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Abstract

Over the past decade, linear and nonlinear surface electromyography (EMG) variables highlighting different components of fatigue have been developed. In this study, we tested fractal dimension (FD) and conduction velocity (CV) rate of changes as descriptors, respectively, of motor unit synchronization and peripheral manifestations of fatigue. Sixteen elderly (69 ± 4 years) and seventeen young (23 ± 2 years) physically active men (almost 3–5 h of physical activity per week) executed one knee extensor contraction at 70% of a maximal voluntary contraction for 30 s. Muscle fiber CV and FD were calculated from the multichannel surface EMG signal recorded from the vastus lateralis and medialis muscles.

The main findings were that the two groups showed a similar rate of change of CV, whereas FD rate of change was higher in the young than in the elderly group. The trends were the same for both muscles.

CV findings highlighted a non-different extent of peripheral manifestations of fatigue between groups. Nevertheless, FD rate of change was found to be steeper in the elderly than in the young, suggesting a greater increase in motor unit synchronization with ageing. These findings suggest that FD analysis could be used as a complementary variable providing further information on central mechanisms with respect to CV in fatiguing contractions.

Keywords: electromyography, vastus lateralis, vastus medialis, muscle fiber conduction velocity, fractal dimension

(Some figures may appear in colour only in the online journal)

Introduction

Neuromuscular fatigue is an important factor in age-related phenomena. Muscle fatigue is defined as an exercise-induced decrease in force-generating capacity during maximal voluntary contractions (MVC), or a failure to maintain a required or expected force (Gandevia 2001, Enoka and Duchateau 2008). Muscle fatigue can arise from many points of the neuromuscular system and can be divided into central and peripheral fatigue according to its origin (Gandevia 2001). Overall, the results to date suggest that both central and peripheral factors may be mechanisms by which age-related differences in fatigue resistance vary during isometric and dynamic contractions. Studies conducted in the past few decades generally indicate that in elderly adults, muscles fatigue relatively less than in young adults (Kent-Braun 2009). This counterintuitive finding is known as the 'fatigue paradox' and is based on the observation that elderly adults exhibit a longer time to task failure than young adults when performing a submaximal isometric contraction (Christie *et al* 2011). Many features of the elderly neuromuscular system can explain this 'paradox': selective atrophy or denervation of type II fibers (Andersen 2003), slowing in the contractile properties, lower motor unit (MU) firing rates, and greater reliance on oxidative metabolism (Kent-Braun 2009).

A number of biological changes occur from the beginning of a fatiguing contraction: altered metabolic milieu; changes in muscle fiber conduction velocity (CV); alterations in the number and firing rate of the recruited MUs (Adam and De Luca 2005). Modifications of surface electromyography (EMG) during sustained contractions can highlight neuromuscular changes before the mechanical task failure (Merletti *et al* 1990). This allows the estimation of indices of fatigue avoiding discomfort related to exhaustive efforts, which is particularly advantageous with the elderly population (Boccia *et al* 2015b). We usually refer to myoelectric manifestations of fatigue as all the changes in surface EMG variables occurring during sustained muscle contractions. Since myoelectric fatigue is a multifactorial process, many indices of EMG fatigue can be estimated to highlight different characteristics of EMG signals (Gonzalez-Izal *et al* 2012). It can be suggested that combining sets of EMG variables provides useful information to characterize muscle fatigue. Consequently, Mesin and colleagues (Mesin *et al* 2009) proposed a novel bi-dimensional vector composed of two components: the rates of change of muscle fiber CV and fractal dimension (FD). They suggested that (during submaximal isometric contraction) changes in CV can be mainly related to peripheral mechanisms of fatigue, whereas changes in FD were mainly related to central ones.

CV is the first component of the index and it seems to be the most suitable variable to relate the modifications in EMG signals with the recruited MUs pool (Farina *et al* 2004).

CV increases gradually when larger MUs are recruited, such as when the intensity of muscle contraction increases (Andreassen and Arendt-Nielsen 1987), since it is positively related to the fiber diameter (Sadoyama *et al* 1988, Blijham *et al* 2006). During sustained contractions, CV decreases have been related to many factors including an increase in muscle acidosis (Brody *et al* 1991, Schmitz *et al* 2012), alterations in blood flow (Sjogaard *et al* 1988), decreasing of extracellular sodium (Na^+) concentration (Overgaard *et al* 1997), and accumulation of extracellular potassium (K^+) ions (Fortune and Lowery, 2009). Elderly sedentary people showed lower decrements of CV with respect to young subjects during sustained contraction (Merletti *et al* 2002, Bazzucchi *et al* 2004, Bazzucchi *et al* 2005), but the long term trained elderly did not show such a difference (Casale *et al* 2003).

The second component of the index is based on the quantification of the signal's geometrical complexity, which is defined as FD (Kauffman 1986, Gitter and Czerniecki 1995). It was initially used to characterize the levels of muscle activation (Anmuth *et al* 1994, Gupta *et al* 1997, Talebinejad *et al* 2009) and patterns of MU recruitment (Xu *et al* 1997). Later, Mesin and colleagues (Mesin *et al* 2009) compared FD with other electromyographic fatigue indices computed from synthetic sEMG signals.

