CHAPTER 18

Motor unit firing behavior in the aged

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INTRODUCTION

During the last few decades, we have greatly increased our understanding of the neuromuscular changes which accompany normal aging. It is now well accepted that aged individuals sometimes exhibit characteristics which might otherwise be symptomatic of a disease process, yet often execute activities of daily living with relative ease. The first part of this chapter will briefly review neuromuscular characteristics of the aging system relevant to any discussion of motor unit firing behavior, as well as electromyographic observations which characterize the aging process. Comprehensive reviews are beyond the scope of this chapter, as these have been published elsewhere (Gutmann and Hanzlikova, 1972; McComas, 1977; Mortimer et al., 1982; Charness, 1985; Woollacott, 1986). A report on preliminary observations of motor unit behavior in aged adults will then be presented.

Relevant changes in the neuromuscular apparatus
Since nerve conduction velocity has been a major tool in the neurologist's diagnostic armamentarium, it is understandable that we have recognized an age effect on nerve conduction velocity for many years. Motor and sensory conduction velocities are both slowed with age (Gardner, 1940; Wagman and Lesse, 1952; Dorfman and Bosley, 1979; Ludin, 1980; Desmedt and Cheron, 1981). A partial cause for the decrease in the conduction velocity is the loss of the number of fibers which are able to propagate signals (Corbin and Gardner, 1937;

Swallow, 1966; O'Sullivan and Swallow, 1968), especially the larger myelinated ventral root axons (O'Sullivan and Swallow, 1968; Mittal and Logmani, 1987). Although other deleterious changes in axon ultrastructure also reduce transmission capability (Vizoso, 1950; Lascelles and Thomas, 1966). The decline in the number of active motoneurons corresponds to a decrease in the total number of functional motor unit (Brown, 1973; Campbell et al., 1973; McComas et al., 1973; Sica et al., 1976).

To some extent, the age-related decline in the integrity of the neuromuscular apparatus resembles the changes which accompany peripheral neuropathic changes. The loss of axonal innervation of muscle fibers has been attributed to end plate changes resulting in deterioration of the muscle fiber (Gutmann and Hanzlikova, 1965). However, it is also possible that muscle fiber degeneration occurs first, and that the loss of neural innervation is secondary to spontaneous fiber degeneration (Frolkis et al., 1976). In any case, it would seem that either a change in activity pattern or in trophic influences leads to clear morphological alterations in muscle.

While there have been several reports that muscle fiber type composition is altered towards a predominance of slow-twitch fibers, there is also contradictory evidence of no change in muscle fiber type composition (Grimby, 1983; Aniansson et al., 1986). Nevertheless, the size of the muscle fiber decreases (Rebeiz et al., 1972; Aniansson et al., 1986; Essen-Gustavsson and Borges, 1986;

Poggi et al., 1987), and there are a variety of histochemical, morphological, and physiological changes which reflect a clear tendency towards a predominance of slow muscle characteristics (Gutmann and Hanzlikova, 1972; Larsson et al., 1982; Vandervoort and McComas, 1986; Poggi et al., 1987). The extent of pathologic changes observed in muscle fiber ultrastructure (Tomonaga, 1977; Scelsi et al., 1980; Poggi et al., 1987) suggests that some fibers may deteriorate altogether.

Electromyographic correlates of aging
Recording by traditional concentric needle electrodes in aged individuals often reveals a prevalence of abnormal potentials. Indeed, sufficient reports are available to warrant the following observations:

(1) Concentric needle-recorded signals obtained from older adults often exhibit an increase in polyphasic potentials. A number of satellite potentials may also be present (Carlson et al., 1964; Fudel-Osipova and Grishko, 1963; Mitolo, 1968; Desmedt, 1981).

(2) The size of the action potentials tend to be larger in older adults (Sacco et al., 1962; Mitolo, 1968; Campbell et al., 1973; Hayward, 1977).

(3) The duration of the motor unit action potential is longer (Buchthal and Rosenfalck, 1955; Sacco et al., 1962; Carlson et al., 1964; Colston and Fearnley, 1967; Campbell et al., 1973; Dominicus, 1977; Desmedt, 1981; Rakowicz, 1983).

