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The influences of muscle fibre proportions and areas upon EMG during maximal dynamic knee extensions

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Abstract This study is an investigation of the relationship between muscle morphology and surface electromyographic (EMG) parameters [mean frequency of the power spectrum (MNF), signal amplitude (root mean square, RMS) and the signal amplitude ratio (SAR; i.e. the ratio between the RMS level during the passive part of the contraction cycle and the RMS level during the active part of the contraction cycle)] during 100 maximal dynamic knee extensions at $90° \cdot s^{-1}$. Each contraction cycle comprised of 1 s of active knee extension and 1 s of passive knee flexion. The surface EMG was recorded from the vastus lateralis muscle. Twenty clinically healthy subjects participated in the study, and muscle biopsy samples of the vastus lateralis were obtained from 19 of those subjects. The relationships between muscle morphology and EMG were investigated at three stages of the test: initially, during the fatigue phase (initial 40 contractions), and at the endurance level (the final 50 contractions). Major findings on correlations are that SAR and MNF tended to correlate positively with the proportion of type 1 fibres, and RMS correlated positively with the proportion of type 2 muscle fibres. The muscle fibre areas showed little correlation with the EMG variables under investigation. The results of the present study showed that the three EMG variables of a dynamic endurance test that were investigated (RMS, MNF and SAR) were clearly correlated with the proportions of the different fibre types, but only to a small extent with fibre areas. These findings contradict some of the theoretical models of the EMG, especially for parameters in the frequency domain.

Key words Dynamic · EMG · Enzyme histochemistry · Knee extensors · Morphology

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Introduction

A sustained static contraction often results in typical changes in the surface electromyogram (EMG); a spectral shift towards lower frequencies and an increase in the signal amplitude (Basmaijan and DeLuca 1985). An initial steep decrease (during the initial 40–60 contractions) in force output and mean frequency (MNF) of the EMG (the fatigue phase) followed by a plateau (the endurance level) with no further decrease occurs during repetitive maximum dynamic (isokinetic) contractions (for references see Lindström et al. 1997; Lundblad et al. 1998). The reported behaviour of the signal amplitude [root mean square, RMS or integrated (i) EMG] of the EMG during the fatigue phase are heterogeneous (both increases and decreases have been reported), according to the literature. Thereafter, RMS is stable or decreases slowly.

Models of the EMG suggest that the muscle fibre areas (diameters) are the major factor behind the wave form of the registered motor unit action potential trains (MUAPT) and the conduction velocity of the muscle fibre membranes (MFCV), which is linearly related to MNF or median frequency (MDF; Lindström and Magnusson 1977; Basmajian and De Luca 1985). Experimental data support this model, since linear relationships have been reported to exist between MNF and MFCV (Sadoyama et al. 1983; Arendt-Nielsen and Mills 1985). There are

conflicting opinions regarding the mechanism underlying the decrease in MNF that occurs during fatigue. The decrease in the MFCV has often been favoured as the major cause, but the picture is not unambiguous (for references see Gerdle et al. 1997). Increasing synchronisation of the firing frequency, decreases in the number of active motor units and changes in intrinsic muscle properties have also been discussed as contributors to the shift in MNF that occurs during fatigue (for references see Gerdle et al. 1997). Moreover, the relevance of the different factors during fatigue might be force dependent (for references see Gerdle et al. 1997). The model of Lindström and Magnusson (1977) has been criticised since it is based on an assumption that the proportions of different fibre types have no influence. Both studies in the unfatigued and the fatigued state indicate that the fibre type proportions might influence the MNF or MDF during static (Moritani et al. 1985; Kupa et al. 1995; Gerdle et al. 1997) and dynamic contractions (Komi and Tesch 1979; Elert et al. 1992b; Gerdle et al. 1988). Recently, Mannion et al. (1998) reported that there was no correlation between fibre type distribution and MDF in the unfatigued state in back muscles. During static fatigue they found that MDF shifts were significantly related to fibre type area distribution.

Recently, our group reported that different groups of patients with chronic pain (i.e. fibromyalgia, work-related myalgia and chronic whiplash-associated disorders) have a significantly reduced ability to relax their muscles in the pauses between maximum repetitive concentric isokinetic contractions compared to clinically healthy subjects (Elert et al. 1992b; Fredin et al. 1997). The relative inability to relax was indicated by the signal amplitude ratio (SAR); the ratio between the RMS level during the passive part of the movement cycle and the RMS level during the active part of the contraction cycle. At present it is unclear whether muscle fibre distribution and fibre areas have any influence upon SAR.

