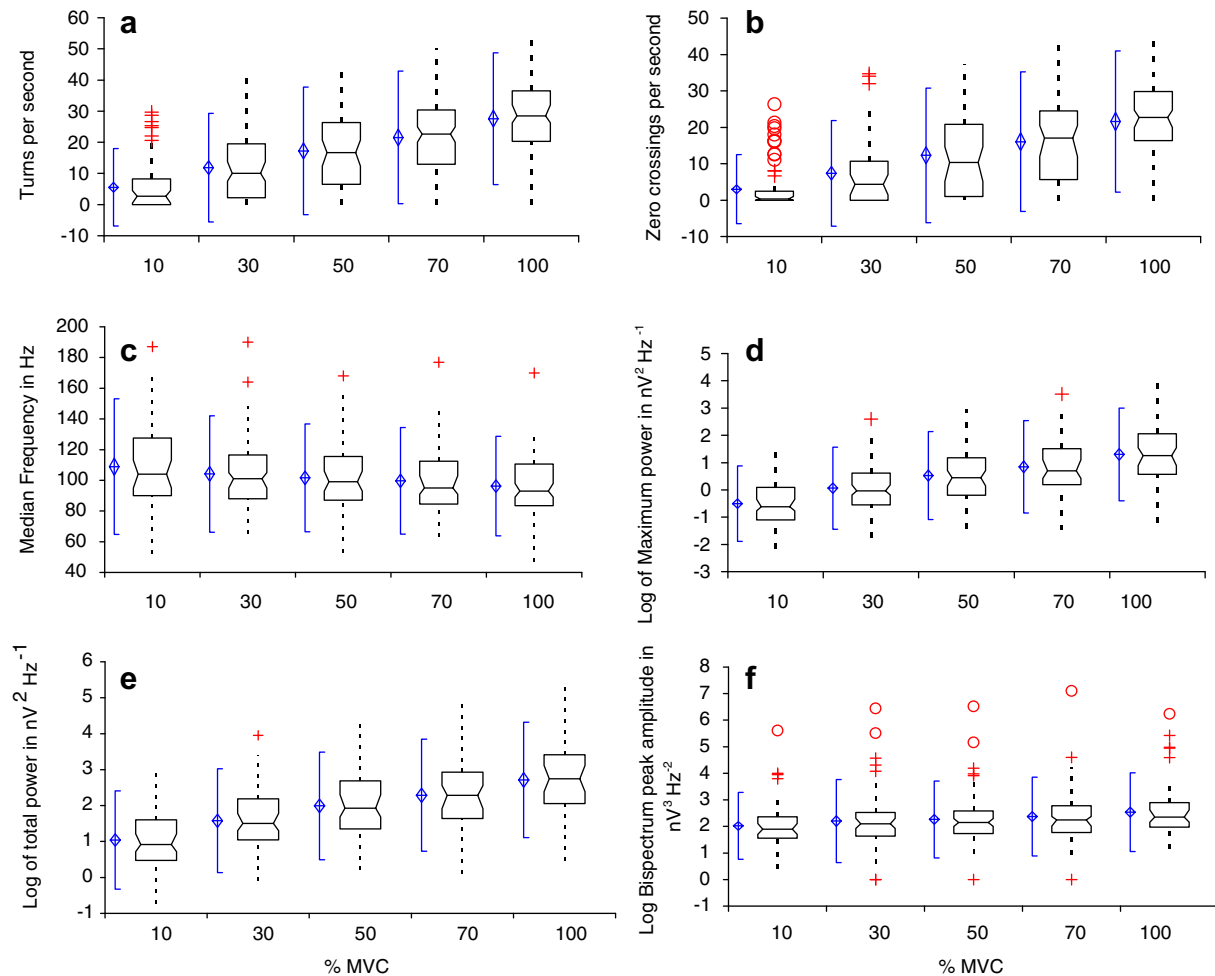


Fig. 2. Box-plots of parameters analysed that are influenced significantly with force level (see Table 6). The notched lines next to all descriptive boxes represent the 95% of the parametric percentile range of that measurement, whereas the diamond shape figures, show the mean and the requested confidences around it. The notched-boxes, (non-parametric statistics) show the median, lower and upper quartiles and the confidence interval around the median. The dotted lines connect the nearest observations within 1.5 of the inter quartile range (IQR) of the lower and upper quartiles. Finally, crosses (+) and circles (o) indicate possible outliers, observations more than 1.5 IQR and 3.0 IQR from the quartiles, respectively.