(4) The size of the recorded macro EMG potential (Stålberg, 1980) is greater in aged individuals (Stålberg and Fawcett, 1982), and the fiber density is greater (Sacco et al., 1962; Stålberg and Thiele, 1975; Thiele and Stålberg, 1975).

Considered in toto, these observations support the postulate that an active and continual denervation-reinnervation process occurs in an attempt to maintain the integrity of neuromuscular transmission. Although some have suggested that this process begins at some threshold age of perhaps 60

years (Brown, 1973; Tomlinson and Irving, 1977), or that some changes occur around age 30–40 with only moderate deterioration thereafter (Dominicus, 1977), it would seem more likely that this is a continual process which begins quite early, and may preferentially affect some nerves (e.g., common peroneal) more than others (Ochoa and Mair, 1969; Hayward, 1977; Rakowicz, 1983; Lexell et al., 1986).

Motor unit behavior in aged adults
While the study of motor unit action potential (MUAP) amplitudes, durations and shapes is readily conducted using a concentric needle electrode and conventional electromyographic apparatus, a description of motor unit firing behavior in the aged has not been presented previously, owing to the difficulty inherent in recording a reasonable sample of MUAPs at moderate contraction levels. However, the development of a new technique for the identification of MUAP firing occurrences during moderate force exertion has increased our understanding of motor unit behavior. The decomposition procedure, described by De Luca and co-workers (LeFever et al., 1982a,b; Mambrito and De Luca, 1983, 1984) uses recordings obtained from a specially designed quadrifilar electrode in conjunction with an algorithm which incorporates both template matching and motor unit firing history to identify individual motor unit firing occurrences with an accuracy often approaching 100%.

Previous experiments using this MUAP identification procedure have reported generally faster firing rates and greater use of rate coding in small muscles than in large muscles, an orderly pattern of motor unit recruitment-deactivation (De Luca et al., 1982a), and a common modulation of motor unit firing rates for units within a single muscle (De Luca et al., 1982b; De Luca, 1985). In the following section, we describe the results of some preliminary experiments utilizing the decomposition procedure to study motor unit firing behavior in older adults.

METHODS

Motor unit firing patterns were studied in the first dorsal interosseous (FDI) and the tibialis anterior (TA) muscles in ten aged (75 ± 10.1 years, range 63–100 years) individuals with no specifically identified neuromuscular disorders. Recordings from the FDI were obtained while the subject sat comfortably, the fingers of the right hand placed in a mold to restrict movement. For the TA recordings, the subject was seated in a modified dental chair, with the foot placed in a trough designed to immobilize the foot and record force in the ankle flexion-extension plane. Each individual performed a series of slow, isometric muscle contractions at 45–55% of maximal voluntary contraction (MVC), each contraction lasting approximately 20 s, with rate of tension development and relaxation not exceeding 10% MVC/s.

During the contraction, motor unit activity was recorded by a specialized quadrifilar needle electrode (Mambrito and De Luca, 1984) consisting of four wires placed in a 25-gauge cannula and exposed at a side port with an inter-electrode distance of 200 μm. The wire diameters were either 50 μm (for FDI recordings) or 75 μm (TA recordings). The recording configuration used yielded three channels of electromyographic information. These EMG signals were filtered (1–10 kHz) and stored on FM tape along with the force from the transducer. They were later digitized off-line at 50 kHz. An operator-interactive decomposition algorithm (Mambrito and De Luca, 1984) using both template matching and motor unit firing statistics was used to identify individual motor unit firing times. Typically, 4–6 motor unit action potential trains were identified from each contraction. An update on the decomposition technique may be found in chapter 3 of this volume.