They used two parameters to simulate synchronization, as proposed by Yao and colleagues (Yao *et al* 2000): the percentage of firings in each MU train synchronized with the firings of the other MUs; the number of firings synchronized together for each synchronization event, expressed as a percentage of the total number of MUs. During the simulation of fatiguing contractions, they found that FD was the EMG parameter least affected by CV changes, weakly affected by fat layer thickness, and most related to the level of synchronization, and so it is a promising index of central response to fatigue. Decrease in FD has been recently considered as an indicator of increased MU synchronization during sustained contractions (Beretta-Piccoli *et al* 2015).

MU synchronization is defined as a higher occurrence of simultaneous discharge of action potentials from different MUs than expected by chance. The most commonly used technique to estimate MU synchronization utilizes intramuscular EMG to assess the cross-correlation of pairs of single MU action potential trains (Nordstrom *et al* 1992). However, only a very small MU population of the active muscle is typically examined when estimating MU synchronization by needle EMG (Semmler 2002). The representativeness of this small population and thus the physiological implications of the results can be questioned. On the other hand, many methods to obtain MU synchronization from the sEMG signal (Kleine *et al* 2001, Farina *et al* 2002, Del Santo *et al* 2006) provide a more representative index, but are dependent on CV and therefore need un-fatigued contractions since CV is affected by fatigue (Arendt-Nielsen *et al* 1989). Since FD is the EMG index least affected by CV changes (Troiano *et al* 2008, Mesin *et al* 2009), it has been considered as a promising index to monitor levels of synchronization in response to fatigue.

Distinguishing the contribution of MU synchronization from other myoelectric manifestations of fatigue could be important to gain insight into the muscle changes during fatigue and to differentiate for age among groups. Hence, the aim of the study was to use a bi-dimensional index to compare healthy young versus elderly subjects during a sustained contraction of knee extensor muscles. With regard to CV, the hypothesis was to confirm the results of Casale and colleagues (Casale *et al* 2003) for which CV rate of change was found to be similar between moderately trained young and elderly subjects. Meanwhile, we aimed to test if the FD rate of change could differentiate between the two groups as observed for other EMG parameters in the vastus lateralis (VL) and vastus medialis (VM) muscles, both in young (Rainoldi *et al* 2008) and in elderly subjects (Boccia *et al* 2015a).
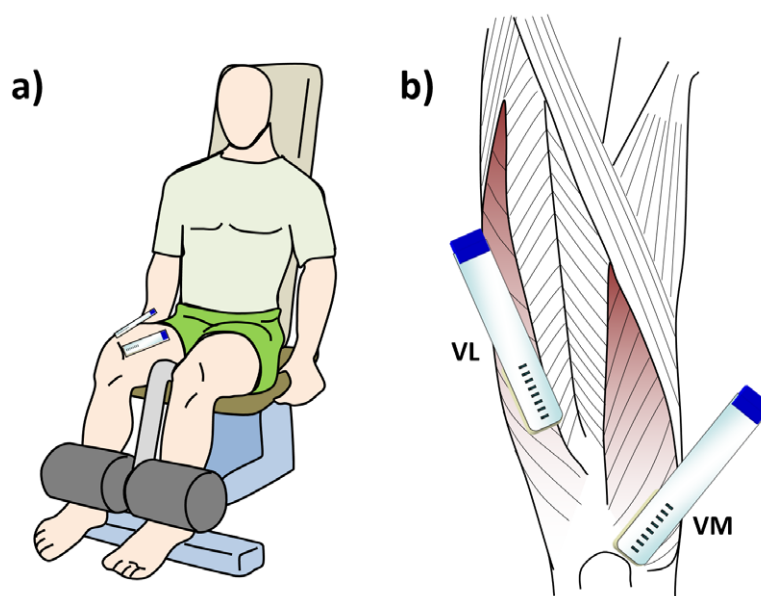
Figure 1. Participants were seated upright on the dynamometer chair (a). EMG signals were recorded from vastus lateralis (VL) and medialis (VM) muscles during an isometric knee extensor contraction of the dominant leg. EMG was recorded using linear adhesive electrode arrays of eight electrodes with 5 mm inter-electrode distance (b).

Methods

Sixteen elderly men (age 69 ± 4 years; height 171 ± 6 cm; weight 77 ± 7 kg) and seventeen young men (age 23 ± 2 years; height 178 ± 7 cm; weight 77 ± 7 kg) participated in the study. Part of this sample also participated in our previous study (Boccia *et al* 2015a). Both young and elderly participants were moderately trained and they were typically involved in 3–5 h of physical activity per week. Young participants were recruited from the Sport Science University population whereas elderly participants were recruited from a local physical activity program in which they have participated for more than three years. Participants were excluded from the study if they had any musculoskeletal or neurological disorders affecting the spine or the lower limb. Participants were asked to refrain from performing strenuous physical activity 24 h before the experimental session. All participants gave written informed consent before the participation in the experiments. The research was previously approved by the Ethic Committee of Department of Neurological and Movement Science, University of Verona.