In the first study of the present project we found that the peak torque of an isokinetic endurance test of the knee extensors correlated strongly with the fibre type areas, whilst the proportions of the fibre types had little importance (Gerdle et al. 1998). The main aim of the present study was to investigate the relationships between surface EMG (MNF, RMS and SAR) and proportions of fibre types and areas in the vastus lateralis during maximum isokinetic knee extensions.

Methods

Subjects

Twenty healthy volunteers consisting of 11 males and 9 females (age 20–38 years) participated in the study (Table 1). The males ranged in height from 174 to 194 cm and in body mass from 70 to 110 kg; the females ranged from 160 to 173 cm and 55 to 73 kg, respectively. The study was approved by the Ethical Committee of Umeå University and was performed after each subject gave their informed consent.

Table 1 Anthropometric data for all of the subjects and separately for the two genders. Mean (SD) values are given

Variables	All (n = 20)	Males (n = 11)	Females (n = 9)
Weight (kg)	72.0 (13.2)	81.0 (12.0)	62.9 (5.3)
Height (cm)	177.0 (9.8)	184.1 (6.8)	168.2 (3.7)
Thigh circumference (cm)	58.9 (8.3)	58.8 (5.7)	59.0 (10.8)

Methods

The study consisted of maximal repetitive isokinetic contractions of the right knee extensors. Torque, knee joint position and EMG were recorded simultaneously and continuously while subjects performed the 100 isokinetic knee extensions scheduled in the protocol.

Surface EMG

For all subjects throughout the exercise protocol, EMG signals were recorded from the right vastus lateralis muscle by surface electrodes that were positioned prior to the exercise. The skin was first dry-shaved and then cleaned with an alcohol and ether solution (4:1). Two silver-chloride recording electrodes (Medicotest, Ølstykke, Denmark, dimensions: 3 mm × 6 mm), abraded with redux paste (Medicotest, were placed 2 cm apart on the skin above the muscle. The EMG was recorded by a bipolar isolated amplifier (EMGAmp, Braintronics, ISO-2104, Almere, The Netherlands).

Biopsy sampling, enzyme histochemistry, and morphometry

One or 2 days after exercise, an open surgical biopsy sample was obtained from the vastus lateralis muscle at a point 20–25 cm proximal to the lateral femoral condyle (i.e. the biopsy sample was taken from the same site at which the surface EMG of the vastus lateralis was recorded). After local anaesthesia (1% lidocaine) a 2-cm-long incision was made over the muscle belly, parallel to the direction of the fibres. The fascia was divided and a segment of muscle measuring 15 mm in length and 10 mm in diameter was removed. The muscle specimen was removed along with some fascia in order to facilitate orienting the muscle for histology. For enzyme histochemistry and immunohistochemical analysis, specimens were secured by OTC compound (Tissue Tek, Miles Laboratories, Naperville, Ill. USA) in a transverse arrangement and immersed in liquid propane that had been prechilled by liquid nitrogen (−160°C). The frozen specimens were stored in a freezer (−80°C) until ready for use. Serial cross sections, 7–10 μm thick, were cut in a cryostat microtome, mounted on glass slides and stained in various ways to detect differences in fibre types and to isolate specific cellular components. Myofibrillar adenosine triphosphatase (mATPase – EC 3.6.1.3) activity was assessed at acidic and alkaline preincubations to indicate differences in fibre types (Brooke and Kaiser 1970). The criteria for fibre-type identification have been described previously (Staron and Hikida 1992), and are as follows:

1. Type 1 – unstained at pH 10.3, dark stained at pH 4.6 and 4.3.
2. Type 2a – dark stained at pH 10.3, unstained at pH 4.6 and 4.3.
3. Type 2b – dark stained at pH 10.3 and 4.6, unstained at pH 4.3.
4. Type 2ab – dark stained at pH 10.3, light stained at pH 4.6, unstained at pH 4.3.
5. Type 2c – dark stained at pH 10.3, 4.6 and 4.3.

Sections were also treated with a rabbit antiserum to laminin (EY Laboratories, San Mateo, Calif., USA) in order to identify fibre borders and facilitate computerised measurements of fibre areas. Specimens were photographed with a photomicroscope (Zeiss, Axiophot, Germany) and area measurements were determined with an image analysis system (IBAS, Kontron Bildanalyse,

Munich, Germany). Fibre types were identified for these specimens with the aid of mATPase-stained serial sections. The mean fibre area, irrespective of muscle type, was computed as: [(% type 1 × area type 1) + (% type 2a × area type 2a) + (% type 2b × area type 2b) + (% type 2c × area type 2c) + (% type 2ab × area type 2ab)]/100. The mean area of the type 2 muscle fibres only was computed in a similar way: [(% type 2a × area type 2a) + (%type 2b × area type 2b) + (% type 2c × area type 2c) + (% type 2ab × area type 2ab)]/(% type 2a + % type 2b + % type 2c + % type 2ab).

