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Loss of muscle strength and power in older women and adaptation to resistance training

by
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CONTENTS

ABSTRACT

The studies described in this thesis aimed to examine some of the mechanisms underlying the lower levels of muscle strength and power in older women, who are at higher risk than men for age-related disability, and some of the adaptations in response to resistance training.

The initial study showed that it is not only a smaller contractile muscle volume, estimated separately from the intramuscular non-contractile tissue, which accounts for differences in quadriceps muscle strength, expressed as torque, between young and older women, but also a higher level of coactivation of the antagonist muscles.

Lower limb explosive power, which depends on both strength and speed of movement, and is more predictive of functional difficulties than strength *per se*, was then compared between young and older women during a single leg-press action after optimisation of load. The older women could not even move the resistance at which the young women achieved maximum power. Their lower levels of power, which appear to be more affected by ageing than isometric strength, were due to lower levels of both force and velocity at which maximum power was measured.

In the third study, the neural adaptations to a short-term resistance-training programme were investigated by analysing the time and frequency-domain characteristics of the surface electromyogram measured on the biceps-brachii muscle during constant-force sustained-isometric contractions. Older women responded to the same training programme with a lower increase in strength than the young women. This was accompanied by a different electromyographic response in the two groups.

Finally, three modalities of resistance-training, which were carried out for 16 weeks on a cycle-ergometer at either high-resistance and low-speed, low-resistance and high-speed, or a combination of both, were shown to be equally effective in improving power, strength and selected functional abilities in a healthy population of 65-74 year-old women.

The findings of these studies are discussed in relation to the current knowledge on mechanisms and adaptations of muscle strength and power in the older woman.

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CHAPTER 1

INTRODUCTION

Human muscle strength, which can be defined as the maximum force generated by an individual, reaches its peak between the second and third decades, shows a slow or imperceptible decrease until about 50 years of age and then begins to decline thereafter at the rate of approximately 12% to 15% per decade, with more rapid losses above the age of 65 years (Asmussen and Heeboll-Nielsen, 1962; Larsson et al., 1979; Viitasalo et al., 1985; Vandervoort and McComas, 1986; Borges, 1989; Narici et al., 1991; Metter et al., 1997; Lindle et al., 1997). Since this trend has been measured in studies with cross-sectional design, it would not be appropriate the use of words such as "decrease", "decline", "drop", etc., which imply that the strength of the older participants in their younger age was the same as that of the younger participants. This is a dangerous assumption, because the older people are of a different generation, with a lifetime of physical activity, health and nutrition that is probably unlike the habits of their young counterparts. However, as it is common practice in the literature, words such as "decrease", "decline", "drop", etc., will be used throughout this thesis even if inappropriate. There are few investigations with a longitudinal design that have determined how strength changes with ageing and, to the best of the author's knowledge, the same individuals were followed for no longer than 12 years (Aniansson et al., 1986; Kallman et al., 1990; Bassey et al., 1993; Greig et al., 1993; Winegard et al., 1996; Rantanen et al., 1997a; Frontera et al., 2000a). Most of the studies indicate that the decline in strength occurs at a higher rate than reported in cross-sectional investigations (Aniansson et al., 1986; Kallman et al., 1990; Bassey et al., 1993; Winegard et al., 1996; Frontera et al., 2000a), although no change (Greig at al., 1993) or even a slight increase in strength (Rantanen et al., 1997a) have both been measured. Direct comparisons between groups of young and older individuals have shown that the quadriceps muscles of older people aged around 70 years have approximately 60% of the force generating ability of young individuals aged 20-30 years (Young et al., 1984; Young et al., 1985; Klitgaard et al., 1990; Häkkinen and Häkkinen, 1991; Overend et al., 1992a; Frontera et al., 2000b), ranging from a minimum of 56% (Klitgaard et al., 1990) to a maximum of 76% (Häkkinen and Häkkinen, 1991; Overend et al., 1992a). It is likely that this variability of strength differences reflects different study populations, levels of physical activity, muscle groups investigated and testing methodologies. Moreover, Short and Nair

(1999) pointed out that the decline of muscle function in the whole population may be even greater than that reported, because many older individuals are excluded from research studies for the presence of disease. Finally, further evidence of this inevitable process of decay is given by measurements performed on master athletes, whose performance inexorably decline as they age, although 70 year-old athletes can have levels of strength, power and other functional capacities equivalent to 20 year-old sedentary individuals (Moore, 1975; Meltzer et al., 1994; Pearson et al., 2002).

The loss of strength with ageing is apparently true for both men and women (Danneskiold-Samsoe, 1984; Vandervoort and McComas, 1986; Borges, 1989; Frontera et al., 1991; Lindle et al., 1997). The early study of Asmussen and Heeboll-Nielsen (1962) reported that women began to decline at an earlier age than men, but this observation was not confirmed in further studies. However, it is evident that women are weaker than men in absolute strength of various muscle groups in all stages of life (Danneskiold-Samsoe, 1984; Vandervoort and McComas, 1986; Borges, 1989; Frontera et al., 1991; Lindle et al., 1997). For example, Frontera et al. (1991) reported that women had 60 and 59% the strength of men in the lower extremities when they were tested at slow and fast isokinetic speeds, respectively (the term isokinetic indicates that the movement of the displaced body segment is performed at constant angular speed). Similarly, Borges (1989) found women in different age groups to have 66% and 53% the isokinetic peak torque of men in the knee-extension and knee-flexion, respectively. Although males and females appear to show comparable age-related trends when maximal strength is referred to the unit of muscle cross-sectional area (CSA) (Vandervoort and McComas, 1986; Winegard et al., 1996; Lindle et al., 1997), in the latter stages of life absolute values of maximal strength in women can approach the minimal levels necessary to accomplish daily activities, thus suggesting that women should be the first target group in intervention and rehabilitation studies (Skelton et al., 1994).

Regional anatomical differences in the loss of strength have also been reported in the literature (Viitasalo et al., 1985; Frontera et al., 1991; Rantanen et al., 1997a; Lynch et al., 1999). The proximal muscles of the lower extremities are more affected by strength losses than those of the upper extremities, which in older people has been ascribed to a decreasing use of lower compared with upper limb muscles (Viitasalo et al., 1985; Frontera et al., 1991; Lynch et al., 1999). This is supported by the fact that age-related morphological changes are more pronounced in the quadriceps than in the biceps brachii muscle (Aniansson et al., 1986). By contrast, longitudinal data of Rantanen et al. (1997a) showed that older men and women slightly increased their knee extensor strength from 75 to 80 years, as opposed to a decrease in upper extremity and trunk strength. The investigators suggested that everyday activities at low intensity might have provided sufficient stimulus to the knee extensor musculature. This is in contrast, however, with the evidence that activities of daily living require little quadriceps strength, as during normal walking when quadriceps is activated only briefly at the beginning and end of the gait cycle (O'Toole, 1997). Moreover, individuals with weak quadriceps tend to supplement knee extensor movements with other muscles, such as arm muscles to get up from a chair, or alter their behaviour to avoid activities such as climbing stairs.

Muscle strength can be tested using three different modalities: isometric, dynamic or isokinetic (Frontera et al., 1989; Abernethy et al., 1995). Isometric or static strength is the maximum force that can be exerted against an immovable object, which corresponds to the maximum that can be measured in humans. Dynamic strength is the heaviest weight that can be lifted, whilst isokinetic strength is the maximal torque that can be exerted against a pre-set rate-limiting device. Maximum strength is measured during isometric contractions, in which there is no change in muscle length, whilst power is generated in actions that involve movement and is calculated as the product of force and speed at which movement occurs. In this thesis, muscle power will be considered as that generated in a single explosive movement, lasting a fraction of a second, where muscle metabolism does not limit the performance. This is different from "sustained power", which describes the ability to maintain a submaximal level of power output in activities of longer duration such as cycling or running (Sargeant, 1994). Fewer studies have been conducted on muscle power as compared to strength, possibly due to methodological difficulties, as will be discussed later in this chapter.

Lower levels of strength and, to a greater extent, power, are associated with functional limitations in daily living activities (Aniansson et al., 1980; Avlund et al., 1994; Skelton et al., 1994; Foldvari et al., 2000). In addition, muscle weakness is associated with an increased risk of falls (Tinetti et al., 1988; Campbell et al., 1989; Wolfson et al., 1995), hip fractures (Aniansson et al., 1984; Langlois et al., 1998) and adverse physiological changes such as loss of bone mineral density (Sinaki et al., 1986), which may predispose to osteoporosis.

The introduction of this thesis begins with a systematic examination of the main causes of muscle strength loss in old age. This is then followed by a review of the few studies specifically investigating muscle power, with power being more related to daily functional activities than strength *per se*. Finally, the focus is on how these age-related changes in muscle function can be improved through appropriate training programmes. Some of the studies on strength training in older people will be critically scrutinised, followed by the more limited number of investigations specifically aimed at improving muscle power and the few works looking at the effects of training on selected functional abilities.

Muscle size and morphology

Muscle size is reduced with ageing and this quantitative loss of muscle, referred to as "sarcopenia" (Evans, 1995), affects the generation of force. Sarcopenia has been measured using various techniques, which include measurements of total body potassium (Allen et al., 1960) or creatinine excretion (Tzankoff and Norris, 1977), histochemical analysis of muscle fibres, in either biopsy (for example Larsson et al., 1979) or autopsy (Lexell et al., 1983; Lexell et al., 1988) specimens, and imaging methods such as ultrasonography (Young et al., 1984; Young et al., 1985; Häkkinen and Häkkinen, 1991), computerised tomography (CT) (Rice et al., 1989; Klitgaard et al., 1990; Overend et al., 1992b) and, more recently, magnetic resonance imaging (MRI) (Jubrias et al., 1997; Kent-Braun and Ng, 1999; Kent-Braun et al., 2000).

In the early study of Allen et al. (1960) muscle mass was reduced by 23% in individuals from 20 to 80 years, as estimated from measurements of total body potassium. Similarly, Tzankoff and Norris (1977), at the end of the seventies, reported that the active muscle mass, as revealed by creatinine excretion, was 35% less in 80 year old individuals as opposed to those in their twenties. Grimby and Saltin (1983) later pointed out that the loss of muscle mass, which had been reported in the studies of Allen et al. (1960) and Tzankoff and Norris (1977), was in the same order of magnitude as the decline of strength in leg, back and arm muscles, thus relating weakness of older people entirely to muscle wasting.

Starting in 1977 with Tomonaga, many investigators have carried out a quantitative histochemical-analysis of muscle samples, obtained either by biopsy (for example Larsson et al., 1979) or autopsy (for example Lexell et al., 1983; Lexell et al., 1988), and have attributed the loss of muscle mass in older people, at microscopic level, to a reduction in the number and size of muscle fibres. An extensive review of these studies is beyond the purposes of this thesis and therefore the reader is referred to the work of Lexell (1995). According to the traditional histochemical classification, which is based on the differential sensitivity to an altered pH of the enzyme ATPase, two distinct fibre types have been identified and classified by their contractile and metabolic characteristics, slow-twitch fibres (type I) and fast-twitch fibres (type II). The type II fibres' speed of shortening and tension development is three to five times higher than type I, with type II depending almost entirely on anaerobic metabolism for energy, as opposed to aerobic metabolism in type I. In turn, type II fibres are further classified into IIa and IIb, with type IIa being considered intermediate, in that their fast speed of shortening and tension development is combined with a moderately well-developed capacity for both aerobic and anaerobic energy transfer. The loss of muscle tissue in older people has been attributed to reduced number of both slow-twitch fibres and fast-twitch fibres, plus a reduction in the CSA of single fibres, especially of type II. Fast-twitch fibres are intrinsically stronger than slow-twitch fibres and therefore muscles with the same area, but occupied by a relatively smaller area of fast-twitch fibres, will be able to generate less force (Jones and Round, 1990).

With the introduction of modern radiological imaging techniques, it has been possible to estimate muscle mass more directly. Sarcopenia has been documented with ultrasound imaging in the works of Young et al. (1984, 1985), who measured a 25% and 33% smaller quadriceps CSA in older men and women, respectively, (age range 70-81 years) than in young individuals (age range 20-29 years). Also Häkkinen and Häkkinen (1991) have shown a 27% smaller mid-thigh CSA of the quadriceps in older women aged between 66 and 75 years, as compared to the young, aged between 26 and 35 years. In these studies, however, muscle CSA may have been overestimated, particularly in older people, due to the presence of fat and connective tissue within the muscle belly, which cannot be detected and separated in the ultrasound scan. This problem has been overcome by the use of CT and MRI (Rice et al., 1989; Overend et al., 1992b; Kent-Braun et al., 2000), which enable not only to outline the muscle compartment area on each scan, at different levels of section, but also to estimate the muscle contractile component separately from the intramuscular non-contractile tissues (i.e., connective and fat tissue). The correlation coefficient between cadaver sections of human skeletal muscle and corresponding CT or MRI scans approached the unity, with the relative difference between cadaver and imaging measurements being 1.3% for both techniques (Mitsipoulos et al., 1998). The use of both these advanced imaging techniques has given further evidence of the wasting of contractile muscle occurring in older people with a substantial increase of fat and connective tissue, both within the muscle and in the overall body (Rice et al., 1989; Overend et al., 1992b; Jubrias et al., 1997; Kent-Braun and Ng, 1999; Kent-Braun et al., 2000; Janssen 2000). In particular, the recent data of Janssen et al. (2000), which present reference values for whole body skeletal mass of 468 individuals from 18 to 88 years, show a decline after the end of the fifth decade of 1.9 and 1.1 kg/decade in men and women, respectively, with a preferential decrease in the lower body.

Comparing the time-course of the decline in muscle mass with that of the decline in force indicates that the decline in force with ageing is generally greater and starts sooner than that of muscle bulk (Bruce et al., 1997). Similarly, Kallman et al. (1990) have shown that there is no relationship between how quickly subjects lose muscle mass, as indicated by the slope of creatinine excretion versus age, and how fast they lose grip strength, as indicated by the slope of grip strength versus age. This suggests that there may be other causes contributing to the decline in strength, other than muscle wasting, which are specific to the remaining muscle. In further support of this observation, some investigators have shown that muscle strength of the knee extensors is highly correlated with muscle size, but this relationship is higher in young than older populations (Häkkinen and Häkkinen, 1991; Overend et al., 1992a). In most of the research studies, however, it is the ratio between muscle strength and CSA, referred to as specific strength, which has been compared between young and older people, or examined across the life span, in order to determine whether strength losses could be attributed entirely to reduced muscle mass or other factors had to be taken into account (Young et al., 1984; Young et al., 1985; Klitgaard et al., 1990; Häkkinen and Häkkinen, 1991; Phillips et al., 1993; Jubrias et al., 1997; Kent-Braun and Ng, 1999; Frontera et al., 2000b). The results of these studies are still controversial. Young et al. (1985) and Klitgaard et al. (1990), have reported that the isometric specific strength of quadriceps muscle was 19% and 27% smaller, respectively, in young than older sedentary men. Similarly, other studies have observed a drop of isometric (Phillips et al., 1993) and isokinetic (Jubrias et al., 1997) specific strength of adductor pollicis and quadriceps muscles, respectively, in older subjects of both genders. Conversely, Kent-Braun and Ng (1999) and Frontera et al. (2000b) have reported no age-related differences in isometric strength of the ankle dorsiflexors and isokinetic strength of the knee extensors, respectively, after adjusting for CSA. Young et al. (1984) and Häkkinen and Häkkinen (1991) have also indicated that the quadriceps weakness of healthy women in their seventies can be adequately explained by the similarly smaller size of the muscle group. All of these investigators (Young et al., 1984; Young et al., 1985; Klitgaard et al., 1990; Häkkinen and Häkkinen, 1991; Phillips et al., 1993; Jubrias et al., 1997; Kent-Braun and Ng, 1999; Frontera et al., 2000b) have used the area of muscle cross-section at right angle to the long axis of the limb, referred to as anatomical CSA, to interpret data on muscle strength relative to muscle size in ageing muscle. However, in pennate muscles, such as the quadriceps, fibres run obliquely to the force-generating axis and insert into the tendon with an angle, referred to as "angle of pennation" (Narici and Capodaglio, 1998). Therefore, the anatomical CSA cuts a limited number of fibres, whilst it is the sum of the cross-sectional areas of all the muscle fibres within the muscle which should be used. This has been referred to as physiological CSA (PSCA), which can be calculated by measuring, with a combined use of MRI and ultrasonography, three parameters: muscle volume, fibre length and pennation angle. It has been recently found that pennation angle and fibre length in the human gastrocnemius were 13% and 8% less in older than young individuals, respectively (Narici et al., 1999). Therefore, PCSA is expected to decrease with ageing at a different rate than anatomical CSA, which may lead to a misinterpretation of the ratio between force and CSA (Narici, 1999).

Muscle excitability and contractility

Narici (1999), in his influential review of studies on the changes of muscle contractile properties with ageing, has attributed the loss of strength in older people not only to reduced muscle mass but, more exhaustively, to reduced excitable muscle mass. Therefore, it is suggested to take into account only the amount of muscle that is functionally active, as indicated by the term "excitable". This is strictly dependent, in turn, on the integrity of both the muscle fibres and the nerve cells that control them, namely the motoneurons. Neural and muscular system cannot therefore be separated and it is appropriate to consider muscle fibres and motoneurons as a whole. A single motoneuron and its family of innervated muscle fibres have been defined by Sherrington (1929) as the motor unit (MU). Fast-twitch MUs are composed by relatively large motoneurons with fast conduction velocities, which generally innervate between 300 and 500 muscle fibres (McArdle et al., 1996). On the contrary, slow-twitch MUs are composed by smaller motoneurons with slow conduction velocities, which innervate a smaller number of fibres. There are at least nine electrophysiological techniques of MU estimation in humans, most of which involve applying electric shocks of varying intensity to a peripheral nerve and measuring the evoked responses in the muscle (for review see McComas, 1998). The number of MUs is obtained by comparing an average parameter of the single MU, usually its action potentials, with the corresponding parameter of the whole muscle. The relative size of MUs is determined by comparing their mechanical responses to single or maximal repetitive stimulation, which are referred to as twitch or tetanic contractions, respectively. MUs have been shown to be reduced with ageing in both number and size, thus affecting the capacity of skeletal muscles to produce force (Brown et al., 1988; Doherty and Brown, 1993; Doherty et al., 1993). This is in agreement with previous evidence of a reduced number of limb motoneurons, in the human lumbosacral cord, by approximately 25% from the second to the tenth decade (Tomlinson and Irving, 1977). Consistent with this observation is the reduction in the number and diameter of motor axons in the ventral roots (Kawamura et al., 1977a; Kawamura et al., 1977b), which is accompanied by slower axonal conduction velocity (Metter et al., 1998; Wang et al., 1999). In animal studies, the selective atrophy of fast-twitch fibres, which has been reported earlier in this chapter, has been ascribed to the progressive loss of motoneurons in the spinal cord with initial denervation of fast-twitch fibres and reinnervation of these fibres by axonal sprouting from adjacent slow-twitch MUs (Brooks and Faulkner, 1994). This phenomenon of remodelling is supported, at the microscopic level of muscle analysis in humans, by morphological changes similar to those occurring in motoneuron diseases and chronic neuropathies, which include the presence of larger groups of muscle fibres of the same histochemical type, referred to as fibre type grouping, small and dark fibres with a peculiar geometrical shape, referred to as angulated fibres, and group atrophy (Jennekens et al., 1971; Lexell et Downham, 1991). Recent results of increased coexpression of myosin heavy chain (MCH) isoforms in the same fibre, as measured with electrophoretic techniques, which will be presented later in this chapter, are further evidence of this process of ongoing denervation and reinnervation (Andersen et al., 1999).

Results of Galea et al. (1996) suggest that the reduction of excitable muscle mass in the upper limbs is of neuropathic origin, i.e. denervation of MUs due to loss of peripheral motoneurons, for distal muscles, but of myopathic origin, i.e. atrophy of muscle fibres, in proximal muscles. The neuromuscular excitability has been evaluated by measuring the muscle electrical response evoked by the electrical stimulation of the motor nerve. M-wave is the result of the direct depolarisation of the motoneurons that innervate directly muscle fibres, with its area and amplitude being a measure of their excitability. The number of MUs has been estimated by comparing the average area of a sample of MU action potentials, which are obtained by incremental stimulation of the peripheral nerve, and the area of the maximum M-wave, which is the compound action potential of a muscle. The authors studied the number of MUs and the maximum M-wave of both the thenar muscle, a distal muscle, and the biceps brachii, a proximal muscle, in individuals in their eighties as compared to those in their twenties. In the thenar muscle, older individuals showed the maximum M-wave area and amplitude 22% and 33% lower, respectively, than young subjects, with a 50% lower number of MUs, thus revealing a loss of MUs with the presence of collateral reinnervation. On the contrary, in the biceps brachii, the area and amplitude of maximum M-waves were 50% and 30% less in the older than in the young, respectively, with no significant differences in the number of MUs, thus indicating the presence of less excitable muscle mass entirely due to fibre atrophy.

The older muscle not only is atrophied, but is also slower (Vandervoort and McComas, 1986; Narici et al., 1991; Roos et al., 1999), tetanizes at lower fusion frequencies (Narici et al., 1991; Kamen et al., 1995; Connelly et al., 1999; Roos et al., 1999), and is more resistant to fatigue than the young muscle (Narici et al., 1991; Bilodeau et al., 2001a). Slowing in the contractile properties has been demonstrated in various muscles of the lower limbs (Vandervoort and McComas, 1986; Roos et al., 1999), and in the adductor pollicis muscle (Narici et al., 1991), by measuring the duration of twitch contraction. Tibialis anterior, tibialis posterior (Vandervoort and McComas, 1986) and vastus medialis (Roos et al., 1999) are slower in individuals over 73 than young in their twenties, as demonstrated by the longer time taken not only to reach the peak of tension but also to relax after the twitch. Similarly, maximum relaxation rate has been shown to decline from 20 to 91 years of age in the adductor pollicis muscle (Narici et al., 1991). The reason for this slower relaxation rate (or longer twitch contraction duration) is probably related to the selective atrophy of type II fibres. The muscle would relax at a lower rate as a result of the predominance of type I fibres, which are slower. At microscopic level of muscle analysis, the slower relaxation rate can be ascribed to a reduction in sarcoplasmic reticulum activity (Klitgaard et al., 1989; Delbono et al., 1997; Hunter et al., 1999) and actin sliding speed on myosin (Höök et al., 2001). As a result of slowing of relaxation and probably of type II fibre atrophy, it has been shown that muscles of older individuals demonstrate tetanic fusion, i.e. a maximum maintained contraction in response to repetitive stimulation, at lower frequencies of stimulation than young adults, thus enabling the individual MUs to use lower firing frequencies to achieve a full contraction (Narici et al., 1991; Kamen et al., 1995; Connelly et al., 1999; Roos et al., 1999). Slowing of relaxation and type II atrophy may also explain why older people demonstrated more resistance to isometric fatigue that young individuals (Narici et al., 1991), a process which is referred to as "fatigue-paradox" (Narici, 1999).

Recently, Scaglioni et al. (2002) have shown that the excitability in the spinal reflex pathway, expressed as the ratio between the maximum H-reflex and the maximum M-wave, is functionally impaired in older male individuals. The Hoffman reflex, or H reflex, is an artificially elicited response used to test the efficacy of transmission of an applied stimulus as it passes from the afferent fibres, through the motoneuron pool, to the efferent fibres (Enoka, 2002). A submaximal stimulation produces a characteristic H-wave that is the result of the motoneuron discharge evoked by the activation of the Ia fibres of muscle spindles, whilst increasing the stimulus intensity results in the direct depolarisation of the alpha-motoneurons'axons (M-wave). The ratio between the maximum H-reflex and the maximum M-wave can be used as an index of the level of reflex excitability of the motoneuron pool, although presynaptic inhibitions can also modulate the transmission between the Ia fibres and the alpha-motoneurons and cannot therefore be discounted (Schieppati, 1987; Maffiuletti et al., 2001). Scaglioni et al. (2002) concluded that the impaired functionality of the reflex pathway with ageing, in addition to the lack of changes following resistance-training, as will be mentioned later in this chapter, suggest that the Hmax/Mmax ratio may be related to degenerative phenomena rather than physical deconditioning.

Surface electromyography is a non-invasive method that has been often used to monitor changes due to ageing in the overall neural activation of both agonist and antagonist muscles which, in turn, affects the generation of force (Merletti et al., 1992; Esposito et al., 1996; Häkkinen et al., 1998a; Izquierdo et al., 1999; Merletti et al., 2002). When a muscle is voluntary activated, a pair of electrodes above the skin detects an electrical signal that is referred to as surface electromyogram (sEMG). Many authors pointed out that there is need for standardisation of sEMG recordings, since several factors can affect the measurement, such as the electrode's material, size and shape, the presence of gel or paste, alcohol applied to cleanse the skin, skin abrasion, shaving of hair, interelectrode distance, electrode location, orientation over the muscle with respect to tendons, motor point and fibre direction (De Luca, 1997; Merletti et al., 2001). Standards for reporting EMG data, which have been strictly followed in the experimental studies of this thesis, have therefore been agreed by the International Society of Electromyography and Kinesiology (Merletti et al., 1999). SEMG signals can be processed in both the time domain, by quantifying the signal amplitude with a parameter referred to as root mean square (RMS), which coincides with the standard deviation of the distribution, and in the frequency domain, by estimating the signal harmonics, which form the "spectrum" and are obtained by means of Fast Fourier Analysis (Merletti et al., 2001). The most common parameters to quantify the power spectrum are the median frequency (MDF), which is the frequency value that splits the spectrum into two parts containing equal power, and the mean frequency (MNF), which is the centre of gravity of the spectrum. The physiological meaning of RMS is to reflect the overall number, firing rate and synchronisation of the active MUs (Basmajian and De Luca, 1985; Esposito et al., 1996). However, as each of several MUs in the uptake area of the surface electrodes fire several times, resulting in the so-called interference sEMG (Enoka, 2002), firings and action potentials of the individual MUs cannot be recognised in such parameter. The parameters of the myoelectric power spectrum (MDF and MNF) are influenced, to a great extent, by the action potential conduction velocity (Stulen and De Luca, 1981; Solomonow et al., 1990) and have been shown to correlate with muscle fibre composition both *in vivo* (Moritani et al., 1985; Wretling et al., 1987; Gerdle et al., 1991) and *in vitro* (Kupa et al., 1995). MDF and MNF have therefore the potential to be used for non-invasive fibre typing (Merletti et al., 2001).

Inter-subjects comparisons in the sEMG parameters as indicators of muscle function are limited by the presence of skin, subcutaneous and fat layers between the muscle and the recording electrodes, which have a filtering effect on the signal (De Luca et al., 1997). Therefore, although it is evident from the data reported in various studies (Moritani and de Vries, 1980; Häkkinen and Häkkinen, 1995; Häkkinen et al., 1998c) that the absolute values of sEMG amplitude were lower in groups of older individuals as compared to young or middle-aged subjects, most of the investigators did not remark the physiological meaning of this difference, with the exception of Esposito et al. (1996) and Merletti et al. (2002). The authors have speculated that the lower RMS in the biceps brachii of individuals in their seventies, as compared to those in their twenties, may be due not only to the different thickness or conductivity of the layers between the muscle and the recording electrodes, but also to the different MU firing rates between the two groups. This is supported by the observation of a decrease in the maximal MU firing rate with ageing in studies where the intramuscular EMG signal has been recorded (Kamen et al., 1995; Erim et al., 1999; Connelly et al., 1999). The lower sEMG amplitude in older people has also been ascribed to the reduced number of MUs (Esposito et al., 1996), in agreement with the observation made by others with electrophysiological techniques of MU estimation (Brown et al., 1988; Doherty and Brown, 1993; Doherty et al., 1993), which have been reported at the beginning of this paragraph. Esposito et al. (1996), regardless of the differences in absolute values between young and older individuals, showed that in the two groups there was a similar trend in the increase of RMS as a function of the level of force, suggesting a similarity in MU activation patterns. Some authors (Häkkinen et al., 1998a; Izquierdo et al., 1999), alternatively, used the sEMG to measure the coactivation of antagonist muscles, which is referred to the maximum EMG activity of the same muscle group during the agonist action. In this measure the influence of subcutaneous and skin layers can be discounted, although it may increase the danger of cross-talk from nearby muscles (Solomonow et al., 1994), thus contaminating the signal and misleading its interpretation, as will be discussed in chapter 2. Coactivation, also referred to as cocontraction, may serve to protect and stabilise the joint during forceful contractions (Baratta et al., 1988). The higher levels of antagonist coactivation, which have been observed in 70 year-old men and women as opposed to 40 year-old individuals, could be an additional explanation for the age-related decline in force production (Häkkinen et al., 1998a; Izquierdo et al., 1999). In other words, the net force exerted about a joint during a given action, e.g. knee extension, would be reduced in older people due to the greater simultaneous activation of the muscles exerting a torque in the direction which is opposite to that of the movement (i.e. hamstrings).

Comparisons between young and older individuals in the frequency-domain parameters of sEMG have been performed during sustained-isometric contractions of the biceps-brachii (Bilodeau et al., 2001b; Merletti et al., 2002) and tibialis-anterior muscles (Merletti et al., 1992). A decline in MDF, MNF or other parameters of the power spectrum, which can be attributed to muscle fatigue, has been observed in both young and older individuals, with the rate of decrease of spectral parameters being lower in the older. This observation further supports the "fatigue-paradox" reported in the previous paragraph (Narici et al., 1999), which can be ascribed to selective atrophy of type II fibres, slowing in the contractile properties, and lower MU firing rates of the older muscle. By contrast, Hara et al. (1998) and Bilodeau et al. (2001a) did not find significant differences between young and older subjects in the decline of spectral parameters of the abductor digiti minimum and elbow flexors, respectively, during sustained contractions. The interpretation of these results is unclear. Hara et al. (1998) have explained the occurrence of a similar decline in spectral parameters of young and older individuals with ischemia, which is due to a stronger muscle contraction in the young and to less capillary bed in the older subjects. This would result in a similar decrease in the two groups of the pH of interstitial fluids, as blood flow determines the rate of metabolites' removal, thus affecting the decline in spectral parameters. Merletti et al. (2002) attributed the results of Bilodeau et al. (2001a) to the lack of specific criteria in selecting the best electrode location.

Finally, there are still conflicting results on the possibility of a reduction in the descending drive from supraspinal centres to the motoneurons during maximum voluntary contractions in older individuals, which would be a further explanation for the loss of muscle strength with ageing (Phillips et al., 1992; De Serres and Enoka, 1998; Harridge et al., 1999b; Yue et al., 1999; Kent-Braun and Ng, 1999; Connelly et al., 1999; Roos et al., 1999; Bilodeau et al., 2001a; Jakobi and Rice, 2002; Scaglioni et al., 2002). Some experimenters showed by twitch interpolation technique, a method based on delivering one or a brief series of electrical stimuli to the motor axons of muscles during maximum voluntary contraction, that older adults were not able to maximally activate a muscle or muscle group (Harridge et al., 1999b; Yue et al., 1999; Bilodeau et al., 2001a). Other investigators, however, demonstrated that a superimposed stimulus, either in the form of a single twitch or a short tetanus, added little or nothing to the volitional force of older people (Phillips et al., 1992; De Serres and Enoka, 1998; Kent-Braun and Ng, 1999; Connelly et al., 1999; Roos et al., 1999; Jakobi and Rice, 2002; Scaglioni et al., 2002). It must be noted that central failure in activation was measured in very-old individuals by Harridge et al. (1999b) and that not enough practice may have been given to the subjects in measuring maximum voluntary contraction by Yue et al. (1999) and Bilodeau et al. (2001a). The possibility of underestimating the "real" maximum should therefore be discounted if at least one session of familiarisation is practised (Jakobi and Rice, 2002) and if the subjects are not too old. Narici (2001) pointed out that activation capacity could be muscle specific, as it appears to be preserved in distal muscles of both upper and lower extremities (Vandervoort and McComas, 1986; Phillips et al., 1992), but this issue deserves further investigation as conclusive results on the activation capacity of a muscle may largely depend on the stimulation technique that is adopted. In fact, Behm et al. (2001) have recently indicated that tetanic stimulation superimposed upon single maximal or multiple contractions seems to provide the most valid measure of muscle inactivation. Finally, the author of this thesis suggests that voluntary strength testing should be preferred, since electrical stimulation determines a full synchronisation of MUs (Solomonow et al., 1994), which is unlikely to occur in real life.

Hormonal factors

Although hormonal levels have not been measured in the experimental studies of this thesis, a brief mention has to be made to their potential role in determining sarcopenia and other factors that effect strength losses in older people. A decline in the levels of many hormones has been measured, particularly growth hormone (GH) (Rudman, 1990; Welle et al., 1996a), insulin-like grow factor 1 (IGF-1) (Butterfield et al., 1997), testosterone (Tenover, 1992; Urban et al., 1995; Baumgartner et al., 1999) and oestrogen (Phillips et al., 1993; Taaffe et al., 1995; Bassey et al., 1996; Skelton et al., 1999; Onambele et al., 2001), but how these changes are related to strength and power is still largely unclear (Short and Nair, 1999).