Procedure

This investigation was an experimental, cross-sectional study. Participants were involved in one test session during which EMG signals were recorded from the quadriceps muscle during a submaximal isometric knee extensor contraction (figure 1). Participants were seated upright on the dynamometer chair (Cybex Norm, Ronconcoma, USA) and secured using a seatbelt; a strap was placed on the exercising thigh in order to minimize the participants' movements. The participants were familiarized with the device by performing 10 submaximal isometric contractions at $60°$ of knee flexion ($0° =$ full extension). Then, two MVCs were exercised

at 60°, separated by 5 min of rest. If MVCs differed more than 5% from each other, a third MVC was performed. During MVCs strong verbal encouragement was given by an operator to induce the participant to reach his highest level in each trial. Each MVC attempt lasted 3–5 s. Participants received a visual feedback by Cybex software, and the highest MVC was considered to calculate sub-maximal loads.

Five minutes after the last MVC, participants were involved in one fatiguing contraction at 70% of the torque exerted during the MVC. They were instructed to maintain a constant knee extension at 60° for 30 s. Participants received visual feedback on a display about the actual knee angle and were instructed to hold the target value of 60°. The task was considered failed when the limb moved ±5° for more than 3 s. Standardized encouragement was provided by an operator to keep the limb as stable as possible.

EMG measurements

Myoelectric signals were recorded from VM and VL muscles of the dominant leg in a single differential configuration using linear adhesive electrode arrays of eight electrodes with 5 mm inter-electrode distance (OT Bioelettronica, Torino, Italy). Before the placement of the electrode arrays the skin was slightly abraded with paste and cleaned with water in accordance with SENIAM recommendation for skin preparation (Hermens *et al* 2000). Anatomical landmarks were adopted as described in previous methodological work (Rainoldi *et al* 2004). The optimal position and orientation of the array was sought for each muscle on the basis of visual inspection of the sEMG signals. The sites with clear propagation of muscle fiber action potential and the main innervation zones were identified using a dry linear array of 16 electrodes with 5 mm inter-electrode distance (OT Bioelettronica, Torino, Italy). The adhesive electrode arrays were then placed parallel to muscle fibers, distally with respect to the innervation zone, where unidirectional propagation of the MU action potentials was detected. To assure proper electrode–skin contact, electrode cavities of the arrays were filled with 20–30 μl of conductive paste (Spes-Medica, Battipaglia, Italy). The electrode arrays were fixed using extensible dressing (Fixomull®, Beiersdorf). The sEMG signals were amplified, sampled at 2048 Hz, bandpass filtered (3 dB bandwidth, 20–450 Hz, 12 dB/oct slope on each side), and converted to digital data by a 12-bit A/D converter (EMG-USB, OT Bioelettronica, Torino, Italy). Samples were visualized during acquisition and then stored in a personal computer using OT BioLab software (version 1.8, OT Bioelettronica, Torino, Italy) for further analysis.

At the end of the measurement session, participant's subcutaneous tissue layer thickness was measured with an ultrasound scanner (Acuson P50, 7.5 MHz linear array transducer, Siemens, Germany), in the location where the adhesive arrays were positioned.

Data analysis

The sEMG signals were visually inspected in order to select the best channels to use for variable estimations. The CV of sEMG signals were computed off-line with numerical algorithms (Merletti *et al* 1990) using non-overlapping signal epochs of 0.5 s. CVs were calculated among all the accepted channels. CV was computed as *e/d*, where *e* is the inter-electrode distance and *d* is the delay time between the signals obtained from the two double differential arrays spaced 5 mm apart. The value of *d* was obtained by identifying the time shift required to minimize the mean square error between the Fourier transforms of the two double differential signals. The correlation coefficient between the two adjacent double differential signals was calculated: if the correlation coefficient was less than 0.80, the recorded signals were excluded from the analysis.
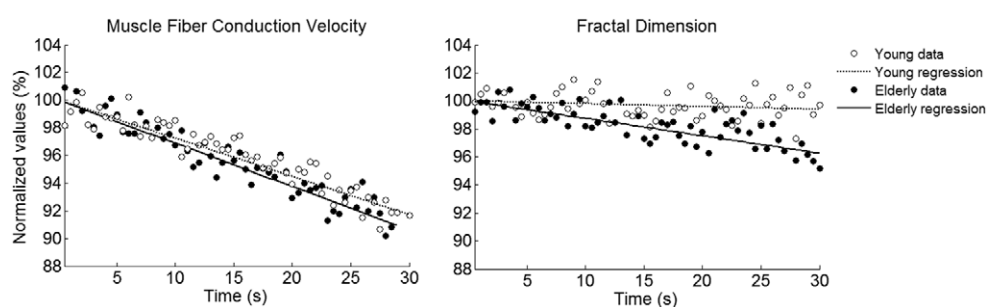
Figure 2. Time courses of muscle fiber conduction velocity (CV) and fractal dimension (FD) for young (white) and elderly (filled) representative participants. The surface EMG signals reported here were recorded from the VL during an isometric contraction at 70% of MVC. Each EMG variable is normalized with respect to its initial value and the slope of the regression line represents an index of myoelectric fatigue: the greater the rate of change of surface EMG variables, the greater the manifestations of fatigue.