cially during ramp contractions. The range of normal values of Pf_{med} found by Krivickas et al. (1998) in attempting to evaluate clinically muscle fatigue was so broad that his group forecasted that Pf_{med} would preclude the clinical use of spectral analysis to evaluate muscle fatigue. In this study it is shown that Pf_{med} decreases significantly with force level, which is in full agreement with the findings of a review paper (Haig et al., 1999) where it is stated “the analysis of decline in median frequency with fatigue or increasing force is a measure which has no single correlate in standard needle EMG”.

Frequency at maximum power. The effect of force level on the frequency at maximum power was examined by a limited number of studies. One study (Muro et al., 1982) has shown that the frequency at maximum power does not provide any statistically significant difference with respect to the level of force. Gander and Hudgins (1985) have shown that with an increase in torque (Nm), the frequency at maximum power increased and decreased

slightly throughout the recording process, without following a consistent pattern. This study has shown that frequency at maximum power remains fairly constant with force level, whereas the changes in the first and third quartile ranges are insignificant.

Maximum and Total power. To the best of our knowledge, no study has investigated the maximum power influence with FL. Even more, total power has not been fully investigated. Merletti and De Luca (1989) stated that large muscles, such as the BB, present a non-linear relationship with force increase. This statement is in agreement with the findings of this study where the maximum power was found to increase considerably with force in a non-linear way.

4.3. Bispectrum domain analysis

Gaussianity and linearity test. Our results are in agreement with Pattichis and co-workers (Pattichis et al.,

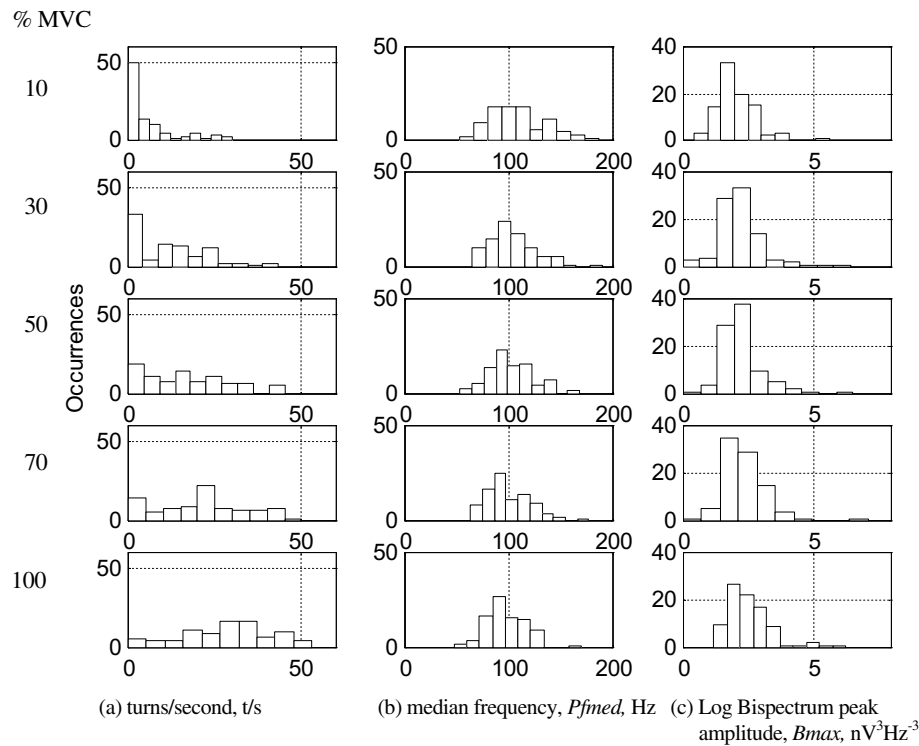


Fig. 3. Histogram distributions with force level for: (a) turns/second (b) median frequency and (c) log bispectrum peak amplitude.