Exercise protocol

An isokinetic dynamometer (Kin-Com 500 H, Chattecx, Tennessee, USA) was used to measure torque and knee-joint position. Subjects were secured by body straps and seated comfortably in the dynamometer chair with an angle of ≈110° between the alignment of the spine and the femur. Following electrode placement, each subject performed a series of 100 repetitive isokinetic contractions using the right leg knee extensors from 90° of flexion to 0° (full extension). The dynamometer was motor driven at a constant velocity of $90° \cdot s^{-1}$ (i.e. degrees/s). As the arm of the dynamometer moved up from 90° to 0°, subjects were encouraged to perform maximally for each contraction throughout the full range of motion (i.e. the active phase of the contraction cycle). The subjects relaxed as the dynamometer arm moved back to 90° (the passive phase of the contraction cycle). Therefore, each contraction and relaxation period lasted 1 s, and the total time of the contraction cycle was thus 2 s. All subjects were able to complete the full 100 contractions.

Data acquisition and processing

The EMG was recorded by a bipolar isolated amplifier (EMGAmp, Braintronics). Signals from the EMG amplifier and the dynamometer were acquired simultaneously by a data acquisition processor (DAP 2400/6 Microstar Laboratories, Bellevue, USA) running in parallel with a host personal computer (PC). The sampled signals were buffered before being sent to the PC, which freed the PC to perform other functions momentarily (e.g. displaying and saving the data).

It is well known that the bandwidth of the EMG signals obtained from surface electrodes is less than 1 kHz. The EMG signals were therefore sampled at a rate of 2 kHz. The torque and position signals were sampled at a rate of 40 Hz. All signals were amplified and analogue-to-digital converted with 12-bit accuracy in the signal range ±5 V. An analogue low-pass filter was used to eliminate aliasing of the sampled signals: EMG at 800 Hz, torque at 10 Hz. To avoid the influence of movement artefacts and low-frequency noise of the EMG signal a high-pass filter of 16 Hz was used. Data analysis was performed off-line using MATLAB software (The MathWorks, Natick, Massachusetts, USA). The MNF (Hz), and signal amplitude, denoted as the RMS (μV), were computed from the EMG signal for both phases of the contraction cycle. The power-density spectrum was obtained after Hamming windowing, using the fast Fourier transform (FFT) technique. To yield a spectral resolution of approximately 2 Hz, a 1024-point FFT was selected. The ratio of the RMS (SAR) between the passive phase and active phase of the contraction cycle was also calculated.

Statistical analyses

Analyses were made using SPSS for Windows (version 7.5, SPSS, Chicago, Ill., USA) and SIMCA (Umetri AB, Umeå, version 6.01). Results in the text and tables are given as either mean values or the mean (SD). Regression analysis was used to minimise the effects of random variations for all variables. From each individual analysis the coefficient of correlation (r), the intercept (m) and the regression coefficient (k) were determined for the initial 40 contractions. The following EMG variables of the vastus lateralis have been defined and used in the present study: initial MNF (the intercept of MNF), MNF slope [the regression coefficient (slope) of MNF], MNF endurance level (mean value of contractions numbers 51–100), initial RMS (the intercept of RMS after normalisation), RMS slope (the regression coefficient of RMS after normalisation), RMS endurance level (mean value of contractions numbers 51–100 after normalisation), initial SAR (the intercept of SAR), SAR slope [the regression coefficient (slope) of SAR], SAR endurance level (the mean of contractions numbers 51–100).

Relative values are expressed as percentages of the intercept of the actual variable versus time (normalised). Principal component analysis (PCA) using SIMCA was performed to detect whether a number of variables reflect a smaller number of underlying components (missing data tolerance: 50%) and to analyse correlations between variables. Components with Eigenvalues ≥1.00 (Kaiser's criterion) were considered as nontrivial factors. The loading expresses the degree of correlation between the item and the component. Variables loading upon the same component are correlated; variables with loadings with the same sign are positively correlated, and variables with loadings with different signs are negatively correlated. The level of statistical significance was set at $P < 0.05$.

