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ORIGINAL ARTICLE

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Time and frequency domain analysis of electromyogram and sound myogram in the elderly

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Abstract The aim of this work was to evaluate the influence of the ageing process on the time and frequency domain properties of the surface electrical and mechanical activity of muscle. In 20 healthy elderly subjects (10 men and 10 women, age range 65–78 years) and in 20 young controls, during isometric contractions of the elbow flexors in the 20%–100% range of the maximal voluntary contraction (MVC), estimations were made of the root mean square (rms) and the mean frequency (MF) of the power density spectrum distribution, from the surface electromyogram (EMG) and sound myogram (SMG) signals, detected at the belly of the biceps brachii muscle. Compared to the young controls, the MVC was lower in the elderly subjects ($P < 0.05$); at the same %MVC the rms and the MF of EMG and SMG were lower ($P < 0.05$) in elderly subjects; the rms and MF of the two signals increased as a function of the effort level in all groups. Only in the 80%–100% MVC range did the EMG-MF level off and the SMG-rms decrease; in contrast the young controls, at 80% MVC the high frequency peak in the SMG power spectrum density distribution was not present in the elderly subjects. The results for MVC and %MVC can be related to the reduction in the numbers of muscle fibres in aged subjects. In particular, the lack of fast twitch fibre motor units (MU), attaining high firing rates, might also explain the result at 80% MVC. In 80%–100% MVC range the two signals rms and MF behaviour may have been related to the end of the recruitment of larger MU with high conduction velocity, and to the further increment of MU firing rate in the biceps brachii muscle beyond 80% MVC, respectively. Thus, the coupled analysis of the EMG and SMG with force suggests that in the elderly subjects the reduction of the number of muscle fibres may have co-existed with a MU activation pattern similar to that of the young subjects.

Key words Muscle sound · Surface electromyogram · Soundmyogram · Isometric exercise · Ageing

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Introduction

Loss of strength is a characteristic of elderly people and it has been associated with a shrinking of the muscle mass and reduction of the muscle cross-section area (Lexell et al. 1983; Frontera et al. 1991). These changes have been attributed to the influence of ageing on the neurological (Brown et al. 1988; Howard et al. 1988; Merletti et al. 1992) or morphological (Lexell et al. 1983; Frontera et al. 1991) properties of the motor units (MU). However, it has been reported that the ageing process does not seem to affect the relative proportion of the MU with type I and type II fibres in the biceps brachii muscle (Grimby 1988; Doherty et al. 1993).

The MU activation pattern adopted by the muscle to increase strength consists, basically, of a combination of recruitment and an increased firing rate of the active MU. The percentage of the maximal voluntary contraction (MVC) at which recruitment is completed and the firing rate is the sole tool of providing further increases in force is specific to each muscle. It has been shown that for the small hand muscles this value is about 50% MVC; for larger muscles, such as biceps brachii, between 60% and 80% MVC (Kukulka and Clamann 1981; Basmajian and De Luca 1985).

The investigation of muscle performance is commonly carried out by measuring the output force and by the analysis of the electrical activity during contraction. The surface electromyogram (EMG) is an interferential signal in which the action potentials of each active MU are summated. In particular, the EMG time and frequency domain analysis has been shown to provide data on the degree of activation of the muscle MU pool and on the changes in the overall muscle fibre conduction velocity (Basmajian and De Luca 1985).

In addition to the force developed during contraction, another signal having a mechanical origin, the sound myogram (SMG), can be detected from a muscle. This is also an interferential signal which has been shown to derive from the composition of the mechanical activities of the fibres of the recruited MU (Gordon and Holbourn 1948; Barry et al. 1985; Orizio 1993). It can be detected at the muscle surface by contact sensors or microphones (for a review on the SMG detection techniques see Orizio 1993). These transducers have been shown to record the pressure waves generated by the dimensional changes of the active fibres during contraction (Oster 1984; Orizio 1993). It has been suggested that information about MU recruitment and firing rate is retrievable from analysis of the SMG time and frequency domain (Keidel and Keidel 1989; Orizio et al. 1989, 1990; Zhang et al. 1992).