Table 7

Parameter pairs presenting an excellent and good correlation based on spearman correlation test utilizing a 95% confidence interval, CI

Parameter pair	Correlation coefficient	95% CI	Classification
$t/s-zc/s$	0.65	0.59 to 0.70	Good
$t/s-P_{\max}$	0.67	0.62 to 0.72	Good
$t/s-P_{\text{total}}$	0.73	0.69 to 0.77	Good
$zc/s-P_{\max}$	0.69	0.64 to 0.71	Good
$zc/s-P_{\text{total}}$	0.66	0.61 to 0.71	Good
$P_{\max}-P_{\text{total}}$	0.87	0.85 to 0.89	Excellent
$Pf_{\text{med}}-B_{\max}$	-0.65	-0.7 to -0.6	Good
$Bx-B_{\max}$	-0.62	-0.68 to -0.56	Good
$By-B_{\max}$	-0.6	-0.66 to -0.54	Good
$Bx_{\text{slope}}-By_{\text{slope}}$	0.84	0.81 to 0.87	Excellent
$Pf_{\text{med}}-Bx_{\text{slope}}$	0.6	0.53 to 0.65	Good
$Bx-By$	0.71	0.66 to 0.75	Good
$Bx-Bx_{\text{slope}}$	0.62	0.57 to 0.68	Good
$Bx-By_{\text{slope}}$	0.73	0.68 to 0.77	Good
$By-Bx_{\text{slope}}$	0.69	0.64 to 0.73	Good
$By-By_{\text{slope}}$	0.64	0.58 to 0.69	Good
$Bx_{\text{slope}}-B_{\max}$	-0.71	-0.75 to -0.66	Good

1993), whose results were obtained with needle electrodes. With the exception of Pattichis and co-workers (Pattichis et al., 1993), no other groups examining this parameter were traced in the literature. Their study showed that the mean bicoherence values increased continuously with FL.

Unfortunately, no studies examining the behaviour of the bispectrum peak, its coordinates and its slope in the x and y -directions were traced in the literature for comparison.

4.4. Other findings

Parameter pairs presenting an excellent and good correlation are presented in Table 4. Inbar and co-workers (Inbar et al., 1986) examined the correlation between zero crossings and median frequency, which were found to be excellently correlated, which is in opposition with the findings of this study. Age dependence examined showed no significant differences on all 13 parameters examined, using the Wilcoxon test ($p < 0.05$). However, based on the experience gained through the project, the authors recommend the use of a smaller electrode block and with smaller inter-electrode distance than the one used in this study, when examining young children (< 9 years of age).

Skin and fat fold layers were not measured, although they should be encouraged for future measurements. This study did not detect any significant differences with gender either. However, Bilodeau et al. (1992), found differences between the two genders for Pf_{med} but not for MPF. The group states that the difference in skinfold layer is the main contributor for differences between the two parameters, although no significant differences were noted for the BB muscle (1 mm difference, $p > 0.05$). Furthermore they had stated that increase in spectrum parameters were more obvious when using ramp contractions as opposed to step contractions, which is in opposition with the findings of Gerdle et al. (1990). The mean standard error of the mean (SE) found by Bilodeau et al. (1992), was 4.0, which is nearly double than the average (SE) found in this study for the five force levels used here, being 2.3. A recent study

(Ollivier et al., 2005) has shown that the highest repeatability of the Root Mean Square (RMS), parameter was higher at high force levels, whereas the repeatability of other parameters seem to be independent with FL.