Results

Muscle morphology

Descriptive data on the morphology has been published elsewhere (Gerdle et al. 1997); only a brief review is given here. A predominance of type 2 muscle fibres was found in the vastus lateralis muscles (Gerdle et al. 1997. Table 2). The most prevalent muscle fibre type was type 2a [40 ± (15)%]. No statistical difference in the proportions of the fibre types was found between men

Table 2 Proportions (%) and areas (μm^2) of muscle fibres in the vastus lateralis muscle. Mean (SD) values are given. Statistical comparisons were made between the two genders and P-values are given if significant (*ns* no statistical difference). These results were taken from Gerdle et al. 1997

Variables	All (n = 20)	Males (n = 11)	Statistics P	Females (n = 9)
Proportion type 1 (%)	35 (11)	35.9 (9.1)	ns	34.2 (14.3)
Proportion type 2a (%)	40 (15)	40.8 (16.0)	ns	38.1 (14.8)
Proportion type 2b (%)	7 (6)	6.7 (5.5)	ns	7.1 (6.1)
Proportion type 2ab (%)	1 (1)	0.7 (1.2)	ns	1.2 (1.5)
Proportion type 2c (%)	17 (11)	15.9 (11.5)	ns	19.4 (11.2)
Area type 1 (μm^2)	4801 (1020)	5086 (874)	ns	4409 (1142)
Area type 2a (μm^2)	5841 (2036)	6872 (1865)	0.005	4422 (1310)
Area type 2b (μm^2)	5208 (1737)	6305 (1367)	0.001	3798 (963)
Area type 2ab (μm^2)	4309 (1434)	5173 (2181)	ns	3662 (1806)
Area type 2c (μm^2)	4765 (1776)	5747 (1434)	0.010	3660 (1491)

and women. The muscle fibre areas of types 2a, 2b and 2c in the males were significantly larger than in the females. A significant gender difference ($P = 0.005$) was found for the mean fibre area [4222 (1100) μm^2 and 6049 (1373) μm^2 for females and males, respectively]. Moreover, in the men the type 2 fibres were larger than the type 1 fibres. In general, the opposite situation was found for the female group (Gerdle et al. 1997).

The relationships between the morphological variables (fibre proportions and areas) were investigated using PCA (Table 3). Three significant components were identified [R^2(cum) = 0.74]. The first component appeared to reflect mainly the positive correlations between the fibre type areas. The second component described a negative relationship between, on the one hand, the proportion of type 2a fibres and, on the other hand the proportions type 2ab, type 2c and type 1 fibres. The third component described mainly the negative relationship between, on the one hand, proportion of the type 1 fibres and, on the other, the proportions of type 2b and type 2c fibres.

EMG

The variables under investigation are given in Table 4. As reported elsewhere in detail, peak torque decreased significantly (≈50%) (Gerdle et al. 1998). MNF and SAR decreased significantly from the initial non-fatigued state (i.e. the intercept) to the endurance level. No significant changes occurred for the RMS of the EMG of the vastus lateralis. No significant differences existed between men and women for any of the EMG variables.

Relationships between the initial EMG and morphology (non-fatigued state)

A PCA using the initial EMG variables and morphology (Table 5) identified four components (p1–p4); (R^2(cum) = 0.74). The first component (p1; $R^2 = 0.29$) reflected mainly negative relationships between muscle fibre areas and the initial RMS. For the second component (p2; $R^2 = 0.18$), initial MNF, initial SAR, and the proportions of type 1, and type 2ab fibres were positively correlated, the proportion of type 2b fibres was negatively correlated. With regard to the third component ($R^2 = 0.17$), the highest loadings were some of the morphological variables. The fourth component ($R^2 = 0.10$) reflected mainly initial SAR, the proportion of type 1 fibres, and there was a negative correlation with initial MNF and the proportion of type 2c fibres.

To summarise:

1. Initial MNF was positively correlated with the proportion of type 1 and type 2ab fibres, and negatively correlated with the proportion of type 2b fibres (component p2).
2. Initial RMS was correlated negatively with the areas of the fibre types (component p1).
3. Initial SAR correlated positively with the proportions of type 1 and type 2ab fibres, and negatively with the proportions of type 2b fibres (component p2).