FD was calculated with the box-counting method, as previously reported (Gitter and Czerniecki 1995, Mesin *et al* 2009). As expressed in Mesin *et al* (2009): 'a set of square boxes are used to cover the signal. When decreasing the side of the boxes in a dichotomic process, the number of boxes required to cover the signal increases exponentially. Plotting the logarithm of the number of boxes required to cover the signal versus the logarithm of the inverse of the box area, an approximately linear relation is obtained. The slope of the interpolation line (estimated in the least mean squared sense) is the fractal dimension'. FD is defined in the following expression as:

$$\mathrm{FD} = \frac{\log N}{\log \frac{1}{L}}$$

where N is the number of boxes required to cover the signal and L is the box side, with the ratio indicating the slope of the interpolation line.

Median power spectral frequency (MDF) and FD estimates were computed using non-overlapping signal epochs of 0.5 s and were averaged among all the accepted channels. Data were analyzed by custom-written software in MATLAB R2014a (Mathworks, Natick, Massachusetts).

Statistical analysis

Linear regression has been demonstrated to be the best model to fit EMG data during fatiguing contractions (Rainoldi *et al* 1999). Linear regressions were used to calculate the initial value and the rate of change (calculated as the percentage ratio between the change of EMG estimates in 1s and the initial value, expressed as %/s) of the EMG variables. Linear regression Kolmogorov–Smirnov tests were used to determine the normality of distributions. A two-way ANOVA (2 groups $\times$ 2 muscles) was conducted to detect differences in sEMG variables (CV, FD, and MDF). When the ANOVAs results were significant, the post hoc analysis was performed using the t test with Bonferroni correction. The paired t test was used to identify differences in MVC and subcutaneous tissue between groups. The threshold for statistical significance was set to $p < 0.05$. Data were expressed as mean $\pm$ SD.

Results

The young showed higher MVC torque than the elderly group (young: 326 ± 50 Nm; elderly: 236 ± 28 Nm; Cohen's $d = 2.2$; $p < 0.001$). No differences were detected in sub-cutaneous tissue thickness between groups both in VM (young: 4.0 ± 1.7 mm; elderly: 3.6 ± 0.9; $p = 0.412$) and VL (young: 3.4 ± 0.8 mm; elderly: 3.9 ± 1.1 mm; $p = 0.562$). All CV estimates were found in the physiological range (ranged from 3.6 to 5.6 m s^{-1}) and double differential signals showed a high correlation coefficient (ranging from 86% to 94%): consequently all EMG signals were included in the analysis.

CV and FD values for two young participants were classified as outliers (outside the interval mean $\pm$ 3SD) and thus removed from further analysis. Consequently, the analysis was performed only on 15 young and 16 elderly participants. Representative examples of CV and FD time course are reported in figure 2. The Kolmogorov–Smirnov tests ($p > 0.05$) showed normal distributions of data after removing the outliers.

CV

The initial values of CV showed significant group $\times$ muscle interaction ($F = 6.4$, $p = 0.017$). There was a significant main effect for group ($F = 4.7$, $p = 0.037$) whereas there was not a significant effect for muscle ($F = 0.5$, $p = 0.451$). The slope of CV did not show significant group x muscle interaction ($F = 0.3$, $p = 0.563$), and there was no significant main effect for muscle ($F = 0.1$, $p = 0.728$) and group ($F = 0.4$, $p = 0.527$). Post-hoc analysis is reported in table 1.

FD

The initial value of FD did not show significant group x muscle interaction ($F = 0.2$, $p = 0.612$). There was a significant main effect for group ($F = 5.7$, $p = 0.022$) whereas there was not a significant effect for muscle ($F = 2.7$, $p = 0.110$). The slope of FD did not show significant group x muscle interaction ($F = 0.7$, $p = 0.406$). There was a significant main effect for group ($F = 8.4$, $p = 0.007$) whereas there was not a significant effect for muscle ($F = 0.2$, $p = 0.635$). Post-hoc analysis is reported in table 1.

MDF

The initial value of MDF did not show a significant group x muscle interaction ($F = 2.2$, $p = 0.148$). There was a significant main effect for muscle ($F = 6.5$, $p = 0.017$) whereas there was not a significant effect for group ($F = 1.2$, $p = 0.276$). The slope of MDF did not show a significant group x muscle interaction ($F = 0.7$, $p = 0.408$). There was not an effect for group ($F = 0.7$, $p = 0.396$) and for muscle ($F = 0.01$, $p = 0.983$). Post-hoc analysis is reported in table 1.

Discussions

We investigated knee extensor muscles of physically active elderly compared to physically active young men using multichannel surface EMG during a fatiguing contraction. The main results were that the two groups showed a similar rate of change of CV, whereas FD rate of change was higher in the young than in the elderly group. The trends were similar for both VM and VL muscles.

Table 1. Initial values and slopes (i.e. normalized rate of change) of muscle fiber conduction velocity (CV), fractal dimension (FD), and median power spectral frequency (MDF) calculated during a fatiguing contraction at 70% of maximal voluntary contraction.