RESULTS

During data acquisition some differences between the EMG signals obtained from aged subjects and those of young subjects (< age 30) studied earlier were evident. Quite often, our recording configuration yielded records which contained only 1–3 motor units at 40–50% MVC. In subjects under age 30, we have commonly recorded from eight or more units from the FDI muscle at force levels exceeding 30% MVC. For this reason, we generally select the electrode with 50 μm wire diameters which has a smaller pick-up area and attenuates the low-level activity from distant muscle fibers. However, in the aged subjects tested, as well as several subjects aged 30–40, we have often observed a smaller sample of units. A smaller number of units was always recorded from the TA muscle. These observations support earlier reports of a reduced number of motor units with age and, as discussed above, indicate that the process of denervation and reinnervation may begin as early as age 30.

While the motor unit action potential shapes recorded with these specialized electrodes often contained few phases, a large number of poly-
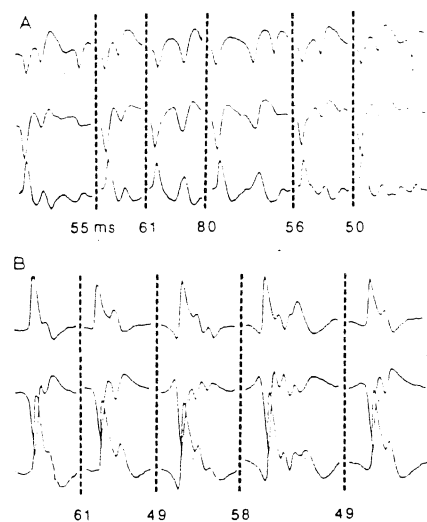

Fig. 1. Consecutive motor unit action potentials recorded from two aged subjects. Three channels from the quadrifilar electrode are shown for each unit. In each case, the top two channels are from a bipolar configuration; the bottom channel is a monopolar recording. *A*: 100-year-old male, FDI muscle. *B*: 63-year-old female, TA muscle. Interspike intervals (ms) are shown at the bottom.

phasic potentials were recorded, and these were more frequent in the TA muscle than in the FDI. The recorded potentials were usually less stable than those obtained from younger subjects. Fig. 1 is an example of two motor units recorded from two different subjects. Consecutive firings are shown for each unit, and one can see that the unit shapes tend to vary from firing to firing. Although we normally expect some change in the shape of the potentials over a period of several seconds, consecutive firings recorded from younger subjects are usually much more consistent than those in Fig. 1. Moreover, as previously reported from studies with concentric needle electrodes, the units recorded with this quadrifilar electrode tended to

be larger and longer in duration than those recorded from younger subjects.

The onset firing rates were similar in both FDI (12.5 pps) and TA (11.1 pps). However, peak firing rates at 50% MVC were significantly higher in FDI (27.9 pps) than in TA (19.3 pps, $P < 0.05$). This peak firing rate for FDI is similar to that reported by De Luca et al. (1982a) at 40% MVC.