EMG and morphology relationships during the fatigue phase

PCA of the EMG variables from the fatigue phase and morphological variables resulted in four significant

Table 3 Loadings and components (p1–p3) from a principal component analysis (PCA) of the morphological variables (proportions and areas) under investigation [R^2(cum) = 0.74]. Eigenvalue and R^2 values are given for each component. For each component, the highest loadings are given in *bold*

Variables	p1	p2	p3
Proportion type 1 (%)	0.11	**0.39**	**−0.58**
Proportion type 2a (%)	−0.14	**−0.62**	−0.14
Proportion type 2b (%)	−0.16	−0.00	**0.59**
Proportion type 2ab (%)	−0.05	**0.44**	−0.16
Proportion type 2c (%)	0.15	**0.37**	**0.52**
Area type 1 (μm^2)	**−0.37**	0.29	0.04
Area type 2a (μm^2)	**−0.50**	0.07	−0.05
Area type 2b (μm^2)	**−0.46**	0.16	0.01
Area type 2c (μm^2)	**−0.56**	−0.09	−0.07
Eigen-value	3.25	2.08	1.36
R^2 (%)	36.15	23.09	15.14

Table 4 Initial value, endurance level and slope of the mean frequency of the power spectrum (MNF), Signal amplitude (RMS) and Signal amplitude ratio (SAR) of the vastus lateralis. Mean (SD) values are given. Statistical comparisons were made between the initial situation and the endurance level and the *P*-values are given if significant; *ns* denotes no significant difference between the initial value and the endurance level

Variables	Initial	Slope	Endurance level	Statistics *P*
MNF (Hz)	86.1 (11.6)	−0.49 (0.25)	66.2 (11.2)	0.001
RMS	1.14 (0.14)	0.001 (0.006)	1.16 (0.29)	ns
SAR (%)	4.5 (2.8)	−0.03 (0.07)	3.3 (1.6)	0.018

Table 5 The loadings and components [p1–p4] from a PCA of morphological variables and initial electromyographic (EMG) variables (the non-fatigued situation); R^2(cum) = 0.74. Eigenvalue and R^2 values are given for each component. The highest loadings of each component are given in *bold*

Variables	p1	p2	p3	p4
Initial MNF	−0.08	**0.50**	−0.26	**−0.34**
Initial RMS	**0.30**	−0.23	0.22	0.22
Initial SAR	0.04	**0.40**	−0.05	**0.51**
Proportion type 1 (%)	0.10	**0.47**	0.19	0.01
Proportion type 2a (%)	−0.15	−0.20	**−0.57**	0.27
Proportion type 2ab (%)	−0.07	**0.32**	**0.34**	0.29
Proportion type 2b (%)	−0.13	**−0.39**	0.19	0.09
Proportion type 2c (%)	0.17	−0.07	**0.43**	**−0.46**
Area type 1 (μm^2)	**−0.32**	−0.05	**0.38**	**0.38**
Area type 2a (μm^2)	**−0.49**	−0.01	0.09	−0.11
Area type 2b (μm^2)	**−0.45**	0.09	0.15	−0.12
Area type 2c (μm^2)	**−0.52**	−0.04	−0.02	−0.14
Eigen-value	3.51	2.17	2.08	1.15
R^2	0.29	0.18	0.17	0.10

Table 6 The loadings and components (p1–p4) from a PCA morphological variables and EMG variables measured during the fatigue phase; R^2(cum) = 0.72. Eigenvalue and R^2 values are given for each component. The highest loadings of each component are given in *bold*

Variables	p1	p2	p3	p4
MNF slope	0.02	0.08	0.10	**0.59**
RMS slope	−0.17	−0.18	**−0.48**	**0.30**
SAR slope	0.14	**0.43**	0.27	**−0.30**
Proportion type 1 (%)	0.06	**−0.41**	−0.17	**−0.37**
Proportion type 2a (%)	−0.07	**0.52**	**−0.40**	0.10
Proportion type 2ab (%)	−0.16	**−0.42**	−0.10	0.13
Proportion type 2b (%)	−0.14	0.09	**0.39**	**0.48**
Proportion type 2c (%)	0.12	−0.26	**0.54**	−0.01
Area type 1 (μm^2)	**−0.40**	−0.13	0.16	−0.05
Area type 2a (μm^2)	**−0.50**	0.08	0.06	−0.15
Area type 2b (μm^2)	**−0.49**	−0.04	0.07	0.02
Area type 2c (μm^2)	**−0.49**	0.26	0.05	−0.20
Eigen-value	3.33	2.41	1.56	1.36
R^2	0.28	0.20	0.13	0.11

Table 7 The loadings and components (p1–p4) from a PCA of morphological variables and EMG variables measured during the endurance level; R^2(cum) = 0.71. Eigenvalue and R^2 values are given for each component. The highest loadings of each component are given in *bold*