Following the Gordon and Holbourn (1948) statement that "the muscular sound is the mechanical counterpart of the electrical activity of the motor units", it appears that simultaneous analysis of EMG and SMG signals may provide a reliable tool to investigate the relationship between the electrical and the mechanical activities of the MU at different intensities of muscle contraction. Such electromechanical analysis has never been attempted in aged subjects. Thus, the aim of this study was to describe the properties of EMG and SMG during increasing isometric effort in the elderly. Moreover, by means of the relationship between the EMG and SMG parameters and the effort level it was intended to gain some insight into the possible influence of ageing on the role played by recruitment and firing rate of the MU in determining the force output during isometric contractions.

Methods

Subjects

A total of 40 healthy subjects signed an informed consent and participated in the study after full explanation of the purpose of the experiments and of the procedures to be followed. Of this group, 20 were sedentary elderly individuals (10 men and 10 women, age range 65–78 years) and 20 were young sedentary controls (10 men and 10 women; age range 20–34 years). None of them was involved in any specific training programme of the upper limb musculature, either at the time of the study or in the previous year. Table 1 gives the anthropometric characteristics of the subjects together with values of their MVC, the muscle-bone area (MBA) and the MVC per unit of MBA. The MBA was anthropometrically determined according to the method suggested by de Koning et al. (1986).

Apparatus

The experiments were carried out during isometric contractions of the elbow flexor muscles. The preferred arm of the subject was positioned in an anatomical device allowing an angle of 115° between the arm and the forearm. The hand was maintained in a position halfway between pronation and supination. The output force was recorded using a calibrated load cell (Interface, SM-1000 N, linear from 0 to 1000 N) strapped to the subject's wrist. The EMG and SMG were detected from the belly of the biceps brachii muscle by means of a purpose-designed probe. This probe was made up of two silver bar electrodes (diameter 1 mm), 1-cm spaced and 1-cm long, and of the tip of a piezo-electric contact sensor transducer (Hewlett-Packard model 21050 A, bandwidth 0.02–2000 Hz) placed in between. The SMG was then amplified by a medium gain amplifier (Hewlett-Packyard model 8802 A, filter bandwidth 2–120 Hz). The EMG was amplified by a differential amplifier (Hewlett Packard 8802 A) and filtered (bandwidth 3–500 Hz). The SMG and EMG were displayed on a two-channel oscilloscope (Tektronics model 2211) to control the quality of the signals on-line and were stored on a portable computer hard disk (Toshiba model T 5200)

Table 1 Values for age, body mass, height, and muscle-bone area (*MBA*) of the arm of elderly and young subjects. The mean values of the maximal voluntary contraction (*MVC*) and *MVC* per unit of *MBA* are also given

		Age (years)	Body mass (kg)	Height (cm)	MBA (cm^2)	MVC (N)	MVC/MBA ($N \cdot cm^{-2}$)
Men							
Elderly	Mean	70	73.0	170	50.5	196	3.9
	SEM	1	2.2	2	1.8	15	0.4
Young	Mean	27	76.2	179	64.3	353	5.5
	SEM	2	3.0	3	3.4	16	0.4
Women							
Elderly	Mean	71	65.9	158	42.9	137	3.2
	SEM	2	2.6	2	1.4	4	0.2
Young	Mean	25	54.0	163	35.9	186	5.2
	SEM	1	2.2	2	1.8	7	0.1

after analogue-to-digital conversion (Analogue Device model RTI 815). The sampling rates were 128 Hz (force), 512 Hz (SMG) and 1024 Hz (EMG).

Signal analysis

The analysis of EMG and of SMG was performed in time and in frequency domain by calculating the power content of the signals as root mean square (EMG-rms and SMG-rms) and the power spectrum density distribution, respectively. As in our previous studies (Orizio et al. 1990, 1992), the spectra of the two signals were calculated using the maximal entropy spectrum estimation method and the mean frequency (MF) of each spectrum was calculated.

Experimental procedure

After skin abrasion with fine sand paper and cleaning with ethyl alcohol, the probe was applied to the muscle belly by an elastic band. Previous studies (Orizio et al. 1992) have shown that the maximal pressure applied by the elastic band was less than 100 g at all intensities of contraction and thus no interference with the transducer response was expected.