The action of GH, which is known to promote growth, protein synthesis and fat mobilisation, is mediated by IGF-1 (Rooyackers and Nair, 1997). The hormone deficiency, which has been measured in older individuals (Rudman, 1990), determines a reduction in muscle mass and an increase in fat mass. The administration of recombinant human GF to healthy older adults for one month increased circulating IGF-1 and led to a 50% increase in mixed muscle protein synthesis, as measured using biopsy samples (Butterfield et al., 1997). However, three months of treatment with slightly higher doses did not produce any significant change in protein synthesis of another group of older subjects, although muscle mass and strength increased (Welle et al., 1996a). Yarasheski at al. (1992, 1995) have suggested that, as adding GH to a 12 or 16 week resistance training programme led to an increase in fat-free mass and whole body protein synthesis but not in mixed muscle protein synthesis, the hormone enhanced protein synthesis in non-muscle tissues. Taaffe et al. (1994, 1996) gave evidence that administering GH during the final 10 weeks of a 24-week resistance-training programme did not produce any further gains in muscle size and strength. Harridge and Young (1998), in their notable review on skeletal muscle in older people, pointed out that a treatment for life with GH may lead to gains that may be equally achieved with exercise training, with the latter having no undesirable side effects of drug administration. Undesirable side effects were also observed after administration of IGF-I (Butterfield et al., 1997), which was associated with an increase in protein synthesis, but muscle strength and size were not monitored, thus requiring further investigation.

It is known that testosterone has a trophic action on skeletal muscle, which is mediated by androgen receptors in the myofibrils (Celotti and Negri Cesi, 1992). Serum testosterone, which is reduced in older men, increased following hormone replacement to a level comparable to that of young men, with a significant gain in muscle mass after 3 months (Tenover, 1992). In the study of Urban et al. (1995), administering testosterone to hormone-deficient men for 4 weeks was accompanied by an increase in both strength and mixed protein synthesis. Kraemer et al. (1999) have shown that older men showed a significant increase in testosterone levels in response to resistance training. Häkkinen and Pakarinen (1994) suggested that the balance between anabolic and catabolic hormones in ageing men is associated with muscle atrophy and decreased voluntary force production, as the ratio between circulating levels of serum testosterone and serum cortisol correlated with muscle CSA and strength. Izquierdo et al. (2001) have shown that serum total testosterone and free testosterone correlated with the magnitude of the training–related increase in strength and power output in both groups of middle-aged and older men. Androgens also appear to be responsible for the reduced release of neurotransmitters and other neurotrophic agents that, in turn, effect the partial denervation of muscle fibres and the consequent sarcopenia (Gutmann and Hanzlìkovà, 1970, cited in Narici, 1999), as reported earlier in this chapter. In a recent cross-sectional study, which involved 121 male and 170 female volunteers aged 65-97 years (Baumgartner et al., 1999), a significant correlation between muscle mass and serum free-testosterone was found in men, whilst there was no association between oestrogen levels and strength in women. However, oestrogen levels in women, which fall at menopause, may play a role in the loss of force, but conflicting results have been found in postmenopausal women who were receiving hormone replacement therapy (HTR) (Phillips et al., 1993; Taaffe et al., 1995; Bassey et al., 1996; Skelton et al., 1999; Onambele et al., 2001). In the study of Phillips et al. (1993), 25 post-menopausal women, who had been on HRT between 1 and 25 years, showed a 26% higher specific strength in the adductor-pollicis muscle than those not receiving HRT. Similarly, another group of post-menopausal women treated with HRT for 6-12 months increased their strength by 12%, as opposed to a slight decline in the control group, with both groups being accompanied by no significant change in muscle CSA (Skelton et al., 1999). A follow-up study after 2-4 years on the same population showed that the benefit of HRT on isometric muscle strength of adductor pollicis was maintained in those women who continued treatment beyond 1 year, although no further increase in muscle strength was found (Onambele et al., 2001). However, other studies suggest that oestrogen status does not have any effect on the maximal muscle strength of older women (Taaffe et al., 1995; Bassey et al., 1996). In the experimental study of this thesis, in light of the possible interaction between hormone administration and force and power production, women undertaking any kind of HRT were strictly excluded.

Levels of physical activity

It has been shown that the amount of physical activity decreases with ageing but it is unclear whether this is a cause or an effect of the age related loss of muscle function (Harridge and Young, 1998). It seems that the decrease in strength with ageing cannot be explained only on the basis of a decreased level of physical activity, since also highly competitive veteran sportsmen inexorably decline (Meltzer at al., 1994; Pearson et al., 2002). In addition, muscle disuse results in a reduction in muscle fibre size (Ferretti et al., 1997) and not, like ageing, in muscle fibre number (Larsson et al., 1979; Lexell et al., 1988). As a limitation of current studies, habitual physical activity levels have often been reported in descriptive rather than quantitative terms, making them difficult to interpret (O'Toole, 1997). For example, individuals were classified as inactive if they participated in normal activities of daily living or sedentary leisure-time activities and active if they participated in moderated physical activity more than once a week or had physically demanding jobs (Borges, 1989). In another study (Rantanen et al., 1997a), the active category was made by individuals reporting at least 1 or 2 hours a week of moderate activity, but include also individuals involved in strenuous activities several times a week. Interestingly, O'Toole (1997) pointed out in her editorial that it is intuitive to think that higher activity levels should preserve strength better, but further studies are required to see whether habitual low to moderate intensity activity for just a few hours a week can provide an adequate stimulus to maintain muscle strength and function. The author reported the results of Rantanen et al. (1997a), who observed similar rates of changes in strength over a period of 5 years in individuals classified as active, who maintained their level of physical activity, and those classified as sedentary and remained sedentary. However, individuals who were sedentary initially and became more active were able to slow down their decline in strength, even though their level of strength remained lower than active individuals. Those who were active initially but for some reason became sedentary, without changes in their health status, incurred in the highest rate of strength decline.

Muscle power, i.e. the rate of performing mechanical work, is also significantly reduced with advancing age (see for example Bassey et al., 1992; Ferretti et al., 1994; De Vito et al., 1998). Skelton et al. (1994) have reported that, between the ages of 65 and 89 years, its decline occurs at an even higher rate than isometric strength (3-4% per annum as compared to 1-2% of a 77-year old value), thus revealing that power is more vulnerable than strength to the ageing process. This loss of power has been demonstrated to have severe functional consequences (Bassey et al., 1992; Krebs et al., 1998; Suzuki et al., 2001). Bassey et al. (1992) indicated that very old adults who require the use of aids to perform functional tasks, such as stair climbing, raising from a chair and walking, had 42-54% less leg extensor power than those who could complete these tasks without assistance. Suzuki et al. (2001) have recently demonstrated a positive association between muscle power of the ankle flexors and functional limitations in community-dwelling older women. Among a group of sedentary, community-dwelling older women, aged between 70 and 95 years, leg power was the strongest predictor of functional status, as compared to other physiological parameters (Foldvari et al., 2000). Rantanen et al. (1997b) have suggested that diminished leg extensor power may be a key predictor for mobility problems. Improved knowledge on the mechanisms of power decline is therefore crucial with regard to the development of effective prevention and treatment programmes for restoring mobility and independence in older people.

As reported earlier in this chapter, power is the product of force and speed at which movement occurs. The amount of force produced during a muscle contraction varies with the velocity of shortening, as first demonstrated by Fenn and Marsh in 1935 and then further investigated by Hill in 1938, who described a "characteristic equation" for the speed of shortening under a load in isolated animal muscle (Figure 1.1). Maximum force is produced when velocity is zero (i.e. isometric force; P_0), which is dependent on the number of simultaneous cross-bridge formations. As velocity increases the force produced decreases as fewer cross-bridges attach due to

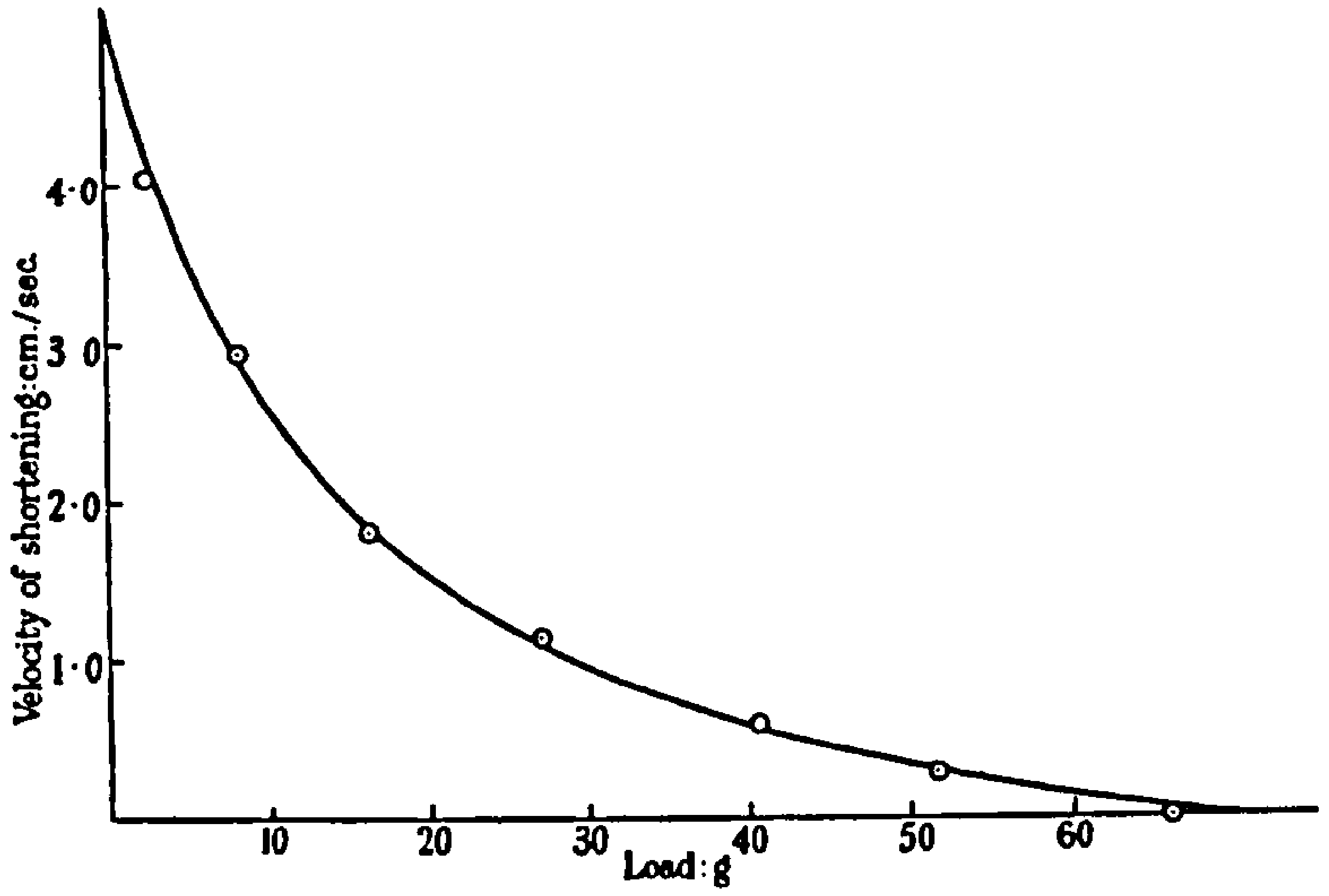

Figure 1.1. The classical force-velocity relationship in an isolated muscle, described by the formula: $(P + a)(V + b) = (P_0 + a)b$, where P is the force during shortening, V is the velocity of shortening, P_0 is the force during isometric tetanus, and a and b are constants with the dimensions of force and velocity, respectively. From Hill (1938).

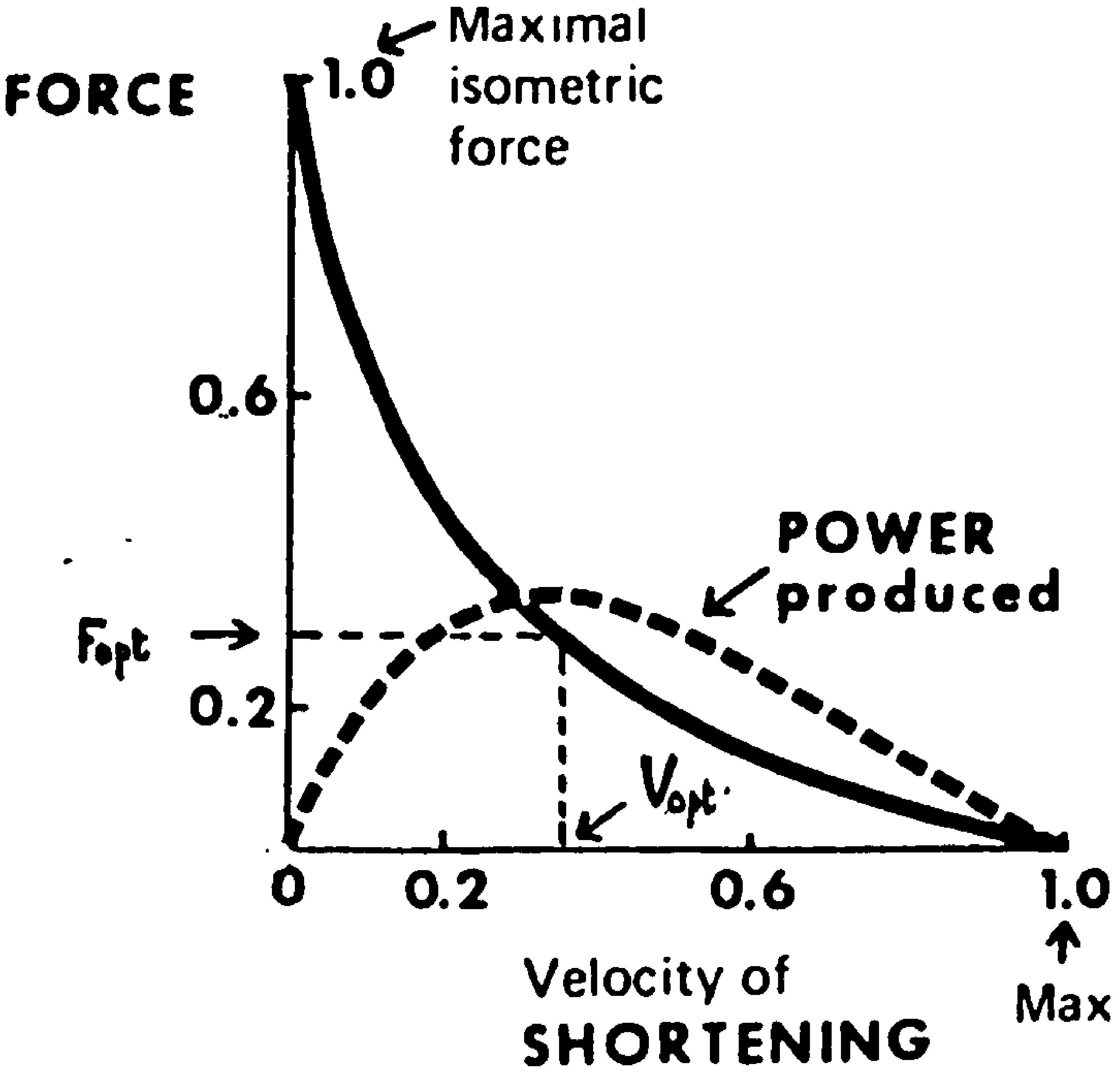

Figure 1.2. The classical force-velocity relationship in an isolated muscle, with the dotted line showing power, i.e. the product of force and velocity of contraction. The highest power is attained when velocity of shortening (optimal velocity - V_{opt}) is 25 to 30 percent of the maximal value; the force (optimal force - F_{opt}) is about 30 percent of the maximal isometric force. Modified from Åstrand and Rodahl (1986).

the limited time during which detachment and re-attachment can occur. The decline in force has a hyperbolic shape and is represented by a/P_0 that indicates the relative contribution from P_0 and maximum shortening velocity (V_{max}). At V_{max} zero force is produced and reflects the maximum rate of cross-bridge turnover but is independent of the number of cross-bridges that are operating (for review see Woledge et al., 1985). The nature of the force-velocity relationship dictates that power will have its own distinct relationships with force and velocity of movement. Thus, there is an optimum force and an optimum velocity at which maximum power is developed (Figure 1.2). In isolated animal muscle, these correspond to about 30% of P_0 and 25-30% of V_{max}, respectively (Åstrand and Rodahl, 1986). However, measurements of force-velocity and power-velocity relationship in humans *in vivo*, represent the resultant of relatively complex situations, as human muscles are attached to bones via tendons that cross over one or two articular joints in order to produce a moment. Not only the contractile elements of muscle cells must be considered, but also factors such as neural influences, muscle architecture and intercellular connective tissue. The optimal values of force and speed for maximum power production *in vivo* may therefore be different from those recorded in isolated muscles or skinned single fibre preparation.

In the literature, investigations looking at muscle power in older people are not as numerous as those carried out on muscle strength. According to Earles et al. (2000), this is due to the fact that muscle power in single explosive movements is much more difficult to measure than muscle strength. Isokinetic dynamometers allow power to be assessed in single muscle groups from the torque measured whilst the limb rotates at constant angular velocity, but do not reflect everyday activity where older subjects have to work against resistance and overcome speed (Harridge et al., 1999a). Moreover, maximum speed of isokinetic devices (about 300 degrees/s) is too low with respect to the maximum that can be achieved during "unloaded" movements of human limbs (estimated at 832 degrees/s, as reported by Perrine, 1986), which limits the measure of power above these values of speed. Explosive power has been traditionally measured in older people using a simple whole body movement, that is a vertical jump on a force platform (Grassi et al., 1991; Ferretti et al., 1994; De Vito et al., 1998). Force platforms essentially operate like a scale for measuring weight.

Velocity of movement of the individual's body centre of gravity is calculated by double integration of the vertical component of the ground reaction force (VGRF) and power is the product of force (obtained by subtracting body weight to VGRF) and velocity of movement (Davies and Rennie, 1968). This method presents two limitations: a) it may not be safe in very-old frail individuals; b) older people have to lift their body weight, which represents a high percentage of their maximum strength, and therefore may be forced to work in a less favourable portion of the force-velocity curve, thus performing the movement at slower speed that is away from the optimal speed for maximum power production. The first problem has been overcome by Bassey and Short (1990), who developed a piece of apparatus that measures the average power generated by the lower limb muscles during a single leg extensor thrust against a pedal which, in turn, accelerates a heavy flywheel of a known inertia. This however, does not solve the second issue, in that both young and older individuals have to overcome the same fixed inertia, with weak-old individuals being forced to use a relatively greater proportion of their maximum force generating ability. Pearson et al. (2001) have recently introduced a variable inertial testing system mounted in the apparatus designed by Bassey and Short (1990), which has the potential to overcome the limitations due to the use of a single inertia. Power can also be tested at different inertial loads by using instrumented weight-stack machines, where force is measured by a transducer or derived by the mass of the stack, and velocity by an electrogoniometer at the individual's joint (Harman, 1995). However, the masses of plates in weight-stack machines have been found both to be variable and to differ from labelled values, thus complicating the measurement technique. All things considered, also dynamic force testing, which is performed by measuring the maximum weight that can be lifted, is a test of power, as the individual is exerting a given force at a given speed that, however, is not measured, thus not enabling the calculation of power. Thomas et al. (1996), have developed a pneumatic system mounted on a double leg-press machine that also allows to use the optimal resistance for maximum power, expressed as a percentage of maximum dynamic strength. To the author's knowledge, there is only one study in which explosive power has been compared between middle-aged and older men after optimising the load (Izquierdo et al., 1999), but no study to date has compared young versus older women.

As power is the product of force and velocity, anything that will affect force production or speed of shortening of a muscle will also affect its power output. Therefore, all of the factors that have been reviewed in the previous paragraph to explain the loss of muscle strength in older age can be transferred to power. In addition, all of the factors that may affect speed of shortening must be taken into account. The selective atrophy of type II fibres with advancing age may partly explain power losses, because the power output of type II muscle fibres is four times that of type I fibres, as reported in animal studies (Faulkner et al., 1986). The speed at which a muscle fibre shortens is determined by the expression of the different isoforms of the MHC, as measured with a technique based on identification of MHC as molecular marker with gel electrophoresis (Harridge et al., 1996). Type I, IIa and IIb fibres of the traditional classification, based on ATPase sensitivity to pH, express mainly MHC-I, MHC-IIA and MHC-IIX isoforms, respectively. Fast fibres have the potential to generate higher power output, with greater forces and higher speed of shortening, than slow fibres. The significant reduction in the size of type II fibres, as described earlier in this chapter (Lexell et al., 1988), would result in a decrease in the proportion of the muscle that is occupied by fast contracting MHC isoforms (Harridge and Young, 1998). Moreover, it has been shown, by using of electrophoretic techniques, that fibres in older muscle co-express more than one MHC isoform (hybrid fibres) to a greater extent than fibres in young muscle (Klitgaard et al., 1990; Andersen et al., 1999). This higher presence of hybrid fibres, which had not been clearly identified by the earlier technique based on ATPase reaction, may indicate a shift towards a slower older muscle (Harridge and Young, 1998) and, as reported earlier in this chapter, is a further evidence of the process of ongoing denervation and reinnervation of the ageing muscle (Vandervoort, 2002). The shift towards a slower muscle with ageing has been confirmed by studies on the contractile mechanics of single fibres, in which it has been shown that both MHC-I and MHC-IIA single fibres have lower specific tension and maximum shortening velocity if they originate from the muscles of an older person as opposed to a young person (Larsson et al., 1997; Frontera et al., 2000b). Moreover, Höök et al. (2001) recently reported an age-related slowing in the actin sliding speed on myosin by studying an *in vitro* motility assay, in which myosin is extracted and immobilised from a 2- to 4-mm single muscle fibre segment, in order to focus on actomyosin interactions without interference from cytoskeletal or regulatory proteins. As previously pointed out, measurements taken on skinned single fibre preparation or *in vitro* motility assay have the advantage to allow researcher to study directly the contractile elements of muscle cells, thus ruling out the confounding effects of factors such as neural influences, muscle architecture, intercellular connective tissue (Frontera et al., 2000b). However, these factors should be taken into account when examining the speed of shortening of the whole body segments *in vivo* and the exact interpretation of these phenomena is still unknown. Metter et al. (1997) speculated that normal ageing changes in the basal ganglia, consisting in a continuing loss of dopaminergic neurons in the substantia nigra (Morgan et al., 1994), could be a contributor to the observed slowing in speed, coordination and power, together with peripheral changes such as slowing in nerve conduction velocities (Norris et al., 1953). Another potential cause for lower power production could be an age-related decrease in tendon stiffness, which has been recently measured as the ratio between force and tendon elongation (in the interval 60-100% of maximum isometric force) in a group of 6 older individuals in their seventies with respect to a control group of 6 healthy young adults in their twenties (Maganaris, 2001). Decreased tendon stiffness would reduce the effectiveness of both force and power transmission.

THE EFFECT OF RESISTANCE TRAINING ON MUSCLE STRENGTH, POWER AND SELECTED FUNCTIONAL ABILITIES IN OLDER INDIVIDUALS

Strength

At the end of the eighties, Frontera et al. (1988) reported that a heavy-resistance training programme led to an increase in strength of the quadriceps muscles of older men aged between 60 and 72 years, which was accompanied by an increase in muscle fibre size. Since then, a growing number of studies each year continue to document the benefits of resistance training in older people, even in individuals over 90 years of age. Resistance-training programmes are based on the application of the overload principle, which states that muscles worked close to their force-generating capacity will increase in strength (McArdle et al., 1996). The term exercise session refers to the block of time devoted to the training. The number of training sessions completed each per week is termed frequency. The basic unit of a resistance training session is the repetition which, for a given training movement, is the completion of a whole cycle from the starting position, through the end of the movement and back to the start. When a series of repetitions is completed this is termed a set. Volume is typically calculated as the product of repetitions and sets (Fry and Newton, 2002). Intensity refers to the relative load or resistance that the muscle is exercising against, usually expressed as percentage of the maximum weight that could be lifted once, i.e. 1 repetition maximum (1-RM). In the older population, these programmes have a similar structure to those undertaken by younger people, for example they can have a duration of 12 weeks, with a frequency of 3 times per week, where subjects perform 3-4 sets of 8 repetitions at an intensity equal to 80% of 1-RM. To elicit gains in muscle strength, the loads must be progressively increased so that the relative intensity remains high enough to provide an adequate overload throughout the whole duration of the training programme. The results of some of the studies that have examined the effects of heavy-resistance training on muscle strength and size on the most frequently studied muscle, the quadriceps group, are summarised in Table 1.1.

Table 1.1. Effect of resistance training on muscle strength and size of the quadriceps muscle in older individuals.

Authors	Subjects			Training programme						% Change				
	Age	Gender	N	Exercise movement	Duration (weeks)	Sessions per weeek	Sets	Repetitions	% of 1RM	Strength		CSA	Fibre size increase	
										1RM	MVC		Type I	Type II
Frontera et al., 1988	60-72	M	12	KE	12	3	3	8	80	107	17	CT: 9	34	28
Fiatarone et al., 1990	86-96	M/F	10	KE	8	3	3	8	80	174	-	CT: 11	-	-
Charette et al., 1991	64-86	F	13	LP, KE	12	3	6	6	75	28-93	-	-	7 NS	20
Grimby et al., 1992	78-84	M	9	KE	8-12	3	3	8	Isok	10 at 30°s^{-1}		CT: 3	8 NS	5 NS
Pyka et al., 1994	61-78	M/F	25	LP, KE	52	3	3	8	75	53-95	-	-	59*	67*
Lexell et al., 1995	70-77	M/F	23	KE	11	3	3	6	85	163	-	-	-4 NS	-8 NS
McCartney et al., 1996	60-80	M/F	113	LP	84	2	3	12	80	32	-	CT: 9	-	-
Sherrington and Lord, 1997	64-94	M/F	21	GWBE	4	7	-	-	-	-	22	-	-	-
Häkkinen et al., 1998b	61	M	10	KE	10	3	3-6	3-15RM	-	-	17	MRI: 9	23	27
Häkkinen et al., 1998c	70	M/F	20	KE	26	2	3-6	3-15	50-80	26%	-	Ultr: 6 (F)	-	-
Harridge et al., 1999b	85-97	M/F	11	KE	12	3	3	8	80	134	37	MRI: 10	-	-
Taaffe et al., 1999	65-79	M/F	46	LP, KE	24	1	3	8	80	23-71	-	-	-	-
Tracy et al., 1999	65-75	M//F	23	KE	9	3	3	5-10RM	-	28	-	MRI(vol): 12	-	-
Hunter et al., 1999	64-79	M/F	11	KE	12	3	3	8RM	-	39	-	-	-4 NS	-2 NS
Hortobágyi et al., 2001	66-83	M/F	27	LP	10	3	5	4-12	40-80	35	26	-	-	-
Häkkinen et al., 2001	71	M/F	21	LP	26	2	3-6	10-18	70-80	26	26	-	32 (F)	32 (F)

M, male; F, female; KE, knee extension; LP, leg press; GWBE, general weight bearing exercises; 1RM, one repetition of maximum weight that could be lifted; 5RM, five repetitions of maximum weight that could be lifted; MVC, maximal voluntary contraction; Isok, isokinetic; CT, computerised tomography; MRI, magnetic resonance imaging; vol, volume; Ultr, ultrasonography; NS non-significant; * after 30 weeks.

Compiled by the author from published data.

One of the main problems of between study comparisons is the variation in the population of subjects. Studies have been performed on males, females and mixed populations. The mean age of the participants has also varied greatly, with older people ranging from those in their 60's (Häkkinen et al., 1998b) to those in their 90's (Fiatarone et al., 1990; Harridge et al., 1999b). The presence of medical conditions and the baseline fitness of participants are among other variables that have to be taken into account (Greig et al., 1994). Additional factors that make the comparison between studies problematic are the duration and frequency of the training programme, the number of sets and repetitions of each session, and finally the intensity at which these repetitions are performed. Resistance training programmes in older people varied considerably in length from just 4 weeks (Sherrington and Lord, 1997) to 84 (McCartney et al., 1996). On average, however, most resistance training studies lasted 8-12 weeks (Frontera et al., 1988; Fiatarone et al., 1990; Charette et al., 1991; Grimby et al., 1992; Lexell et al., 1995; Häkkinen et al., 1998b; Harridge et al., 1999b; Tracy et al., 1999; Hunter et al., 1999; Hortobágyi et al., 2001). Most studies involved subjects performing 3 training sessions per week, but the number could be as great as 7 per week (Sherrington and Lord, 1997). Recently, Taaffe et al. (1999) have demonstrated that strength gains can be obtained even with a training frequency of once per week. The number of sets was 3 in most of the studies, but could vary up to 6 (Charette et al., 1991; Häkkinen et al., 1998b; Häkkinen et al., 2001). The number of repetitions also changed from study to study, with the most common number of repetitions being 8, although it ranged between 3 (Häkkinen et al., 1998b; Häkkinen et al., 1998c) and 18 (Häkkinen et al., 2001). The intensity of heavy-resistance training was around 80% in most studies and there have been also few studies comparing low- versus high- intensity resistance training (Pruitt et al., 1995; Hortobágyi et al., 2001; Fielding et al., 2002). Strength changes have been quite variable across studies, which is likely a reflection of the key design factors that have just been reviewed. Moreover, variability in the results depends on the modalities used to test strength (isometric vs. 1-RM), which have been defined at the beginning of this chapter. It is important to remark that even very old people can benefit from progressive resistance training (Fiatarone et al., 1990; Harridge et al., 1999b). Lexell (2000) pointed out that the lower the initial levels of strength, like in individuals in their 90's, the higher the magnitude of the percentage increase with respect to the baseline.

Various factors can contribute to strength gains following heavy-resistance training in both young and older subjects. These include, in the first phase of training (about 1-2 weeks), a rapid improvement in the ability to perform a training exercise, such as lifting weights, which is mainly the result of a learning effect. The learning effect, which is mediated by changes in motor skill coordination and level of motivation, can be substantial especially when the test adopted to evaluate muscle strength requires high levels of skill (Jones and Round, 1990). In the second phase, which lasts 3-4 weeks, muscle strength gains are obtained without a matching increase in size of the trained muscles. The improvement in this phase has been mainly attributed to neural adaptations (Moritani and de Vries, 1980; Sale, 1988; Häkkinen et al., 2001). The term neural adaptations includes many elements such as an increased activation of prime mover muscles (number of recruited MUs or firing rate and synchronisation of the individual MUs), a better coordination of synergistic and antagonist muscles, and an increased neural drive from the highest levels of the central nervous system (Sale, 1988). There are, however, few studies investigating changes in neural properties following strength training in aged humans (Rice, 2000). Some investigations have shown significant improvements in agonist sEMG with concurrent reductions in the activity of antagonist muscles (Häkkinen et al., 1998b; Häkkinen et al., 1998c). An increase in M-wave potentials following strength training has been measured in older individuals by Hicks et al. (1992), thus suggesting a training induced increase of muscle membrane excitability. However, Scaglioni et al. (2002) have recently shown that the modulation of neuromuscular excitability, expressed as the ratio between the maximum Hoffman reflex and the maximum M-wave, did not change in older male adults following 16 weeks of resistance training of plantar flexor muscles. A 30 % increase in maximal MU firing rate has been measured in the tibialis anterior muscle of 6 older individuals in their seventies following 2 weeks of training (Patten and Kamen, 2000). However, the same authors (Patten et al., 2001) reported a bimodal response of maximal MU discharge rate of the adductor digiti minimi to 6 weeks of isometric training – an initial increase followed by a return towards baseline – which is surprising and difficult to explain.