In most cases, an orderly manner of recruitment-deactivation was found. However, there were some instances in the FDI in which an aberrant mode of recruitment-deactivation was observed. As seen in Fig. 2, the early recruited units were activated and deactivated in a normal manner, but the latter recruited units failed to stop firing until
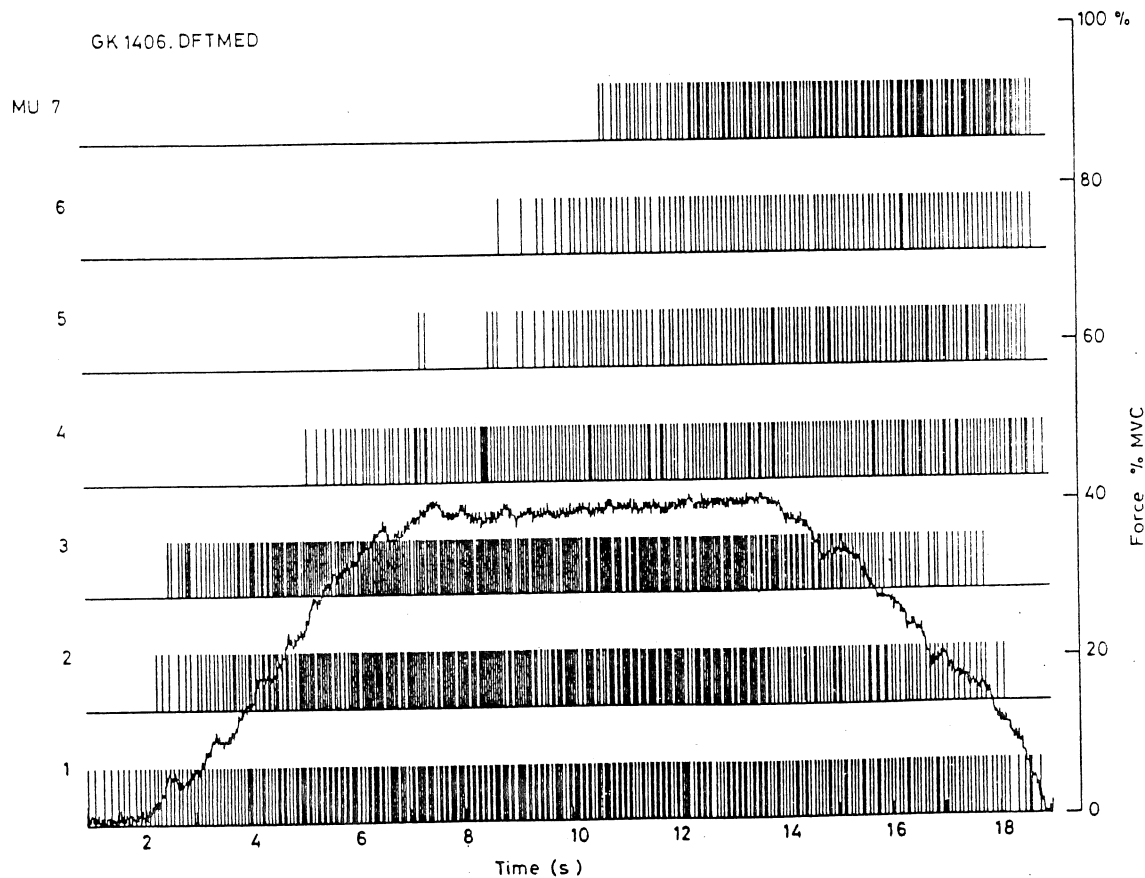

Fig. 2. An example of aberrant motor unit behavior in an aged subject. Firing times of seven motor units are shown during a 20 s contraction of the FDI. Each vertical line represents one firing. The solid line is the force trace. Note the delayed deactivation times for the upper four motor units.

the very end of the contraction. In other words, an abnormal firing pattern was seen in the high-threshold motor units. To date, we have observed this type of behavior in four subjects.

One possible explanation for this behavior is that these contractions were fatiguing, and so the higher-threshold units maintained their activity for a longer time to compensate for the reduction in contractile force. However, this fatigue explanation does not seem likely, since (1) one would expect the high-threshold units to be more sensitive to muscular fatigue (Burke et al., 1971), (2) it seems unlikely that these 20 s contractions, with less than 10 s at 50% MVC would be fatiguing, and (3) the force trace in Fig. 2 is quite stable. Were the contraction fatiguing, one would normally expect either an inability to maintain the 50% MVC level, or considerable tremor in the force recording.