All subjects familiarised themselves with the experimental set-up for 1 week before the actual test to maintain the required output force constant at the different levels of effort with the aid of a visual feedback (target force shown on the screen of the portable computer). The experiment began with the determination of the individual MVC of the elbow flexors as the highest of three MVC each lasting 3 s. Between one effort and the following one, about 5 min of recovery were allowed. Then the subjects were required to perform in a randomised sequence five levels of 4-s isometric contractions at 20%, 40%, 60%, 80% and 100% MVC. All the subjects were able to maintain the requested force within $\pm 5\%$ of the target absolute value during each contraction. During recovery the subjects remained with their arm in the stirrup with the probe in place. In all experiments only the middle 2 s of each 4-s exercise were analysed to avoid transient phenomena from rest to exertion.

Statistical analysis

Multiple regression analysis was carried out to evaluate the relationship among age and sex, anthropometric parameters, MBA and MVC. Regression analysis was also applied to the percentage MVC and EMG as well as SMG parameters. A two-way ANOVA was used to compare each variable (anthropometric variables, force, EMG and SMG parameters) as a function of age and sex. When a statistically significant difference was found, a more conservative posthoc method with orthogonal contrasts (Scheffé test) was performed. The accepted level of significance was set at $P < 0.05$.

Results

MVC and anthropometric variables of the arm

In Table I the characteristics of the subjects, the anthropometric variables, the mean MVC and the MVC per unit of MBA values of the four groups are shown.

The elderly men were weaker than their young counterparts ($P < 0.05$). The MVC was only 56% of that attained by the young subjects, although their MBA was 79% with respect to the young controls. The MVC per unit of MBA of the elderly men was 71% of that of young men ($P < 0.001$). Also elderly women were weaker than young women ($P < 0.05$). Even when they had a higher MBA ($P < 0.001$) than their young counterparts, MVC was only 74%, and MVC per unit of MBA was 62% ($P < 0.05$). The elderly women were weaker than the elderly men (-30%; $P < 0.05$) and their MBA was statistically lower than in the elderly men. When corrected for unit of MBA this difference was not statistically significant. In the young subjects, both MVC and MBA were considerably lower in the women than in the men ($P < 0.05$). The MVC did not present statistical differences between the young women and the young men when standardised per unit of MBA.

EMG signal

Figure 1 shows the mean values of rms as a function of the percentage of MVC found in the men (upper panel) and the women (lower panel) of both age groups. The

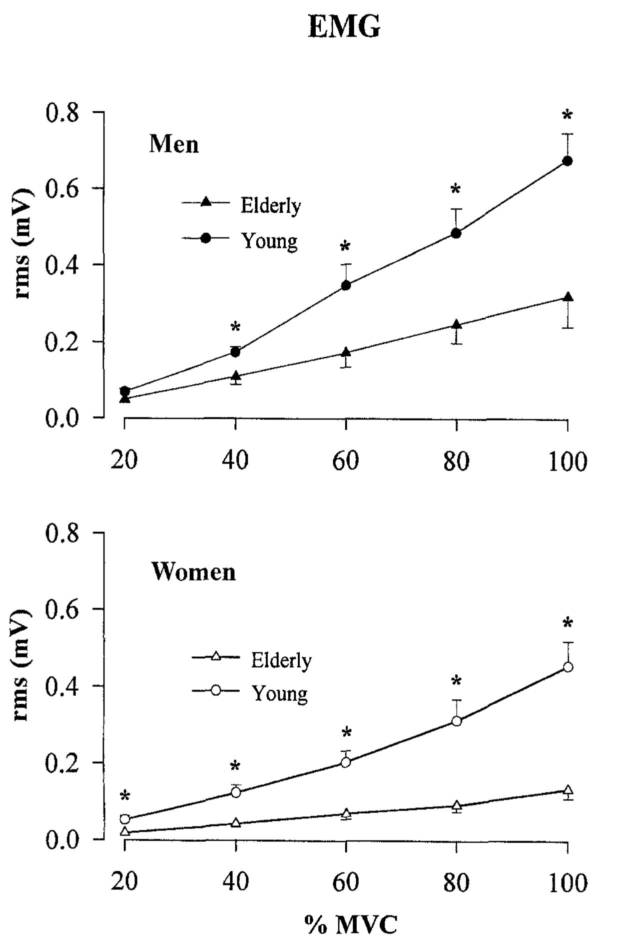

Fig. 1 Average and SEM values of the root mean square (*rms*) of the electromyogram (*EMG*) as a function of the percentage of the maximal voluntary contraction (%*MVC*). $^*P < 0.05$