The third phase of adaptation to strength training (> 6 weeks) is characterised by an increase in both size and strength of the exercised muscles. Muscle size has been measured before and after training using various non-invasive techniques, such as ultrasonography (Häkkinen et al., 1998c), CT (Frontera et al., 1988; Fiatarone et al., 1990; Grimby et al., 1992; McCartney et al., 1996) or MRI (Häkkinen et al., 1998b; Harridge et al., 1999b). Notable is the recent study of Tracy et al. (1999), who measured a 12% increase in quadriceps muscle volume, by MRI, following 9 weeks of resistance training in both groups of 65-75 years old men and women. Both type I and type II fibres retain their capacity for hypertrophy in response to resistance training (Frontera et al., 1988; Brown et al., 1990; Charette et al., 1991; Pyka et al., 1994; Häkkinen et al., 1998b; Häkkinen et al., 2001), although some studies demonstrated little or no change (Grimby et al., 1992; Lexell et al., 1995; Hunter et al., 1999). Häkkinen et al. (1998b) have reported a type MHC II subtype transformation going from type MHC IIb to IIab to IIa in older men, similar to previous training studies in young individuals (Adams et al., 1993; Harridge et al., 1998). In a further study (Sharman et al., 2001), the same result was found also in a group of 65 year old women following 24 weeks of heavy resistance training. Williamson et al. (2000) have measured a significant increase in the expression of MHC I as a result of 12 weeks of low-intensity resistance training, thus indicating that higher-threshold MUs may have not been recruited during the programme. Recent investigations on single fibres indicated that 12 weeks of progressive resistance-training increased muscle cell size, strength and peak power in both older men (Trappe et al., 2000) and women (Trappe et al., 2001). Interestingly, in contrast with the older men, no change in fibre unloaded shortening velocity or peak power normalised to cell size was observed in older women, thus suggesting that men and women respond differently, at the cell level, to the same resistance-training stimulus. The mechanisms of this phenomenon are still unknown. Some studies (Yarashesky et al., 1995; Welle et al., 1999) have also given evidence that resistance training led to an increase in protein synthesis, which was accompanied by significant improvements in muscle strength. Less is known about the long-term effects of resistance training in older people, as most of the available studies did not continue after 12-24 weeks. Following a 1-year exercise trial involving 25 individuals aged between 61 and 78, Pyka et al. (1994) measured increases in strength ranging from 30 to 97% over the first 3 months, which then maintained a plateau in the remaining months of the experiment. Similarly, Morganti et al. (1995) showed that a 1-year training programme with a frequency of twice a week resulted in strength gains of various muscle groups, ranging from 4% to 74%, in a population of 39 healthy postmenopausal women, with the greatest gains seen in the first 3 months of training. McCartney et al. (1996) reported instead progressive strength gains and moderate muscle hypertrophy in an older group that continued to participate in a resistance-training programme for 2 years. Rapid detraining will result if programmes are interrupted, but the initial gains can be maintained with a reduced exercise frequency of even once per week (Lexell et al., 1995; Taaffe et al., 1999; Trappe, 2002).

Although several investigations have shown that the capacity to improve muscle strength is not impaired with increasing age (see the studies of Table 1.1), few investigations have made a direct comparison of the magnitude of the responses in older and young individuals to the same training programme. Jozsi et al. (1999) have shown that 60 year old individuals can improve strength and power in response to 12 weeks of resistance training, with the same magnitude as that of individuals in their twenties. Welle et al. (1996b) found that the increase in specific tension following 3 months of resistance training in young (22-31 years) and older (62-72 years) individuals was similar for the elbow flexion (about 20%) and knee extension (about 35%), but was more than double in the older for the knee flexors. Larsson (1982), on the contrary, had previously shown that the average increase in isokinetic strength of the knee extensors following 15 weeks of training at low-resistance and high-repetition tended to be higher in a group of 56-65 year-old males (7.5%) as compared to the 20-39 year-old group (2.9%).

Power

In recent times, greater attention has been focused on the need to design exercise strategies in order to increase muscle power (Evans, 2000; Earles et al., 2000; Fielding et al., 2002). "The preservation of muscle power into late life can greatly decrease the risk of disability and enhance functional independence" (Evans, 2000). As pointed out by Earles et al. (2000), it is important to determine whether high-velocity training is comparable or superior to low-velocity high-resistance programs in order to improve function and quality of life in older individuals. Table 1.2 summarises the results of the training studies in which, to the author's knowledge, explosive power has been measured. The subject's age and gender, training mode and testing methodology are included.

To date there is only one study, to the author's knowledge, which was specifically designed to increase power in older people (Fielding et al., 2002). Older women in their seventies with mild functional limitations were randomised into one of two groups: high-velocity (HI) and low-velocity (LO), in which absolute training force and total work performed were similar between groups, but power output was significantly higher in HI, since individuals were asked to perform each repetition as fast as possible. HI and LO have improved leg-press power output by 97% and 45%, respectively, over 16 weeks of training. This training programme was designed starting from the assumption that muscle-strengthening exercises may not always produce an optimum increase in power. The authors pointed out that traditional low-velocity resistance training resulted in small but significant increase in muscle power ranging from 18% to 25% (Fiatarone et al., 1994; Skelton et al., 1995; Joszi et al., 1999) despite much larger increases in muscle strength. Fiatarone et al. (1994) showed that in frail very-old nursing-home residents progressive resistance exercise over a 10-week period produced 113% and 28% increase in muscle strength (knee-extension 1-RM) and power output, respectively, with power being assessed during a stair-climbing test (Bassey et al., 1992). Similarly, in 20 healthy, independent, very old women, Skelton et al. (1995) observed a 27% increase in knee-extension isometric strength and an 18% increase in leg-extension power standardised for body

Table 1.2. Effect of resistance training on muscle power of various muscle groups in older individuals.

Authors	Subjects			Training programme						Testing movement	Power gain	Measurement apparatus
	Age	Gender	N	Exercise movement	Duration (weeks)	Sessions per weeek	Sets	Repetitions	% of 1RM			
Frontera et al., 1988	60-72	M	12	KE	12	3	3	8	80	KE	None	Isokinetic dynamometer
Fiatarone et al., 1994	72-98	M/F	100	KE, HE	10	3	3	8	80	SC	28%	Stair-climbing
Skelton et al., 1995	76-93	M/F	20	Elastic tubing or rice bags	12	3	3	4-8	-	LP	18% (NS)	Nottingham Rig
De Vito et al., 1999	60-70	F	11	Low-intensity general conditioning	12	3	-	-	-	VJ	24%	Force platform
Joszi et al., 1999	56-66	M/F	17	KE, AP	12	2	3	8-12	80	KE, AP	10-26%	PRM
Izquierdo et al., 2001	64±2	M	11	KE, HS, BP	16	2	3-4	8-15	50-80	KE, HS, BP	21-37%	Instrumented weight-stack machines
Earles et al., 2000	77±5	M/F	18	LP	12	3	3	10	50-70	LP	22%	PRM
Fielding et al., 2002	73±1	F	30	LP	16	3	3	8-10	70	LP	HI: 97% LO: 45%	PRM

M, male; F, female; KE, knee extension; HE, hip extension; SC, stair climbing; LP, leg press; VJ, vertical jump; AP, arm pull; HS, half-squat; BP, bench press; 1RM, one repetition of maximum weight that could be lifted; HI, high velocity; LO, low velocity; PRM, pneumatic resistance machine; NS non-significant.

Compiled by the author from published data.

weight, which was measured using the Nottingham Power Rig (Bassey and Short, 1990). Jozsi et al. (1999) found that 12 weeks of progressive resistance-training in men and women in their sixties resulted in an increase in strength of knee extension and arm pull movements of 30% and 18%, respectively, versus an increase of 26% and 10% in power, with power being measured with a pneumatic resistance machine (Thomas et al., 1996). Also Frontera et al. (1988), in their notable study that has been cited in the previous paragraph on the effects of resistance training on strength, examined the effect of resistance training on quadriceps power, with power being measured with an isokinetic dynamometer, but did not see any significant change. It can be speculated that the effect of training on muscle power may have been seen if power had been measured with the same dynamometer used to carry out the training programme. Even a low-intensity general conditioning programme has been successful in obtaining a 24% increase in peak power during a vertical jump on a force platform in 20 healthy older women in their sixties (De Vito et al., 1999), but higher improvements may have been observed if the programme had been more specific. Earles et al. (2000) have therefore pointed out the importance of performing movements at high velocity during resistance training in order to increase power output. Forty-three volunteers over the age of 70 years were randomised into 1 of 2 groups: the power group, in which individuals participated in high-velocity resistance exercise 3 times a week, and the walking group, in which individuals performed moderate intensity exercise 30 minutes daily, 6 days per week. Leg-press power and maximal knee extensor strength substantially increased in the first group, but not in the second. Similarly, Izquierdo et al. (2001) reported that in middle-aged and older men a prolonged total strength training programme, which included high velocity movements, led to gains in maximal strength and power of the upper and lower extremity muscles, with the improvements being limited in magnitude possibly due to neuromuscular or age–related endocrine impairments.

As reported in the paragraph entitled "muscle power in older people", there is an optimum value of force and velocity at which maximum power is generated. De Vito et al. (1999), showed that the training-induced increase in peak power output, which was measured by performing a vertical jump on a force platform, was due to an increase in both optimal force (18%) and optimal velocity (13%) at which maximum power was measured. However, as argued earlier in this thesis, explosive power output on a force platform was assessed using a fixed inertia, which is the subjects' body weight and corresponds to a high percentage of their maximum, thus not representing the optimal value of force for maximum power production. Other authors have overcome this problem by measuring power output using different loads before and after training (Joszi et al., 1999; Earles et al., 2000; Izquierdo et al., 2001; Fielding et al., 2002), but do not seem to have focused much of their attention on whether the training induced changes in maximum power were due to an increase of optimal force, optimal velocity or both. Most of the investigators (Joszi et al., 1999; Izquierdo et al., 2001; Fielding et al., 2002) showed how power output varied as a function of different loads, expressed as a percentage of 1-RM, thereby identifying the load at which maximum power was measured, but they did not discuss the role of velocity of movement in maximum power generation. In the work of Earles et al. (2000), both power output and velocity of movement were plotted in two different graphs against the resistance used, expressed as % of body mass. However, also these authors did not discuss the relative role of both optimal force and velocity, but simply commented that minimal improvements in power were measured at low resistance, whilst large improvements occurred at higher resistance, in agreement with the principle of specificity of training (McCafferty and Horvath, 1977). From a closer analysis of the graphical results of Earles et al. (2000), it is clear that maximum power was measured before and after training at 30% and 50% of body mass, respectively, with the optimal speed at maximum power being decreased after training, although this was not remarked upon by the authors. Improvements in power can therefore be interpreted with the fact that individuals were able to push higher loads despite a decrease in optimal speed of movement.

Possible mechanisms underlying the improvement in peak power may include specific increases in the CSA of type II muscle fibres and increases in specific force and shortening velocity of single muscle fibres, as speculated by Fielding et al. (2002). Notably, Van Cutsem et al. (1998) have shown that changes in single MU behaviour contribute to the increase in contraction speed after dynamic training in humans, which could justify training induced changes in power. These changes in MU behaviour include earlier MU activation, extra doublets, i.e. brief (2-5 ms) MU interspike intervals, and enhanced maximal firing rate. Also Izquierdo et al. (2001) have speculated that power increases could be due to training induced changes in the neural component, which they vaguely refer to as "voluntary or reflex/induced rapid neural activation of MUs". Indeed, the various factors included under the term "neural adaptations", which have been presented in the previous paragraph to explain gains in strength following heavy-resistance training, i.e. increased activation of the prime mover muscles, better coordination of synergistic and antagonist muscles and increased neural drive from the highest levels of the central nervous system, can also explain improvements in power. However, studying these mechanisms during dynamic contractions by sEMG or other electrophysiological techniques could be problematic, as various mechanical, physiological, anatomical and electrical modifications occur throughout the contraction that affect, in substantial ways, the relationship between signal amplitude and muscle force (De Luca et al., 1997). Also the slowing in nerve conduction velocities due to ageing (Norris et al., 1953) may be a mechanism to be recovered following power training. However, Scaglioni et al. (2002) have recently shown that conduction velocity of the posterior tibial nerve did not change in older male adults following 16 weeks of resistance training of plantar flexor muscles, thus suggesting that decreased nerve conduction velocity may be due to degenerative phenomena rather than disuse. Moreover, if decreased tendon stiffness, as recently shown *in vivo* on human individuals by Maganaris et al. (2001), is another potential cause for decreased power with ageing, an appropriate training intervention may also affect this mechanism. Preliminary results of Reeves et al. (2003) showed that tendon stiffness of the quadriceps muscle increased by 64% in 74 year old men following 14 weeks of resistance training, which was accompanied by 17% increase in dynamic strength.

Selected functional abilities

Functional ability can been described as an individual's competence in performing everyday physical tasks, like rising from a chair, climbing stairs or lifting shopping bags (Harridge et al., 1999a). Although, as reported in the previous paragraph on muscle power, it has been shown that muscle strength and power correlate with the ability to perform functional tasks (Bassey et al., 1992; Skelton et al. 1994; Suzuki et al., 2001; Foldvari et al., 2000; Rantanen et al., 1997b), this is an area of research that still remains unclear. Some authors (Skelton et al., 1994; Levy et al., 1994, cited in Harridge et al., 1999a; Buchner et al., 1996) have attempted to identify functional "threshold" values of muscle performance below which older people lose their ability to perform basic daily tasks. Skelton et al. (1994), who measured the greatest height of step that could be mounted without using the hands in healthy men and women aged from 65 to 89 years, found a significant correlation between step height and lower limb extensor power, but failed to identify a universally applicable threshold value, even after adjusting for limb length. In contrast, Levy et al. (1994, cited in Harridge et al., 1999a) reported that unilateral power/weight ratios of 1.5 and 2.5 W/kg could be considered as threshold values for mounting a 30 and 50 cm step, respectively. Buchner et al. (1996), who used a slightly different model based on an inverse transformation of strength, found a significant correlation between lower limb strength and self-chosen walking speed. However, they also concluded that a "universal threshold" might not exist due to a compensation for deficiencies in strength by using reserve capacity in other determinants of walking speed. Regardless of the difficulties in identifying a precise value, this "threshold" concept make it easy to recognise that small changes in physiological capability can have large effects on the functional ability of a frail person, but little or no effect in a more robust person.

There are few studies that have investigated the effects of training protocols on selected functional abilities in older people (Table 1.3). It should be noted that in most of these studies (Judge et al., 1993; Fiatarone et al., 1994; Hunter et al., 1995; Skelton et al., 1995; Skelton and McLaughlin, 1996; Sherrington and Lord, 1997; Rooks et al., 1997) the age-range of participants is wide-spread, with both individuals in their 90's and their 60's or 70's being included in the same group. As these

Table 1.3. Effect of resistance training on selected functional abilities in older individuals.

Authors	Subjects				Training programme							Functional ability investigated	Gain %
	Age	Gender	N	Health and functional status	Practice of functional task	Exercise movement	Duration (weeks)	Sessions Per wk	Sets	Reps	% of 1RM		
Fiatarone et al., 1990	86-96	M/F	10	frail institutionalised	NO	KE	8	3	3	8	80	CR, MWV, tandem gait speed	48*
Judge et al., 1993	71-97	M/F	31	relatively healthy	NO	KE, HA, AD, HE, KF, PCE	12	3	3	8-12	75-80	MWV, usual gait velocity	8*
Fiatarone et al., 1994	72-98	M/F	100	frail institutionalised	NO	KE, HE	10	3	3	8	80	Habitual gait velocity	12
Hunter et al., 1995	60-77	F	14	healthy independent	NO	LP, BP, EF, EE, KE, HA	16	3	2	12RM	-	MWV, iEMG during CR, CB	18 §
Skelton et al., 1995	76-93	F	20	healthy independent	NO	Elastic tubing, rice bags	12	3	3	4-8	-	FR, SC, WR, SR, HR, BL, CR, FRS, KR, BS	Only KR, BS
Skelton and McLaughlin, 1996	74-89	F	18	relatively independent	YES	Elastic tubing, tin cans, sponge balls	8	1S-2U	1-3	4-8	-	FR, CR, TUG, MWV, SR, FRS, SC, BT	11-22 in only five
Sherrington and Lord, 1997	64-94	M/F	21	indep. after hip fracture	NO	GWBE	4	7	-	-	-	FR, habitual walking velocity	n.r.#
Rooks et al., 1997	65-95	M/F	37	independent community dwelling	YES •	HE, KE, AD, PF, EF	43	3	3	8-15	sp	SC time; pen pick-up task	20; -24
Taaffe et al., 1999	65-79	M/F	46	healthy	NO	LP, KE	24	1	3	8	80	CR, backward tandem walk	24 ^{X}
Häkkinen et al., 2000	62-77	M/F	10	healthy active	NO	LP, KE, BP, KF, EF, SU	24	2	3-5	8-12	50-80	MWV	13
Earles et al., 2000	77±5	M/F	18	highly functioning	YES ^{S}	LP, HF, SU, CR, PF	12	3	3	10	50-70	CR; 8-foot walk; 6-min walk	None

M, male; F, female; LP, leg press; KE, knee extension; KF, knee flexion; HE, hip extension; HF, hip flexion; HA, hip abduction; AD, ankle dorsiflexion, PF, ankle plantarflexion; BP, bench press; EF, elbow flexion; EE elbow extension; PCE, postural control exercises; GWBE, general weight bearing exercises; SUT, sit-up for the trunk flexors; SU, step-up; CR, chair raise time; iEMG, integrated electromyogram; CB, carrying box; FR, functional reach; SC, self-paced stair climbing speed; WR, self-paced walking rate; MWV, maximum walking velocity; SR, self-paced step rate; HR, heart rate during stair climbing or corridor walk; BL, bag lifting; FRS, floor rising; KR, kneel rise time; BS, box stepping; TUG, timed up and go; BT, time of getting in and out of a bath; 1RM, one repetition of maximum weight that could be lifted; sp, self-paced; S, supervised; U, unsupervised; * tandem gait speed only; * usual only; § descreased iEMG in CR and CB by36% and 40%, respectively; • SC only; ^{X} CR only; n.r.# habitual walking velocity only; percentage increase not reported.

Compiled by the author from published data.

investigations, with the exception of Fiatarone et al. (1994), were carried out on a relatively small number of individuals, the interpretation of results might have been limited by pulling together subjects within a wide age-range, since in the very old individuals small changes in physiological capability are likely to have larger effects on functional ability than in relatively younger subjects. Health and functional status also vary considerably between studies, with the participants ranging from frail-institutionalised (Fiatarone et al., 1990; Fiatarone et al., 1994) to relatively independent (Judge et al., 1993; Skelton and McLaughlin, 1996) or healthy active (Häkkinen et al., 2000; Earles et al., 2000), thus limiting inter-study comparisons. Regardless of these limitations, the relationship between resistance training and the ability to perform functional tasks remains unclear. As reported in Table 1.3, the effects of resistance training on selected functional abilities vary from no change (Earles et al., 2000) to 48% gain (Fiatarone et al., 1990), with most of the studies reporting improvements in only some of the functional abilities investigated (Skelton et al., 1995; Sherrington and Lord, 1997; Rooks et al., 1997; Taaffe et al., 1999). Skelton and McLaughlin (1996) have concluded that improvements in functional abilities may be a carried over effect of strength and power training, but are more likely to occur if the functional task is also practised. More recently, also Earles et al. (2000) have pointed out that power training *per se* may not necessarily improve functional task performance. Following a 12-week high-velocity training programme, 34 individuals of both genders in their late seventies increased their muscle strength and peak power of lower limb muscles by 22%, but did not improve functional task performance. Rooks et al. (1997), on the contrary, noted a 20% improvement in stair climb time after 10 months of moderate-resistance high-velocity training, but similar changes were also observed in a group of individuals performing a walking programme.

Three selected functional abilities appear to be the most frequently used in assessing the effects of intervention programmes: chair raising, stair climbing and maximum or self-selected walking speed. Chair raising is usually assessed as the time taken by older individuals to rise from a standard chair (seat height 43 cm) with their arms folded (Fiatarone et al., 1990; Skelton et al., 1995; Skelton and McLaughlin, 1996; Taaffe et al., 1999; Earles et al., 2000). Stair climbing normally consists of ascending and often descending a staircase without stopping at a comfortable pace, with or without using the handrail (Fiatarone et al., 1994; Skelton et al., 1995; Skelton and McLaughlin, 1996; Rooks et al., 1997). The time to complete of the task is timed. Maximum walking speed is measured by asking the subjects to walk as fast as possible over a distance, which is usually around 6 metres, and recording the time taken to cover that distance (Hunter et al., 1995; Skelton and McLaughlin, 1996). Other authors have measured the so-called "usual" or "habitual" velocity, by instructing the subjects to walk as they normally do (Fiatarone et al., 1990; Fiatarone et al., 1994; Judge et al., 1993; Skelton et al., 1995; Sherrington and Lord, 1997). In same cases, subjects were asked to walk placing the heel of one foot directly in front of the toe of the other with the shoe touching, which is referred to as tandem walk (Fiatarone et al., 1990), or walking backward using the same pattern (Taaffe et al., 1999). It is reasonable to expect that the choice of discriminatory tests of functional abilities in a population of older individuals who are healthy and active, as selected in the last study of this thesis, could be more problematic than in a group of frail individuals.

RATIONALE AND AIMS OF THE EXPERIMENTAL CHAPTERS

Muscle strength and power inexorably decline with ageing. Women in their 7th–8th decade have been identified as the first target group of intervention and rehabilitation studies, as they can reach levels of muscle strength and power below the threshold necessary to perform basic daily activities. Many of the causes of strength and power decline have been identified, as extensively reviewed in the introduction of this thesis, as well as many of the beneficial effects of resistance training on muscle function have been demonstrated. However, there are still some mechanisms and adaptations that need to be clarified. The overall aim of this thesis was therefore to examine some of the mechanisms underlying the lower levels of muscle strength and power in older women and some of the adaptations in response to resistance training.

The following research questions were addressed in each experimental chapter:

Chapter 2.

Rationale. It is still controversial whether specific tension (the ratio between muscle strength and size) declines with ageing. Some investigators reported that this ratio was similar in young and older individuals, thus suggesting that the lower levels of strength in older people may be totally explained by smaller muscle mass. By contrast, other investigators showed that the ratio between muscle strength and size was higher in young than older subjects, thus suggesting that the older muscle may be weak for its size. This controversy could be partly attributed to the method adopted to assess specific tension. It has been recently suggested that determination of muscle volume is a way of approximating its physiological CSA. This represents the sum of the CSAs of all the muscle fibres within a pennate muscle, such as the quadriceps, which run obliquely to the force-generating axis and insert into the tendon with an angle. Moreover, recent imaging techniques, such as MRI, enable not only to precisely assess muscle volume, but also to estimate the muscle contractile component separately from the intramuscular non-contractile tissues (i.e., connective and fat tissue). No investigators have expressed specific tension as the ratio between maximum isometric torque and contractile muscle volume, distinguished from intramuscular non-contractile tissue. In addition, no investigators have measured in the same population specific strength and neural activation of agonist-antagonist muscles, which could be an additional factor to explain the lower levels of force production in older women.

Research questions. Is the lower isometric strength in older women entirely due to a smaller contractile muscle mass, when estimated separately from the intramuscular non-contractile tissue, or are there other factors that may play a role? Among these factors, what is the role of the neural activation of the agonist muscles and the coactivation of the antagonist muscles?

Chapter 3.

Rationale. Lower limb explosive power, which is more predictive of functional difficulties than strength *per se*, with women being more at risk than men for disability, has been previously compared between young and older women using systems with a fixed inertia. Individuals may have been obliged to use a percentage of their maximum strength that is not ideal to perform the movement at the optimum speed for maximum power output. To the authors knowledge there is only one study in which explosive power has been compared between middle-aged and older men after optimising the load, but no study to date has considered this issue in women. Moreover, the two determinants of power output, i.e. optimal force and optimal speed, have not been considered.

Research question. When explosive power output is assessed during a single leg-press action, which is a functional movement, after optimisation of load, is the expected lower level of power due to lower levels of strength, speed or both?

Chapter 4.

Rationale. Neural adaptations account for most of the initial increase in maximum strength observed during the first few weeks of resistance training. However, there are few studies investigating changes in neural properties following isometric strength training in older individuals. The combined analysis of surface EMG in both the time and frequency domain could provide important information on both central and peripheral characteristics of MU activation. A constant-force sustained isometric contraction at high intensity and short duration is an optimal model for studying training-induced neural adaptations and, at the same time, is a good indicator of the ability to maintain daily activities in older people.

Research questions. Are there any differences between young and older women in the response to a short-term specific training programme aimed at increasing the capacity to sustain constant-force isometric contractions at high intensity? Are there any differences in the time and frequency-domain characteristics of the surface electromyogram, as a measure of training-induced neural adaptations?

Chapter 5.

Rationale. In recent times, greater attention has been focused on the need to design exercise strategies in order to increase muscle power. It is controversial whether high-speed low-resistance training is comparable or superior to low-speed high-resistance training in order to improve function and quality of life in older individuals. It is also controversial whether the ability to perform functional tasks may improve as a carry-over effect of power training or if the functional task must also be practised.

Research question. How do older women respond to different training regimens, one at high-intensity and low-speed, another at low-intensity and high-speed, and a third made by a combination of both, specifically designed to improve power, strength and selected functional abilities?

CHAPTER 2

CONTRACTILE MUSCLE VOLUME AND AGONIST-ANTAGONIST COACTIVATION ACCOUNT FOR DIFFERENCES IN TORQUE BETWEEN YOUNG AND OLDER WOMEN

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SUMMARY

It is controversial whether specific tension (the ratio between muscle strength and size) declines with ageing. Therefore, contractile muscle volume was estimated separately from the intramuscular non-contractile tissue by magnetic resonance imaging and maximum isometric torque was measured in the knee extensors and flexors of 10 young (22.8 ± 5.7 years) and 10 older (69.5 ± 2.4 years) healthy active women. Specific tension was lower in the older women both in the extensors (93.1 ± 20.1 $kN.m^{-2}$ vs. 112.1 ± 12.3 $kN.m^{-2}$; $P < 0.05$) and in the flexors (100 ± 31 $kN.m^{-2}$ vs. 142.7 ± 23.9 $kN.m^{-2}$; $P < 0.01$). This was accompanied by an increase in the percentage coactivation of the knee flexors during knee extension. These data suggest that the lower level of muscle torque in the older women can be explained not only by smaller contractile muscle mass but also by increased coactivation of the antagonist muscles during knee extension.

INTRODUCTION

Loss of muscle mass is an important factor contributing to the decline of muscle strength in older subjects (for review, see Vandervoort, 2002). Previous investigators reported that the decline in strength may be totally explained by smaller muscle cross-sectional area (CSA) as opposed to any intrinsic loss of strength within the muscle (Young et al., 1984; Häkkinen and Häkkinen, 1991; Overend et al., 1992a; Kent-Braun and Ng, 1999; Frontera et al., 2000b). By contrast, other investigators showed that the ratio between muscle strength and CSA was higher in young than older subjects, thus suggesting that older muscle may be weak for its size (Young et al., 1985; Klitgaard et al., 1990; Phillips et al., 1993; Jubrias et al., 1997). This controversy continues, despite the use of precise imaging techniques for the assessment of CSA, such as computed tomography (Klitgaard et al., 1990; Overend et al., 1992a; Frontera et al., 2000b) or magnetic resonance imaging (MRI) (Jubrias et al., 1997; Kent-Braun and Ng, 1999). These techniques can be used not only to outline the muscle compartment area on each scan, at different levels of section, but also to estimate the muscle contractile component separately from the intramuscular non-contractile tissues (e.g., connective tissue and fat).

It has been suggested that age-related differences in muscle strength between young and older subjects are not solely explained by structural changes in the muscle itself (Larsson et al., 1979; Lexell et al., 1988; Frontera et al., 2000b), but also by changes in the neural activation of agonist muscles and coactivation of antagonist muscles (Häkkinen et al., 1998a; Izquierdo at al., 1999).

During their 7th-8th decade, women may reach levels of strength below the threshold necessary to accomplish basic daily activities; therefore, it has been suggested that they should be the first target group of intervention and rehabilitation studies (Skelton et al., 1994). In particular, the knee extensor/flexor muscles appear to be more affected by atrophy and loss of strength than muscles of the upper extremities (Frontera et al., 1991), and it is therefore important to study these muscle groups.

Previous investigators (Young et al., 1984; Young et al., 1985; Klitgaard et al., 1990; Häkkinen and Häkkinen, 1991; Overend et al., 1992a; Phillips et al., 1993; Jubrias et al., 1997; Kent-Braun and Ng, 1999; Frontera et al., 2000b) used the area of muscle cross-section at right angle to the long axis of the limb, i.e., anatomical CSA, to interpret data on muscle strength relative to muscle size in ageing muscle. In pennate muscles, however, the anatomical CSA cuts a limited number of fibres and is therefore smaller than the physiological CSA (Fukunaga et al., 1992; Narici and Capodaglio, 1998). It has been recently suggested that determination of muscle volume is a way of approximating its physiological CSA (Miyatani et al., 2001). Moreover, because the muscle volume can be expressed as a product of physiological CSA and muscle fibre length, torque relative to muscle volume may theoretically be considered as an index with the same dimension as that of muscle force relative to physiological CSA, i.e., specific tension ($kN \cdot m^{-2}$) (Miyatani et al., 2001). In the present study, the ratio between maximum isometric torque and contractile muscle volume, distinguished from intramuscular non-contractile tissue, was used to compare specific tension of the knee extensors and flexors between young and older women. A secondary purpose of this study was to examine differences between young and older women in the coactivation of the antagonist muscles as an additional factor to explain the reduced level of force production in older women.

METHODS

Subjects. With local ethics committee approval, a total of 20 women volunteered for the study. There were 10 older women (mean age 69.5 ± 2.4 years, stature 1.58 ± 0.04 m, mass 67.5 ± 14.5 kg) and 10 young women (mean age 22.8 ± 5.7 years, stature 1.64 ± 0.05 m, mass 58.9 ± 11.1 kg). The percent body fat of the subjects, as a percentage of body mass, determined by the sum of four skinfolds (biceps, triceps, subscapular and supra-iliac) (Durnin and Womersley, 1974), was 38.4 ± 3.3 % in the older and 26.8 ± 4.8 % in the young women. Most subjects performed recreational physical activities, but none had any background in regular strength training or competitive sports. Subjects were selected according to the exclusion criteria to define "medically stable" older subjects for exercise studies, as proposed by Greig et al. (1994).

MRI. A 1.0T Impact Expert Scanner (Siemens, Erlangen, Germany) was used to perform T1-weighted volume acquisitions through the whole of both femurs. Subjects lay on the scanner in a supine position and the images were acquired coronally to minimise acquisition time and artefacts from subject movement. Image parameters were: repetition time (TR) 11.4 ms, echo time (TE) 4.4 ms, flip angle 12°, slab thickness 249 mm, field of view 475 mm^2, and matrix 256 x 256 mm. The scan time was 9 min. The three dimensional volume acquisition was then re-cut into axial sections of 1.7 mm covering the complete length of the femur. Calibration of the scanner with a physical phantom ensured that the volume presented was within 0.9 % of actual value.

CSA per each axial section was calculated by drawing a region of interest around the relevant muscles using Scion Image Analysis Software (Scion Corp., Frederick, USA). This program read the dicom image files and converted them to a grey scale ranging from 0 (white) to 255 (black) units. The intramuscular non-contractile tissue (e.g., connective and fat) was separated from the muscle contractile component by determining an individual threshold for pure muscle in each subject. Non-contractile tissue was assumed to cover a range of signal intensities above the mean individual muscle signal similar to Kent-Braun et al. (2000). Quadriceps and hamstrings contractile CSAs were calculated by subtracting non-contractile tissue from the related muscle compartment area. Muscle length was defined as the distance between the most proximal and distal images in which the muscle was visible. Muscle volume was the distance between sections multiplied by the contractile CSAs of the entire muscle length, according to the Cavalieri principle (Gadeberg et al., 1999). The Cavalieri principle refers to the integration of the measured CSAs of any tissue of interest in the serial slices throughout an object. In other words, to compute the volume of an object, the object is sliced into thin slices and their volumes are added. The volume of each slice is its thickness times the area of its face. In addition, a line was drawn to calculate the subcutaneous thickness between the electrodes and muscle fibres.

Strength testing. Subjects warmed up on an exercise bicycle for 5 min at a light resistance before performing any strength test. All subjects were familiarised with the experimental procedures on at least one occasion, 3-4 days before the testing session. Muscle torque during maximum isometric voluntary contraction (MVC) of the knee extensor and flexor muscles, in the dominant leg, was recorded using a dynamometer (Kin-Com, Chattanooga, USA). Subjects were seated comfortably in the dynamometer chair, with their trunk erect and fastened by three belts. They were positioned so that a 90° angle at the knee joint was obtained. The MVC task consisted of rapidly increasing the force exerted by the knee extensors or flexors to a maximum. A target line was always set on the computer screen at a value 20% higher than the best performance. Subjects followed their performance on the computer screen and were verbally encouraged to achieve a maximum, in an attempt to exceed the target force, and to maintain it for at least 2 s before relaxing. MVC was calculated as the largest 1-s average reached within any single force recording. A minimum of three maximal attempts were performed, for both extension and flexion, separated by 3 min to recover from fatigue, and the best performance was chosen for further analysis. Subjects were asked to make a further attempt if the MVC of their last trial exceeded that of previous trials. The same experimenter performed the measurements in all subjects.