			Young	Elderly	Difference (95%IC)	Cohen's *d*	*P* value
CV	VM	Initial value (m s^{-1})	5.0 ± 0.3	4.8 ± 0.4	−0.2 (−0.1 to −0.4)	0.56	0.357
		Slope (%/s)	−0.24 ± 0.17	−0.25 ± 0.16	0.01 (−0.11 to 0.13)	0.06	0.851
	VL	Initial value (m s^{-1})	5.1 ± 0.3	4.6 ± 0.4	−0.5 (−0.1 to −0.7)	**1.41**	**0.004**
		Slope (%/s)	−0.23 ± 0.13	−0.29 ± 0.20	0.06 (−0.07 to 0.18)	0.35	0.408
FD	VM	Initial value	1.603 ± 0.025	1.625 ± 0.031	0.022 (−0.043 to −0.001)	−0.78	0.065
		Slope (%/s)	−0.033 ± 0.045	−0.081 ± 0.056	0.047 (0.009 to 0.085)	**0.94**	**0.015**
	VL	Initial value	1.593 ± 0.029	1.620 ± 0.035	0.026 (−0.050 to −0.002)	**−0.84**	**0.031**
		Slope (%/s)	−0.027 ± 0.039	−0.083 ± 0.059	0.055 (0.018 to 0.092)	**1.23**	**0.004**
MDF	VM	Initial value (Hz)	99.0 ± 14.0	100.5 ± 16.0	1.4 (−13.3 to 16.2)	−0.06	0.851
		Slope (%/s)	−0.36 ± 0.24	−0.42 ± 0.28	−0.05 (−0.30 to 0.18)	0.23	0.538
	VL	Initial value (Hz)	87.0 ± 15.1	98.0 ± 19.2	11.0 (4.9 to 25.9)	−0.64	0.072
		Slope (%/s)	−0.33 ± 0.26	−0.45 ± 0.26	−0.11 (−0.35 to 0.12)	0.46	0.166

Note: The differences between young and elderly trained men are reported as means (95%IC). Statistically significant differences are highlighted in bold.

During voluntary contractions, changes of CV are affected by both sarcolemmal function (peripheral mechanism) and MU recruitment (central mechanism) (Farina *et al* 2004). In the present study we aimed to separate the contribution of synchronization (which is influenced by central mechanisms (Farina and Negro, 2015)) from other manifestations of fatigue (being central or peripheral). Here we found that the two groups were similar in terms of CV changes but remarkably different in terms of FD changes. This finding appears to be important for gaining insight into the neuromuscular changes during fatigue and to distinguish among groups of different age.

CV rate of change

The physically active elderly group did not show differences in CV rate of changes with respect to the young group in knee extensor muscles (table 1). Accordingly, well-trained elderly subjects did not show differences with respect to young subjects in the tibialis anterior muscle (Casale *et al* 2003), notwithstanding sedentary elderly subjects showed lower decrements of CV (Merletti *et al* 2002, Bazzucchi *et al* 2004, Bazzucchi *et al* 2005) with respect to the sedentary young. Despite this, CV rate of change cannot be used to deduce the relative activation of muscle fiber types due to a number of confounding factors (Farina *et al* 2004); a lower proportion of type II muscle fibers has been demonstrated to generate a lower decrease of CV over time (Sadoyama *et al* 1988, Kupa *et al* 1995, Mannion *et al* 1998). However, regardless of fiber type composition, a lower decrease of CV over time has been considered as the EMG evidence of lower fatigability of the elderly with respect to young persons (Merletti *et al* 2001, Merletti *et al* 2002). Despite the fact that the analysis of the power spectral frequency was beyond the scope of this study, MDF showed trends similar to CV results. Indeed, the rate of change of MDF did not show a difference between the young and the elderly. Our results suggest that the older group showed the same fatigability as the young group, likely because long-term training performed by elderly subjects might have counteracted the aging effect usually observed in the muscles of sedentary subjects.

The isometric contraction used to assess fatigability was a task highly standardisable and easy to accomplish for the participants. However, such a task is far from real-life movement and everyday physical demands. The isometric contraction was chosen since it is the most reliable contraction for calculating CV. A high contraction level was chosen to recruit the whole available MU pool, thus excluding MU rotation (that is the MU recruitment/de-recruitment) (Bawa *et al* 2006) during the course of the contraction, which can bias CV estimates. Furthermore, we did not adopt a low-intensity task since it could have been affected by changes in central activation (Taylor and Gandevia, 2008), thus limiting the insight on peripheral fatigue as underlined by changes of CV.

FD rate of change

The negative FD rates of change in both groups suggest an increase in MU synchronization during the endurance contraction, probably as a result of an adaptation to muscle fatigue by the central nervous system. This is in agreement with a number of previous studies showing an increase in MU synchronization during fatiguing contraction with intensity from 25% to 100% of MVC (Holtermann *et al* 2009, Talebinejad *et al* 2010, Kumar *et al* 2011, Arjunan *et al* 2014, Beretta-Piccoli *et al* 2015). Two other studies conducted at an intensity of 20% (Contessa *et al* 2009) and 10% of MVC (Semmler *et al* 2000) did not report an increase in MU synchronization during the time course of the contraction. Taken together, these results suggest that during fatiguing contraction an increase in MU synchronization occurs at an intensity