increase in the power content of EMG (expressed as rms) in relation to the level of force was statistically significant in all the groups for the whole range of efforts. At 20% MVC the mean values ranged between 0.02 mV and 0.07 mV for all the subjects, reaching at 60% MVC the mean values of 0.18 mV and 0.35 mV for the elderly and the young men, respectively. For the women the corresponding values at 60% MVC were 0.07 mV (elderly women) and 0.20 mV (young women). With a further increase in the relative force the rms continued to increase with a slightly steeper slope up to 100% MVC, reaching the mean values of 0.32 mV and 0.68 in the men (elderly and young, respectively), and 0.14 and 0.46 mV in the women (elderly and young, respectively). Statistically significant differences were found between the elderly and the young subjects of both sexes at all relative efforts, except at 20% MVC in the men. Within the same age group the difference between the men and the women was statistically significant at 40% MVC, 60% MVC, 80% MVC and 100% MVC.

The mean values of MF are given in Fig. 2 as a function of the percentage of MVC. The observed increase in MF in relation to the level of effort was statistically significant in the four groups from 20% to 80% MVC. The MF ranged between 62 Hz and 89 Hz at 20% MVC and between 73 Hz and 108 Hz at 80% MVC, then it levelled off or even decreased slightly up to 100% MVC (range 72 Hz–99 Hz). The differences between the elderly and the young men were always statistically significant. In contrast, no statistical differences were found between the two age groups in the women. The elderly men and women differed statistically in all relative efforts. The same was also true for the young men and women.

SMG signal

In Fig. 3 the mean values of the power content of SMG are plotted as a function of the percentage of MVC in the men (upper panel) and the women (lower panel). The observed increase in rms in relation to the level of effort was statistically significant in all groups from 20% to 80% MVC. From 20% MVC (range

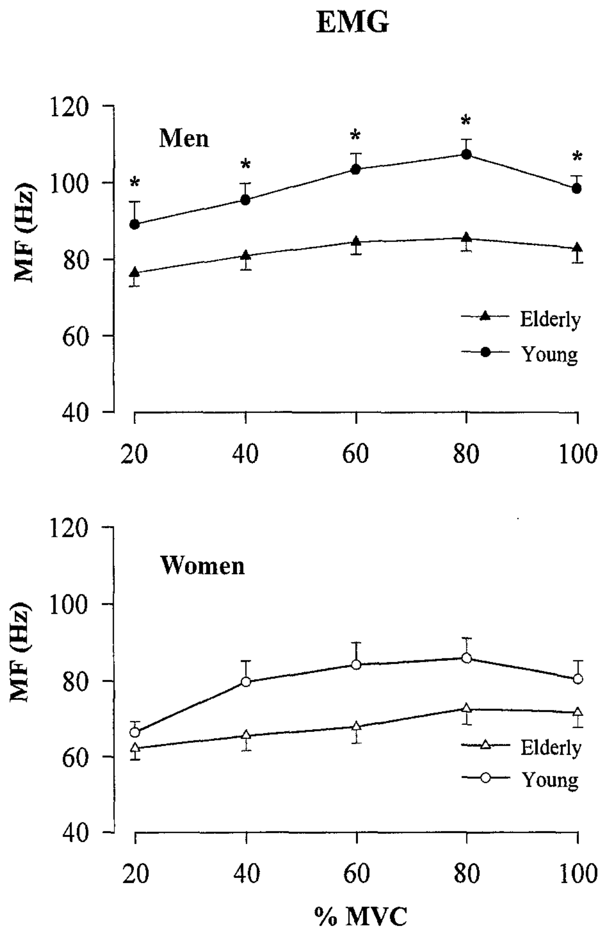

Fig. 2 Average and SEM values of the mean frequency (*MF*) of the electromyogram (*EMG*) as a function of the percentage of the maximal voluntary contraction (%*MVC*). $*P < 0.05$