Variables	p1	p2	p3	p4
MNF endurance level	0.02	0.15	**0.56**	−0.05
RMS endurance level	0.14	−0.16	−0.01	**0.68**
SAR endurance level	0.12	0.27	**0.39**	0.12
Proportion type 1 (%)	0.11	−0.27	**0.45**	**−0.32**
Proportion type 2a (%)	−0.12	**0.59**	−0.13	**0.33**
Proportion type 2ab (%)	−0.05	**−0.39**	0.27	**0.50**
Proportion type 2b (%)	−0.18	−0.11	**−0.40**	−0.12
Proportion type 2c (%)	0.14	**−0.40**	−0.13	−0.10
Area type 1 (μm^2)	**−0.36**	**−0.31**	−0.06	0.17
Area type 2a (μm^2)	**−0.50**	−0.05	0.10	−0.03
Area type 2b (μm^2)	**−0.44**	−0.10	0.17	0.06
Area type 2c (μm^2)	**−0.55**	0.14	0.13	−0.07
Eigen-value	3.34	2.16	1.88	1.20
R^2	0.28	0.18	0.16	0.10

components (p1–p4) [R^2(cum) = 0.72; Table 6]. The areas of the fibre types were not correlated with the EMG variables during the fatigue phase (p1). The most important variables for the second component (p2) were SAR slope, and the proportion of type 2a fibres, and there was a negative correlation with the proportions of type 1 and 2ab fibres. According to the third component (p3), negative correlations existed between, on the one hand, the proportions of type 2b and 2c fibres and, on the other hand, RMS slope and the proportion of type 2a fibres. The most important variables inferring positive loading upon p4 were MNF slope, RMS slope and the proportion of type 2b fibres. Negative loading was inferred by SAR slope and the proportion of type 1 fibres.

To summarise:

1. MNF slope correlated positively with the proportion of type 2b fibres, and negatively with the proportion of type 1 fibres (component p4).
2. RMS slope correlated positively with the proportion of type 2a and 2b fibres, and negatively with the proportion of type 2c and type 1 fibres (components p3 and p4).
3. SAR slope correlated positively with the proportion of type 2a fibres, and negatively with the proportions of types 1, 2ab and 2b fibres (components p2 and p4).

EMG and morphology relationships at the endurance level

From the PCA using the variables of the endurance level [R^2(cum) = 0.71] it can be concluded that the fibre type areas were loaded mainly upon the first component (R^2 = 0.28; Table 7). The second component (R^2 = 0.18) reflected mainly the negative relationship between the proportions of type 2a, type 2ab and type 2c fibres (cf component p2 of Table 3). From the third component (R^2 = 0.16), it can be concluded that the MNF and SAR endurance levels correlated positively with the proportion of type 1 fibres, and negatively with that of type 2b fibres. The fourth component (R^2 = 0.10) indicated a positive relationship between RMS endurance level and the proportions of type 2a and type 2ab fibres on the one hand, and negatively with the proportion of type 1 fibres on the other.

To summarise:

1. MNF and SAR at the endurance level correlated positively with the proportion of type 1 fibres, and negatively with that of type 2b fibres (component p3).
2. RMS endurance level correlated positively with the proportions of type 2a and 2ab fibres, and negatively with that of type 1 fibres (component p4).

Discussion

The results of the present study indicate that common EMG variables, both in the unfatigued and the fatigued states, are significantly correlated with the muscle fibre proportions, which must be considered when interpreting surface EMG in different clinical applications.

Major results of the present study that will be discussed are:

1. MNF and SAR were correlated mainly with the proportion of type 1 fibres.
2. RMS during the fatigue phase and at the endurance level was correlated positively with the proportion of type 2 fibres.
3. The muscle fibre areas had little correlation with the EMG variables under investigation.

MNF

Several studies have been published that have focused on the EMG frequency spectrum during repetitive dynamic contractions, for instance ergometer cycling, running

and isokinetic dynamometer exercise (for references see Ament et al. 1996). The interpretation of frequency spectrum variables from dynamic contractions might be difficult because the movement introduces additional factors that might affect its characteristics; for instance force/torque changes throughout the range of motion, changes in fibre and muscle length, the effect of angular velocity, and problems with the non-stationarity of the signal. Even though there is a relative dearth of studies concerning the validity and reproducibility of EMG variables during dynamic contractions, there exist studies that support them in the frequency domain during dynamic contractions (Shankar et al. 1989; Sleivert and Wenger 1994; Potvin and Bent 1997; Larsson et al. 1999). For the MNF of the quadriceps muscles, no significant effects of angular velocity have been found during isokinetic knee extensions between 0.57 and 3.14 $rad \cdot s^{-1}$ (30–180°s^{-1}) (Gerdle et al. 1988).