The older individuals exhibited substantial difficulty in following the required force trajectory. Quite often, it seemed that the subjects were not able to produce smooth force gradations. Rather, they would produce a stable force level, and then reach a new force level by recruitment of an additional motor unit. As seen in Fig. 3, although the
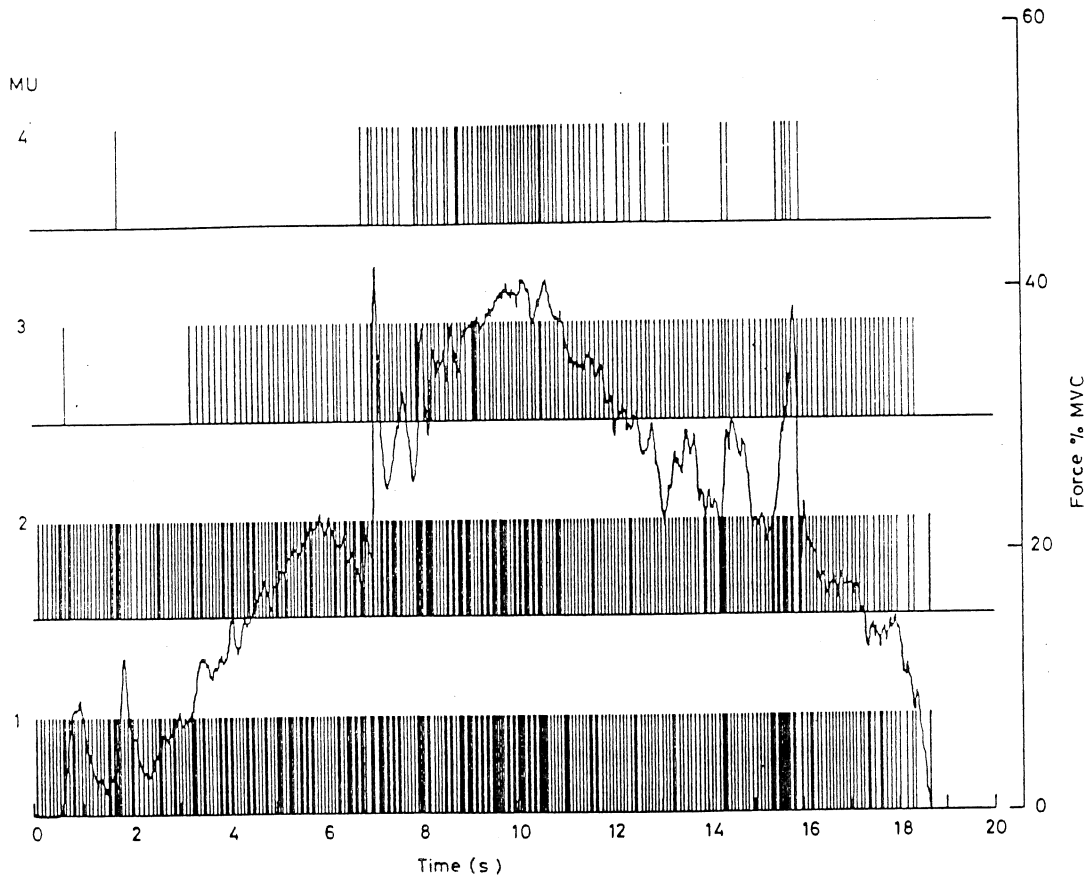

Fig. 3. The firing times of four motor units are shown along with the force trace (solid line). The subject was required to produce a slow increase in force to 50% MVC at 10 s, followed by a slow relaxation, achieving 0% MVC at 18 s. The subject was unable to produce a smooth force trajectory. Note that activation of the top motor unit occurs concurrently with a large increment in force. In this example, the subject also produced a similar increase in force during the descending phase of the contraction. Some other subjects exhibited similar jumps in force during the relaxation phase.

subject was required to produce a smooth increase in force to approximately 50% MVC using the FDI muscle, the final 'step' to the achieved force level was accomplished by the recruitment of a new unit and (see Fig. 4) by firing the earlier recruited units in doublets. As well, the relaxation process was marked by a sudden force increase and then the deactivation of the highest-threshold unit. This was approximately the tenth practice trial for this subject and the earlier trials were also marked by an inability to produce a smooth force trajectory. Indeed, many of the older subjects had difficulty producing fine gradations of muscular force.

One logical explanation for this behavior assumes that morphological changes have occurred in the muscle. As the number of active motor units

decreases, along with an increase in fiber density, and a decrease in muscle fiber diameter, it may well be that the main priority of the neuromuscular apparatus is to maintain maximal contractile capability. This is achieved by attempting to maintain 100% muscle fiber innervation from collateral fibers. However, a reduction in the number of active motor units sacrifices a level of fine control. While this is not the only plausible explanation (e.g., some change in nigrostriatal activity, etc.), it would certainly account for the results obtained.