higher than 20% of MVC. The FD rate of change was steeper in the elderly than in the young group, suggesting that the elderly subjects relied on MUs synchronization more than the young ones. Conversely, two previous studies, which adopted contraction levels of 50% and 10% of MVC, respectively, showed that MU synchronization was similar between young and elderly subjects (Kamen and Roy 2000, Semmler *et al* 2000). The divergence between previous results and ours is likely explained by the contraction level. We can speculate that the difference in MU synchronization between young and elderly subjects occurs only in fatiguing contraction at an intensity as high as 70% of MVC but not at a lower intensity, as occurred in previous studies. However, since we evaluated only one contraction level, definitive physiological conclusions cannot be drawn. Furthermore, in the process of age-related neuromuscular changes, it cannot be distinguished whether increased synchronization could be either beneficial or detrimental for the older individual (Kamen and Roy 2000). In this study, the FD variable appears more sensitive than the MDF variable in detecting differences between young and elderly men when fatigue occurred. This is in accordance with the observation of previous studies in which the MU synchronization descriptors were more sensitive to fatigue than power spectral frequency descriptors (Talebinejad *et al* 2010, Kumar *et al* 2011).

Initial values

The initial values of FD were higher in the elderly than in the young (reaching statistical significance in VL, table 1), suggesting that at the beginning of contraction the MU synchronization was lower in the elderly than in the young VL muscle. However, fat layers and skin properties (influencing myoelectric volume conduction and electrode–skin impedance) varied considerably between subjects and groups. These subject-dependent factors influenced (biased) the FD of the signal, but not the change of FD of a subject in time (Mesin *et al* 2009). As a result, single values of the FD will not necessarily reflect the actual MU synchronization level. However, the MU synchronization index (the rate of change of FD) avoids the subject-dependent bias providing a valid estimate of the actual change in MU synchronization level.

Since CV is positively related to muscle fiber diameter (Blijham *et al* 2006), it can be used to highlight fiber size differences in the superficial volume of VL and VM muscles. In agreement with our previous data (Boccia *et al* 2015b), the initial values of CV were higher in the young than in the elderly subjects (reaching statistical significance in VL but not in VM, table 1). It is possible to argue that the difference in muscle fiber size between the groups is evident only at VL but not in VM. However, greater details concerning this issue would be beyond the scope of this paper and are reported in our previous study (Boccia *et al* 2015b).

Limitations

The first limitation of the present study was that mechanical fatigue was not quantified (e.g. by means of time to task failure). Moreover, we were not able to distinguish between central and peripheral fatigue in the fatiguing contraction, since techniques such as interpolated twitch technique and evoked contractile properties were not used. It is likely that the firing rate influences the fractal properties of the surface EMG signal. Furthermore the development of muscular fatigue has been associated with a decline in MU firing rates and has been found in older adults (Kamen *et al* 1995) and during prolonged contractions in both populations (Christie and Kamen 2009). Hence, the combination of these factors has partially affected our results. For these reasons, future researches should focus on simultaneous estimation of MU synchronization and firing rate.

Finally, in recent years, alternative descriptors of MU synchronization, with low dependency on CV (e.g. sub-band skewness, Piper rhythm), have been developed and tested (Gronlund *et al* 2009, von Tscharner *et al* 2011), but were not taken into account in the present study.

Conclusion

In conclusion, young and elderly moderately trained men showed non-different CV rate of changes indicating non-different fatigability, and likely non-different muscle fiber composition, between groups. Nevertheless, FD rate of change was found to be steeper in the elderly subjects than in the young, suggesting a greater increase in MU synchronization during the contraction. Our results suggest that FD analysis could be used as a complementary variable providing information on central mechanisms with respect to CV in fatiguing contraction.

Conflict of interest

The authors declare that they do not have a conflict of interest.

References

Adam A and De Luca C J 2005 Firing rates of motor units in human vastus lateralis muscle during fatiguing isometric contractions *J. Appl. Physiol.* **99** 268–80

Andersen J L 2003 Muscle fibre type adaptation in the elderly human muscle *Scand. J. Med. Sci. Sports* **13** 40–7

Andreassen S and Arendt-Nielsen L 1987 Muscle fibre conduction velocity in motor units of the human anterior tibial muscle: a new size principle parameter *J. Physiol.* **391** 561–71

Anmuth C J, Goldberg G and Mayer N H 1994 Fractal dimension of electromyographic signals recorded with surface electrodes during isometric contractions is linearly correlated with muscle activation *Muscle Nerve* **17** 953–4

Arendt-Nielsen L, Mills K R and Forster A 1989 Changes in muscle fiber conduction velocity, mean power frequency, and mean EMG voltage during prolonged submaximal contractions *Muscle Nerve* **12** 493–7

Arjunan S P, Kumar D K and Naik G 2014 Computation and evaluation of features of surface electromyogram to identify the force of muscle contraction and muscle fatigue *Biomed. Res. Int.* **2014** 197960

Bawa P, Pang M Y, Olesen K A and Calancie B 2006 Rotation of motoneurons during prolonged isometric contractions in humans *J. Neurophysiol.* **96** 1135–40

Bazzucchi I, Felici F, Macaluso A and De Vito G 2004 Differences between young and older women in maximal force, force fluctuations, and surface EMG during isometric knee extension and elbow flexion *Muscle Nerve* **30** 626–35