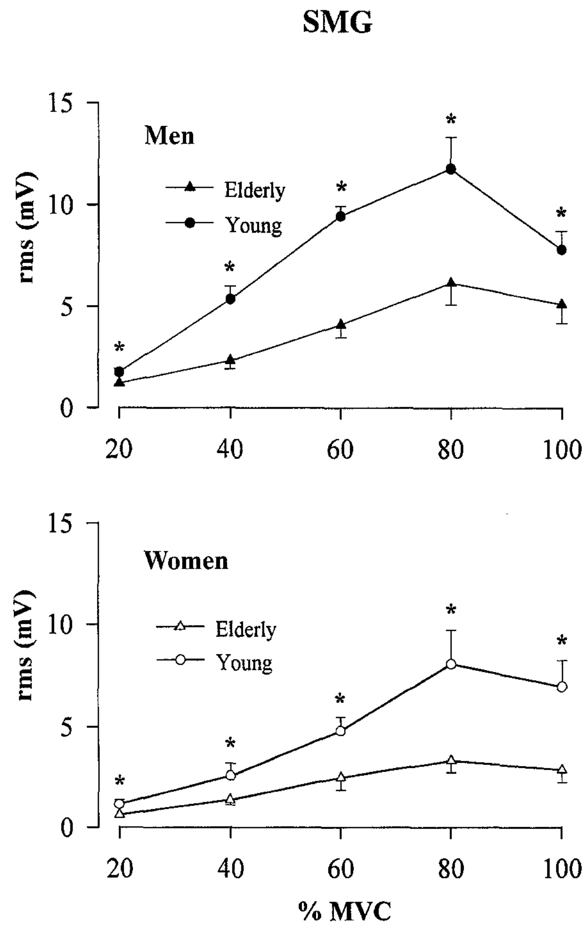

Fig. 3 Average and SEM values of the root mean square (*rms*) of the sound myogram (*SMG*) as a function of the percentage of the maximal voluntary contraction (%*MVC*). $*P < 0.05$

0.6 mV–1.8 mV) SMG increased in the four groups up to 80% MVC (range 3.3 mV–11.8 mV) and then declined to 100% MVC, where rms ranged between 2.9 mV and 7.8 mV. The decrease of rms from 80% to 100% MVC achieved statistical significance only for the young and the elderly men. Statistically significant differences between the elderly and young subjects of the same sex were observed at all contraction intensities. The sex differences were statistically significant between the young men and women, but not between the two elderly groups.

The power spectrum density distribution of SMG presented a typical shape in relation to the percentage of MVC and to the age of the subject. In Fig. 4 examples of the power spectrum in an elderly man (71 years, MVC = 196 N) and in a young man (22 years, MVC = 337 N) at 20% MVC and at 80% MVC are given. Similar shapes of the spectra were also found in all the subjects of the same age group. In the young controls the power spectrum distribution was clearly unimodal at 20% MVC (peak at about 12 Hz) and bimodal at 80% MVC (a peak at about 12 Hz and a second peak at about 40 Hz). In the elderly subject, the power spectrum distribution was unimodal both at 20% and 80% MVC, with a well-defined peak only at about 12 Hz. At 80% MVC a residual power still existed beyond 40 Hz.

The mean values of MF are shown in Fig. 5 as a function of the percentage of MVC. The observed increase in MF in relation to the level of effort was statistically significant in all groups from 20% to 80% MVC, but from 80% to 100% MVC only for the young men.

The MF at 20% MVC ranged between 8.9 Hz and 11.4 Hz, then there was a continuous increase up to 100% MVC (range 15.4 Hz–21.9 Hz). The statistical analysis of MF for any given percentage of MVC showed that the elderly men had lower MF values ($P < 0.05$) than the young men at the highest level of effort (100% MVC), while the elderly women showed considerably lower values ($P < 0.05$) at 20%, 40% and 60% MVC when compared with the young women. Statistical differences between sexes were observed at the lower levels of effort (20%, 40% and 60% MVC) between the elderly men and the elderly women and at 100% MVC between the young men and the young women.