In some of the older adults examined, considerable ability to regulate motor unit firing rates has been shown. An example of motor unit firing rates from a 72-year-old adult can be seen in Fig. 5. Here the subject is contracting the FDI muscle,
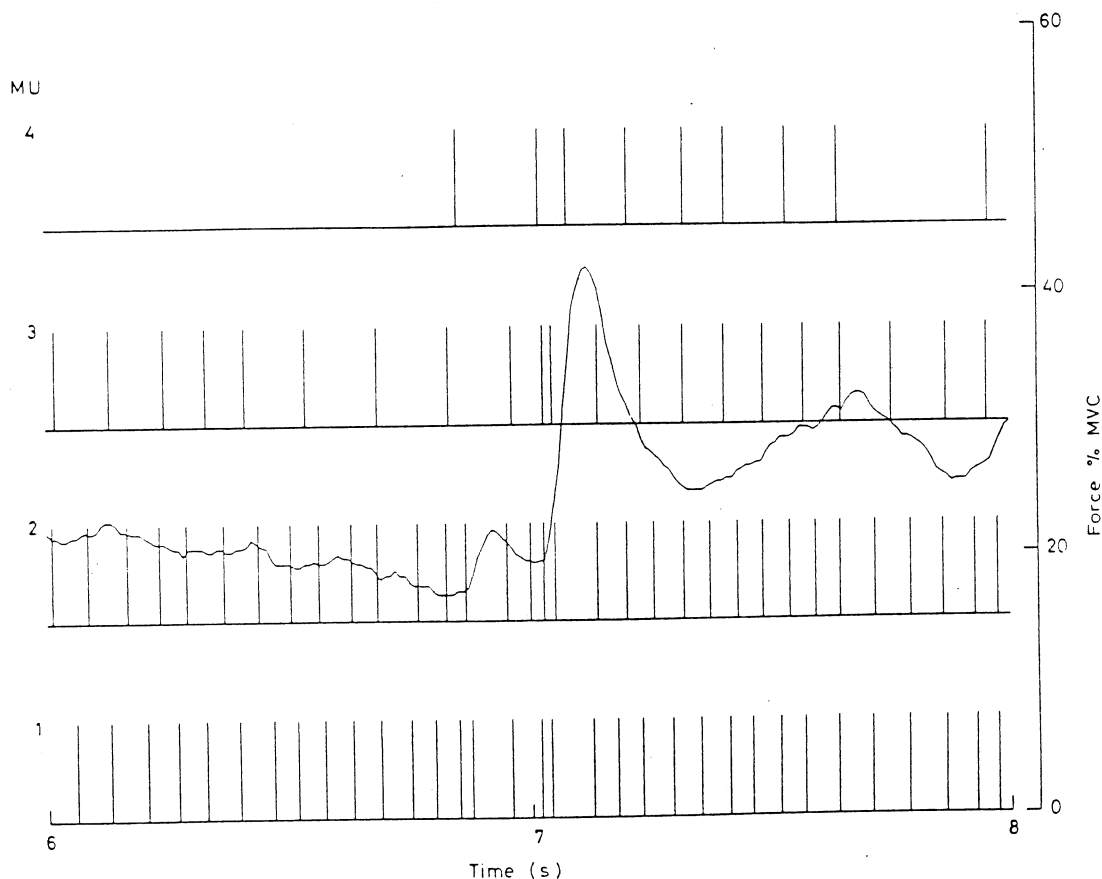

Fig. 4. The same contraction as that shown in Fig. 3, expanded during the period from 6 to 8 s. Note the doublet firing of the lower three motor units during the sudden jump in force.

attempting to maintain a 50% MVC force level. The firing rates of three motor units are shown, filtered with a Hanning window using a filter width of 400 ms. The earliest recruited motor unit (no. 1, threshold 7% MVC) has a higher firing rate than units 2 and 3, both recruited at 35% MVC. In general, changes in force produce reversals in firing rate direction of the earlier recruited unit (no. 1) before the two later-recruited units. This phenomenon of firing rate reversal in low-threshold units prior to high-threshold units has been demonstrated earlier (De Luca, 1985) and, assuming low-threshold units fire at generally higher rates than high-threshold motor units, is a mechanism by which individuals can produce accurate gradation (and reversal) in force. So, at least in this older

subject, a mechanism for the fine control of force has been preserved. We should note, however, that considerable variability in firing rate reversal has been observed among older subjects.