Bazzucchi I, Marchetti M, Rosponi A, Fattorini L, Castellano V, Sbriccoli P and Felici F 2005 Differences in the force/endurance relationship between young and older men *Eur. J. Appl. Physiol.* **93** 390–7

Beretta-Piccoli M, D'Antona G, Barbero M, Fisher B, Dieli-Conwright C M, Clijsen R and Cescon C 2015 Evaluation of central and peripheral fatigue in the quadriceps using fractal dimension and conduction velocity in young females *Plos One* **10** e0123921

Blijham P J, ter Laak H J, Schelhaas H J, van Engelen B G, Stegeman D F and Zwarts M J 2006 Relation between muscle fiber conduction velocity and fiber size in neuromuscular disorders *J. Appl. Physiol.* **100** 1837–41

Boccia G, Dardanello D, Coratella G, Rinaldo N, Schena F and Rainoldi A 2015a Differences in age-related fiber atrophy between vastii muscles of active subjects: a multichannel surface EMG study *Physiol. Meas.* **36** 1591–600

Boccia G, Dardanello D, Rosso V, Pizzigalli L and Rainoldi A 2015b The application of sEMG in aging: a mini review *Gerontology* **61** 877–84

Brody L R, Pollock M T, Roy S H, De Luca C J and Celli B 1991 pH-induced effects on median frequency and conduction velocity of the myoelectric signal *J. Appl. Physiol.* **71** 1878–85

Casale R, Rainoldi A, Nilsson J and Bellotti P 2003 Can continuous physical training counteract aging effect on myoelectric fatigue? A surface electromyography study application *Arch. Phys. Med. Rehabil.* **84** 513–7

Christie A and Kamen G 2009 Motor unit firing behavior during prolonged 50% MVC dorsiflexion contractions in young and older adults *J. Electromyogr. Kinesiol.* **19** 543–52

Christie A, Snook E M and Kent-Braun J A 2011 Systematic review and meta-analysis of skeletal muscle fatigue in old age *Med. Sci. Sports Exerc.* **43** 568–77

Contessa P, Adam A and De Luca C J 2009 Motor unit control and force fluctuation during fatigue *J. Appl. Physiol.* **107** 235–43

Del Santo F, Gelli F, Schmied A, Vedel J P, Rossi A and Mazzocchio R 2006 Motor unit synchonous firing as revealed by determinism of surface myoelectric signal *J. Neurosci. Meth.* **155** 116–21

Enoka R M and Duchateau J 2008 Muscle fatigue: what, why and how it influences muscle function *J. Physiol.* **586** 11–23

Farina D, Fattorini L, Felici F and Filligoi G 2002 Nonlinear surface EMG analysis to detect changes of motor unit conduction velocity and synchronization *J. Appl. Physiol.* **93** 1753–63

Farina D, Merletti R and Enoka R M 2004 The extraction of neural strategies from the surface EMG *J. Appl. Physiol.* **96** 1486–95

Farina D and Negro F 2015 Common synaptic input to motor neurons, motor unit synchronization, and force control *Exerc. Sport Sci. Rev.* **43** 23–33

Fortune E and Lowery M M 2009 Effect of extracellular potassium accumulation on muscle fiber conduction velocity: a simulation study *Ann. Biomed. Eng.* **37** 2105–17

Gandevia S C 2001 Spinal and supraspinal factors in human muscle fatigue *Physiol. Rev.* **81** 1725–89 (PMID: 11581501)

Gitter J A and Czerniecki M J 1995 Fractal analysis of the electromyographic interference pattern *J. Neurosci. Methods* **58** 103–8

Gonzalez-Izal M, Malanda A, Gorostiaga E and Izquierdo M 2012 Electromyographic models to assess muscle fatigue *J. Electromyogr. Kinesiol.* **22** 501–12

Gronlund C, Holtermann A, Roeleveld K and Karlsson J S 2009 Motor unit synchronization during fatigue: a novel quantification method *J. Electromyogr. Kinesiol.* **19** 242–51

Gupta V, Suryanarayanan S and Reddy N P 1997 Fractal analysis of surface EMG signals from the biceps *Int. J. Med. Inform.* **45** 185–92

Hermens H J, Freriks B, Disselhorst-Klug C and Rau G 2000 Development of recommendations for SEMG sensors and sensor placement procedures *J. Electromyogr. Kinesiol.* **10** 361–74

Holtermann A, Grönlund C, Karlsson J S and Roeleveld K 2009 Motor unit synchronization during fatigue: described with a novel sEMG method based on large motor unit samples *J. Electromyogr. Kinesiol.* **19** 232–41

Kamen G and Roy A 2000 Motor unit synchronization in young and elderly adults *Eur. J. Appl. Physiol.* **81** 403–10

Kamen G, Sison S V, Du C C and Patten C 1995 Motor unit discharge behavior in older adults during maximal-effort contractions *J. Appl. Physiol.* **79** 1908–13

Kauffman L H 1986 The fractal geometry of nature—mandelbrot, B *J. Soc. Biol. Struct.* **9** 33–6

Kent-Braun J A 2009 Skeletal muscle fatigue in old age: whose advantage? *Exerc. Sport Sci. Rev.* **37** 3–9