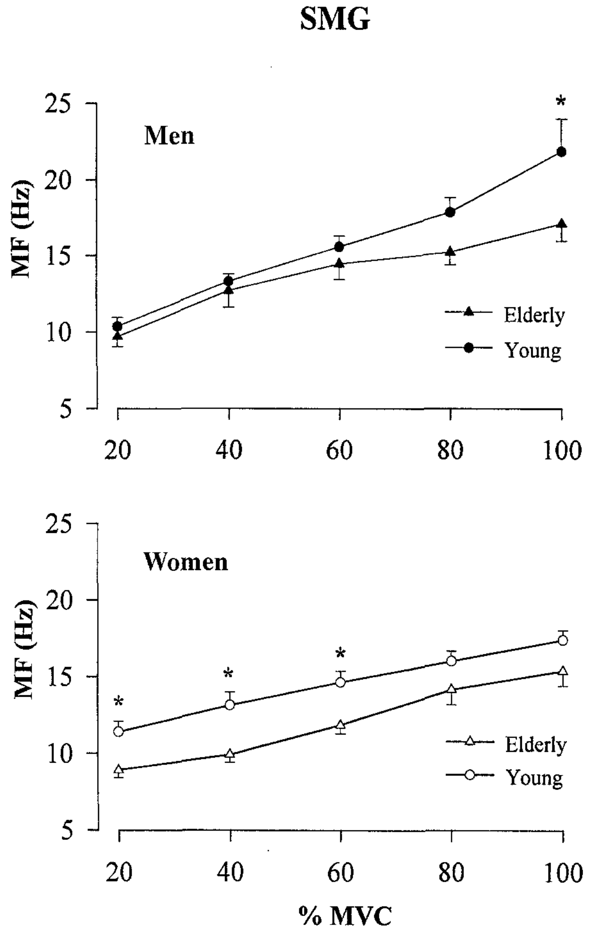

Fig. 5 Average and SEM values of the mean frequency (*MF*) of the sound myogram (*SMG*) as a function of the percentage of the maximal voluntary contraction (% *MVC*). $^{*}P < 0.05$

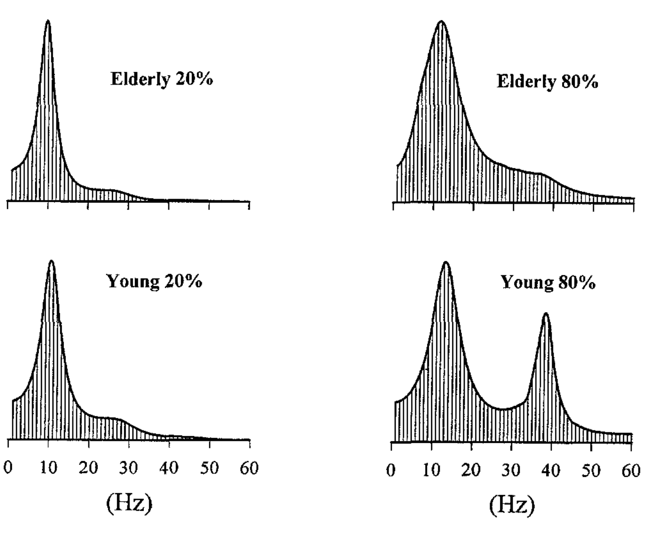

Fig. 4 Normalised power spectra of the sound myogram (*SMG*) at 20% and 80% of the maximal voluntary contraction (*MVC*) of the elbow flexors in a representative elderly and young subject

Discussion

It is well known that in skeletal muscle a reduction in the number of MU takes place with ageing (Brown et al. 1988; Doherty et al. 1993). This reduction involves both MU with type I and type II fibres. However, a significant decrease in type II fibres has been described in some muscles such as the vastus lateralis muscle (Larsson et al. 1979; Grimby et al. 1982; Lexell et al. 1983; Aniansson et al. 1986; Grimby 1988; Klitgaard et al. 1990; Doherty et al. 1993) but not in the biceps brachii muscle (Grimby 1988; Doherty et al. 1993). Apparently, in biceps brachii muscle the fibre typing is not greatly affected by the ageing process. It has been postulated that the relative preservation of type II fibres in this muscle, when compared with the vastus lateralis muscle, might be related to the daily physical activity requiring more forceful contractions of the upper in respect to the lower limbs in elderly subjects (Grimby et al. 1982).