Surface electromyogram. A simultaneous reading of the surface electromyogram (EMG) from vastus lateralis and biceps femoris muscles was recorded during the measure of MVC. The assumption was made that these two muscles were representative of their constituent groups (Carolan and Cafarelli, 1992). Two silver/silver chloride electrodes, pre-gelled, self-adhesive, and 4 mm in diameter (Medicotest A/S, type N-10-A, Denmark) were placed 20 mm apart (centre to centre) on a prepared site of the muscles, half way between the centre of the belly and the distal myotendinous junction. Before applying the electrodes, the skin was gently scratched with fine sand paper and then cleaned with ethyl alcohol. A ground electrode (Dantec Electronics mod. 13S97, UK) was placed around the ankle of the contralateral limb. The EMG signal was band-pass filtered between 5 and 1000 Hz (NeuroLog Filter NL125, Digitimer, UK), pre-amplified (×1000) (NeuroLog remote AC preamplifier NL824, Digitimer, UK), amplified (×2) (NeuroLog Isolation Amplifier NL820, Digitimer, UK), and A-D converted (type 1401; Cambridge Electronic Design, UK) at a sampling rate of 2048 Hz. To ensure that antagonist cross-talk did not contaminate the data, the EMG signals of the two muscles were plotted against each other on an oscilloscope during each trial and, if the plot of the two axes formed an ellipse, the myoelectric signals were discarded (Bernardi et al., 1995). Cross-talk was further assessed after the recordings by using cross-correlation analysis (Winter et al., 1994; Hansen et al., 2001). To quantify the EMG amplitude, expressed as root mean square (RMS), computer-aided analysis was performed over the 1-s epoch corresponding to MVC. The RMS is analytically defined as:

$$\text{RMS} = \sqrt{\frac{1}{T}\int_0^T x^2(t)dt}$$

where $x(t)$ is the sEMG signal and T is the acquisition time.

Statistics. All data were normally distributed in terms of skewness and kurtosis (all values less than $|2|$). Means ± S.D. were calculated. Comparison between young and older subjects was made using a two-sample Student's t test. Statistical significance was accepted if the two-tailed P value was < 0.05.

RESULTS

The older women were on average 43% weaker than the young women in the MVC torque of the knee extensors (78.7 ± 13.6 Nm vs. 138.0 ± 27.0 Nm; $P < 0.001$) and 47% weaker in the MVC torque of the knee flexors (34.6 ± 8.9 Nm vs. 64.9 ± 14.6 Nm; $P < 0.001$).

Older women had significantly greater amounts of intramuscular non-contractile tissue than the young women, expressed as percent volume, in both quadriceps (13.1 ± 7.6 % vs. 5.8 ± 3.7 %; $P < 0.05$) and hamstrings (20.1 ± 5.5 % vs. 14.1 ± 6.4 %; $P < 0.05$). Muscle contractile volume, separately from the non-contractile tissue, was significantly lower in the older women both in the knee extensors ($P < 0.001$) and knee flexors ($P < 0.05$) (Figure 2.1a).

When MVC torque was divided by the contractile volume (specific tension), it remained significantly lower in the older than in the young women, for both extensors ($P < 0.05$) and flexors ($P < 0.01$) (Figure 2.1b).

The level of coactivation of the biceps femoris during the knee extension, expressed as a percentage of maximal biceps femoris RMS measured during the MVC knee flexion, was significantly higher ($P < 0.05$) in the older than young women (Figure 2.2a). By contrast, there was no significant difference between the two groups in the level of coactivation of the vastus lateralis during the knee flexion (Figure 2.2a).

The EMG analysis in the time domain showed that RMS was significantly smaller in the older than in the young women both for the extensors ($P < 0.01$) and flexors ($P < 0.001$) (Figure 2.2b).

The subcutaneous thickness was significantly different in the two groups ($P < 0.05$) for both vastus lateralis (9.94 ± 3.16 mm in the young and 14.14 ± 4.57 mm in the older women) and biceps femoris (12.51 ± 5.38 mm and 17.65 ± 5.18 mm, respectively).

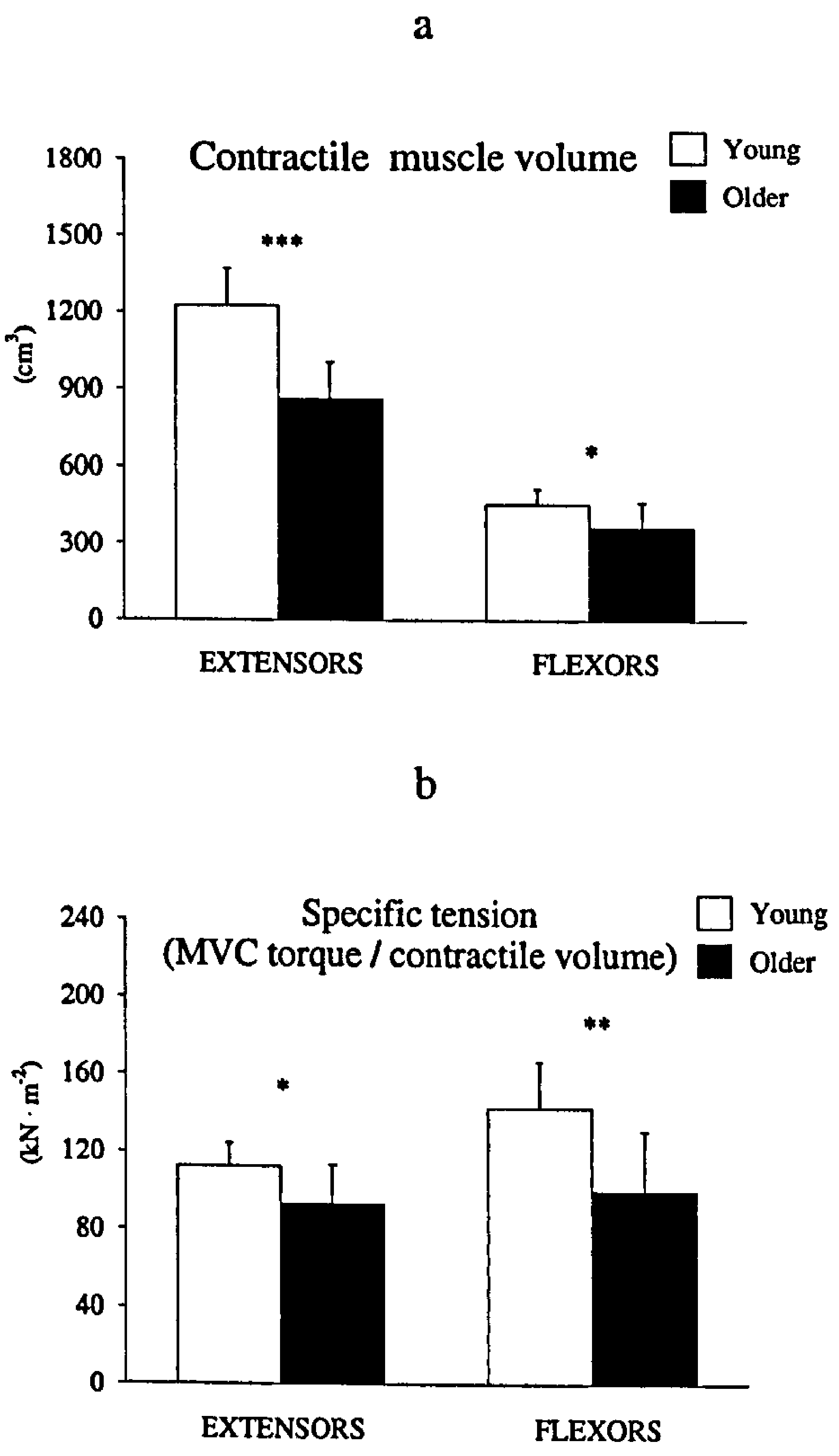

Figure 2.1. **a)** Contractile volume and **b)** specific tension (MVC torque/contractile volume) of the knee extensor and flexor muscles, during maximum voluntary isometric contraction (MVC), in young and older women.

Data are expressed as means ± S.D. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

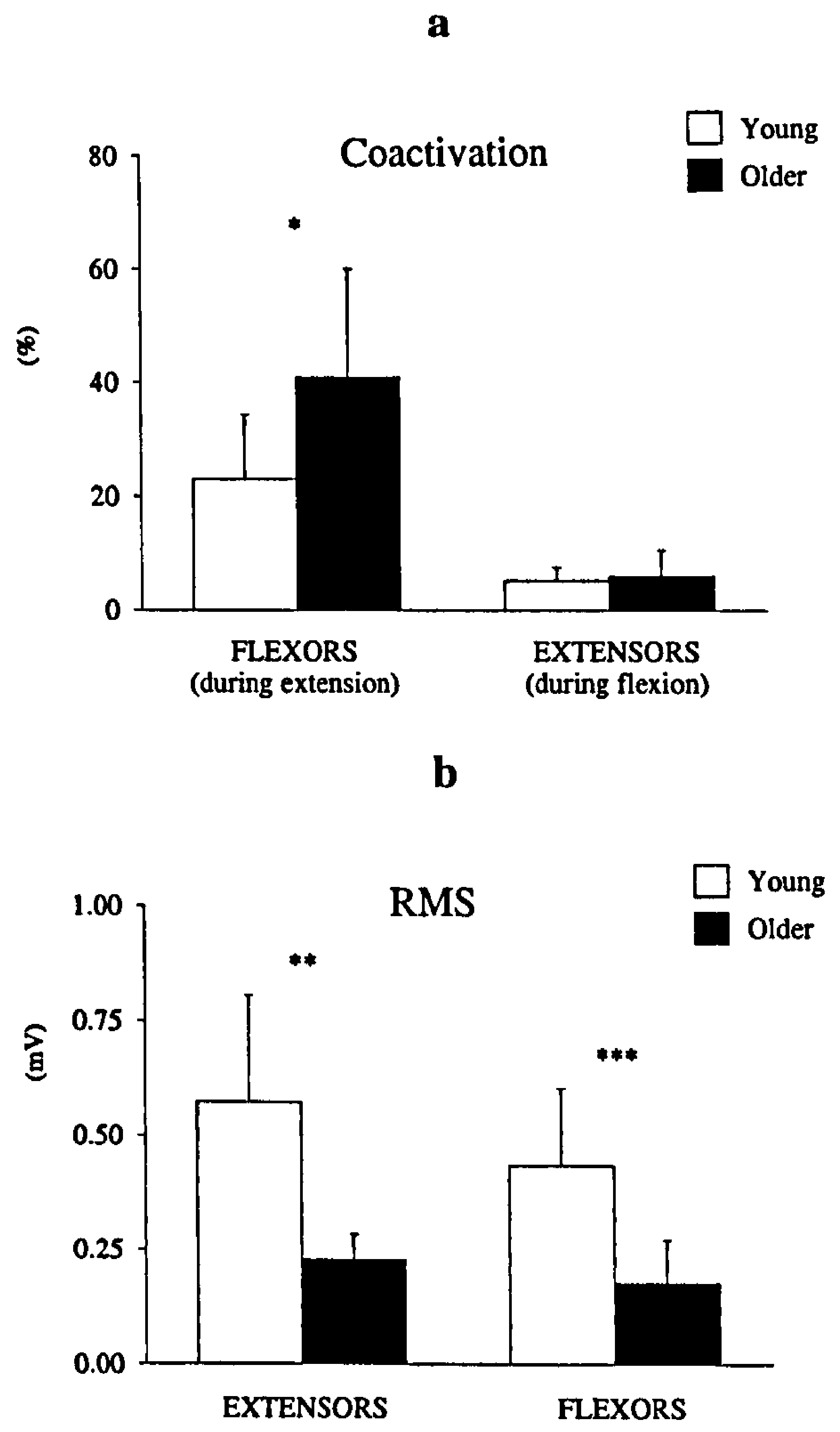

Figure 2.2. Surface electromyogram data: **a)** percentage coactivation of the biceps femoris during the knee extension MVC and of the vastus lateralis during knee flexion MVC in young and older women; **b)** root mean square (RMS) of the knee extensor and flexor muscles during MVC.

Data are expressed as means ± S.D. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

DISCUSSION

The main finding of the present study is that the older women showed a lower specific tension, expressed as torque per unit contractile volume, than the young women. This was associated with an increased level of coactivation of the knee flexors during knee extension. This suggests that the lower level of muscle strength in older women can be explained not only by smaller contractile muscle mass but also, among other factors, by increased coactivation of the antagonist muscles during knee extension.

The reduced MVC of the older women in our study is consistent with the finding of others studying the knee extensors and flexors (Young et al., 1984; Young et al., 1985; Klitgaard et al., 1990; Häkkinen and Häkkinen, 1991; Overend et al., 1992a; Frontera et al., 2000b).

The possibility that the volume occupied by force-generating tissue was overestimated in the older muscle, because of an increase in the proportion of fat and connective tissue, can be discounted. Our results are similar to that of Kent-Braun et al. (2000) in that ageing is shown to be associated with an increase in the non-contractile tissue within muscle, and this was taken into account in our analysis.

Previous investigators have produced equivocal results with regard to the ratio between muscle strength and CSA in older people (Young et al., 1984; Young et al., 1985; Klitgaard et al., 1990; Häkkinen and Häkkinen, 1991; Overend et al., 1992a; Phillips et al., 1993; Jubrias et al., 1997; Kent-Braun and Ng, 1999; Frontera et al., 2000b). A potential limitation of previous studies (Young et al., 1984; Young et al., 1985; Klitgaard et al., 1990; Häkkinen and Häkkinen, 1991; Overend et al., 1992a; Jubrias et al., 1997; Kent-Braun and Ng, 1999; Frontera et al., 2000b) is that in pennate muscles, such as the quadriceps, where muscle fibres attach to the tendons at an angle, measurements of anatomical CSA underestimate the physiologically effective muscle size (Narici, 1999). This limitation has been partially overcome in the present study by assessing contractile muscle volume. At present there is no established method of directly determining physiological CSA in human skeletal muscle (Miyatani et al., 2001). Physiological CSA *in vivo* can be estimated by dividing the product of muscle volume and the cosine of the angle of pennation by the length of the muscle fibres (Narici and Capodaglio, 1998), and this is linearly correlated to muscle volume (Fukunaga et al., 1992). Therefore, determining muscle volume in the present study can be considered a way of approximating muscle physiological CSA (Miyatani et al., 2001). Moreover, torque relative to muscle volume may be theoretically considered as an index with the same dimension as that of muscle force relative to physiological CSA, i.e., specific tension (Miyatani et al., 2001).

The level of coactivation of the flexor muscles during knee extension was higher in the older than young women. Coactivation may protect and stabilise the joint during forceful contractions (Baratta et al., 1988). It has been recently shown that antagonist muscle activation during isometric and dynamic knee extension is greater in men aged 65 than in men aged 40 (Izquierdo et al., 1999). This could reflect lower coordination or skill (Carolan and Cafarelli, 1992) and may be considered as an additional factor to explain the reduced level of force production in older subjects. It has also been shown that antagonist coactivation decreased as a result of resistance training, not only in young (Carolan and Cafarelli, 1992) but also in older subjects (Häkkinen et al., 1998c). A limitation of this and previous studies (Häkkinen et al., 1998a; Izquierdo at al., 1999) is that the presence of greater adipose tissue in older subjects may have increased the danger of cross-talk (Solomonow et al., 1994) and therefore led to inaccurate assessment of coactivation. However, Solomonow et al. (1994), who raised such concerns, also concluded that for surface EMG recording with the appropriate size of electrodes, correct placement over the muscle and short interelectrode distance, the effect of cross-talk could be disregarded in most skeletal muscles of the extremities, spine and upper trunk, with the exception of abdominal and buttock muscles which are covered by a considerable amount of subcutaneous fat. The thickness of the subcutaneous tissue above the muscles investigated in this study (vastus lateralis and biceps femoris) is minimal with respect to the thickness of the adipose tissue above abdominal and buttock muscles and the difference between young and older subjects is in the order of only a few millimetres. Moreover, even if greater cross-talk occurred in the older subjects due to the slightly thicker subcutaneous tissue, it would be balanced in the young subjects by greater cross-talk due to the much greater surface EMG amplitude of the agonist muscle, which in turn increases cross-talk to the antagonist muscles (Solomonow et al., 1994). The net effect would thus be a similar proportion of cross-talk in the two groups.

Another finding of this study is that the RMS was more than halved in the older women. This could be attributed to decreased neural activation of the agonist muscles in agreement with the results of previous studies (Esposito et al., 1996; Häkkinen et al., 1998a; Izquierdo et al., 1999). After all, smaller M-wave amplitudes have been reported in older subjects and this has been attributed to a reduction in the amount of muscle membrane excitation (Hicks et al., 1992). However, the lower RMS may also be due to the dryer skin and greater subcutaneous thickness in older subjects (Basmajian and De Luca, 1985). The results of a recent simulation study by Farina and Rainoldi (1999) can be used to infer that the skin-subcutaneous layer may indeed affect RMS, but would not entirely explain the great difference in RMS between young and older subjects, which was more than halved in the older women. The smaller RMS in the older may thus be attributed to either a smaller number of recruited motor units (MUs) or a decreased firing rate of the individual MUs (Basmajian and De Luca, 1985; Esposito et al., 1996). An additional factor to explain the smaller RMS is decreased MU synchronisation (Milner-Brown et al., 1975). However, the relative roles played by MU recruitment, MU firing rate and synchronisation of the individual MUs cannot be distinguished with surface EMG (Esposito et al., 1996). Lower EMG amplitude could also partly relate to the fact that there is less contractile muscle mass beneath the electrodes in the older subjects. In addition, a decrease of muscle activation in older subjects may also be due to a reduction of the output from supraspinal centres (Jones and Round, 1990), but a superimposed stimulus, either in the form of a single twitch or a short tetanus, add little to the volitional force of older people (Phillips et al., 1992; De Serres and Enoka, 1998; Kent-Braun and Ng, 1999).

In conclusion, this study has provided new information on the ratios between knee extensor/flexor torque and contractile volume, in young and older women. Older women are significantly weaker than young women in both isometric extension and flexion, and their lower level of strength is not completely explained by the decrease in their contractile muscle mass. One potential explanation for the reduced level of force production in older women is an increase in the level of coactivation of the flexor muscles during knee extension, and another is a decrease in the neural activation of the agonist muscles, both during knee extension and flexion.

CHAPTER 3

COMPARISON BETWEEN YOUNG AND OLDER WOMEN IN EXPLOSIVE POWER OUTPUT AND ITS DETERMINANTS DURING A SINGLE LEG-PRESS ACTION AFTER OPTIMISATION OF LOAD

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SUMMARY

Lower limb explosive power, which is more predictive of functional difficulties than strength *per se*, with women being more at risk than men for disability, has been previously compared between young and older women using systems with a fixed inertia. Individuals may have been obliged to use a percentage of their maximum strength that is not ideal to perform the movement at the optimum speed for maximum power output. This study was designed to compare explosive power output during a leg-press action between young and older women after optimising the load for maximum power production. The experiments were carried out on twenty women in good physical condition, 10 older, aged between 65 and 74 years and 10 young, aged between 18 and 30. Explosive power output was measured by setting the initial load at different percentages of maximum isometric strength and measuring the corresponding speed of movement during a leg press action of the dominant leg. Maximum peak power, which was obtained at 60% of maximum isometric strength in both young and older, was 61% lower in the older ($P < 0.0001$). This was due to a 52% lower optimal force ($P < 0.0001$) and 21% lower optimal speed ($P < 0.01$). The ratio of peak power to maximum isometric strength was 22.1% lower in the older women ($P < 0.01$). After optimising the load, both lower speed of movement and lower strength determine the lower levels of power in older women. Power, not surprisingly, is more affected by ageing than isometric strength.

INTRODUCTION

The ability to perform physical tasks of everyday life in old age, such as rising from a chair, climbing stairs or using public transport, depends on the maintenance of critical levels of muscle strength and power (Harridge and Young, 1998). Explosive power output, which can be defined as the ability to generate work over a fraction of a second, has been shown to be more predictive of functional difficulties than strength *per se* in older people (Harridge and Young, 1998; Fiatarone Singh, 2000; Foldvari et al., 2000). Its decline is particularly evident in women who have been identified as the primary target group for intervention and rehabilitation studies (Bassey et al., 1992; Skelton et al., 1994). There is evidence that explosive power output declines with ageing at a higher rate than maximum isometric strength, thus suggesting that the decreased ability to generate power is due to an inferior ability to develop both dynamic strength and speed (Davies et al., 1983; Skelton et al., 1994; Metter et al., 1997; Izquierdo et al., 1999). However, in previous studies (Bosco and Komi, 1980; Davies et al., 1983; Grassi et al., 1991; Ferretti et al., 1994; Skelton et al., 1994; Metter et al., 1997; De Vito et al., 1998) explosive power output has been assessed using a fixed inertia, either during a vertical jump, where the inertia was represented by the subject's body weight (Bosco and Komi, 1980; Davies et al., 1983; Grassi et al., 1991; Ferretti et al., 1994; De Vito et al., 1998), or by a flywheel system (Skelton et al., 1994; Metter et al., 1997). This is a limitation because the weaker subjects may be disadvantaged, since this inertia would correspond to a high percentage of their maximum and consequently not represent the optimal value of force for maximum power production (Harridge and Young, 1998; De Vito et al., 1998). In other words, when older subjects are required to push a high resistance, such as their body weight during a vertical jump, or the same inertia as stronger subjects during a single leg extension on the Nottingham power rig (Bassey et al., 1990), they must use a high percentage of their maximum strength. Therefore, they may perform the movement at slower speed, which is away from the optimal speed for maximum power production. To the author's knowledge, there is only one study in which explosive power has been compared between middle-aged and older men after optimising the load (Izquierdo et al., 1999), but no study to date has considered this issue in women. Moreover, the two determinants of power output, i.e. optimal force and optimal speed, have not been considered.

The present study was designed to compare explosive power output between young and older women by assessing power at the optimal force and speed for maximum power production during a leg-press extension, which is a functional action. It is perhaps obvious that older women will be weaker and less powerful than young women, but is the inferior ability to generate power due to a lesser ability to develop force or speed or both?

METHODS

Subjects. Twenty women, 10 older (age range 65-74 years) and 10 young (age range 18-30 years), volunteered for the study. The physical characteristics of the participants are presented in Table 3.1, together with values of their quadriceps cross-sectional area (CSA) of the dominant limb, determined by Magnetic Resonance Imaging (see details below).

Table 3.1. Age, stature, body mass and quadriceps cross-sectional area (CSA) of the dominant limb in young and older subjects.

Group	Age (years)		Stature (m)		Body Mass (kg)		CSA (cm^2)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Young (n=10)	22.8	5.7	1.64	0.05	58.9	11.1	55.4	5.4
Older (n=10)	69.5	2.4	1.58	0.04	67.5	14.5	41.5	4.2

Subjects were selected according to the exclusion criteria to define "medically stable" older subjects for exercise studies, as proposed by Greig et al. (1994). Most subjects were habitually physically active, but not practising any kind of systematic training. The experimental procedures were approved by the Ethics Committee of the University of Strathclyde and all subjects gave their informed consent for participation in the study.

Maximum voluntary isometric strength and maximum power output. Subjects warmed up on an exercise bicycle for 5 min at a light resistance before performing any strength or power test. All the subjects were previously familiarised with the experimental procedures on at least one occasion, 3 or 4 days before the testing session. Both isometric and power measures were made on the dominant lower limb using a dynamometer (Kin Com, Chattanooga, USA) in the leg press position. As shown in Figure 3.1, the seat was modified in order to have a firm support placed behind the buttock. The trunk was fastened by three belts and each subject's leg was positioned so that a starting angle of 90° at the hip, knee and ankle joint was

Figure 3.1. Dynamometer adopted to perform both isometric and power measures during the leg-press of the dominant limb. The seat was modified in order to have a firm support placed behind the buttock. The trunk was fastened by three belts and each subject's leg was positioned so that a starting angle of 90° at the hip, knee and ankle joint was obtained.

obtained. The maximum voluntary isometric strength (MVC) task consisted of rapidly increasing the force exerted during the leg-press to a maximum. A target line was always set on the computer screen at a value 20% higher than the best performance. Subjects followed their performance on the computer screen and were verbally encouraged to achieve a maximum, in an attempt to exceed the target force, and to maintain it for at least 2 s before relaxing. The MVC was calculated as the largest 1-s average reached within any single force recording. At least three maximal attempts were performed, separated by 3 min, and the best performance was chosen as MVC. Subjects were asked to make a further attempt if the MVC of their last trial exceeded that of previous trials. The power measures were performed setting the dynamometer in the "isotonic" mode, with the initial load at 30% of MVC. The test was then repeated with the initial load increased, in 10% increments, up to 80% of MVC, in a random order. Each subject was required to push forward, as strong and quickly as possible, until the leg was fully extended, throughout a range of motion of 0.2 m. Three trials for each level of initial load were performed, in a random order. Figure 3.2 shows a typical example of force, speed and displacement in one of the subjects, when the initial load was set at 60% of MVC. Although the dynamometer used in this investigation has been set in the "isotonic" mode, it is clear that force is not kept constant during the movement, which cannot therefore be referred to as isotonic. The dynamometer attempts to hold the lever arm resistance at the user-selected level by reading the loadcell signal and adjusting the speed of the motor potentiometer throughout the full range of motion, but the sampling rate of the instrument (100Hz) is such that the adjustment is not quick enough to obtain a constant trace. However, it must be clarified that this is not relevant to this study. In order to test the hypothesis of this investigation it was necessary to adopt a dynamometer that enabled to measure velocity of movement with the subjects exerting a given level of average force throughout the movement, which corresponded to various percentages of isometric force. The initial loads the subjects were asked to push were almost equal to the user-selected level, for all of the percentages of maximum force which were tested, and were highly correlated with both the forces at PP ($R^2 = 0.98$; $P < 0.0001$) and the average forces measured during the thrust ($R^2 = 0.97$; $P < 0.0001$). Peak power output (PP) was calculated by the

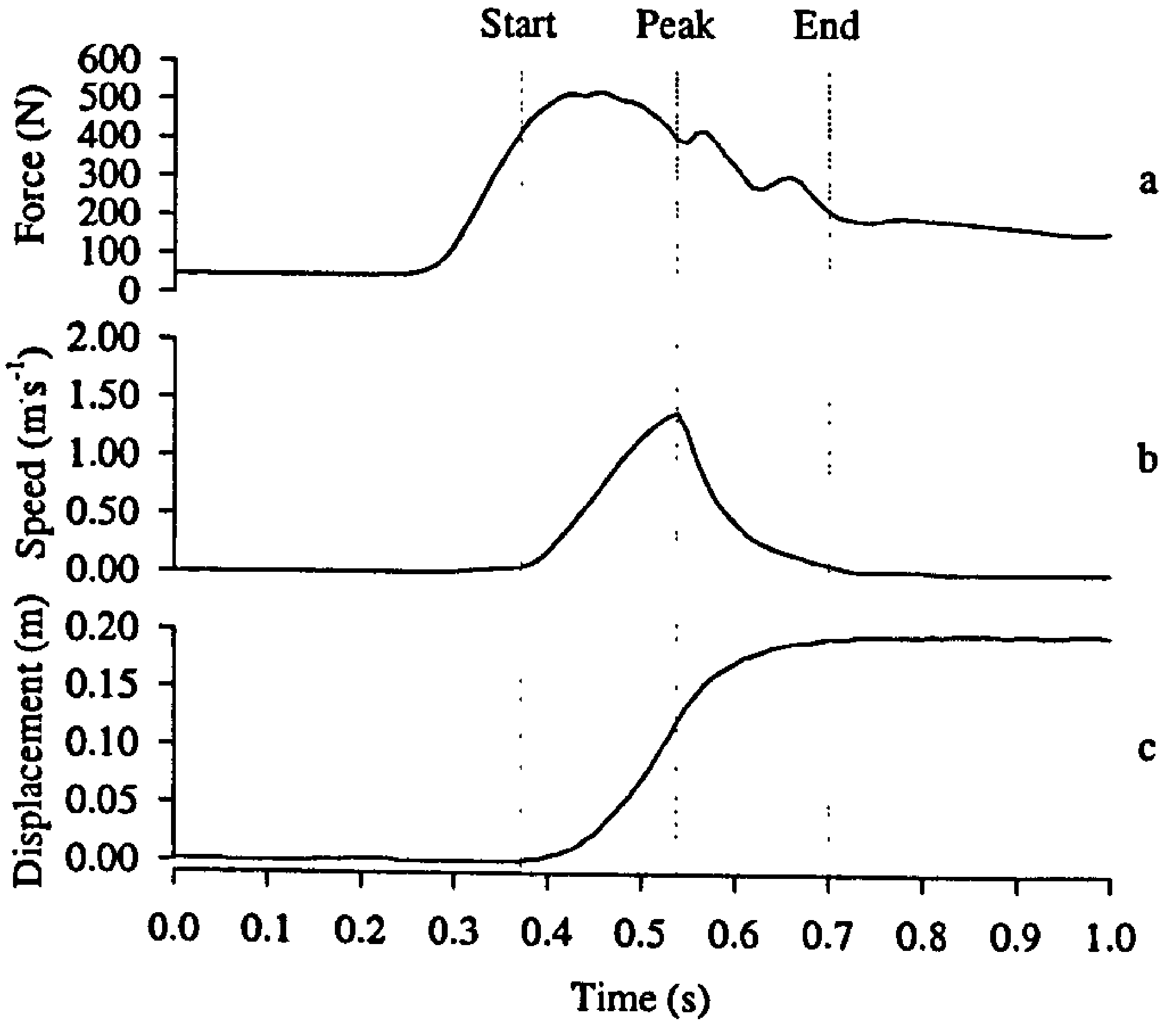

Figure 3.2. Force (a) and speed of movement (b) during a leg press movement plotted, along with the displacement (c), against time for one subject. Initial load was set at 60% of MVC (400N). Peak power output (PP) was calculated as the product of peak speed (1.38 $m \cdot s^{-1}$) and the corresponding force (400N). Average power output (AP) was calculated by multiplying the average speed (0.57 $m \cdot s^{-1}$) with the corresponding average force (402N) measured during the thrust.

product of peak speed and the corresponding force. Average power output (AP) was calculated by multiplying the average speed with the corresponding average force measured during the thrust. Measurements at 30% of MVC were discarded, as the system reached speed saturation in most individuals. Repeatability of the measurements was assessed in all subjects 3 or 4 days after the testing session. Coefficients of variation in young and older subjects, respectively, were 3.8% and 2.6% for MVC, 3.4% and 3.1% for PP, 3.4% and 3.2% for AP.

Muscle Cross Sectional Area. CSA of quadriceps muscle was measured by Magnetic Resonance Imaging as detailed in chapter 2. Briefly, a 1.0T Impact Expert Scanner (Siemens, Erlangen, Germany) was used to perform T1-weighted volume acquisitions through the whole of both femurs. Images were acquired coronally to minimise artefacts from any subject movement and the three dimensional volume acquisition was then re-cut into axial sections of 1.7 mm covering the complete length of the femur. CSA per each axial section was calculated by drawing a region of interest around the quadriceps muscle using Scion Image Analysis Software (Scion Corp., Frederick, USA). The intramuscular non-contractile tissue (e.g., connective tissue and fat) was separated from the muscle contractile component by determining an individual threshold for pure muscle in each subject. The greatest contractile CSA of the quadriceps muscle, which is reported in Table 3.1, corresponded to the mid-thigh scan.

Statistics. All data were normally distributed in terms of skewness and kurtosis (all values less than $|2|$). Means ± S.D. are presented. Comparisons between young and older subjects were made using a two-sample Student's t test. Statistical significance was accepted if the two-tailed P value was < 0.05.

RESULTS

Figures 3.3a and b show the results of PP and AP, respectively, with the corresponding values of speed and force at PP and AP, for the different initial loads, and MVC, in young and older individuals. Force is plotted on the x-axis, because the independent variable is the load the subjects have to work with, as it happens in real life. Both maximum PP and AP were reached when the initial load was set at 60% of MVC and these values were used for the statistical comparison between young and older women. The older women generated 60.9 % less maximum PP (358 ± 115 vs. 917 ± 168 W; $P < 0.0001$), 54.7 % less maximum AP (188 ± 83 vs. 415 ± 99 W; $P < 0.0001$) and 50.4 % less MVC (583 ± 105 vs. 1177 ± 180 N; $P < 0.0001$) than the young women. Both maximum PP and AP were generated by pushing a significantly lower peak (344 ± 77 vs. 709 ± 104 N; $P < 0.0001$) and average (343 ± 61 vs. 673 ± 98 N; $P < 0.0001$) optimal force and achieving a significantly lower peak (1.03 ± 0.18 vs. 1.29 ± 0.15 $m \cdot s^{-1}$; $P < 0.01$) and average (0.50 ± 0.12 vs. 0.61 ± 0.07 $m \cdot s^{-1}$; $P < 0.01$) optimal speed, respectively, than those of the young women. Figure 3.4 shows that after normalisation for quadriceps CSA of PP, AP and MVC, there was still a significant difference ($P < 0.0001$ for PP; $P < 0.01$ for AP; $P < 0.001$ for MVC) in all of these parameters between young and older subjects. The ratio between PP and MVC was significantly lower ($P < 0.01$) in the older (0.61 ± 0.15) than the young women (0.78 ± 0.12), thus suggesting that power is more vulnerable than strength to the ageing process.