Kleine B U, Stegeman D F, Mund D and Anders C 2001 Influence of motoneuron firing synchronization on SEMG charateristics in dependence of electrode position *J. Appl. Physiol.* **91** 1588–99 (PMID: 11568140)

Kumar D K, Arjunan S P and Naik G R 2011 Measuring increase in synchronization to identify muscle endurance limit *IEEE Trans. Neural Syst. Rehabil. Eng.* **19** 578–87

Kupa E J, Roy S H, Kandarian S C and De Luca C J 1995 Effects of muscle fiber type and size on EMG median frequency and conduction velocity *J. Appl. Physiol.* **79** 23–32 (PMID: 7559225)

Mannion A F, Dumas G A, Stevenson J M and Cooper R G 1998 The influence of muscle fiber size and type distribution on electromyographic measures of back muscle fatigability *Spine* **23** 576–84

Merletti R, Farina D, Gazzoni M and Schieroni M P 2002 Effect of age on muscle functions investigated with surface electromyography *Muscle Nerve* **25** 65–76

Merletti R, Knaflitz M and De Luca C J 1990 Myoelectric manifestations of fatigue in voluntary and electrically elicited contractions *J. Appl. Physiol.* **69** 1810–20 (PMID: 2272975)

Merletti R, Rainoldi A and Farina D 2001 Surface electromyography for noninvasive characterization of muscle *Exerc. Sport Sci. Rev.* **29** 20–5

Mesin L, Cescon C, Gazzoni M, Merletti R and Rainoldi A 2009 A bi-dimensional index for the selective assessment of myoelectric manifestations of peripheral and central muscle fatigue *J. Electromyogr. Kinesiol.* **19** 851–63

Nordstrom M A, Fuglevand A J and Enoka R M 1992 Estimating the strength of common input to human motoneurons from the cross-correlogram *J. Physiol.* **453** 547–74

Overgaard K, Nielsen O B and Clausen T 1997 Effects of reduced electrochemical Na$^+$ gradient on contractility in skeletal muscle: role of the Na$^+$-K$^+$ pump *Pflugers Archiv: Eur. J. Physiol.* **434** 457–65

Rainoldi A, Falla D, Mellor R, Bennell K and Hodges P 2008 Myoelectric manifestations of fatigue in vastus lateralis, medialis obliquus and medialis longus muscles *J. Electromyogr. Kinesiol.* **18** 1032–7

Rainoldi A, Galardi G, Maderna L, Comi G, Lo Conte L and Merletti R 1999 Repeatability of surface EMG variables during voluntary isometric contractions of the biceps brachii muscle *J. Electromyogr. Kinesiol.* **9** 105–19

Rainoldi A, Melchiorri G and Caruso I 2004 A method for positioning electrodes during surface EMG recordings in lower limb muscles *J. Neurosci. Methods* **134** 37–43

Sadoyama T, Masuda T, Miyata H and Katsuta S 1988 Fibre conduction velocity and fibre composition in human vastus lateralis *Eur. J. Appl. Physiol. Occup. Physiol.* **57** 767–71

Schmitz J P, van Dijk J P, Hilbers P A, Nicolay K, Jeneson J A and Stegeman D F 2012 Unchanged muscle fiber conduction velocity relates to mild acidosis during exhaustive bicycling *Eur. J. Appl. Physiol.* **112** 1593–602

Semmler J G 2002 Motor unit synchronization and neuromuscular performance *Exerc. Sport Sci. Rev.* **30** 8–14

Semmler J G, Steege J W, Kornatz K W and Enoka R M 2000 Motor-unit synchronization is not responsible for larger motor-unit forces in old adults *J. Neurophysiol.* **84** 358–66

Sjogaard G, Savard G and Juel C 1988 Muscle blood flow during isometric activity and its relation to muscle fatigue *Eur. J. Appl. Physiol. Occup. Physiol.* **57** 327–35

Talebinejad M, Chan A D, Miri A and Dansereau R M 2009 Fractal analysis of surface electromyography signals: a novel power spectrum-based method *J. Electromyogr. Kinesiol.* **19** 840–50

Talebinejad M, Chan A D C and Miri A 2010 Fatigue estimation using a novel multi-fractal detrended fluctuation analysis-based approach *J. Electromyogr. Kinesiol.* **20** 433–9

Taylor J L and Gandevia S C 2008 A comparison of central aspects of fatigue in submaximal and maximal voluntary contractions *J. Appl. Physiol.* **104** 542–50

Troiano A, Naddeo F, Sosso E, Camarota G, Merletti R and Mesin L 2008 Assessment of force and fatigue in isometric contractions of the upper trapezius muscle by surface EMG signal and perceived exertion scale *Gait Posture* **28** 179–86

von Tscharner V, Barandun M and Stirling L M 2011 Piper rhythm of the electromyograms of the abductor pollicis brevis muscle during isometric contractions *J. Electromyogr. Kinesiol.* **21** 184–9

Xu L, Zhang D and Xian X 1997 Fractal dimensions of coals and cokes *J. Colloid Interface Sci.* **190** 357–9

Yao W, Fuglevand R J and Enoka R M 2000 Motor-unit synchronization increases EMG amplitude and decreases force steadiness of simulated contractions *J. Neurophysiol.* **83** 441–52 (PMID: 10634886)