At present, these findings are compared with signals recorded from patients suffering with neuromuscular diseases like motor neuron disease (Amyotrophic Lateral Sclerosis etc.) or Myopathy (Duchenne, Limb girdle etc). Preliminary findings suggest that certain differences exist between normal SEMG findings and corresponding findings analysed from patients. Also, our group will investigate the use of SEMG in the assessment of treatment followed. Most importantly, a more realistic scenario of the use of SEMG qualitative analysis findings in a clinical context, would be to combine these findings with the clinical assessment, muscle biopsy and, or nerve biopsy data, biochemical findings, and genetic and molecular genetic findings, in a decision support system for the assessment and monitoring of neuromuscular disorders. This approach was followed by our group but with needle EMG quantitative analysis findings with very promising results (Pattichis et al., 1993). With some minor modifications in our set-up, multi-channel SEMG can be applied, eliminating a number of drawbacks present with multi-channel invasive techniques (Östlund et al., 2006). Furthermore, the normal SEMG findings reported in this study, although recorded at a short duration (5 s) at different force levels, could easily be exploited in the rehabilitation laboratory for monitoring the elderly and the disabled, in the patient home monitoring (telemonitoring), or in the sports and occupational medicine laboratories for the assessment of sports trauma or injuries, or workers subject to stress (Pattichis et al., 1999).

Last but not least, it is generally accepted that the wide spread of the use of SEMG is hindered by the lack of standardised algorithms, digital libraries, reference values, and training (Schizas et al., 1994). The EU funded SENIAM project (Hermens et al., 1999) contributed significantly in the first two directions, with this study contributing significantly in the third direction, towards, the creation of an extensive digital library with normal values for the Biceps Brachii muscle only. The need for creating reference values for the other muscles still exists. The rehabilitation doctors and therapists, or the sports and occupational medicine experts could use only the time domain parameters, t/s and zc/s, that are very easily to interpret and compute. To a lesser extent this is also applicable to the power spectrum total power and median frequency.

5. Conclusions

The aim of this study was to compute reference SEMG values of parameters extracted in the time, frequency, and bi-frequency domains, and to investigate the influence of force level on 13 different parameters from SEMG signals

recorded from the BB muscle of 94 normal subjects. The findings of this study can be summarised as follows:

- (i) The time domain parameters turns per second and number of zero crossing increase significantly with force level.
- (ii) From the power spectrum, the median frequency parameter decreases significantly with force level, whereas max power and total power increase significantly with force level. It should be noted however, that both maximum and total power increase up to the fourth decade (30–39 years), and then as expected gradually decrease.
- (iii) The bispectrum parameter maximum amplitude increases significantly with force level. Although, the test for Gaussianity and linearity show no significant difference with force level, the SEMG signal exhibits a more Gaussian distribution with increase of force up to 70% MVC. The SEMG linearity test shows that the signal is more constant at MVC and less constant at 70% of MVC.
- (iv) The time domain parameters were found to have a good correlation between them as well as, between each one of them and maximum and total power. Maximum and total power, exhibit an excellent correlation between them. The median frequency has a good correlation with the bispectrum peak amplitude (–ve) and its slope in the x -direction. A good correlation was found between all possible pair combinations of the coordinates and slope of the bispectrum peak. The bispectrum peak amplitude presents also a good (–ve), correlation with its coordinates in the x and y direction as well as with its slope in the x -direction. Finally, the slope of the bispectrum peak in the x -direction presented an excellent correlation between the slope of the bispectrum peak in the y -direction.
- (v) No significant differences exist between values based on gender or age.

Acknowledgement

This work was made possible through the kind support of the Cyprus Institute of Neurology and Genetics.