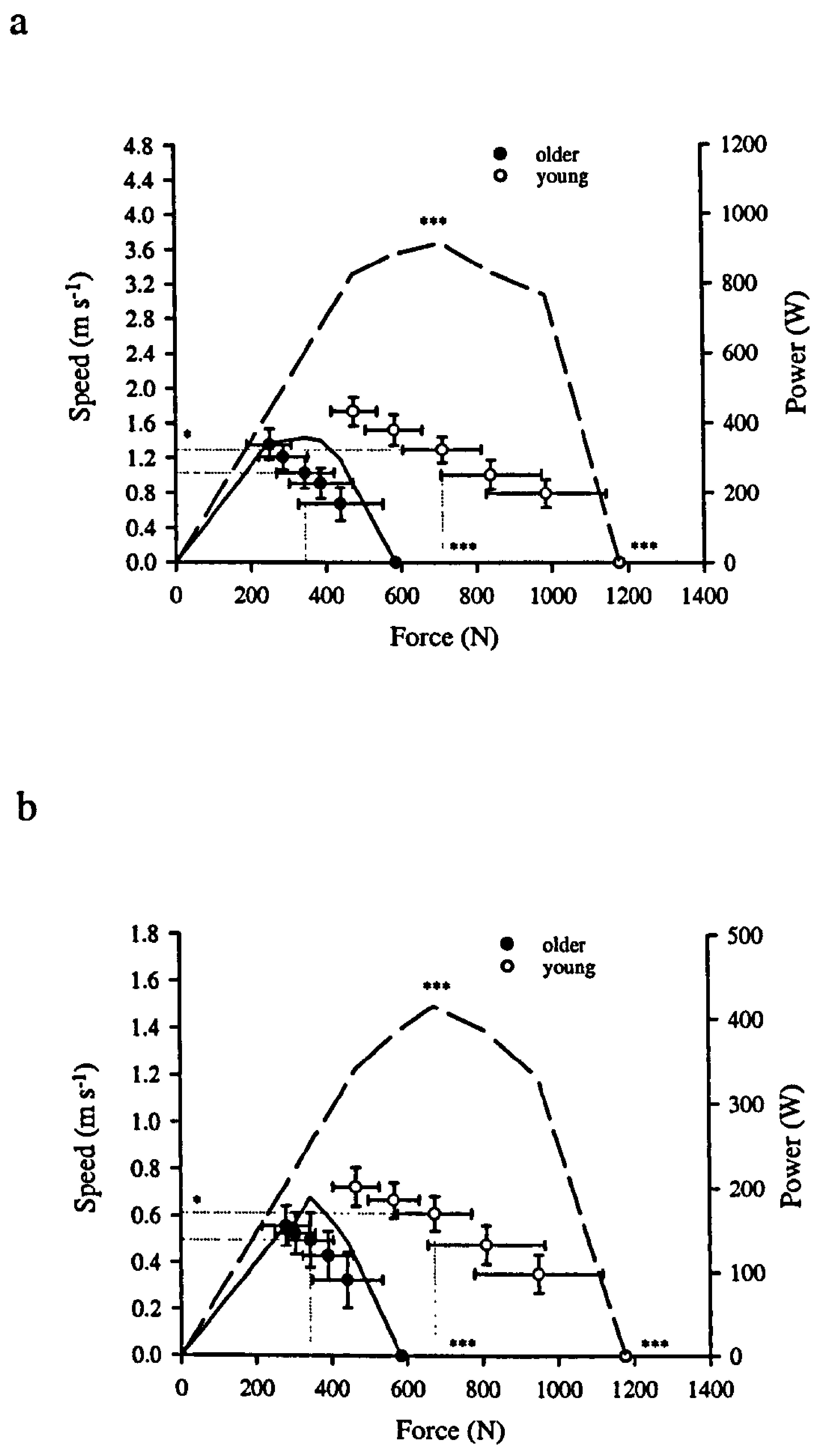

Figure 3.3. Peak (a) and average (b) speed of movement in the young (open circles) and the older women (filled circles) plotted as a function of force at 40, 50, 60, 70 and 80% of maximum isometric force (MVC). The dotted line represents the corresponding power output in the young women and the solid line in the older women. Optimal speed and optimal force at peak power (PP) (a) and average power (AP) (b) are highlighted. *** $P < 0.0001$; * $P < 0.01$: significantly different from older.

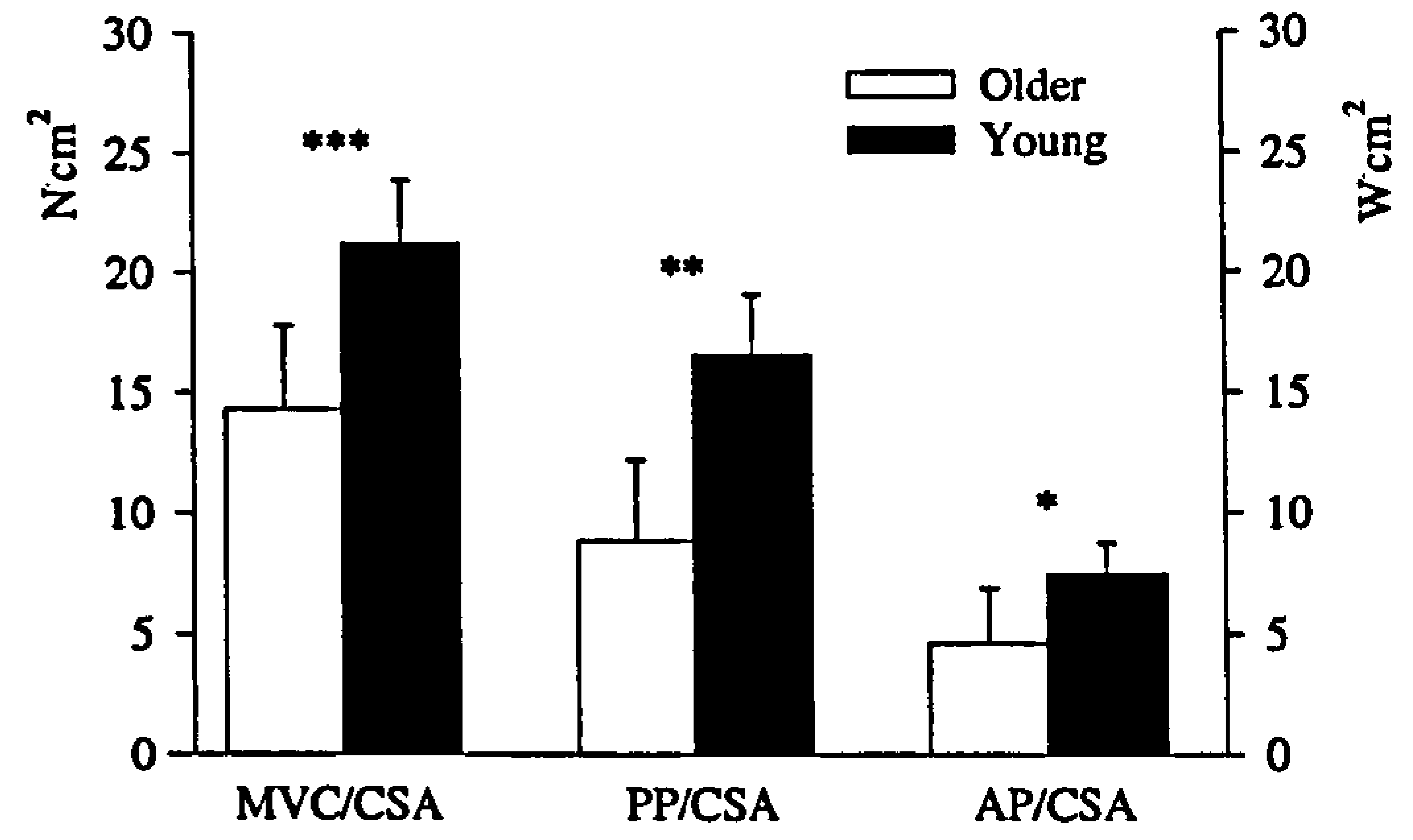

Figure 3.4. Maximum isometric force (MVC), peak power (PP) and average power (AP) normalised to quadriceps cross-sectional area (CSA), in young and older women.

Data are expressed as means ± S.D. * $P < 0.01$; ** $P < 0.001$; *** $P < 0.0001$: significantly different from older.

DISCUSSION

In the present study, for the first time, explosive power output has been compared between young and older women after optimising the load for maximum power production during a multiarticular functional gesture “in vivo”, which involves lower-limb muscles used during activities of daily living. The fact that the older women could not even push the resistance at which the young women achieved maximum power, as shown in Figure 3, emphasises the importance of optimising the load of the measurement apparatus when measuring power in functional studies involving older individuals. It is likely that in previous studies (Bosco and Komi 1980; Davies et al. 1983; Grassi et al. 1991; Ferretti et al. 1994; Skelton et al. 1994; De Vito et al. 1998) muscle power was underestimated in older people, in that individuals were obliged to use a high percentage of their maximum strength, therefore performing the movement at slower speed, which was away from the optimal speed for maximum power production. Similarly, it is likely that maximum power was also underestimated in young individuals, in that they pushed a resistance which was lower than optimal force for maximum power production.

The inferior ability to generate explosive power was due to a lesser ability to develop both force and speed of movement, as shown in Figure 3. In fact, optimal speed and optimal force were significantly smaller in the older women at both maximum PP (Figure 3a) and AP (Figure 3b). As optimal speed was measured when optimal force was the same percentage of MVC in the two groups (60%), thus standardising for differences in optimal force, it can be concluded that the older women generated less power because they were slower than the young even when using the same percentage of their maximum strength. Our finding is in contrast with the recent results of Pearson et al. (2002), who compared a population of weightlifter athletes with untrained healthy subjects by using a variable inertial testing system (Pearson et al., 2001) mounted in apparatus designed for measuring explosive power in older people (Bassey and Short, 1990). In their study, weaker individuals achieved maximum power output at lower inertial loads than stronger individuals, but the speed component was found to be not significantly different between the two groups.

The discrepancy with our results could be ascribed to the different study population and testing methodology. Moreover, since the inertial load was not standardised to a similar percentage of MVC in the two groups, this makes the comparison with our data even more problematic.

Data of force and speed plotted in Figure 3 may be fitted by a regression curve, according to Hill's equation (Hill 1938), and the MVC extrapolated from this curve would be higher than the MVC values that have been measured in this study. This could be interpreted with the fact that MVC was measured at an angle which may have been away from the optimum angle for MVC (Sale 1991). This angle is also different from that of optimal force at peak power. These results are in agreement with the findings of Rahmani et al. (2001), who have shown that the force measured during an isometric half-squat at a knee angle of 90 degrees was different from the isometric force extrapolated from the force-velocity relationship. However, in our study the possibility of underestimating MVC would apply to both young and older individuals, thus not affecting the relative differences in power and its determinants between the two groups, which is the main point of this investigation.

It has been established that loss of muscle mass is an important factor contributing to the reduction of muscle strength and power in older subjects (for review, see Vandervoort, 2002). In our study, the smaller muscle mass did not totally explain the lower levels of strength and power, since the differences between young and older women still existed after normalisation for CSA (Figure 3.4). The push phase of the leg press movement is mainly effected by the extensor muscles of the thigh, which justifies normalisation of MVC and power values with respect to contractile CSA of the quadriceps muscle. However, this presents a limitation, because in a multiarticular gesture like the leg-press action other muscles play a role, such as the hip extensors. Furthermore, the area of muscle cross-section at a right angle to the long axis of the limb, i.e., anatomical CSA, cuts a limited number of fibres and is therefore smaller than the physiological CSA (Fukunaga et al., 1992; Narici, 1999). Despite these limitations, it is reasonable to infer that structural changes in the muscle itself (Larsson et al., 1979; Lexell et al., 1988; Frontera et al., 2000b), especially a reduction in specific tension and speed of shortening (Larsson et al., 1997; Frontera et al., 2000b), and neural changes such as lower muscle membrane excitation (Hicks et al., 1992) and axonal conduction velocity (Wang et al., 1999), contribute to the lower muscle performance in the older women. These physiological factors would also explain the significantly lower ratio of PP to MVC in the older women, thus indicating that power output, which depends on both strength and speed, is lost to a greater extent than isometric strength. This is in agreement with Skelton et al. (1994), who reported a decline in average power of healthy older people aged from 65 to 89 years of 3.5% per annum as opposed to a decline in isometric strength of 1.5% per annum.

In conclusion, this study has provided new information on MVC and maximum power output at different loads during a multiarticular functional action in young and older women. The older women of this study could not even move the resistance at which the young women achieved maximum power, thus revealing the importance to optimise the initial level of load in measuring power output. The inferior ability to generate explosive power is due to a lesser ability to develop both force and speed of movement. Differences in strength and power between young and older women still persist after normalisation per muscle mass and power seems to be more vulnerable than strength to the ageing process. Further studies are required to investigate how force and speed of movement respond to resistance training programmes.

CHAPTER 4

ELECTROMYOGRAM CHANGES DURING SUSTAINED CONTRACTION AFTER RESISTANCE TRAINING IN WOMEN IN THEIR 3rd AND 8th DECADES

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SUMMARY

The present study aimed at investigating the neuromuscular adaptations to 6 weeks of resistance training in women in their third (6 experimental, 8 controls) and eighth decades (8 experimental, 8 controls). The surface electromyogram (sEMG) was measured from the biceps brachii muscle during constant-force isometric contractions lasting 12 s at 80% of maximal voluntary contraction (MVC). All the signals were analysed adopting in the time domain the root mean square (RMS) as a measure of amplitude and in the frequency domain the median frequency (MDF) of the power spectrum. Quantitative analysis was performed from the 3rd to the 6th second, to describe the early phase of the contraction ("Early"), starting from the point at which 80% of the MVC was reached, and from the 9th to 12th second, to describe the last part of the constant-force sustained contraction ("Late"). After training, the MVC increased by 22.4% in the young ($P < 0.0001$) and by 13.4% in the older ($P < 0.05$) women. The "Early" RMS increased by 60.4% with respect to the pre-training condition in the young ($P < 0.01$) but not in the older women. In contrast, the "Late" RMS increased by 46.7% in the older ($P < 0.05$) but not in the young women. The MDF remained unchanged in both groups. These results indicate that young and older women showed different training-induced adaptation of the motor unit (MU) activation pattern, as revealed by RMS, in order to keep a constant level of force during a short sustained-isometric contraction at 80% of MVC.

INTRODUCTION

It is widely accepted that in previously untrained subjects most of the initial increase in maximal strength observed during the first few weeks of resistance training results primarily from the neural adaptation of the trained muscles (Moritani and de Vries, 1980; Komi, 1986; Sale, 1988). The technique most widely adopted for assessing training-induced neural adaptation is to measure the integrated surface electromyogram (iEMG) during a maximal contraction, which provides information about the general activation level of the muscle (Moritani and de Vries, 1980; Häkkinen and Häkkinen, 1995; Häkkinen et al., 1998c).

However, assessing the effects of training on short-term muscular endurance (sustained intense isometric contraction), rather than maximal strength, may provide new information about the ability to maintain normal daily activities, and this is particularly important for older people (Bemben, 1998). In addition, a constant-force sustained intense isometric contraction is an optimal model for studying training-induced neural adaptation, especially when the force is kept constant within a narrow range of the target value (De Luca et al., 1996).

Furthermore, a more detailed description of neural adaptation is obtained by the combined analysis of surface EMG (sEMG) in both the time and frequency domain, adopting parameters such as the root mean square (RMS) and median frequency (MDF) of the power spectrum density, respectively (Basmajian and De Luca, 1985). The RMS provides a measure of EMG amplitude (De Luca, 1997) and, like the iEMG, reflects both the number and the firing rate of the active motor units (MUs) (Basmajian and De Luca, 1985; Esposito et al., 1996). The MDF is influenced by the overall action potential conduction velocity (CV) and may correlate with muscle fibre composition (Solomonow et al., 1990; Kupa et al., 1995). The changes in the sEMG throughout a constant-force sustained isometric contraction have been widely investigated and they result in an increase of RMS, with a parallel shift of the power spectrum density toward lower frequencies (Basmajian and De Luca, 1985; Esposito et al., 1998). In contrast, to the best of our knowledge, there are no data on the effects of training on the patterns of parameters such as RMS and MDF during constant-force, sustained, intense, isometric contractions.

It has been shown that, during their eighth decade, women can reach levels of strength below the threshold necessary to accomplish basic daily activities; therefore, it has been suggested that they should be the first target group of intervention and rehabilitation studies (Skelton et al., 1994).

The present study was therefore designed to investigate the effects of short-term resistance isometric training on muscle strength and the MU activation pattern, described by coupled time and frequency domain analysis of sEMG (RMS and MDF) measured during constant-force, sustained, isometric contractions of high intensity, in young and older women. Our hypothesis was that young and older women might show a different response to training of the physiological mechanisms to keep a constant level of force during a sustained contraction.

METHODS

Subjects. A total of 32 female subjects volunteered for this study. Sixteen were older (age range 70-79 years) and 16 were young (age range 18-30 years). Fifty percent of the subjects of each age group, randomly selected, was involved in the training programme, while the other 50% served as the control group. Hence, 4 subgroups were obtained: training older (TO), training young (TY), control young (CY) and control older (CO) women. However, 2 experimental subjects in the TY group could not complete all the study phases, one because of a muscle injury and the other for personal reasons. Therefore, only the 6 subjects of the TY group who completed the training programme are included in the analysis. The physical characteristics of the participants are presented in Table 4.1, together with values of their non-dominant arm muscle-bone area (MBA), determined according to the method suggested by de Koning et al. (1986). At the time of the experiment, all subjects were in good physical condition with no signs or symptoms of cardiovascular, respiratory or neuromuscular disease, nor were they taking any pharmacological agents. The subjects were habitually physically active, but not practising any kind of systematic training. They were requested not to perform any extra exercise involving the arm muscles during the whole period of the experiment. The experimental procedures were approved by the Ethics Committee of the University of Strathclyde and all subjects gave their informed consent to participate in the study.

Table 4.1. Age, stature, body mass and left arm muscle bone area (MBA) of subjects in control and experimental groups before training.

Group	Age (years)		Stature (m)		Body Mass (kg)		MBA (cm^2)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
CY (n = 8)	22	4	1.65	0.04	63.6	15.1	49.1	13.5
TY (n = 6)	21	4	1.66	0.05	65.8	13.1	49.9	12.1
CO (n = 8)	76	5	1.57	0.06	58.4	9.0	52.5	10.8
TO (n = 8)	75	2	1.56	0.05	61.0	7.0	56.6	9.4

Apparatus. The sEMG signals were recorded using two silver/silver chloride electrodes, pre-gelled, self-adhesive, 4 mm diameter (Medicotest, type N-10-A, Denmark), placed 20 mm apart (centre-to-centre) on the midline of the biceps brachii muscle belly of the non-dominant arm, half way between the centre of the belly and the myotendinous junction. Before applying the electrodes, the skin was gently scratched with fine sandpaper and then cleaned with ethyl alcohol. The contours of the self-adhesive plastic discs were marked on the skin using dermographic ink, in order to place the subsequent electrodes as close as possible to the original position during the following experiments.

A ground electrode (Dantec Electronics mod. 13S97, UK) was placed around the wrist of the contralateral arm. The sEMG signal was pre-amplified (×100) (NeuroLog remote AC preamplifier NL824, Digitimer, UK), amplified (×5) (NeuroLog Isolation Amplifier NL820, Digitimer, UK) and band-pass filtered from 5 Hz to 1 kHz (NeuroLog Filter NL125, Digitimer, UK). The sEMG signal was displayed on an oscilloscope (Yokogawa, DL1540, Japan) to control its quality and was then stored on a PC (Genie ATX P5/133, Viglen, UK), using an analog-to-digital converter (type 1401, Cambridge Electronic Design, UK). The adopted sampling frequency was 2048 Hz.

The isometric elbow flexion torque of the non-dominant arm was recorded using a dynamometer (Kin-Com, Chattanooga, USA). The subjects were seated comfortably in the chair, with their trunk erect and fastened by two crossing belts; they were positioned so that a 90° angle at the elbow joint was obtained. Their forearm was positioned over a support and fastened by a band with their wrist placed in a cuff attached to the load cell. This position ensured that the relative movements between the muscle and electrodes were minimal. The signals of exerted force were digitised at a sampling rate of 100 Hz.

Experimental procedure. Experimental subjects participated in four experiments, one every 2 weeks (0, 2, 4, 6 weeks) that were designed to assess the MU activation pattern of the biceps brachii muscle during constant-force isometric contractions. Control subjects participated in only two experiments, in the first and sixth weeks. All subjects were familiarised with the experimental procedures on one occasion before the onset of the study. In each experiment, including the familiarisation, the subjects were requested, after a 2-min warm-up, to perform the following two tasks in this order: (1) a maximal voluntary contraction (MVC); and (2) an isometric contraction at 80% of MVC.

The MVC task consisted of gradually increasing the flexion force exerted by the arm to a maximum. Subjects were able to follow their performance on the computer screen and were verbally encouraged to achieve a maximum and to maintain it for at least 3 s before relaxing. The MVC was calculated as the largest 2-s average reached within any single force recording. Three attempts were performed, separated by 5 min, and the greatest of the 3 attempts was chosen as MVC.

The subjects then performed an isometric contraction, at 80% of their MVC level, lasting 12 s. During the tests, both the target force and the actual force were displayed on the computer screen to provide feedback to the subjects. This allowed the subjects to maintain the requested force constant to within ± 5% of the target torque value during each contraction. Figure 4.1 shows a typical example of force and EMG patterns measured during a constant-force isometric sustained contraction at 80% MVC in one of the young subjects.

Signal analysis. To quantify the sEMG amplitude and frequency components, computer-aided analysis was performed over subsequent 1-s epochs of the sEMG signal, with 50% overlap (Felici et al., 1997). The analysis was performed starting from 3 s into the contraction to avoid transient phenomena.

The RMS is analytically defined as:

$$\mathrm{RMS} = \sqrt{\frac{1}{T}\int_0^T x^2(t)\,dt}$$

where $x(t)$ is the sEMG signal and T is the acquisition time.

The spectral parameters were evaluated by standard Fast Fourier Transform (FFT) over 2048 samples. The MDF, which is the frequency value that divides the spectrum into two regions of equal power, is defined as:

$$\mathrm{MDF} = \int_0^{f_{med}} P(f)\,df = \int_{f_{med}}^{\infty} P(f)\,df = \frac{1}{2}\int_0^{\infty} P(f)\,df$$

where $P(f)$ is the power spectrum density.

Since the main purpose of this study was to compare the response of two different age groups to the same resistance training, the RMS and MDF data were normalised

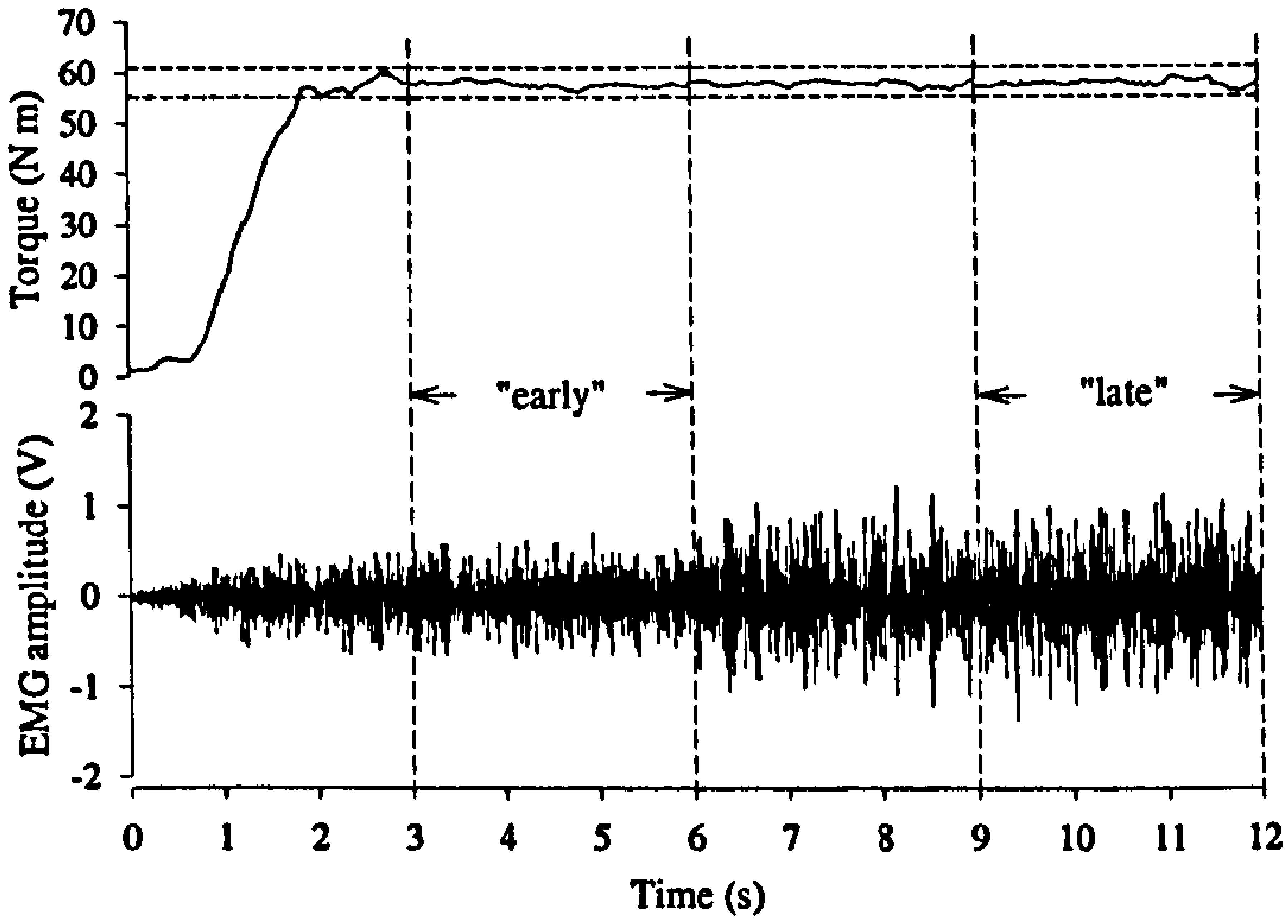

Figure 4.1. Torque and surface electromyogram (*EMG*) during a constant-force, sustained, isometric contraction at 80% of maximum voluntary contraction (*MVC*) in one of the young subjects. The *two horizontal dotted lines* indicate the tolerance limit (5% of target force) over the interval determined to be constant force according to the criteria used in this study.

by dividing them by the initial value of RMS and MDF measured at week 0. An index of initial activation for both RMS ("Early" RMS) and MDF ("Early" MDF) was calculated by averaging normalised data points from the 3rd to the 6th s. Another index of late activation was adopted to describe the behaviour of RMS ("Late" RMS) and MDF ("Late" MDF) in the last part of the sustained contraction, by averaging normalised data points from the 9th to the 12th s.

Strength training. The experimental subjects participated in a 6-week period of isometric resistance training involving the elbow flexor muscles of the non-dominant arm, three times a week, for about 30 min per session. The training was performed in the same laboratory in which all tests were conducted and the same dynamometer and seat position were adopted regardless of whether it was an experimental session or training. Each training session consisted of a total of 15 sets, 10 repetitions each (5 s contraction, 3 s rest). Each subject started with 2 sets at 20%, followed by 2 sets at 40%, 4 sets at 60%, 3 sets at 80% (only 8 repetitions each), 2 sets at 40% and finally 2 sets at 20%. The interval time between each set was 15 s at 20%, 30 s at 40%, 2 min at 60%, 3 min at 80%.

The resting period at the end of each set was 15 s after 20%, 1 min after 40%, and 3 min after 60% and 80%. In order to keep an appropriate training intensity, the load was updated weekly. During the first, the third and the fifth week, 20%, 40%, 60% and 80% of the load was referred to the MVC measured during the previous experimental session, whilst during the second and the fourth week, each percentage was increased by 5% with respect to the load of the previous week.

Statistical analysis. Conventional descriptive statistical methods were used. All the data in this study are referred to as mean ± S.D. All data were analysed for normality of distribution. A two-way analysis of covariance (ANCOVA) was adopted to study the effect of training on the different parameters considered, adopting as covariate factors both the initial MVC and the change in MVC caused by training. The ANCOVA showed that it was unnecessary to carry out any adjustment for the MVC; therefore, a one-way analysis of variance was adopted with a follow-up (when significant) Tukey-based multiple-comparisons procedure. The minimal level of significance was set at $P < 0.05$ for all computations.

RESULTS

Anthropometric variables. The descriptive statistics, including the initial MBA values for the four groups, are shown in Table 4.1. There were no significant differences between experimental and control subjects (in the young and older groups) in any of these parameters at the onset of the study. In addition, there were no significant changes in the mass and MBA of the control and experimental subjects between weeks 0 and 6.

MVC. MVC significantly increased throughout the 6-week strength-training period in both group TY [from mean 59.6 ± 7.5 to 72.9 ± 6.3 Nm ($P < 0.0001$)] and group TO [from 34.4 ± 8.5 to 39 ± 9.5 Nm ($P < 0.05$)]. The percentage increase with respect to the pre-training condition was 22.4% in group TY and 13.4% in group TO. Figure 4.2 shows the time course of the relative changes in MVC (Δ%) during training. In group TY, MVC had increased by 2 weeks; the greatest MVC occurred during week 4 and this was maintained nearly constant until week 6. Group TO showed a similar trend, although the percentage increase was less than that in group TY. No changes were observed in groups CY and CO.

Reproducibility of EMG measures. In order to verify the reproducibility of the EMG measures, two tests were performed 1 week apart on a subgroup of 16 subjects (8 young and 8 older). The tests consisted of a constant-force isometric contraction at 80% MVC. To test the percentage of global variance that can be attributed to the variability between subjects, the intraclass correlation coefficient (ICC) was adopted, as proposed by Rainoldi et al. (1999). Table 4.2 shows the ICC for "Early" and "Late" indexes for both RMS and MDF in older and young subjects respectively. For any given variable, an ICC above 0.6 is considered an index of good reproducibility.

Table 4.2. Intra-day repeatability of EMG measurements during a constant-force, sustained, isometric contraction at 80% MVC. Intraclass correlation coefficient (*ICC*) was calculated on trials performed on two different days in young and older subjects respectively.

Group	"Early"		"Late"	
	RMS	MDF	RMS	MDF
Young (n = 8)	0.88	0.75	0.71	0.86
Older (n = 8)	0.77	0.76	0.91	0.61

RMS. Figure 4.3 shows the time course of RMS during a sustained contraction at 80% MVC in the four groups before (week 0) and after (week 6) the training.

Considering the pre- and post-training experiments, "Early" RMS of group TY significantly ($P < 0.01$) increased to 60.4% of the value prior to training. In group TO, the 33% increase of "Early" RMS was not significant. In group TY, the 44.3% increase in "Late" RMS as an effect of training was not significant. In contrast, the "Late" RMS of group TO increased 46.7% compared to the pre-training condition, and this change was significant ($P < 0.05$).

MDF. Figure 4.4 shows the time course of MDF during a sustained contraction at 80% MVC in the four groups at week 0 and at week 6. There were no statistically significant changes in any of the four groups after the training in either "Early" or "Late" MDF.