MVC changes

A good correlation between muscle cross-section area and maximal force has been reported (Ikai and Fukunaga 1970). The cross-section area has been precisely estimated by computer tomography and is in agreement with the values of muscle-bone area (de Koning et al. 1986), which is the variable calculated in this study. Thus, the observed difference in MVC among the investigated groups was, at least in part, due to the age-related decrease in muscle mass, reflected in MBA changes (see Table 1). However, the changes in MVC in the elderly were not directly related to the calculated MBA. This was particularly evident in the elderly women, in which MBA was larger than that of their young counterparts, as has already been reported by Bishop (1984). The determinants of this finding have not yet been clearly identified. The lack of correlation between the decrease in MVC and the decrease in MBA found in the present study has been supported by Borkan et al. (1983) and Larsson et al. (1979), who have observed fat and connective infiltration in the lean tissue of sedentary elderly subjects. This phenomenon, leading to an overestimation of the functionally available muscle cross-section area, has been described as being particularly evident in women (Frontera et al. 1991).

EMG and SMG changes with force

EMG

The rms versus %MVC and MF versus %MVC relationships have a similar trend in the four groups. For each contraction intensity the rms and the MF values were higher in young than in aged subjects. Both the number and the firing rate of the active MU contribute to the rms. As a consequence, a decrease in rms might have been due to the described reduction of the number of MU with ageing and to a possible impairment for the surviving MU to reach firing rate levels that are usually attained in young counterparts. A direct relationship between the overall conduction velocity of muscle fibres and EMG-MF has been previously described (Arendt–Nielsen and Mills 1985; Sadoyama et al. 1988). The loss in the elderly subjects of fast type II fibres with a high conduction velocity, even if not predominant in respect to the loss of type I fibres, may have contributed to the lower MF values found in the present study in the aged subjects at all contraction intensities.

Moreover, from low to high contraction intensities the maximal increase in rms and MF, in respect of their value at 20% MVC, was larger in the young than in the elderly subjects. This result confirmed previous EMG studies on tibialis anterior muscle in which it was hypothesised "a smaller proportion of muscle fibres with very low and very high conduction velocity in the elderly" resulting in "a more uniform structure of muscle fibres and motor units" (Merletti et al. 1992). In young women the biceps brachii muscles have been found to show a consistent prevalence of type I fibres (Brooke and Engel 1969) determining a rather uniform muscle structure. From this point of view, the ageing process may produce less dramatic effects on the equalisation of the muscle fibres' properties. Indeed, our data showed that between the young and elderly women, at all contraction intensities, no statistically significant differences in EMG-MF were found. The lower values of EMG-rms and MF in the women found in this work confirm previous data from Bilodeau et al. (1992).

SMG

By analogy to the EMG signal, even the lower values of rms and MF of SMG in the aged subjects can be explained by taking into consideration the MU number reduction with age. The SMG parameters have been found to be strongly influenced by the MU firing rate (Keidel and Keidel 1989; Zhang et al. 1992, Orizio et al. 1993). Beyond 80% MVC, the SMG-rms decreases. This is due to the fusion-like situation that leads to a reduction of the muscle fibre dimensional changes between a motor command and the following one and in turn to a reduction of the related pressure waves detected as SMG at the muscle surface. The decrease of SMG-rms from 80% to 100% MVC was less evident in the elderly than in the young subjects. This may have been due to a lower value of the overall MU firing rate attained by the aged subjects, as can be inferred by the work of Howard et al. (1988).

In the frequency domain large differences in MF between the young and elderly subjects were found at high and low contraction levels in the men and women, respectively. This may be in agreement with the observation that in the biceps brachii muscle the larger muscle fibres are the type II and the type I fibres for the men and women respectively (Brooke and Engel 1969). As a consequence, the effect of their loss is more easily detected in the force range of their recruitment, i.e. at low (MU with slow, type I fibres) and high (MU with fast, type II fibres) levels of contraction. Moreover, the results from the SMG spectrum of the young subjects at high levels of contraction were clearly bimodal, with a first peak in the 8 Hz–25 Hz band and a second peak in the 25 Hz–45 Hz. In contrast, the results from the spectrum of the elderly subjects were unimodal, with only one peak essentially in the low frequency range. Evidently, the decrease in fast twitch MU with an input firing rate between 15 and 30 Hz (Burke 1981) was responsible for the absence of a clear second peak.