Note the similar changes in motor unit firing rate for the three units in Fig. 5, especially evident for units 2 and 3 which have similar firing rates. One of the most intriguing findings made possible by the ability to identify MUAPs with close to 100% accuracy involves the concept of common drive (De Luca et al., 1982b). Motor units recorded from the same muscle exhibit in phase (essentially zero time shift) fluctuations in firing rates. This fluctuation in firing rate is observed even when the subject is maintaining a constant force contraction.
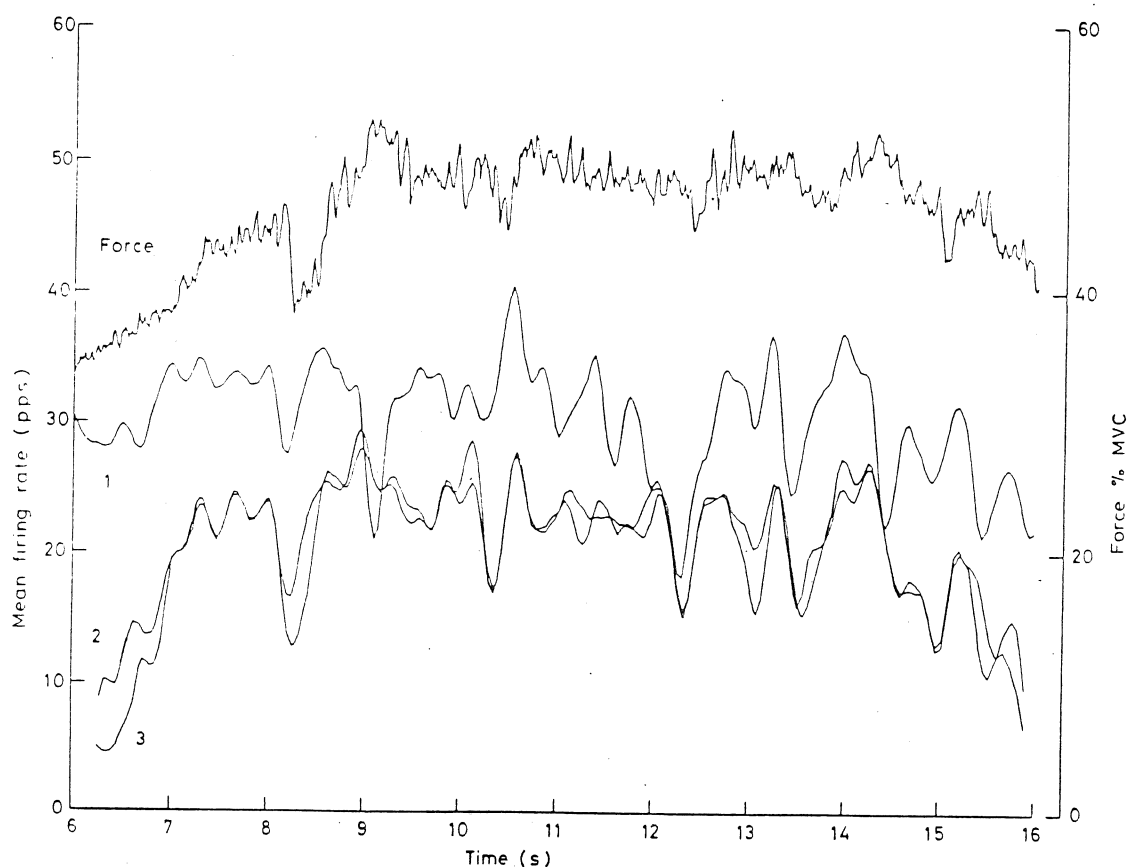