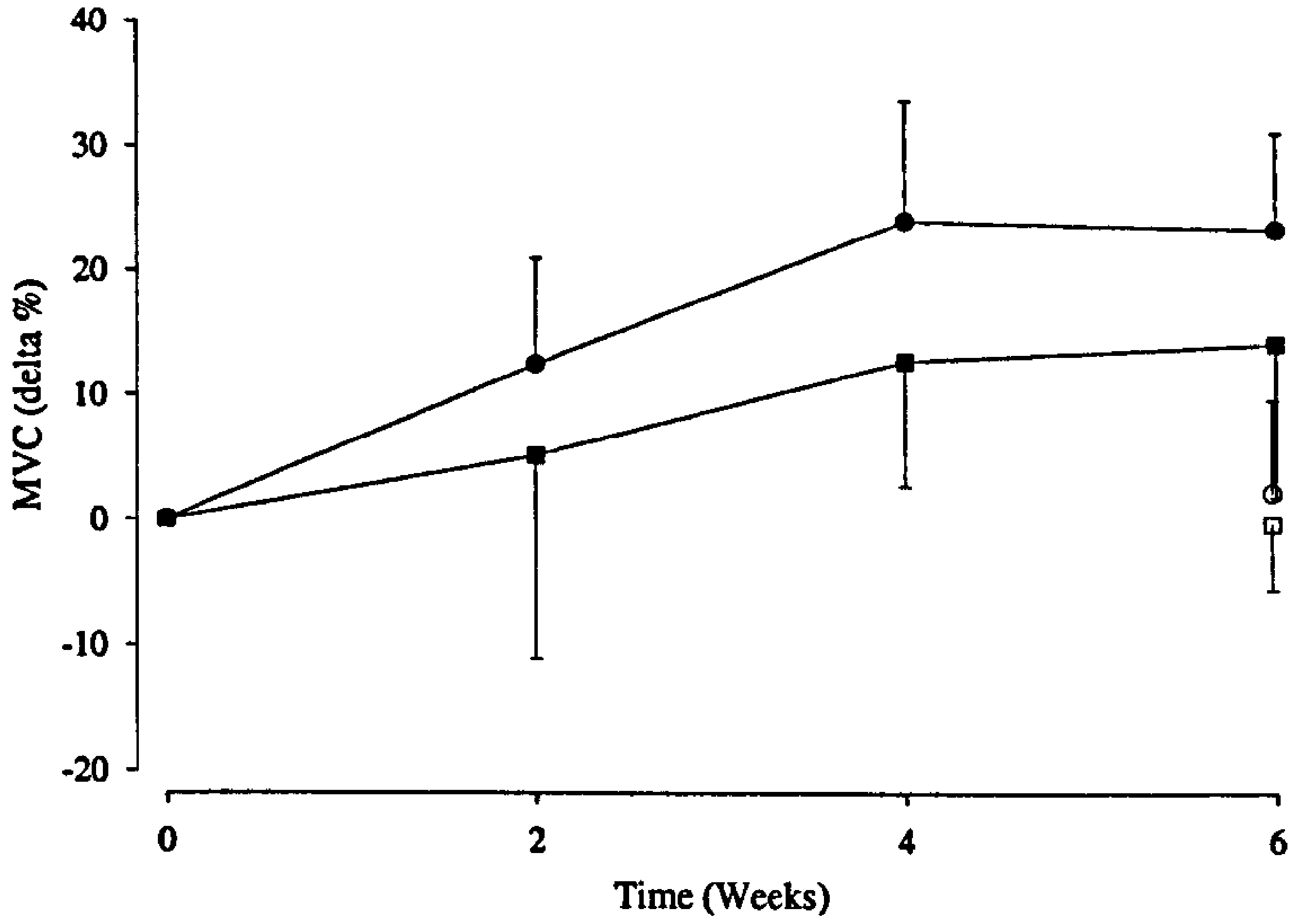

Figure 4.2. Mean ± S.D. relative changes in MVC torque in groups TY (●), TO (■), CY (○), CO (□), during the course of the 6-week training program. (*CO* control older women, *CY* control young women, *TO* training older women, *TY* training young women).

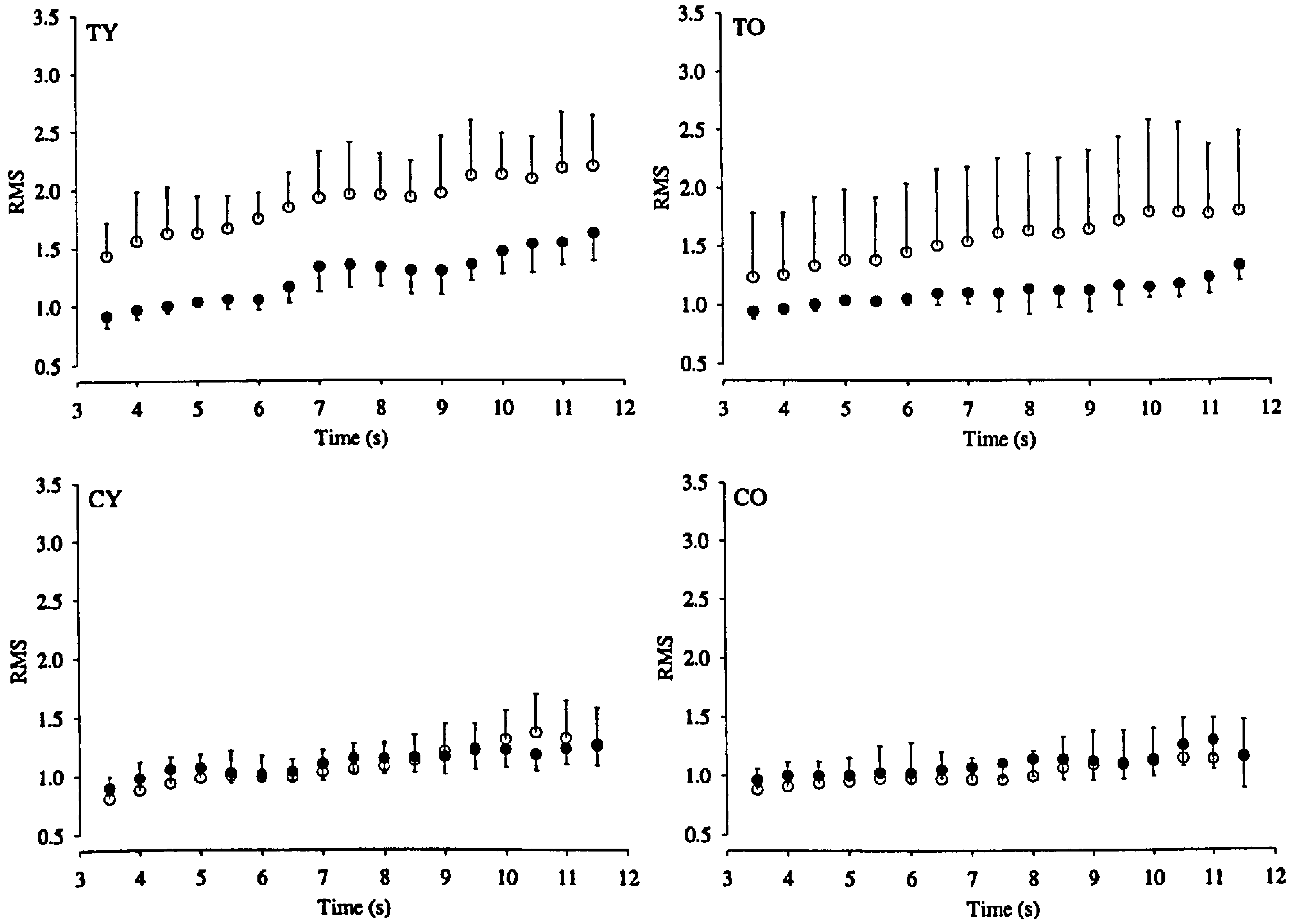

Figure 4.3. Mean ± S.D. of normalised root mean square (*RMS*) at 80% of MVC as a function of contraction time in groups TY, TO, CY and CO, at week 0 (●) and week 6 (○) respectively.

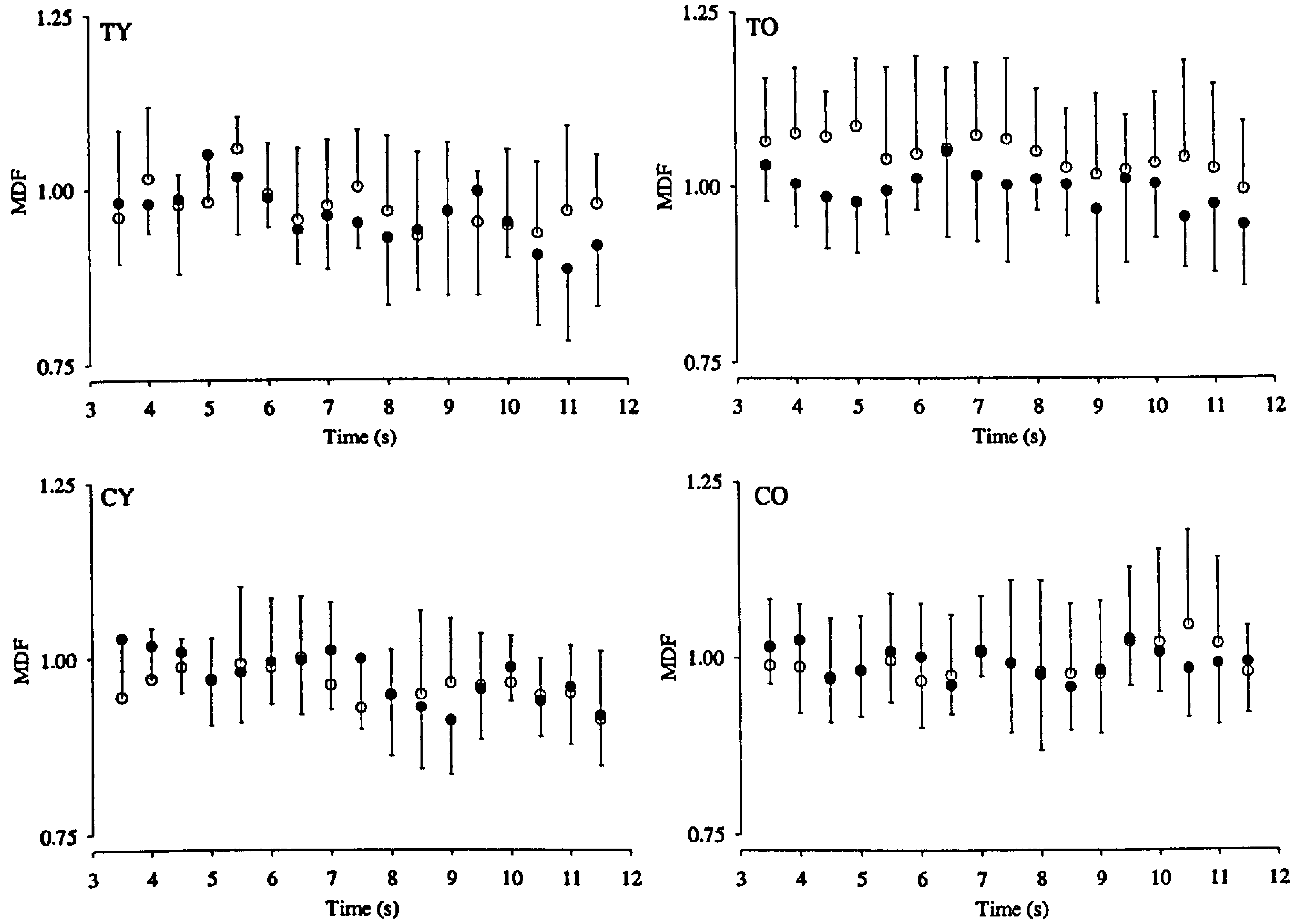

Figure 4.4. Mean ± S.D. of normalised median frequency (*MDF*) at 80% of MVC as a function of contraction time in groups TY, TO, CY and CO at week 0 (●) and week 6 (O) respectively.

DISCUSSION

The most important finding of the present study is that young and older women showed a different training induced adaptation of the MU activation pattern, during constant-force, sustained, isometric contractions of high intensity and short duration. The force gain followed the same temporal pattern in the two groups, but the absolute force increments were different. This was associated with changes in sEMG amplitude (expressed as RMS), which differed in the two age groups, but with no change in the power spectrum (expressed as MDF) during constant-force, sustained, isometric contractions.

MVC and MBA. The 22.4% increase in maximum voluntary strength observed in group TY is similar to that found by others over an equivalent period of training (Darcus and Salter, 1955; Komi et al., 1978; McDonagh et al., 1983). In group TO, the 13.4% increase of MVC was comparable to that observed in previous studies, ranging from no change (Brown et al., 1990) to an average increase of 20% (Moritani and de Vries, 1980). It must be stressed that direct comparison between studies is difficult, since many variables, such as the intensity, the number of sets and repetitions of a given exercise, the muscle groups exercised and the subjects' group (e.g. age, gender), must be considered. However, although the training stimulus was the same for groups TY and TO, the percentage increase in MVC in group TO was lower compared to that in group TY. It may be that the different hormonal status in these two populations partly accounts for the reduced responsiveness of ageing muscles to the training stimulus (Häkkinen and Pakarinen, 1994). It should be noted that after 4 weeks both age groups hit a plateau in MVC, similarly to the findings of Porter and Vandervoort (1997).

The training was not sufficient to induce observable changes in MBA in either training group. Ploutz et al. (1994) showed that the 14% increase in strength following a 9-week resistance training period was accompanied by a small (5%) increase in the cross-sectional area of the trained muscle. Although in the present study it is not possible to exclude the possibility of some concomitant intramuscular adaptation in the early phase of heavy-resistance training, it is reasonable to assume that the earlier strength gains observed in the present 6-week training study can be mainly attributed to neural adaptations (e.g. Sale, 1988).

RMS. The changes in RMS caused by training had different trends in the young and older subjects. There was a significant increase in "Early" RMS in group TY, with no change in "Late" RMS; however, there was a significant increase in "Late" RMS in group TO, with no significant increase in "Early" RMS.

The post-training increase of "Early" RMS observed in group TY data can be attributed to either an increase in the number of MUs recruited or an increase in the firing rate of the individual MUs (Häkkinen, 1994). The increase in "Early" RMS is associated with a new level of strength, which is the same as a percentage of the maximum as in the pre-training condition (80%), but greater in absolute value. An additional factor to explain the increased "Early" RMS could be enhanced MU synchronisation (Lippold et al., 1960; Milner-Brown et al., 1975). However, the relative roles played by MU recruitment, MU firing rate and synchronisation of the individual MUs cannot be distinguished with sEMG (Häkkinen, 1994), certainly when analysing data from the initial part of the sustained contraction.

The post-training increase of "Late" RMS observed in TO is, once again, associated with an increase in force. However, in this case other changes in the MU activation pattern to maintain the sustained isometric contraction must be considered. Several factors have been reported as responsible for the "Late" RMS increase; for example, the recruitment of additional MUs (Maton and Gamet, 1989; Dorfman et al., 1990; Garland et al., 1994), an increase in the firing rate of individual MUs (Person and Kudina, 1972; De Luca and Forrest, 1973), synchronisation between MU firing patterns (Lippold et al., 1960; Milner-Brown et al., 1975), and an increase in the action potential duration due to a decrease in muscle fibre CV (Basmajian and DeLuca, 1985). Recruitment of additional MUs to maintain the constant force during sustained isometric contractions has been suggested (Maton and Gamet, 1989; Dorfman et al., 1990; Garland et al., 1994), but this was only for a contraction lasting more than 30 s. De Luca et al. (1996) showed that when the isometric contractions lasted 10-15 s, as long as the force was kept constant within a narrow range ($<\pm 3\%$)

no additional MU recruitment was observed. Therefore, the amount of time-dependent recruitment that occurs at 80% MVC is assumed to be negligible. The time course of the firing rate of individual MUs during sustained isometric contractions remains controversial. Some investigators have reported a progressive increase in the firing rates throughout constant-force contractions (Person and Kudina, 1972; De Luca and Forrest, 1973), while the recent study of De Luca et al. (1996) reported a decrease in the firing rate of MUs. If the hypothesis that during constant-force sustained isometric contractions lasting 10-15 s no additional MUs are recruited and the firing rate of individual MUs decreases, synchronisation of MUs and increase in the action potential duration, due to a decrease in muscle fibre CV, remain the two physiological correlates to account for the time course increase in RMS. Hence, in this study, the increase in "Late" RMS as an effect of training in TO, could be attributed to either an increased synchronisation of MUs or an increase in action potential duration.

MDF. The analysis of the power spectrum of EMG data has been proposed as an electrophysiological "muscle biopsy" for estimating muscle fibre composition (Kupa et al., 1995). According to Stulen and De Luca (1978), power spectrum modelling establishes evidence for a linear proportionality between the CV of action potentials propagated along the muscle fibres and the MDF of the myo-electric spectrum. These findings were further confirmed by Arendt-Nielsen and Mills (1985). Sadoyama et al. (1988) indicate that muscle fibre composition can be estimated from muscle fibre CV measured non-invasively with surface electrodes. Human muscles composed primarily of fast fibres have a greater action potential CV compared with muscle composed of mostly slow fibres (Linssen et al., 1991). In the present study no significant modification in the MDF of the power spectrum density was observed after the training programme in any of the four groups. It has been theorised that untrained individuals may not be able to voluntarily recruit the highest threshold MUs or maximally activate their muscles (Jones and Round, 1990; Kraemer et al., 1996); therefore, it was reasonable to expect training-induced changes in MDF. But it should be noted that the population studied comprised subjects who, although not practising any kind of systematic muscular training, were habitually physically active and this could partly explain this finding.

In conclusion, the time domain analysis (RMS) during constant-force sustained, isometric contraction at 80% of MVC showed an increase in the amplitude of the signal, with different trends in young and older subjects. "Early" RMS, an indicator of the initial state of muscle activation, increased in the young subjects, whilst it was the "Late" RMS, which describes changes in EMG amplitude during the latter part of a sustained isometric contraction, which increased in the older subjects.

CHAPTER 5

CYCLING AS A NOVEL APPROACH TO PERFORM THREE DIFFERENT REGIMENS OF RESISTANCE-TRAINING LEADS TO A SIMILAR INCREASE OF MUSCLE STRENGTH, POWER AND SELECTED FUNCTIONAL ABILITIES IN HEALTHY OLDER WOMEN

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SUMMARY

The aim of this study was to compare the effects of 3 different programs, using cycling as a novel approach to perform both light and heavy resistance training, on maximum isometric voluntary contraction (MVC), maximum power output of the lower limbs and selected functional abilities in a population of healthy older women aged 65 to 74 years. Thirty-one volunteers (mean age 69 ± 2.7 years) were assigned to one of 3 groups, which were matched for age and MVC: speed (SP), strength (ST) and combination (CB). Training was conducted 3 times a week for 16 weeks on a mechanically braked cycle ergometer. In each session, SP performed 8 sets of 16 pedal revolutions at 40% of the maximum resistance to complete two revolutions (2RM), ST performed 8 sets of 8 revolutions at 80% of 2RM and CB performed 4 sets of 16 revolutions at 40% and 4 sets of 8 revolutions at 80% of 2RM. In each set, all participants were required to pedal as fast as possible with a 2 min interval between sets. All participants were tested on two occasions before (week –4 and 0, control period), during (week 8) and after training (week 16) for MVC, with simultaneous recording of peak power and three selected functional abilities. All training groups significantly increased functional abilities, MVC and power after 8 weeks (from 6.5% to 20.8%) with no further improvement after 16 weeks (except maximal treadmill walking speed), but no significant differences were observed between the groups. Fit older women can improve in functional abilities, as measured by the functional tasks that were not practiced during the training. The "speed" training program (SP group) was shown to be as effective in improving muscle function as the more conventional heavy-resistance training program (ST group).

INTRODUCTION

Critical levels of muscle power, which is the product of both force and velocity of movement, are necessary in older people to accomplish daily living tasks like climbing stairs, rising from a chair, or using public transport (Harridge and Young, 1998). Ageing leads to a considerable decrease in strength and even greater disadvantage in power output (Metter et al., 1997; De Vito et al., 1998). Since the age-related decrease in muscle power is particularly evident in women, who can reach levels below the threshold for an independent life, it is reasonable to consider them as the first target of any intervention programme (Skelton et al., 1994). Moreover, power output has been shown to be more predictive of functional difficulties than strength *per se* (Skelton et al., 1994; Foldvari et al., 2000).

In recent times, greater attention has been focused on the need to design exercise strategies in order to increase muscle power in older populations (Evans, 2000; Earles et al., 2000; Fielding et al., 2002). Traditional low-velocity resistance-training programmes resulted in much larger increases in muscle strength than power (Fiatarone et al., 1994; Skelton et al., 1995; Joszi et al., 1999) and therefore protocols which induce power-specific adaptations have to be identified (Evans, 2000; Earles et al., 2000; Fielding et al., 2002). Some investigators added movements at high-velocity to traditional resistance-training programmes and reported substantial improvement in power of both the upper and lower extremities in older individuals (Earles et al., 2000; Izquierdo et al., 2001). Recently Fielding et al. (2002) have compared high- versus low-velocity training regimens in older women, with the total external mechanical work being the same in the two groups, and observed power gains nearly doubled in the women who exercised at high speed. In contrast, other authors (Pruitt et al., 1995; Hortobágyi et al., 2001) reported similar increases in strength in two groups of older individuals who participated in low and high intensity training programmes, respectively. It is therefore still controversial whether high-velocity low-resistance training is comparable or superior to low-velocity high-resistance training in order to improve function and quality of life in older individuals. It is also controversial whether the ability to perform functional tasks may improve as a carry-over effect of power training or if the functional task must also be practised (Skelton and McLaughlin, 1996; Earles et al., 2000). The present study has therefore been designed to compare the effects of 3 different programmes (one performed at a light intensity with a high speed of movement, another performed at a heavy intensity with a slower speed of movement, and a third based on a combination of both), using cycling as a novel approach to perform both light and heavy resistance training, on maximum isometric voluntary contraction (MVC), maximum power output of the lower limbs and selected functional abilities in a population of healthy older women aged 65 to 74 years.

METHODS

Participants. With ethics committee approval, 31 participants (mean age 69 ± 2.7 years) were selected according to the exclusion criteria to define "medically stable" older participants for exercise studies, as proposed by Greig et al. (1994). Participants were allowed to be involved in regular physical activity no more than 2 times per week and were required to maintain their normal levels of physical activity throughout the duration of the study. They were assigned to one of 3 groups which were matched for age and knee-extension MVC: speed (SP; n= 10), strength (ST; n= 10) and combination (CB; n= 11). The age and physical characteristics of the SP, ST and CB groups are presented in Table 5.1.

Table 5.1. Age, stature and body mass of the three groups.

Group	Age (years)		Stature (m)		Body Mass (kg)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Speed (n=10)	69.0	2.9	1.58	0.05	61.9	7.2
Strength (n=10)	68.6	3.2	1.58	0.06	65.2	17.5
Combination (n = 11)	69.6	2.6	1.58	0.06	65.0	5.65

Training programme. Training was conducted 3 times a week for 16 weeks on a mechanically braked cycle ergometer (Monark, model 824E, Sweden). In order to determine the individual training workload the participants were tested for the maximum resistance to complete two pedal revolutions, which will be referred in this manuscript to as 2-revolution maximum (2RM). A belt was secured around each participant's waist to ensure that she was unable to rise from the seat. Starting from the load at which the participants could not move the pedals, the load was reduced by 0.5 kg decrements until the participants were able to complete two pedal revolutions. Then, in order to ensure that the selected load was effectively the maximum, the participants were required to perform further attempts increasing the load by 0.5 kg increments. The 2RM test was performed prior to the training (week 0), and then every four weeks (week 4, 8, 12, 16) in order to update the training load.

In each training session, SP performed 8 sets of 16 pedal revolutions at 40% of 2RM, ST performed 8 sets of 8 revolutions at 80% of 2RM and CB performed 4 sets of 16 revolutions at 40% and 4 sets of 8 revolutions at 80% of 2RM. In each set, all participants were required to pedal as fast as possible with a 2 min interval between sets.

Testing. After completing the familiarisation procedures, all participants were tested on two occasions before the onset of the training (week -4 and week 0). The four-week interval of time between these two testing sessions was used as a control period, as in other recent training studies (Häkkinen et al., 1998c; Kraemer et al., 1999; Izquierdo et al., 2001; Newton et al., 2002). The measurements were then repeated halfway through the training (week 8) and at the end of it (week 16).

Functional abilities tests. These included: a) maximal treadmill walking speed (MTWS); b) box stepping test and c) vertical jump on a force platform adopting a countermovement-jumping test (De Vito et al., 1998).

a) MTWS was tested on a motorised treadmill (Startrack, USA). Participants were encouraged to walk using their normal gait pattern and to swing their arms by their sides without the use of the handrail although, during the initial familiarisation sessions, the use of the handrail was permitted if the participant experienced problems with balance. Two additional sessions of familiarisation were carried out for this test in order to guarantee that all of the participants were able to walk comfortably. The treadmill was set at an elevation of 5%, which corresponds to the maximum elevation permitted for a 10 metres long wheelchair access ramp (Disability, 2001). It was decided that due to the level of fitness in the group the treadmill should be elevated for the test to be discriminatory and more sensitive to changes in performance. The participants were asked to walk on the treadmill for a 2-minute period walking at a comfortable speed, within a range from 3 to 5 $km \cdot h^{-1}$, with a slope of 0%. The slope was then adjusted to 5% and the speed increased every 5 seconds by 0.5 $km \cdot h^{-1}$ until the participant began to move backwards. The increments were a compromise between avoiding fatigue and allowing the participant to become accustomed to the speed. Each participant completed three trials and adequate time was allowed between trials for recovery. The fastest of the three trials was selected for further analysis.

b) The participants were asked to step up onto a box of variable height (progressively 30, 40 and 50 cm) using their preferred leg, with their hands on their hips, i.e. without the use of their arms for momentum or handrails for assistance, balance or support. The test was performed once at each height until the maximal height was achieved. When the maximal height was achieved, the test was repeated at the participants' maximal height whilst wearing a weight jacket containing 2, 4 and 6 kg, progressively. The height of the box corresponds to the step heights of public transport and the weight in the jacket is considered to be roughly the equivalent of a day's basic necessity shopping (Skelton et al., 1994). The performance in this test was quantified and reported as mechanical work performed (BSW).

c) A vertical jump from both feet was performed on a force platform (Kistler 9261, Switzerland). The participants performed a countermovement jump, starting from a standing position, followed by a rapid countermovement and then a jump. The participants kept their hands on their hips throughout the movement to avoid interference from the arms. Maximal instantaneous peak power was calculated as previously described (De Vito et al., 1998). Each participant performed three jumps with three minutes rest in between and the highest of these attempts was chosen for further analysis.

Dynamometric measures. Both isometric MVC and power output measures were made on the dominant lower limb using a dynamometer (Kin Com, Chattanooga, USA). Participants warmed up on an exercise bicycle for 5 min at a light resistance before performing any strength and power test. MVC was measured during knee extension (KE), knee flexion (KF) and leg press (LP). During the KE and the KF participants were seated comfortably in the dynamometer chair, with their trunk erect and fastened by three crossing belts. They were positioned so that a 90° angle at the knee joint was obtained. During the LP the seat was modified in order to have a firm support placed behind the buttock (as described in chapter 2). The trunk was fastened by three crossing belts and each participant's leg was positioned so that a starting angle of 90° at the hip, knee and ankle joint was obtained. The MVC task consisted of a quick increase to a maximum in the force exerted by the leg. A target line was always set on the computer screen at a value 20% higher than the best performance.

Participants were able to follow their performance on the computer screen and were verbally encouraged to achieve a maximum and to maintain it for at least 2 s before relaxing. MVC was calculated as the largest 1-s average reached within any single force recording. A minimum of three attempts was performed separated by 3 min in between and the highest of these attempts was chosen as MVC. Participants were asked to make a further attempt if the MVC of their last trial exceeded that of previous trials. Power output was measured during the LP, starting from the position adopted to measure MVC. The dynamometer was set in the "isotonic" mode, with the initial load at 40% of MVC. The test was then repeated with the initial load increased, in 10% increments, up to 80% of MVC, in a random order. Each participant was required to push forward, as strong and quickly as possible, until the leg was fully extended, throughout a range of motion of 0.2 m. Three trials for each level of initial load were performed, in a random order. Maximum power output (mPow) was calculated by the product of peak speed and the corresponding force. The highest of these attempts was chosen, regardless of the initial resistance. In addition, at week 0, 8 and 16 each participant was also asked to push the same levels of initial resistance as performed at week –4, in order to compare power output and peak speed measured starting from the same condition.

Surface electromyogram (sEMG). A simultaneous reading of the sEMG from vastus lateralis and biceps femoris muscles was recorded during the measure of the KE MVC. The assumption was made that these two muscles were representative of their constituent groups (Carolan and Cafarelli, 1992). Bipolar electrodes (Medicotest, type N-10-A, Denmark) with a 20 mm inter-electrode distance (centre to centre) were placed on a prepared site of the muscles, half way between the centre of the belly and the myotendinous junction. Before applying the electrodes, the skin was gently scratched with fine sand paper and then cleaned with ethyl alcohol. A ground electrode (Dantec Electronics mod. 13S97, UK) was placed around the ankle of the contralateral limb. The sEMG signal was band-pass filtered between 5 and 1000 Hz (NeuroLog Filter NL125, Digitimer, UK), pre-amplified (x1000) (NeuroLog remote AC preamplifier NL824, Digitimer, UK), amplified (x2) (NeuroLog Isolation Amplifier NL820, Digitimer, UK), and A-D converted (type 1401, Cambridge Electronic Design, UK) at a sampling rate of 2048 Hz. To ensure that antagonist cross-talk did not contaminate the data, the EMG signals of the two muscles were plotted against each other on an oscilloscope during each trial and, if the plot of the two axes formed an ellipse, the myoelectric signals were discarded (Bernardi et al., 1995). Cross-talk was further assessed after the recordings by using cross-correlation analysis (Winter et al., 1994; Hansen et al., 2001). To quantify the sEMG amplitude, expressed as root mean square (RMS), and sEMG frequency content, expressed as median frequency of the power spectrum density (MDF), computer-aided analysis was performed over the 1-s epoch corresponding to MVC. This procedure has been detailed in chapter 2 and 4. The level of coactivation of the biceps femoris during the maximum KE was expressed as a percentage of maximal biceps femoris RMS measured during the MVC KF.

Lower limb volume. Lower limb volume was estimated from anthropometric measurements comprising segmental circumferences and lengths as described by Jones and Pearson (1969). Skinfold measurements were made at four sites; anterior, posterior mid thigh and lateral, medial mid calf using skin callipers (John Bull Ltd, UK). Skinfold corrections were made using the following regression equations (Personal communication Professor P. R. M. Pearson), anterior thigh ($y = 4.0836 + 0.407 \times$ skinfold value), posterior thigh ($y = -9.4016 + 0.992 \times$ skinfold value), medial calf ($y = 1.2729 + 0.477 \times$ skinfold value) and lateral calf ($y = 2.0945 + 0.339 \times$ skinfold value), where y represents the corrected skinfold value used in the calculations.

Statistical analyses. All data were normally distributed in terms of skewness and kurtosis (all values less than $|2|$). A mixed model factorial ANOVA with one independent factor (group) and one dependent factor (time) was used to separate the variance components within the overall design. Tukey's HSD was used for two types of simple-simple effects test: (a) comparisons across time (week 0 vs. week 8 vs. week 16) separately for each group; and (b) comparisons between groups (SP vs. ST vs. CB) at each time point. Fishers LSD with Bonferroni adjustment was used for comparisons within the control period (week -4 and week 0). All significance tests were conducted at an experimentwise alpha level of 0.05.

Intervention safety and compliance. Of the 38 volunteers initially enrolled in the training programme, 31 completed the final testing (82%). Six of the 7 drop-outs withdrew after the first week of training, 2 for health-related issues (back pain and a spur on the heel) and 4 for personal reasons, which included lack of time due to other commitments such as caring for older friends or relatives. Another volunteer abandoned after 8 weeks of training due to family problems. Compliance with the training programme was assessed by the number of exercise sessions attended divided by the number of sessions held. Exclusion criteria set before the onset of the study were (a) missed more than one and a half weeks of consecutive training or (b) performed fewer than 75% of the total number of sessions. No participants were excluded based on these pre-set criteria. Mean participation rate was 93% for SP, 89% for ST, and 91% for CB.

RESULTS

During the control period (from week -4 to week 0), most of the considered outcome variables did not significantly change (see Table 5.2). The significant increase in few outcome variables may be attributed to a learning effect that could have been avoided by performing a higher number of familiarisation sessions.

Table 5.2. Mean ± S.D. of all the outcome variables, for each group, at –4 and 0 weeks (control period).