Relationship between the motor unit activation pattern and the EMG and SMG parameters

The peculiar combination between the recruitment and the firing rates of the active MU used by the muscle to generate force is the so-called MU activation pattern (Basmajian and De Luca 1985). At each contraction intensity a specific level of MU recruitment and of mean firing rate can be found. The MU activation strategy may be inferred by the coupled time and frequency domain analysis of the surface EMG and SMG. It has been found that:

1. The EMG-rms is dependent on the number and firing rate of the active MU (Basmajian and De Luca 1985). It increases continuously from low levels of contraction up to MVC. The MF of the EMG power spectrum is influenced by the overall conduction velocity of the recruited MU (Arendt-Nielsen and Mills 1985; Sadoyama et al. 1988). As a consequence, during orderly recruitment of larger MU according to the Henneman's size principle, the related increase in conduction velocity is paralleled by the increase in EMG-MF. On this basis, it has been shown that the end of recruitment is indicated by the plateau in EMG-MF versus effort intensity relationship (Bilodeau et al. 1991; Sanchez et al. 1993).

2. The SMG-rms is peculiarly affected by the overall MU firing rate and presents a reduction at high firing rates. Moreover, the SMG power spectrum seems to contain information about the mean MU firing rate (Keidel and Keidel 1989; Orizio et al. 1990; Zhang et al. 1992). Thus the sharp increase of frequency rate to obtain more force when recruitment has been completed has been shown to be monitored by the coupled decrease (Orizio et al. 1989) and the steeper increase (Orizio et al. 1990) of the SMG-rms and SMG-MF versus % MVC relationships, respectively.

On the basis of the experimental evidence reported above we would suggest, as has previously been described (Orizio et al. 1994), the identification of the end of MU recruitment and the beginning of the predominant role of firing rate in force generation by the detection of a *divergence* in EMG-rms and SMG-rms versus % MVC relationships as well as in EMG-MF and SMG-MF versus % MVC relationships. The results of the present study indicated that in elderly subjects the MU activation strategy was not modified. In fact, from 20% to 100% MVC such divergences were detected at the same %MVC (80%) as in younger counterparts.

Influence of the skinfold thickness

The degree of accuracy of the technique presented in this study may be influenced by the skinfold thickness between the muscle fibres and the EMG and SMG detecting probe. As has been shown the skinfold thickness acts on the surface EMG as a low pass filter (Basmajian and De Luca 1985). It has been considered that this may reduce the EMG power content in the high frequencies (Bilodeau et al. 1992) and change the EMG spectrum parameter dynamics as a function of force (Bilodeau et al. 1995). On this basis it can be argued that the reduced value, in aged subjects, of the surface EMG parameters we found in our study, from the influence of the above cited phenomena related to the muscle aging process, may be partly due to the increase of the skinfold thickness with age. Similarly to EMG, the subcutaneous layer also acts as a low pass filter for the mechanical waves travelling from the muscle to the skin, as has been underlined by Jorgensen and Lammert (1976) who have indicated that "the magnitude of the mechanical vibrations is determined by the net force acting upon the tissue between the muscle and the skin surface and the mechanical properties of this layer of tissue". However, to the authors' knowledge no accurate studies on the relationship between skinfold thickness and the time and frequency characteristics of SMG have yet been carried out. Considering the subjects of our study, the analysis of the individual EMG and SMG time and frequency domain parameters as a function of the effort level indicates that, despite the interindividual differences in absolute values, their trends showed a similar behaviour within each group investigated. Thus, the experimental findings of the present study support the hypothesis of a similarity of MU activation pattern between young and elderly subjects.

Conclusion

In elderly subjects the EMG and SMG time and frequency domain parameters as a function of force:
1. Are in good agreement with the changes in the muscle due to the ageing process and
2. Suggest that the MU and recruitment is completed and the firing rate begins to play a major role in increasing force at the same % MVC as in younger counterparts.

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