The relationships between proportions of fibre types and fibre areas and the MNF in the *unfatigued* state during maximum dynamic contractions have yet to be established. From the present study, it is obvious that MNF in the unfatigued state is correlated with the proportions of the fibre types (positively with the proportions of type 1 and 2ab fibres, and negatively with that of type 2b fibres). In the unfatigued state, positive correlations between the proportion of type 2 muscle fibres and MNF have been reported for the gastrocnemius (static contraction at 50% maximum voluntary contraction, MVC), vastus lateralis (maximum isokinetic contraction) and trapezius muscles (maximum isokinetic contraction). (Moritani et al. 1985; Gerdle et al. 1988; Elert et al. 1992b). Contrary to these studies, no correlation was found between the MDF and fibre type distribution of back muscles in the unfatigued situation (Mannion et al. 1998). We were not able to confirm these results; indeed a positive correlation between the proportion of type 1 fibres and MNF was found instead of the expected negative relationship. The relationships between the morphology variables under investigation and initial MNF appears to be force dependent when judging from static contractions (Gerdle et al. 1997). At 25% MVC a positive correlation was observed between initial MNF and the total proportion of type 2 muscle fibres. At 70% MVC, initial MNF was correlated mainly with the areas of fibre types 2a, 2b and 2c.

We have no clear explanation for our findings. Indeed, it can be argued that the vastus lateralis muscle demonstrates considerable heterogeneity in fibre type proportions between different portions (Lexell et al. 1983), and also the MNF variable shows considerable variation (Basmajian and De Luca 1985). On the other hand, the registered surface EMG suffers from a relative over-representation of the fibres located near the electrodes, due to filtering effects. To reduce the risk of errors and biased interpretations, especially with small samples of subjects, it is important to obtain the biopsy sample and the EMG recording from the same part of the muscle (as was the case in the present study). Moreover, multivariate statistical methods (for instance PCA) are needed for the correlation analysis. Against our present method of determining initial values of the variables (i.e. linear regression), it could be argued that we are in fact using data from a fatigue test to determine the values in the unfatigued state.

No significant influence of the areas of the different fibre types upon the initial MNF were found. This is interesting, since the proposed theoretical models of EMG in the frequency domain favour the idea that the fibre areas (diameters) are the major factor behind the waveform of the MUAPT and the MFCV, which is linearly related to MNF or MDF (Lindström and Magnusson 1977; Basmajian and De Luca 1985). The model of Lindström and Magnusson (1977) is based on the assumption that the proportion of the fibre types has no major influence on the frequency spectrum. The present result, obtained during dynamic contractions, is evidently not consistent with the assumption of Lindström and Magnusson, since the areas of the muscle fibres had very little influence upon the MNF. Using an in vitro model of rat muscles, Kupa et al. (1995) found a significant positive correlation between initial MDF and average muscle fibre cross-sectional area only for the extensor digitorum longus (≈99% type 2 muscle fibres). In the other muscles that had a more heterogeneous mixture of fibre types, such a relationship did not exist. Hence, only the areas of a subpopulation of the muscle fibres had importance according to this study. In addition, results from static contractions using the same subjects question the model with respect to the assumptions concerning the muscle morphology (Gerdle et al. 1997).

The results from the fatigue phase and the endurance level show clearly that the proportion of fibre types influenced the shift in and level of MNF at the terminal part of the test. During repetitive maximum isokinetic contractions, output and MNF decrease steeply during the initial 40–60 contractions – as in the present study (Table 4) – followed by relatively stable levels for the remaining 100–150 contractions (Gerdle and Fugl-Meyer 1992; Lindström et al. 1997). There are conflicting opinions regarding the mechanism underlying the spectral shift that occurs during fatigue. At fatiguing static contractions of ≤30% MVC, spectrum changes are due mainly to the changes in neural mechanisms, whereas at ≥45% MVC metabolic factors are the main influence according to some authors: Zwarts and Arendt-Nielsen 1988; Brody et al. 1991; Krogh-Lund and Jørgensen 1991. Other possible contributors to the frequency shift are increasing synchronisation of the firing rate, a decrease in the number of active motor units, and changes in intrinsic muscle properties (Bigland-Ritchie et al. 1981; Naeije and Zom 1982; Kranz et al. 1983; Sadoyama et al. 1983). However, the decrease in MFCV has been favoured in the models (Lindström et al. 1970) which, it has been suggested, is attributable to the accumulation of potassium, lactate or

protons (H^+) (Tesch et al. 1983). The roles of H^+ or lactate and a decrease in MFCV as possible mechanisms behind the shift in MNF or MDF have been questioned in several studies (Mills and Edwards 1984; Linssen et al. 1990; Béliveau et al. 1991, 1992). Moreover, the proportion of fibre types appears to influence the spectral shift (Tesch et al. 1983; Häkkinen and Komi 1985, 1986). Patients with 100% type 1 muscle fibres performing intermittent ischaemic contractions at 80% MVC until fatigue showed weak shifts of the MNF to lower frequencies when compared to the controls (Linssen et al. 1991a, b). The present results show that a prominent MNF shift during the fatigue phase was correlated positively with the proportion of type 1 fibres and negatively with that of type 2b fibres, and that as a result of this shift, the endurance level MNF, correlated positively with the proportion of type 1 fibres and negatively with that of type 2b fibres. The results concerning the endurance level are in agreement with our earlier suggestions that MNF reflects the properties of the type 1 fibres (Gerdle and Fugl-Meyer 1992).