Fig. 5. Mean firing rates of three motor units are shown along with the corresponding force trace. Note the similar modulation of firing rate of the three units, especially units 2 and 3 whose firing rates practically overlap.
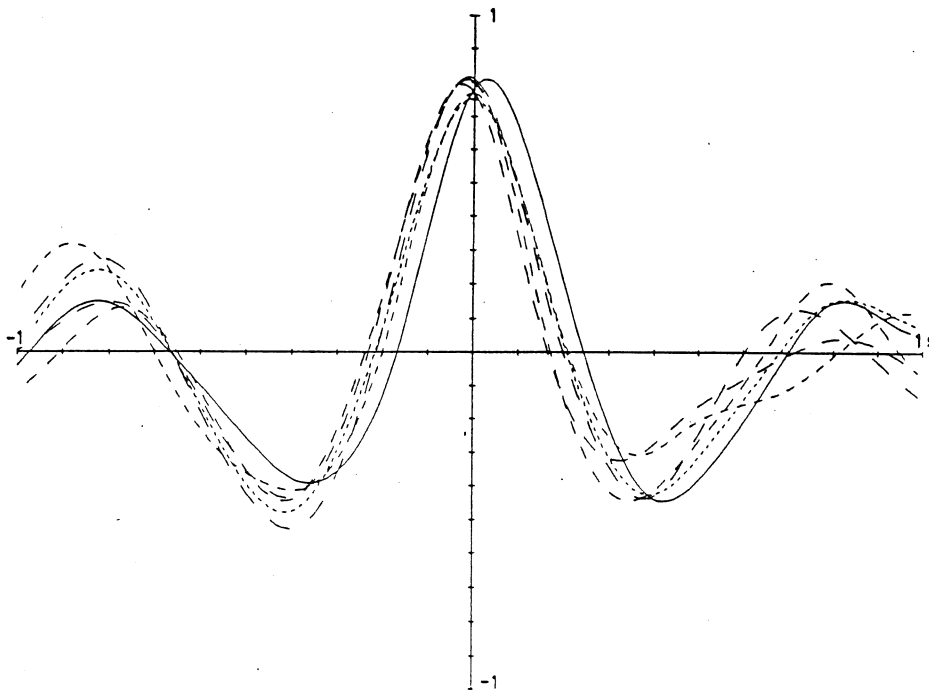
Fig. 6. Cross-correlation functions of five pairs of motor units during contraction of the tibialis anterior muscle.

The simultaneous modulation in motor unit firing rates can be further quantified by cross-correlating the firing rate trains of two simultaneously active motor units (De Luca et al., 1982b). It is important to note that this computation is highly dependent upon the accuracy of motor unit firing time identification, since a small number of missed firings can produce considerable change in the obtained cross-correlation values. In almost all of the old subjects tested so far, we have noted high cross-correlation scores at time lag 0 (see Fig. 6). This would suggest that a common input is controlling the firing rates of a large number of motoneurons in the available pool. The origin of this common firing rate fluctuation has not yet been established. One possibility is that the ensemble descending input to motoneurons and associated interneurons diverges, and exerts an equivalent excitatory/inhibitory effect on a large segment of the motoneuron pool. However, it is also possible that local length changes within muscle compartments result in the simultaneous fluctuations in firing rate. Thus, the fact that common drive can be demonstrated in older adults would seem to suggest that neither the changes involving skeletal muscle fibers nor those involving the intrafusal fibers (Swash and Fox, 1972) result in any impairment of the mechanism producing this common modulation of firing rates.

CONCLUSIONS

These preliminary findings indicate that the motor unit potentials recorded from older individuals tend to be longer in duration, greater in amplitude, and more polyphasic than those recorded from younger subjects. The shape of the motor unit action potentials may change (sometimes considerably) from firing to firing. Fine gradations in force are often quite difficult to achieve for older individuals. Common drive behavior, described

earlier in younger subjects, does not appear to be affected by age. These results suggest that there may be some changes in neuromotor control which accompany the aging process. Additional research on motor unit firing behavior may be helpful in distinguishing normal age-related changes from neuromuscular disease.