Group	Speed		Strength		Combination	
Week	-4	0	-4	0	-4	0
MTWS (m s^{-1})	1.92 (0.15)	1.88 (0.15)	1.89 (0.16)	1.87 (0.13)	1.77 (0.19)	1.85 (0.15)
BSW (Joule)	299.9 (30.3)	290.2 (30.3)	298.4 (65.6)	299.6 (66.7)	298.8 (49.8)	297.6 (50.9)
VJ (W kg^{-1})	24.11 (3.5)	24.65 (2.3)	21.91 (2.9)	25.13 (4.0) *	22.39 (3.9)	23.23 (3.4)
LP MVC (N)	606 (112)	626 (115)	590 (163)	634 (173) *	591 (118)	623 (100)
KE MVC (N)	301 (58)	315 (64)	310 (70)	302 (67)	296 (51)	308 (54)
mPow (W)	451 (97)	452 (84)	456 (125)	486 (127)	461 (81)	494 (66) *
F@mPow (N)	393 (79)	385 (66)	373 (80)	410 (106)	365 (54)	408 (51) *
S@mPow (m s^{-1})	1.16 (0.25)	1.17 (0.13)	1.21 (0.17)	1.19 (0.15)	1.26 (0.16)	1.22 (0.14)
Pow (W)	442 (94)	452 (84)	416 (117)	486 (127) *	446 (86)	494 (66) *
S@Pow (m s^{-1})	1.15 (0.21)	1.17 (0.13)	1.02 (0.20)	1.19 (0.15)*	1.10 (0.18)	1.22 (0.14) *
RMS (mV)	0.26 (0.08)	0.24 (0.09)	0.34 (0.10)	0.34 (0.16)	0.23 (0.06)	0.24 (0.07)
MDF (Hz)	51.7 (6.1)	51.4 (5.5)	49.3 (6.4)	48.6 (7.4)	50.4 (6.3)	50.6 (4.4)
% coact (%)	23.7 (13.4)	19.4 (9.2)	19.6 (8.3)	19.9 (6.1)	19.2 (7.0)	20.6 (7.8)
Llvol (l)	3.074 (0.82)	3.014 (0.63)	2.913 (0.45)	2.938 (0.46)	3.008 (0.47)	2.971 (4.89)

MTWS: maximal treadmill walking speed; BSW: box stepping work; VJ: vertical jump; LP MVC: maximum isometric voluntary contraction during the leg press; KE MVC maximum voluntary contraction during the knee extension; mPow: maximum power output of the LP; F@mPow: force at which mPow was measured; S@mPow: speed at which mPow was measured, Pow: power output of the LP measured pushing the same level of force as at week 0; S@Pow: speed at which Pow was measured; RMS: root mean square and MDF: median frequency of the power spectrum density of the surface EMG in the vastus lateralis during the MVC KE; % coact: percentage coactivation of the biceps femoris during the MVC KE; Llvol: volume of the lower limbs (Llvol); * significantly different from week –4.

Figure 5.1 shows the results of the functional ability tests: MTWS, BSW and vertical jump, respectively. Figure 5.2 shows the results of (a) the 2RM test, (b) the MVC during the LP and (c) the MVC during the KE. Figure 5.3 shows the results of (a) maximum power output of the LP and (b) force and (c) speed at which maximum power was measured; (d) power output of the LP measured pushing (e) the same level of force as at week 0 and (f) speed at which power output was measured in this condition.

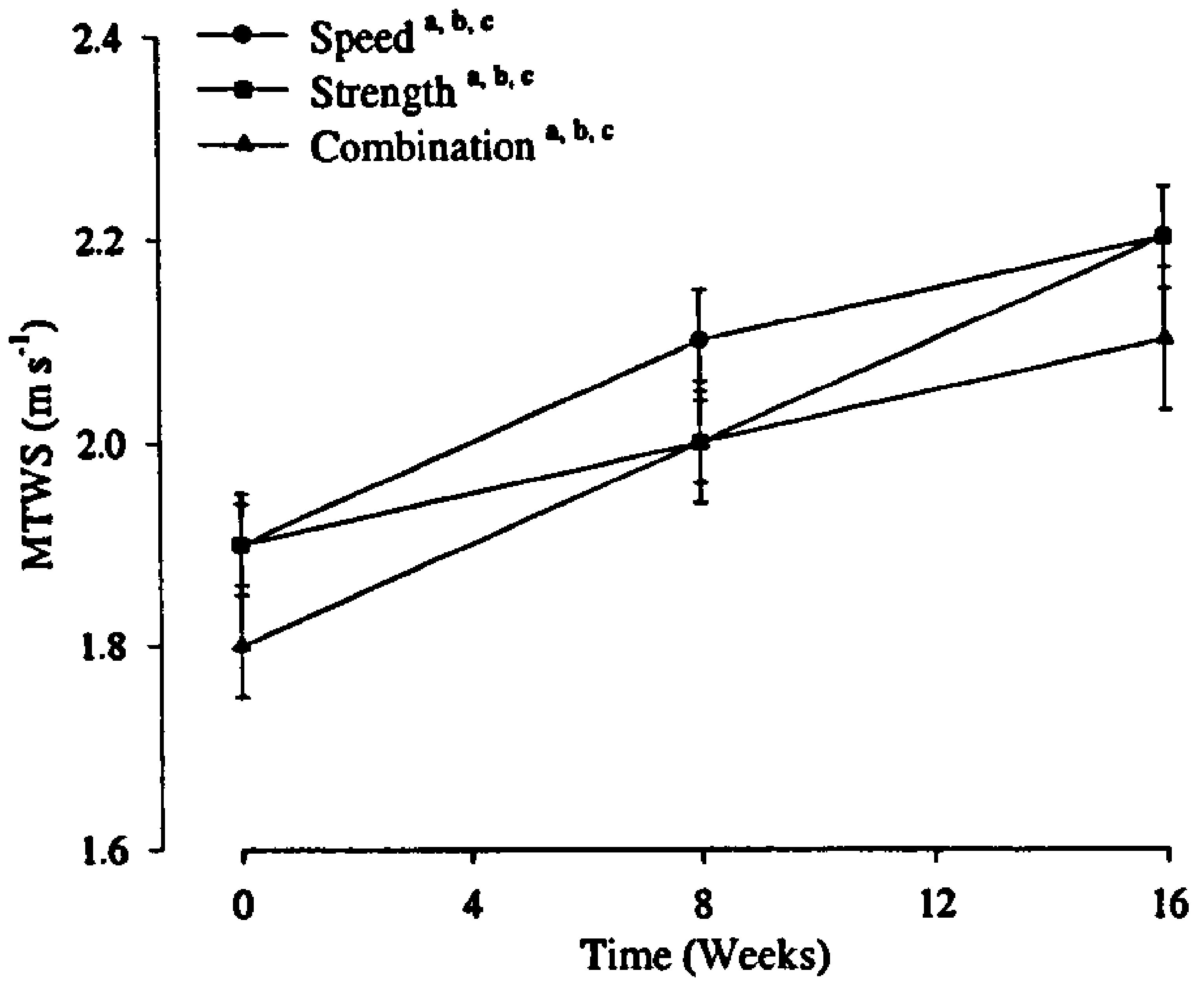
Across time comparisons. During the training period, the functional ability tests, 2RM, MVC in both the KE and LP, and maximum power output of the LP significantly increased in all the 3 groups from wk 0 to wk 8 and from wk 0 to wk 16. Only in two of these outcome variables, MTWS and 2RM, was there a further significant increase from week 8 to week 16.

Between groups comparisons. There were no significant differences between the 3 groups, in any of the outcome variables, at any time point (-4, 0, 8 and 16 weeks). There was a consistent pattern of increase of the two determinants of maximum power output of the LP (force and speed) from week 0 to week 8, but only speed significantly increased, and this was true only for the SP group (Figures 5.3 a, b, c). Power output of the LP (measured pushing the same level of force as at week 0) and the relative speed at power output significantly increased in all the 3 groups from week 0 to week 8 but only in SP from week 0 to week 16 (Figures 5.3 d, f).

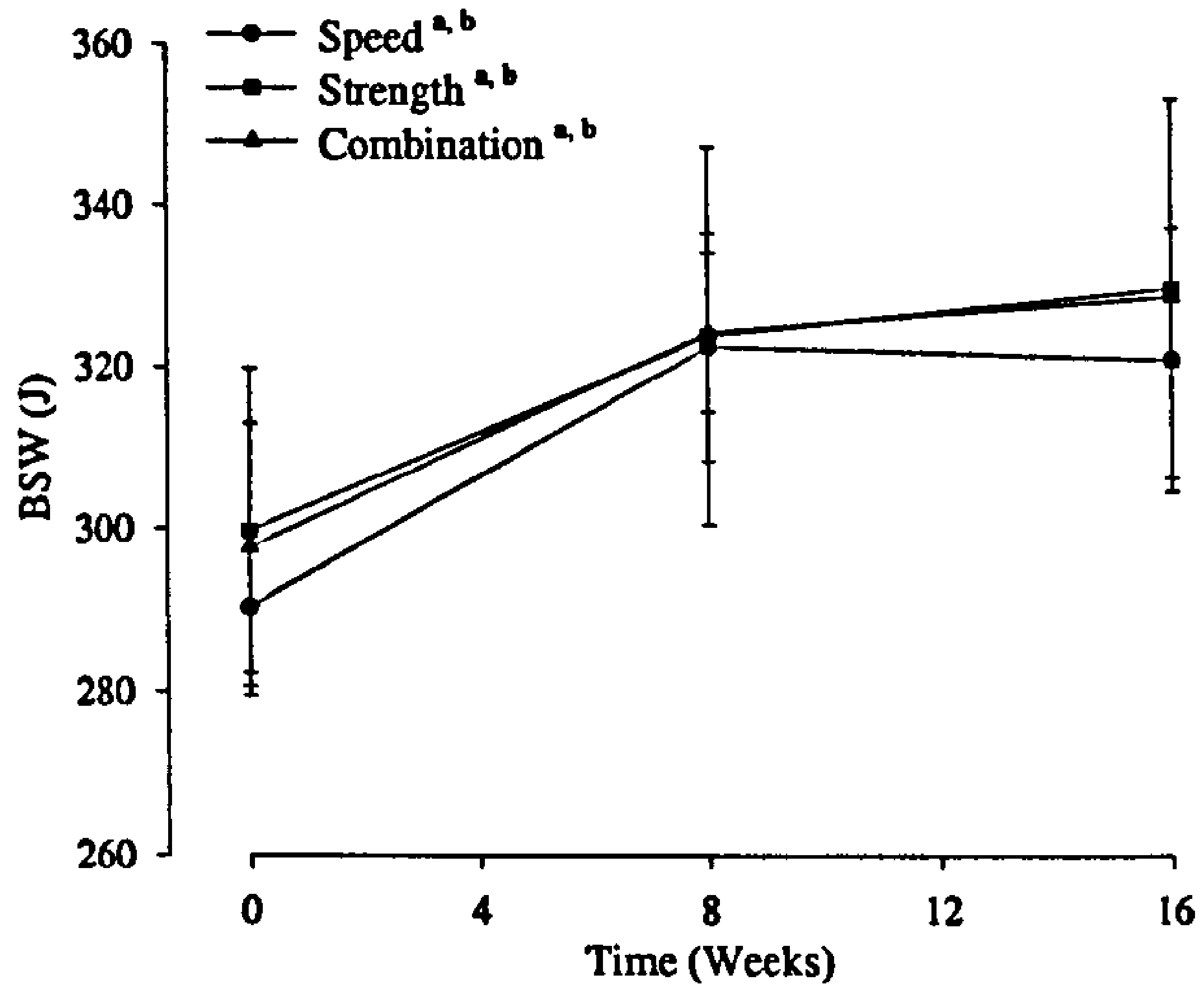
Figure 5.4 shows the results of surface electromyography: (a) RMS and (b) MDF of the vastus lateralis during the MVC KE; (c) percentage coactivation of the biceps femoris during the MVC KE, expressed as a percentage of maximal biceps femoris RMS measured during the MVC KF. In SP and CB, RMS significantly increased from week 0 to week 8 but there was no further significant increase from week 8 to week 16. In ST, RMS did not change from week 0 to week 8 but significantly increased from week 8 to week 16. No significant changes were observed in the level of coactivation of the biceps femoris during the MVC KE between any of the time points, for any of the groups. Similarly, there was no change in MDF between any of the time points, for any of the groups.

There were no significant changes in body mass or lower limb volume between any of the time points, for any of the groups. Additionally, there were no significant differences in body mass or lower limb volume between any of the groups, at any of the time points.

a) Maximal Treadmill Walking Speed (MTWS)



b) Box Stepping Work (BSW)



c) Vertical Jump (VJ)

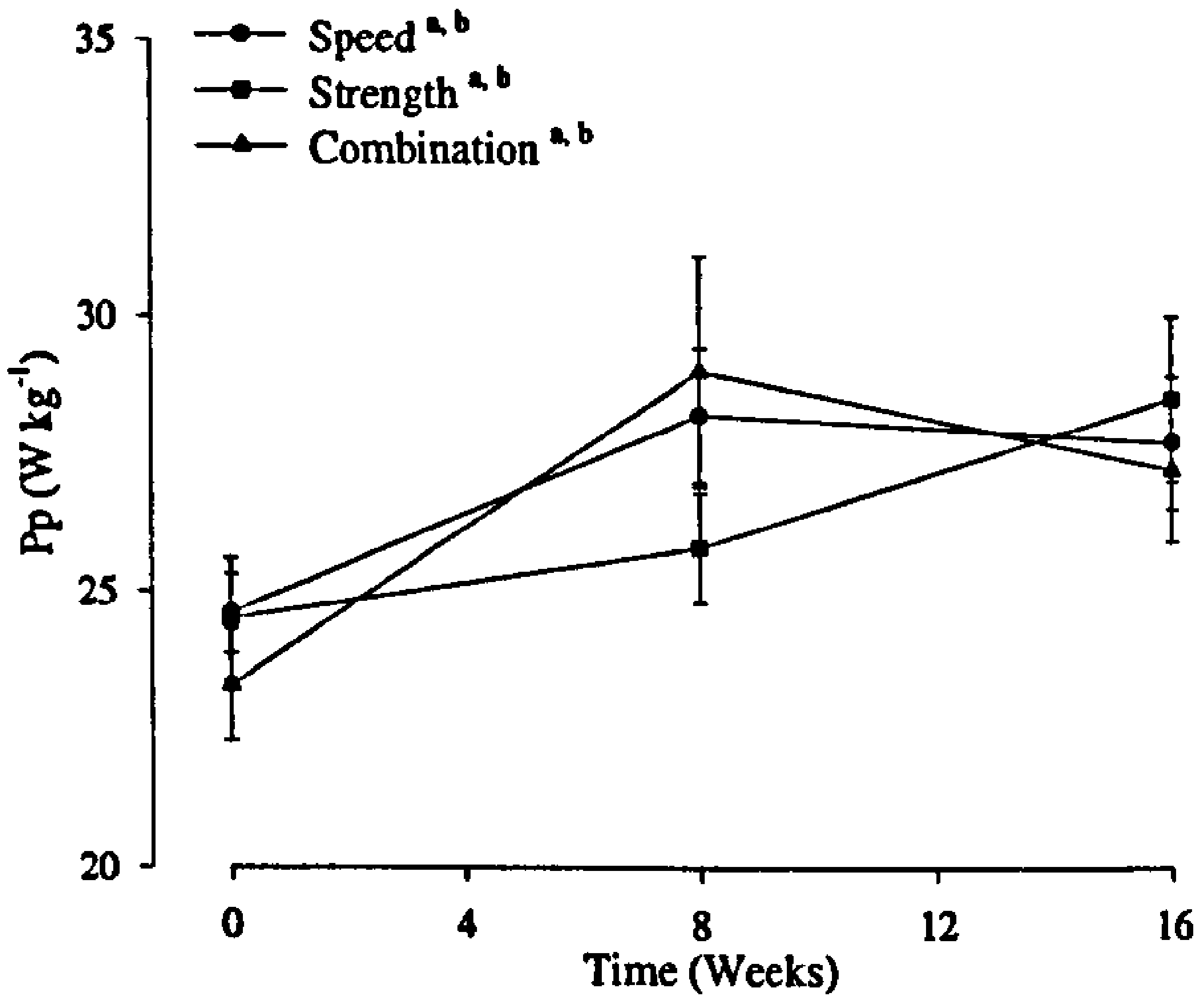


Figure 5.1. Mean ± S.E.M. maximal treadmill walking speed (MTWS), box stepping work (BSW) and vertical jump (VJ) in the three groups; [a] significantly different from week 0 to week 8; [b] significantly different from week 0 to week 16; [c] significantly different from week 8 to week 16.

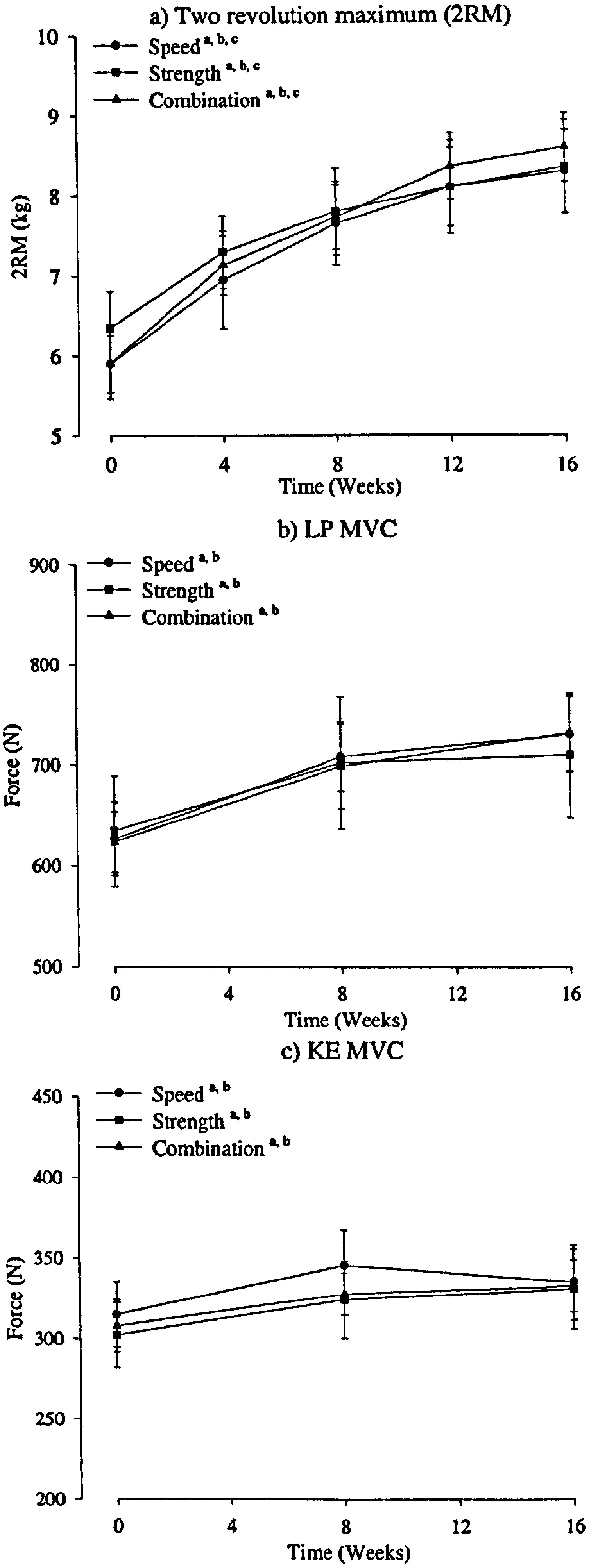
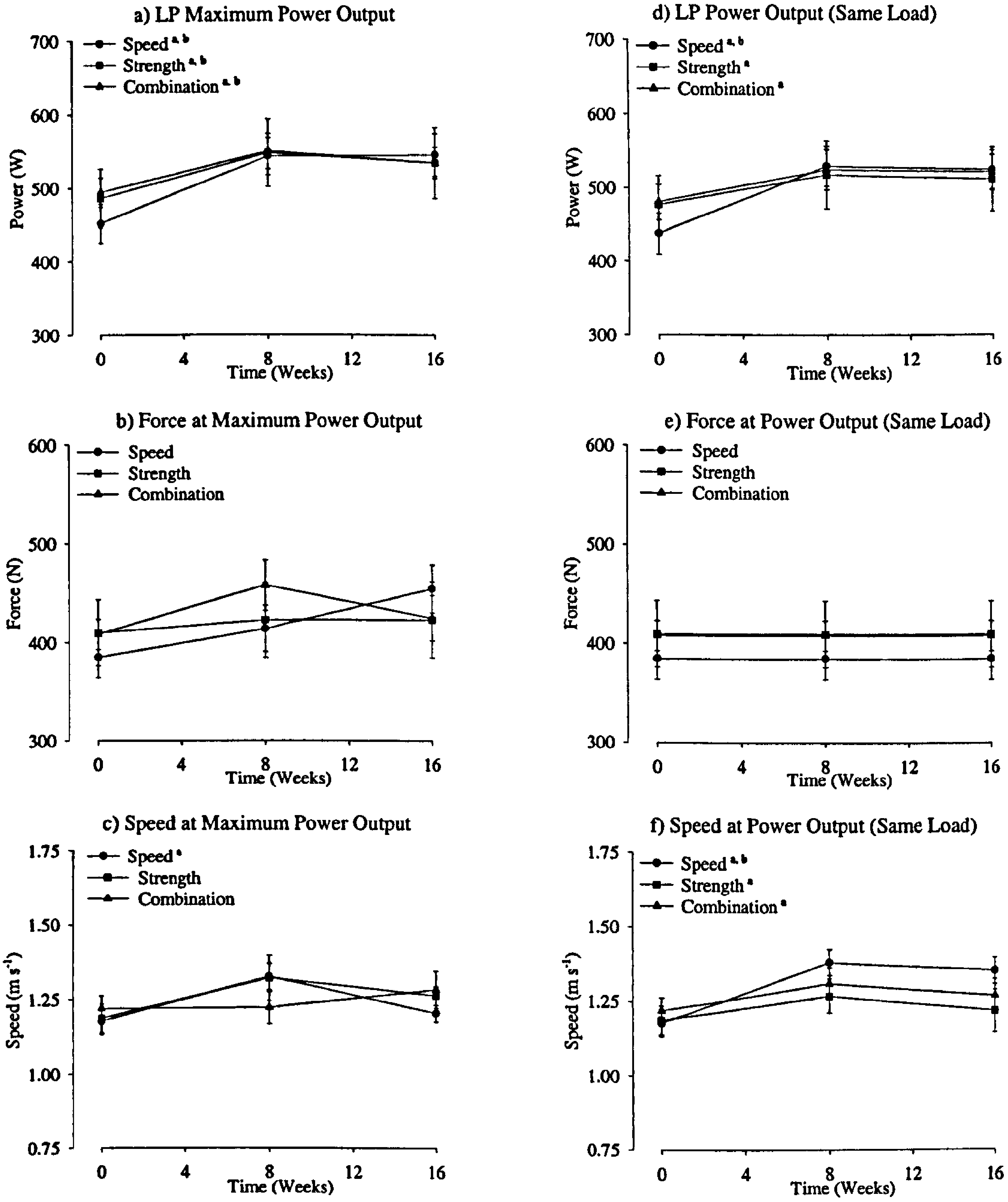


Figure 5.2. Mean ± S.E.M. a) two revolution maximum (2RM), b) maximum voluntary isometric contraction (MVC) during the leg press (LP) and c) MVC during the knee extension (KE) in the three groups; [a] significantly different from week 0 to week 8; [b] significantly different from week 0 to week 16; [c] significantly different from week 8 to week 16.


a) LP Maximum Power Output

d) LP Power Output (Same Load)

b) Force at Maximum Power Output

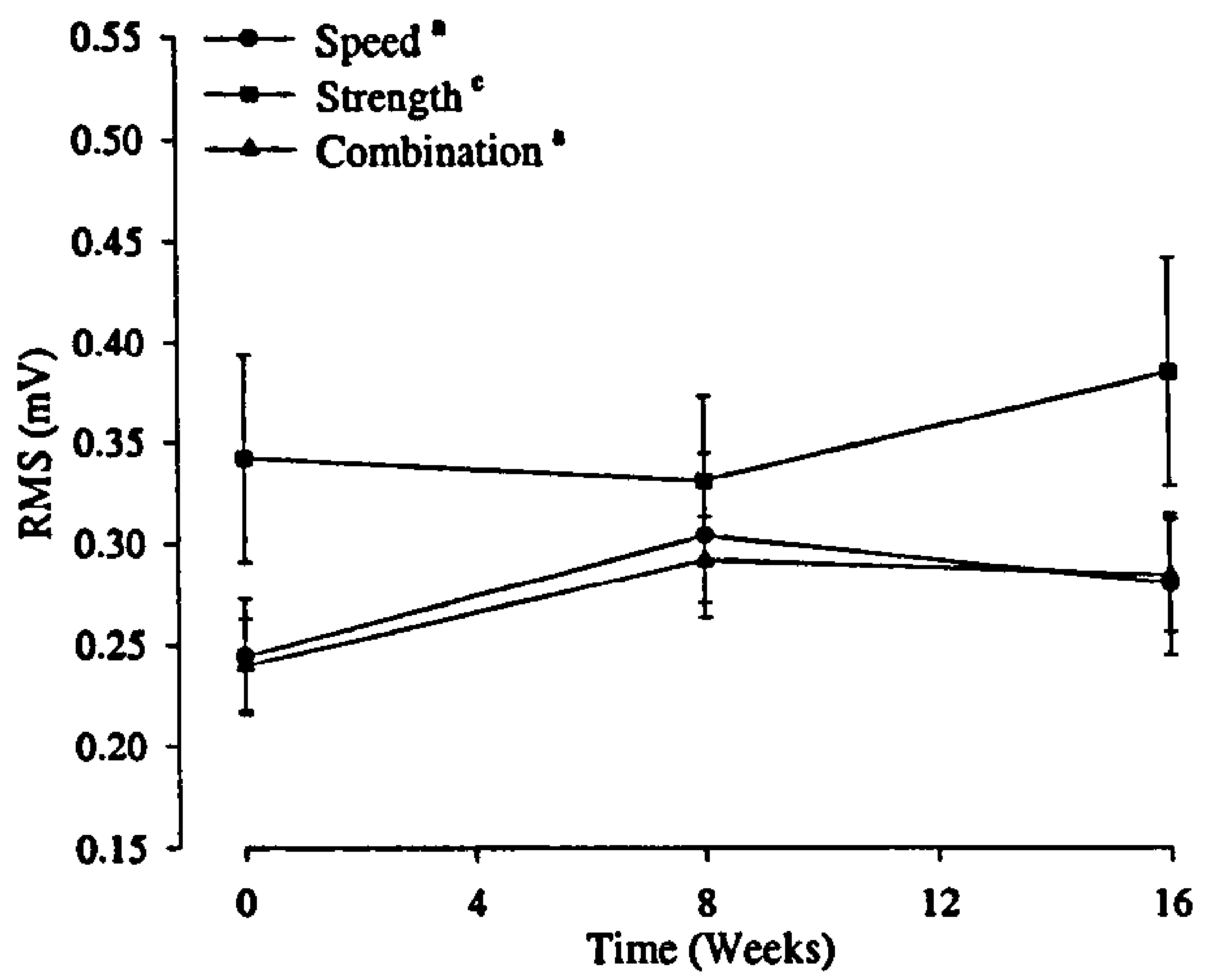
e) Force at Power Output (Same Load)

c) Speed at Maximum Power Output

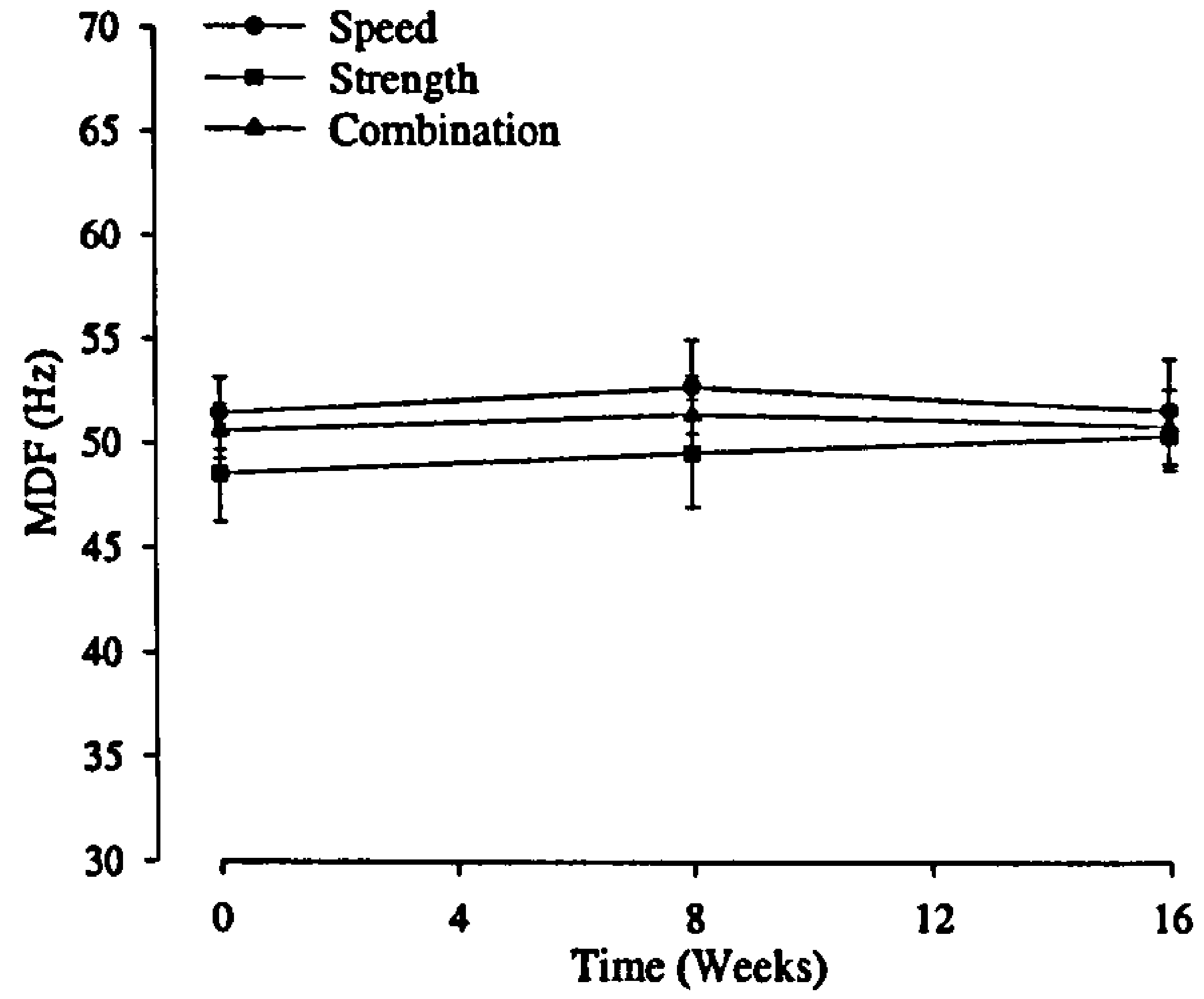
f) Speed at Power Output (Same Load)

Figure 5.3. Mean ± S.E.M. (a) maximum power output of the LP and (b) force and (c) speed at which maximum power was measured; (d) power output of the LP measured pushing (e) the same level of force as at week 0 and (f) speed at which power output was measured in this condition, in the three groups; [a] significantly different from week 0 to week 8; [b] significantly different from week 0 to week 16.

a) RMS of vastus lateralis during KE MVC



b) MDF of vastus lateralis during KE MVC



c) Percentage coactivation of biceps femoris during KE MVC

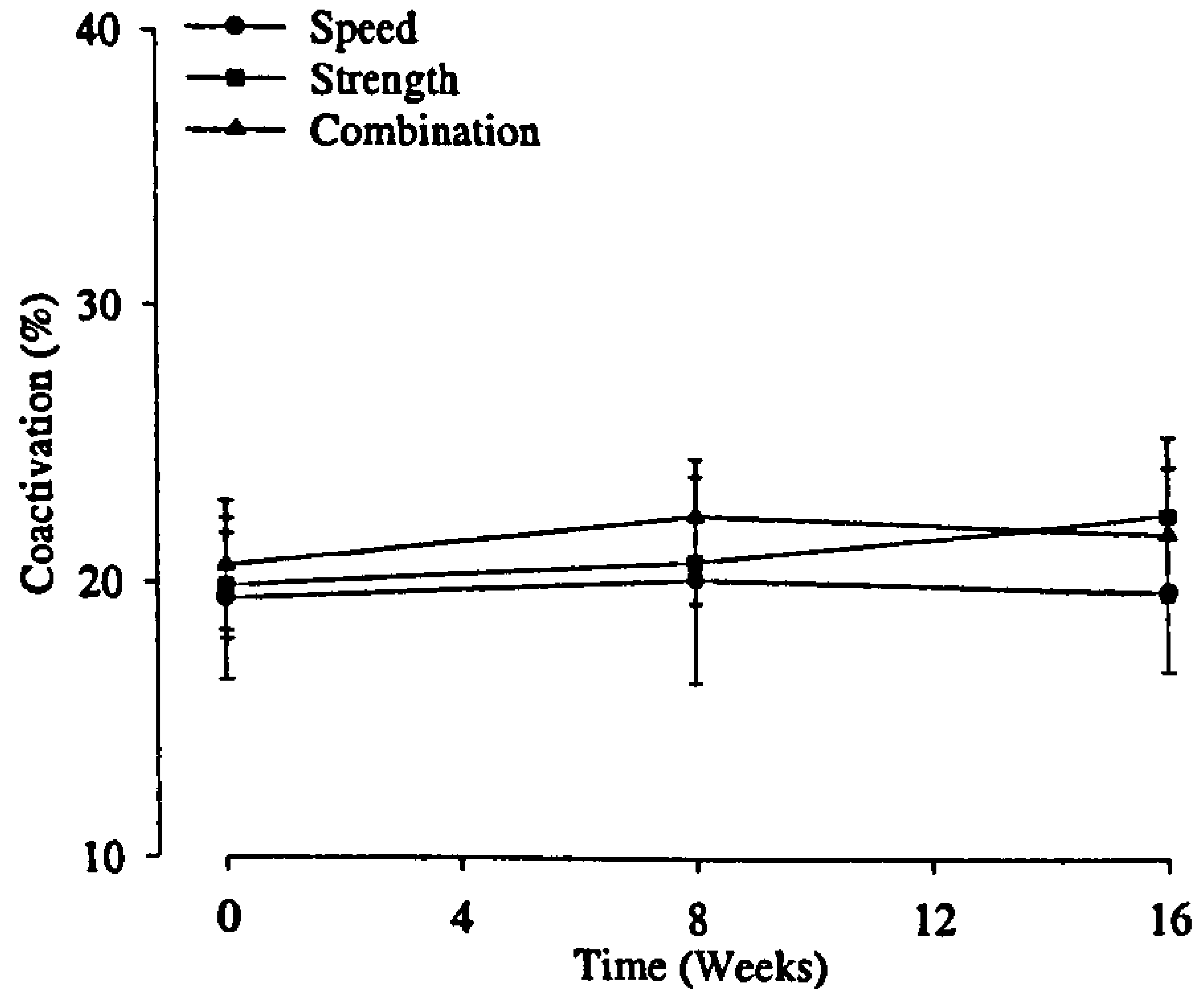


Figure 5.4. Mean ± S.E.M. (a) root mean square (RMS) and (b) MDF of the vastus lateralis during the knee extension (KE) maximum voluntary contraction (MVC); (c) percentage coactivation of the biceps femoris during the KE MVC, expressed as a percentage of maximal biceps femoris RMS measured during the MVC knee flexion (KF), in the three groups; [a] significantly different from week 0 to week 8; [b] significantly different from week 0 to week 16; [c] significantly different from week 8 to week 16.