However, at the present state we are not able to explain why a high proportion of type 1 muscle fibres is correlated with a prominent decrease in MNF. In fact, Komi and Tesch (1979) reported the opposite for repetitive maximum isokinetic contractions. The absolute MDF shift was, to a high degree, determined by the proportion of fibre type by area, especially the fast glycolytic fibres (type 2b) for three rat muscles taken together (Kupa et al. 1995). Similar results have recently been reported in a study of back muscles in humans (Mannion et al. 1998).

Even though the surface EMG has potential as a preventative tool in ergonomic intervention at the work place, it is necessary to better understand how proportions of different fibre types and fibre areas influence frequency spectrum variables, especially since some of these variables (for instance the fibre areas) are correlated strongly with gender and general level of physical condition.

RMS

The initial RMS was correlated negatively with all fibre areas. The interpretation of this correlation is difficult from a physiological point of view since it represents an initial normalisation value. When compared to the initial contraction, no significant change had occurred for RMS at the endurance level. Hence, the prominent increase found during sustained static contractions was not observed at group level during dynamic maximum knee extensions. However, the relative increase in RMS that was observed during static fatigue (using the same subjects) was inversely related to the contraction level (Gerdle et al. 1997). Both during the fatigue phase and at the endurance level, RMS was correlated positively with the proportion of type 2 fibres. However, the subtype of type 2 fibres that had the highest correlation differed somewhat, even though at both stages the proportion of type 2a fibres was positively correlated. Neither during the fatigue phase nor at the endurance level were the fibre areas of importance. From the static knee extensions at two different force levels, we also reported that the RMS behaviour was significantly related to muscle morphology. At 70% MVC a positive correlation existed between RMS slope and the fibre type areas of types 2a, 2b and 2c, while at 25% MVC the situation was more complex; RMS slope was positively correlated with the proportions of fibre types 2b and 2c and the fibre type area of type 1, and was negatively correlated with the proportion of fibre type 2a.

SAR

The ratio between RMS of the passive part and RMS of the active part of the contraction cycle (the SAR) has been presented as a variable for measurement of the relative ability to relax between contractions during repeated maximal isokinetic contractions (Elert et al. 1992b). A significantly higher SAR at the endurance level was found for the shoulder muscles of patients with different kinds of chronic pain conditions (Elert et al. 1992a, b; Fredin et al. 1997). SAR is negatively correlated with biomechanical output, and increases with angular velocity (Elert et al. 1992a, b). Based on the size principle of the recruitment of motor units (Henneman and Olsen 1965; see also Thomas et al. 1987 for references) it can be assumed that it is mainly the type 1 muscle fibres that determine the electrical activity during the passive phase of the contraction cycle (i.e. a low level of muscle activation). This assumption was confirmed in the present study; subjects with a high proportion of type 1 muscle fibres had more difficulty in relaxing during the passive parts of the contraction cycle than subjects with a high proportion of type 2 muscle fibres. In agreement with the present findings and interpretations, we have recently found that a high SAR in the shoulder muscles was correlated with worsening in complaints from the neck and shoulders 1 year later (Lundblad et al. 1998). The present observation of a correlation between SAR and the proportion of type 1 muscle fibres is also interesting since studies of the trapezius muscle in clinically healthy subjects and subjects with work-related myalgia indicate that it is mainly the type 1 fibres that are affected in work-related myalgia (i.e. hypertrophy, lower capillarisation, moth-eaten fibres, ragged-red fibres; Lindman 1992). This indicates that SAR could have a role in a preventative approach to identify subjects with increasing risk of developing myalgia and/or a variable for the evaluation of different interventions at the workplace.

Conclusion

The present study has reported that the three investigated EMG variables of a dynamic endurance test

(MNF, SAR and RMS) are correlated mainly with the proportions of the different muscle fibre types. Even though several studies indicate significant relationships it is unclear how the distribution of different fibres and their areas influence the EMG recorded during static and dynamic contractions, and thus it is premature to formulate a revised EMG model of the surface EMG.

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