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Prodromos A Kaplanis started his undergraduate studies at the Higher Technical Institute Nicosia Cyprus, (Diploma of Technician Engineer 1982) and continued at Portsmouth Polytechnic UK, (B.Sc. in Electrical and Electronic Engineering 1986). He carried on at St Bartholomew's Hospital Medical College, University of London UK, (M.Sc. in Medical Electronics and Physics 1988). He obtained a Ph.D. in 2004 titled "Surface EMG for the assessment of neuromuscular disorders", from Kings College School of Medicine and Dentistry, University of London UK. During the M.Sc. studies he worked as a research engineer at Medici Research Center, designing and producing physiotherapy equipment. From 1989 till 1994 he was employed as the Technical Manager of a Medical Imaging equipment company. In parallel he taught at the Higher Technical Institute for the World Health Organization, from 1990–1992. Since 1994 he is employed as a Medical Physicist with the Ministry of Health. He is teaching Bio-Physics at the Nursing School of Nicosia General Hospital and Medical Imaging as a visiting lecturer at the University of Cyprus. He is an appointed expert of the International Atomic Energy Agency. His research interests include the application of Surface Electromyography in the clinical environment and its adoption towards patient classification and disease assessment, as Medical Imaging applications. He is a past president of the Cyprus Association of Medical Engineering and Physics, a corporate member of IPEN and a Chartered Engineer of the IET.



Constantinos S. Pattichis (S'88–M'88–SM'99). He was born in Cyprus on January 30, 1959 and received his diploma as technician engineer from the Higher Technical Institute in Cyprus in 1979, the B.Sc. in Electrical Engineering from the University of New Brunswick, Canada, in 1983, the M.Sc. in Biomedical Engineering from the University of Texas at Austin, USA, in 1984, the M.Sc. in Neurology from the University of Newcastle Upon Tyne, UK, in 1991, and the Ph.D. in Electronic Engineering from the University of London, UK, in 1992.

He is currently an Associate Professor with the Department of Computer Science of the University of Cyprus. His research interests include health, medical imaging, biosignal analysis, and intelligent systems. He has been involved in numerous projects in these areas funded by EU, the National Research Foundation of Cyprus, the INTERREG and other bodies, like the INTRAMEDNET, INTERMED, FUTURE HEALTH, AMBULANCE, EMERGENCY, ACSRS, TELEGIN, HEALTHNET, IASIS, IPPOKRATIS, and other with a total funding managed in excess of 4 million Euros. He has published 42 refereed journal and 110 conference papers, and 17 chapters in books in these areas. He is Co-Editor of the books *M-Health: Emerging Mobile Health Systems*, published in 2006 by Springer and of the *Information Technology in Biomedicine*, to be published in 2007 by IEEE. He was Guest Co-Editor of the Special Issues on *Emerging Health Telematics Applications in Europe*, and of the forthcoming *Emerging Technologies in Biomedicine*, and *Computational Intelligence in Medical Systems* of the IEEE Trans. on Information Technology in Biomedicine. He was General Co-Chairman of the *Medical and Biological Engineering and Computing Conference* (MEDICON'98), and the IEEE Region 8 *Mediterranean Conference on Information Technology and Electrotechnology* (MELECON'2000), and Program Co-Chair of the *IEEE Information Technology in Biomedicine*, ITAB06. Moreover, he

serves as an Associate Editor of the IEEE Trans. on Information Technology in Biomedicine and the IEEE Trans. on Neural Networks. He served as Chairperson of the Cyprus Association of Medical Physics and Biomedical Engineering (96-98), and the IEEE Cyprus Section (98-00). He is a Senior Member of IEEE.



Leontios J. Hadjileontiadis was born in Kastoria, Greece in 1966. He received the Diploma degree in electrical engineering in 1989 and the Ph.D. degree in electrical and computer engineering in 1997, both from the Aristotle University of Thessaloniki, Thessaloniki, Greece. Since, December 1999 he joined the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece as a faculty member, where he is currently an Assistant Professor. His research

interests are in higher-order statistics, alpha-stable distributions, higher-order zero crossings, wavelets, polyspectra, fractals, neuro-fuzzy modeling for medical, mobile and digital signal processing applications.



Colin Roberts is presently the Chairman of the Royal Cornwall Hospitals in the UK having been formerly Head of Medical Engineering & Physics at King's College Hospital in London and Director of the national Centre of Rehabilitation Engineering. He holds an honorary doctorate of medicine and is a Fellow of several professional institutions including the Institute of Physics & Engineering in Medicine, and the International Academy of Medical & Biological Engineering.