DISCUSSION

In this study, for the first time, healthy older women performed resistance training on a mechanically braked cycle ergometer at different intensities and speeds, and improved their walking speed and other functional abilities with a parallel increase in muscle strength and power. The main new finding is that even fit older women can improve in functional abilities, as measured by the functional tasks that were not practised during the course of the study. Eight weeks of training were sufficient to induce an increase in most of the functional parameters assessed in this investigation. Finally, the "speed" training programme (SP group) was shown to be as effective in improving muscle function as the more conventional heavy-resistance training programme (ST group).

MTWS significantly increased throughout the whole duration of the training programme. This result is of particular importance since walking was not part of the training programme, which would seem to contradict the principle of specificity of training (McCafferty and Horvath, 1977), as cycling involves different patterns of muscle activation than walking (Bijker et al., 2002). The ability to maintain a fast walking pace is crucial when considering that, between the age of 65-74 years, one of the main causes of accidental deaths is represented by road accidents involving pedestrians (Office for National Statistics, 1998). Moreover, the older women in this study were already walking at relatively fast speeds prior to training and it is therefore likely that the improvement would have been even higher if the participants had been less fit (Lexell, 2000). Inclusion of dynamic exercises in training may have explained this improvement, as well as that observed in a previous investigation by Häkkinen et al. (2000).

The box stepping ability of older women improved as an effect of training. This is in agreement with the results of Skelton et al. (1995), who have shown an increase in box stepping following a 12-week resistance training programme. Box-stepping can be associated with the ability to climb stairs and therefore can be considered as a crucial factor contributing to the independence of older people. The box heights used in the protocol were designed to imitate the step heights that would be encountered on public transport, both buses and trains (Skelton et al., 1994). In the present study, the weight jacket was included as an integral part of the test to make it more demanding and discriminatory for the fit population of this study. The weights (2, 4 and 6 kg) were chosen because 4 kg is approximately equivalent to a day's basic necessity shopping (Skelton et al., 1994), although it could be argued that women do not carry their shopping on a backpack.

The jumping test has been adopted in this study since it is a good indicator of functional ability in an older population due to both the dynamic and weight-bearing nature of the test (De Vito et al., 1998). Peak power generated during a countermovement jump on a force platform significantly increased in all 3 groups from week 0 to week 8 and week 0 to week 16. This is in agreement with the results of Häkkinen et al. (2000) who reported an increase in the jumping ability of an older population following a 24-week resistance/dynamic exercise programme. Similarly, De Vito et al. (1999) observed an improvement in maximal instantaneous peak power, measured during a vertical jump on a force platform, in a population of older women following a twelve-week non-specific low-intensity training programme.

MVC of both the LP and KE significantly increased in the 3 groups following 8 weeks of training but there was no further significant increase from week 8 to the end of the training programme. This was similar to the observation of Häkkinen et al. (2001), who reported a plateau after 8 weeks of resistance training in an older population of similar age to that of our participants. In their study, the investigators observed an additional increase in strength only after 21 weeks of training, which could be attributed to the fact that the training intensity was further increased after 16 weeks. In our study, further improvement could have been achieved if the intensity had been increased at more frequent intervals, e.g. weekly. Interestingly, the time-course and the relative magnitude of the increase in MVC were similar for both LP and KE, in agreement with the recent results of Fielding et al. (2002). However, the average higher percentage increase in LP MVC (15%) with respect to KE MVC (8%) could be attributed to the fact LP is closer than KE to the training gesture, i.e. pedalling.

In addition to MTWS, the only other parameter showing a progressive increase also between week 8 and week 16 was the 2RM test. This parameter was not measured at week –4, since it was initially designed only to determine and update the training load (see Figure 5.1a). These results support the findings of previous authors (e.g. Frontera et al., 1988) who reported a greater improvement when the testing procedure was closely linked to the specific training gesture.

Maximum power output was evaluated by means of a recently devised test, described in chapter 3 of this thesis, that allows selection of the optimal load for maximum power production during a multiarticular functional gesture *in vivo* involving lower-limb muscles used during activities of daily living. This can be considered as an improvement with respect to other traditional devices like the force platform (Bosco and Komi, 1980; De Vito et al., 1998) or the Nottingham Rig (Bassey et al., 1992; Skelton et al., 1994), which adopted only a single inertia for all the participants. This is a limitation because the weaker participants may be disadvantaged by pushing a resistance corresponding to a high percentage of their maximum, thus performing the movement at a speed below the optimum for maximum power production. Only recently Fielding et al. (2002) used a pneumatic device which allows the selection of different loads for measuring power output. However, these authors did not comment on optimal force and velocity at which maximum power output was measured. There was a significant increase in LP in the 3 groups following the 16-week training programme. This result was due to a combined increase of both force and speed at which maximum power was measured, although the increase in these two outcome variables was not statistically significant, with the exception of speed at week 8 in the speed group. This exception could reflect a specific adaptation in those participants who were trained to pedal faster. Another specific adaptation of the participants in the speed group was observed when power output of the LP was measured pushing the same level of force of the pre-training test (Figure 5.3e). All of the 3 groups significantly increased speed of execution (Figure 5.3f) and relative power (Figure 5.3d) after 8 weeks, but this improvement was still significant after 16 weeks only in the participants of the speed group.

The improvement in muscle function, either strength or power output, was not different between the 3 groups, thus indicating that the major determinant of training efficacy may be represented by the mechanical work performed irrespective of the speed of execution. This is similar to the results reported by previous authors (Pruitt et al., 1995; Hortobágyi et al., 2001) who have compared the effects on muscle strength of two different training regimens performed with traditional weight-stacked machines, one at high intensity and another at low intensity, with the total mechanical work being the same in the two conditions. However, recent results of Fielding et al. (2002) suggest that this may be true for strength but not for power. In their study, the authors showed that individuals of the high-velocity group improved their strength similar to the individuals of the low-velocity group, with the total work performed being the same in the two groups, but showed a higher improvement in power. The specific increase in power has been attributed to the fact that during training power output was significantly higher in the high-velocity group. In our study, not only was mechanical work similar in the two conditions, but also power output, although this was not systematically monitored. In fact, the time taken to perform either 16 reps at 40% of 2RM or 8 reps at 80% of 2RM was randomly measured in some of the training sessions and was similar in the two conditions. It is therefore likely that the increase in strength depends on the mechanical work performed, regardless of speed of execution, whilst the increase in power is related to power generated during the training sessions.

The surface EMG parameters, when analysed in the time domain, have revealed that there was an increase in the level of neural activation of the agonist muscles during the knee extension (increase in RMS) with no change in the level of coactivation of the antagonist muscles. The first observation is in agreement with previous findings (Moritani and de Vries, 1980; Häkkinen et al., 1998c; Häkkinen et al., 1998b; Häkkinen et al., 2000), whilst the lack of change in coactivation of the antagonist muscles during the knee extension is in contrast with the results of previous studies (Häkkinen et al., 1998c; Häkkinen et al., 2000). This could be attributed to the fact that previous investigators have trained their participants to perform the knee extension and have then tested them using the same specific gesture, whilst the cycling action of our participants may have not affected the coactivation of the knee flexors during the knee extension. It is unclear and difficult to interpret why the temporal pattern of RMS increase was different in ST with respect to SP and CB. The analysis of the sEMG data in the frequency domain showed that no changes occurred in MDF as an effect of training. This lack of change may indicate that either no adaptations in the type and recruitment of MUs took place or, more likely, the analysis of the frequency contents of sEMG is not such a sensitive measure, despite the evidence of correlation with fibre type proportion (Moritani et al., 1985; Wretling et al., 1987; Gerdle et al., 1991; Kupa et al., 1995).

In our laboratory setting, no detailed anatomical measures were possible, nor was it possible to obtain muscle biopsy samples. Lower limb volume was indirectly estimated from anthropometric measures, according to Jones and Pearson (1969), which is a limitation, as it is unlikely that the anthropometric measures could detect any small change in muscle mass following the training programme. Therefore, it is not possible to exclude the possibility that some concomitant intramuscular adaptation took place. These include an increase in muscle mass (Harridge et al., 1999b), which is consistent with an increase in protein synthesis (Yarashesky et al., 1995; Welle et al., 1999), a selective hypertrophy of type II fibres (Hunter et al., 1999) or an adaptation towards faster contracting fibres expressing the same MHC isoform (Trappe et al., 2001). Notably, Van Cutsem et al. (1998) have shown that changes in single MU behaviour contribute to the increase in contraction speed after dynamic training in humans, which could justify training induced changes in power. Moreover, our training intervention may have increased tendon stiffness, as recently shown by Reeves et al. (2003) in 74 year old men following 14 weeks of resistance training, which may have increased the effectiveness of force and power transmission.

The majority of the volunteers showed enthusiasm for the exercise classes and expressed hope that the programme could be continued. One of the main advantages of using a cycle ergometer in carrying out resistance-training programmes is that in the same training session many individuals can be trained at the same time under the strict supervision of one instructor, which is realistic in terms of feasibility and costs if an appropriate number of mechanically braked cycle-ergometers is available. This training programme has been proved to be safe and effective and may be extended to a frail population, including individuals suffering from non-severe arthritis, heart disease and osteoporosis.

CONCLUSION

The main finding of this study is that the novel approach to performing both light and heavy resistance training, based on the use of a cycle ergometer, has been shown to be effective in improving functional abilities, strength and power in a group of healthy women. Even fit older women still have a margin of improvement in muscle function. For most of the outcome variables the improvements were evident after 8 weeks of training with no further improvements at completion (16 weeks). No differences were observed between the 3 training groups and this could indicate that the major determinant of training efficacy is represented by the mechanical work performed, which was similar in all groups, regardless of the speed of execution.

CHAPTER 6

GENERAL DISCUSSION

Older women in their 7th-8th decade have been identified as the first target group of intervention and rehabilitation studies, as they can reach levels of muscle strength and power below the threshold necessary to accomplish basic daily activities. The aim of this thesis was to examine some of the mechanisms underlying the lower levels of muscle strength and power in older women and some of the adaptations in response to specific resistance-training programmes. The first study (chapter 2) demonstrated that specific strength of both the knee extensors and flexors, expressed as the ratio between isometric torque and contractile volume, was lower in the older than in the young women, thus indicating that mechanisms other than smaller muscle mass account for differences in strength between the two groups. Among these are the lower neural activation of the agonist muscles and the greater coactivation of the antagonist muscles, which explain, in part, the lower force production in the older women. In the second study (chapter 3), the two determinants of explosive power, i.e. optimal force and speed of movement, were compared between young and older women, adopting an apparatus with various loads to test a single leg-press, which is a functional gesture. It has been shown that the older women could not even move the resistance at which the young women achieved maximum power, thus revealing the importance to optimise the initial level of inertia in measuring maximum power output. The lower levels of power in the older women were due to lower levels of both optimal force and optimal velocity. The ratio between power output and isometric strength was significantly lower in the older than the young women, thus suggesting, not surprisingly, that power is more vulnerable than strength to the ageing process. The findings of chapter 2 and 3, where muscle function has been measured in both static and dynamic conditions (isometric force and explosive power, respectively), match the observations made by others of morphological and neural changes in the older muscle, as reported in chapter 1. In the training studies of chapter 4 and 5, various intervention programmes were designed to recover both isometric strength and power and to investigate some of the underlying physiological mechanisms of adaptation. Six weeks of isometric training increased the capacity to sustain constant-force isometric contractions at high intensity in the elbow flexors of both young and older women, with the force gain following the same temporal pattern in the two groups, but being lower in the older women (chapter 4). In both groups there were no training-induced changes in the frequency content of the sEMG, expressed as MDF, thus suggesting that no change in the capacity to voluntarily recruit the highest threshold fast MUs took place. There were, however, training-induced increases in the amplitude of sEMG, expressed as RMS, which were peculiar for each of the two groups: "early" RMS, an indicator of the initial state of muscle activation, increased in the young subjects, whilst it was the "late" RMS, which described changes in sEMG amplitude during the latter part of a sustained-isometric contraction, which increased in the older subjects. This indicates that young and older women showed a different training-induced adaptation in the neural strategies to keep a constant level of force during a short-sustained isometric contraction at high intensity. Finally, in the last study of this thesis (chapter 5), cycling was adopted as a novel approach to perform three different regimens of resistance training (one performed at a light intensity with a high speed of movement, another performed at a heavy intensity with a slower speed of movement, a third based on a combination of both) in a population of healthy older women aged 65 to 74 years. All of the participants improved their maximum walking speed and other functional abilities (box-stepping and vertical jumping), with a parallel increase in muscle strength and power, regardless of the training regimen adopted. This was accompanied by electromyographic changes in RMS but not in MDF. Even fit older women still have a margin for improvement in muscle function. The improvements in most of the functional parameters reached significance after 8 weeks of training with no further changes in the following 8 weeks, with the exception of maximum walking speed and the maximum resistance to complete two pedal revolutions.

Some of the procedures used to test the hypotheses in each of the first two experimental studies of this thesis must be remarked for their originality. For the first time, specific strength of both the knee extensors and flexors has been expressed as the ratio between muscle torque and contractile volume and compared between young and older individuals (chapter 2). Determining muscle volume is a way of approximating muscle physiological CSA and the ratio between torque and muscle volume may be theoretically considered as an index with the same dimension as that of muscle force relative to physiological CSA (Miyatani et al., 2001). Remarkably, the amount of fat and connective tissue within the muscle belly, which was higher in the older than the young women as shown in previous studies (Rice et al., 1989; Kent-Braun et al., 2000), has been separated from the contractile tissue, thus obtaining an accurate measure of muscle volume. Moreover, for the first time, the estimate of specific strength has been combined with the recording of sEMG, which has been used to quantify the level of activation of agonist muscles and the coactivation of antagonist muscles. Also unique are the measures of the thickness of subcutaneous layers between the electrodes and the underlying muscles, which were fitted in the simulation model of Farina and Rainoldi (1999), as reported in chapter 2, to infer that they may indeed affect the amplitude of sEMG, but would not entirely explain the great difference in amplitude between young and older subjects. In fact, RMS was more than halved in the older women. In the second study of this thesis (chapter 3), for the first time, explosive power output has been compared between young and older women after optimising the load for maximum power production during a multiarticular functional gesture *in vivo*, which involves lower-limb muscles used during activities of daily living. The fact that the older women could not even push the resistance at which the young women achieved maximum power emphasises the importance of optimising the inertia of the measurement apparatus when measuring power in functional studies involving older individuals.

In the first two studies of this thesis it has been shown that both specific strength, measured in isometric conditions (chapter 2), and explosive power output with its two determinants, optimal force and optimal velocity (chapter 3), are lower in the older than the young women. Both these findings can be interpreted with the observation made by others on morphological and neural changes in the older muscle, as reported in chapter 1. Different techniques and methodologies seem to lead to the same conclusion that it is not only the quantity but also the quality of muscles that is lower in older individuals. As reviewed in chapter 1, the selective atrophy of type II fibres (for review see Lexell, 1995), which is accompanied by the electrophysiological evidence that MUs are reduced with ageing in both number and size (Brown et al., 1988; Doherty et al., 1993; Doherty and Brown, 1993), affects the capacity of skeletal muscles to produce force and power. Fast-twitch fibres are intrinsically stronger and faster than slow-twitch fibres and therefore muscles with the same area, but occupied by a relatively smaller area of fast-twitch fibres, will be able to generate less force and power (Jones and Round, 1990). The selected atrophy of fast-twitch fibres is further supported by the evidence that in the older muscle there is a relative increase in slow MHC content (Klitgaard et al., 1990). In agreement with the results of this thesis is also the slowing in the contractile properties, which has been demonstrated in various muscles of the lower limbs (Vandervoort and McComas, 1986; Roos et al., 1999) and in the adductor pollicis muscle (Narici et al., 1991) by measuring the duration of twitch contraction. At microscopic level of muscle analysis, this has been ascribed to a reduction in sarcoplasmic reticulum activity (Kiltgaard et al., 1989; Delbono et al., 1997; Hunter et al., 1999) and actin sliding speed on myosin (Höök et al., 2001). The shift towards a slower muscle with ageing has been confirmed by studies on the contractile mechanics of single fibres, in which it has been shown that both MHC-I and MHC-IIA single fibres have lower specific tension and maximum shortening velocity if they originate from the muscles of an older person as opposed to a young person (Larsson et al., 1997; Frontera et al., 2000b). However, measurements of force and power *in vivo* represent the resultant of relatively complex situations, where not only the contractile elements of muscle cells must be considered, but also factors such as neural influences, muscle architecture and intercellular connective tissue. As shown in the first experimental study of this thesis (chapter 2) by sEMG, changes in the neural activation of agonist muscles (decrease in number, firing rate and synchronisation of the single MUs) and in the coactivation of antagonist muscles, are additional factors to explain the age-related differences in muscle strength, and possibly power, between young and older individuals. Surface EMG recordings have not been carried out during the measure of power (chapter 3), as in dynamic movements various mechanical, physiological, anatomical and electrical modifications occur throughout the contraction that affect, in substantial ways, the relationship between signal amplitude and muscle force (De Luca et al., 1997). Metter et al. (1997) speculated that normal ageing changes in the basal ganglia, consisting in a continuing loss of dopaminergic neurons in the substantia nigra (Morgan et al., 1994), could be a contributor to the observed slowing in speed, coordination and power, together with peripheral changes such as slowing in nerve conduction velocities (Norris et al., 1953). Another potential cause for lower power production could be an age-related decrease in tendon stiffness (Maganaris, 2001), which would reduce the effectiveness of both force and power transmission. Levels of various hormones do certainly play a role in relation to the capacity to produce force and power, as briefly reviewed in chapter 1, although their functions and mechanisms are still mostly unclear.

Limitations of the first study (chapter 2) include the following points: 1) although determining muscle volume is a way of approximating muscle physiological CSA (Miyatani et al., 2001), a direct measure of physiological CSA has not been performed. At present there is no established method of directly determining physiological CSA in human skeletal muscle (Miyatani et al., 2001), but this could have been estimated *in vivo* by dividing the product of muscle volume and the cosine of the angle of pennation by the length of the muscle fibres, with the angle of pennation being measured by ultrasonography. Therefore, the ratio between muscle strength and physiological CSA in the older muscle would have been even closer to the true measure of specific strength. Unfortunately, ultrasonography was not available in the laboratory setting. 2) The presence of greater adipose tissue in the older subjects may have increased the occurrence of cross-talk from nearby muscles (Solomonow et al., 1994), thus contaminating the signal and misleading its interpretation. However, as discussed in chapter 2, Solomonow et al. (1994), who raised such concerns, also concluded that for surface EMG recording with the appropriate size of electrodes, correct placement over the muscle and short interelectrode distance, the effect of cross-talk could be disregarded in most skeletal muscles of the extremities, spine and upper trunk, with the exception of abdominal and buttock muscles, which are covered by a considerable amount of subcutaneous fat. The thickness of the subcutaneous tissue above the muscles investigated in this study (vastus lateralis and biceps femoris) is minimal with respect to the thickness of the adipose tissue above abdominal and buttock muscles and the difference between young and older subjects is in the order of only a few millimetres. Moreover, even if greater cross-talk occurred in the older subjects due to the slightly thicker subcutaneous tissue, it would be balanced in the young subjects by greater cross-talk due to the much greater surface EMG amplitude of the agonist muscle, which in turn increases cross-talk to the antagonist muscles (Solomonow et al., 1994). The net effect would thus be a similar proportion of cross-talk in the two groups.

In the second study (chapter 3), it has been shown that the system used to assess power output and its determinants, optimal force and optimal velocity, is not a true isotonic system, as force is not kept constant throughout the full range of motion. However, this is not relevant to the results of the investigations presented in chapter 3 and 5 of this thesis. Regardless of whether the movement was isotonic or not, in order to test the hypotheses, it was necessary to adopt a dynamometer that enabled to measure velocity of movement with the subjects exerting a given level of average force throughout the movement, which corresponded to various percentages of isometric force. The initial loads the subjects were asked to push were almost equal to the user-selected level, for all of the percentages of maximum force which were tested, and were highly correlated with both the forces at peak power and the average forces measured during the thrust. The best value of power output was selected for further analysis. This apparatus was therefore suitable to study the two determinants of maximum power output, optimal force and optimal velocity, in both chapter 3 (comparison between young and older women) and chapter 5 (effects of resistance training in older women). Moreover, even if a perfect machine existed, with the external resistance being maintained constant throughout the full range of motion, the movement would not be isotonic for the muscle, because the lever system changes its position during the movement (Perrin, 1993). The muscle is maximally loaded at only one point during the range of motion, with this closely mimicking muscular contractions that occur in real life.

As reported in chapter 1, there are few studies investigating changes in neural properties following strength training in aged humans (Rice, 2000). Therefore, in the first of the two training studies of this thesis (chapter 4), it has been hypothesised that a short-term training-programme designed to increase isometric strength could induce changes in the neural strategies, as revealed by sEMG, to maintain a sustained-isometric contraction of high intensity (80% of MVC) and short duration (12 s). This type of contraction is an optimal model for studying training-induced neural adaptations, especially when the force is kept constant within a narrow range of the target value (De Luca et al., 1996), and plays an important role in older people in order to maintain normal daily activities (Bemben, 1998). After training, in the young women, the level of force increased by 22.4% and the "Early" RMS, an indicator of the initial state of muscle activation, increased by 60.4% with respect to the pre-training condition. This has been interpreted, with reference to the literature (Milner-Brown et al., 1975; Basmajian and De Luca, 1985; Häkkinen, 1994; Esposito et al., 1996), as an increase in the number, firing rate and synchronisation of the recruited MUs, whose relative role, however, cannot be distinguished with sEMG, at least when analysing data from the initial part of the sustained contraction. In the older women, the increase in force (13.4%) was less than in the young women and was accompanied by a tendency towards an increase of "Early" RMS that did not reach significance. In contrast, the "Late" RMS, which described changes in sEMG amplitude during the latter part of a sustained-isometric contraction, increased by 46.7% in the older but not in the young women. This has been attributed by the author, after a logical scrutiny of the findings reported in the literature (Milner-Brown et al., 1975; Basmajian and De Luca, 1985; De Luca at al., 1996), to either an increased synchronisation of MUs or an increase in action potential duration. In conclusion, the training-induced capacity to sustain higher levels of force during a constant-force sustained-isometric contraction at 80% of MVC lasting 12 s, which was higher in magnitude in the young than in the older women, was accompanied by increases in the sEMG amplitude, with peculiar differences in the two groups. An overall increase in sEMG amplitude, expressed as RMS, was also measured in the second training study of this thesis (chapter 5). In this case, sEMG measurements were performed during MVC, which increased as an effect of training, similar to what has been reported by other investigators (Moritani and de Vries, 1980; Häkkinen et al., 1998b; Häkkinen et al., 1998c).

In the first of the two training studies of this thesis (chapter 4), it has also been hypothesised that a short-term training-programme designed to increase isometric strength could induce specific adaptations of fast-twitch MUs, with these adaptations being revealed by the frequency-domain analysis of the sEMG during constant-force sustained-isometric contractions. The analysis of the power spectrum of sEMG data has been proposed as an electrophysiological "muscle biopsy" for estimating muscle fibre composition (Moritani et al., 1985; Wretling et al., 1987; Gerdle et al., 1991;

Kupa et al., 1995). Spectral parameters recorded during a muscle contraction have been shown to correlate with fibre type proportion in both human (Moritani et al., 1985; Wretling et al., 1987; Gerdle et al., 1991) and animal studies (Kupa et al., 1995). Additionally, it has been shown that the conduction velocity of action potentials propagated along the muscle fibres correlates with fibre type proportion (Sadoyama et al., 1988; Linssen et al., 1991) and it is well accepted that action potential conduction velocity is considered as a major determinant of the power spectrum density (Stulen and De Luca, 1981; Solomonow et al., 1990). A training-induced increase in MDF was expected as an indicator of increased capacity to voluntarily recruit the highest threshold fast MUs. However, this change in MDF did not take place. Similarly, in the second training study of this thesis (chapter 5) no significant changes in MDF occurred even after a longer period of training. In the second study, a change in MDF may have been interpreted not only as an increased capacity to voluntarily recruit the highest threshold fast MUs, but also as indirect evidence of a selective hypertrophy of type II fibres or a shift of muscle fibres towards a faster type. After all, Häkkinen et al. (1998b) have reported a type MHC II subtype transformation going from type MHC IIb to IIa in older men following only 10 weeks of resistance-training. The lack of change of MDF in both of the two training studies of this thesis may indicate that either no adaptations in the type and recruitment of MUs took place or, more likely, the analysis of the frequency contents of sEMG is not such a sensitive measure, despite the evidence of correlation with fibre type proportion (Moritani et al., 1985; Wretling et al., 1987; Gerdle et al., 1991; Kupa et al., 1995). Also the reproducibility of MDF could account for this lack of sensitivity, although an ICC above 0.6, as found in our study, has been indicated as an index of good reproducibility (Rainoldi et al., 1999). This explains why using "non-invasive" muscle biopsy by sEMG is a method that has not been implemented much in the current literature. The question on whether or not any change in fibre types took place would have been answered only if muscle biopsies had been taken.

Another finding of the first of the two training studies of this thesis, which has to be remarked upon, is that this is one of the few investigations showing a comparison of the magnitude of the responses in older and young individuals to the same training programme. The force gain followed the same temporal pattern in the two groups, in that after 4 weeks MVC reached a plateau, but the absolute force increments were different, 22.4% in the young and 13.4% in the older women. Our results do not match those of Jozsi et al. (1999) and Welle et al. (1996b), who reported increases in strength of a similar magnitude in young and older individuals in response to resistance training. However, the results of these authors are relative to longer periods of training, 12 and 13 weeks, respectively, and to a population of mixed genders. Moreover, data of Jozsi et al. (1999) suggest that men may experience greater absolute gains than women. In our study, it may be that the different hormonal status in the two populations of young and older women partly accounts for the reduced responsiveness of ageing muscles to the training stimulus (Häkkinen and Pakarinen, 1994).

In the second of the two training studies of this thesis (chapter 5), for the first time a mechanically braked cycle ergometer has been adopted to perform both light and heavy resistance-training. Training-induced adaptations on strength and power have been measured during a single leg-press with same apparatus used in chapter 3, in isometric and dynamic conditions, respectively, with simultaneous recording of sEMG during the isometric action. In addition, three selected functional abilities have been studied: maximum walking speed, box stepping and vertical jumping. These are the novel findings which deserve to be remarked upon: 1) even fit older women still have a margin for improvement in muscle function; 2) although the functional tasks have not been practised as part of the training programme, there was a significant improvement in all of the functional abilities selected for this study. Notable is the progressive increase in maximum walking speed, which seems to contradict the principle of specificity of training presented in chapter 1 (McCafferty and Horvath, 1977), as cycling involves different patterns of muscle activation than walking (Bijker et al., 2002); 3) the training-induced increase in power output was due to a combined increase in both of the two determinants of power, optimal force and optimal velocity; 4) the lack of difference between the three training regimens seems to suggest that it is not the intensity, neither the speed of movement, but the level of mechanical work, with this being similar in the three groups, which represents the training stimulus.

In each of the two training studies of this thesis (chapter 4 and chapter 5) muscle mass has been indirectly estimated from anthropometric measures, the muscle-bone area of the arm according to de Koning et al. (1986) and the volume of the lower limb according to Jones and Pearson (1969), respectively. In our laboratory setting, no detailed anatomical measures were possible, nor was it possible to obtain muscle biopsy samples This is a limitation, as it is unlikely that anthropometric measures could detect any small change in muscle mass following resistance training. Whilst it is reasonable to expect that in the first study (chapter 4) no significant hypertrophy took place after 6 weeks of training, with the early strength gains being mainly due to neural adaptations (Sale 1988), in the second study (chapter 5), which lasted 16 weeks, it is not possible to exclude the possibility of some concomitant intramuscular adaptation. These include an increase in muscle mass (Harridge et al., 1999b) and protein synthesis (Yarashesky et al., 1995; Welle et al., 1999), a selective hypertrophy of type II fibres (Hunter et al., 1999) or an adaptation towards faster contracting fibres expressing the same MHC isoform (Trappe et al., 2001). Training-induced changes in power output, which interestingly in chapter 5 have been found to depend not only on an increase in optimal force but also in optimal velocity, can also be partly attributed to changes in single MU behaviour, as notably measured by Van Cutsem et al. (1998) with intramuscular EMG recordings.

In all of the studies of this thesis, maximum strength was measured during voluntary contractions. This may be criticised by those investigators who showed by twitch interpolation technique that older adults were not able to maximally activate a muscle or muscle group, thus underestimating the measure of maximum muscle strength (Harridge et al., 1999b; Yue et al., 1999; Bilodeau et al., 2001a). However, many other investigators demonstrated that a superimposed stimulus, either in the form of a single twitch or a short tetanus, added little or nothing to the volitional force of older people (Phillips et al., 1992; De Serres and Enoka, 1998; Kent-Braun and Ng, 1999; Connelly et al., 1999; Roos et al., 1999; Jakobi and Rice, 2002; Scaglioni et al., 2002). As already discussed in chapter 1, the possibility of underestimating the "real" maximum should therefore be discounted if at least one session of familiarisation is practised (Jakobi and Rice, 2002) and if the subjects are not too old. However, this issue deserves further investigation as conclusive results on the activation capacity of a muscle may largely depend on the stimulation technique that is adopted (Behm et al., 2001). Finally, the author of this thesis suggests that voluntary strength testing should be preferred, since electrical stimulation determines a full synchronisation of MUs (Solomonow et al., 1994), which is unlikely to occur in real life.

A final comment must be made on the level of physical fitness and health status of the participants in all of the experimental studies of this thesis. Strict criteria were followed for selection. Most subjects performed recreational physical activities, no more than 2 times per week, but none of them had any background in regular strength training or competitive sports. They were required to maintain their normal levels of physical activity throughout the duration of the studies. Volunteers were selected according to the exclusion criteria to define "medically stable" older subjects for exercise studies, as proposed by Greig et al. (1994). It remains a concern that people with personal interest in physical activity may have preferentially been attracted by exercise studies, thus being not representative of the general population. On the other hand, also most of the young women who volunteered for this study were students of sport science or physical education, with the likelihood to be slightly more active than the average population, thus partly levelling the fitness levels in the two groups. However, as pointed out at the beginning of this thesis, comparisons between young and older individuals are limited to describe changes at the population level and cannot determine how a specific individual's muscle function changes with age. It must always be taken into account that older people are of a different generation, with a lifetime of physical activity, health and nutrition that is probably unlike the habit of the younger as they age. As already pointed out, the good level of health and fitness of the participants in the last experiment of this thesis (chapter 5) is an original point of the investigation, as this enabled the author to demonstrate that even fit older women still have a margin for improvement in muscle function.

General conclusions and recommendations for further studies

The main findings of this thesis are:

1) New information has been provided on the ratios between knee extensor/flexor torque and contractile volume, in young and older women. Older women are significantly weaker than young women in both isometric extension and flexion, and their lower level of strength is not completely explained by the decrease in their contractile muscle mass. One potential explanation for the reduced level of force production in older women is an increase in the level of coactivation of the flexor muscles during knee extension, and another is a decrease in the neural activation of the agonist muscles, both during knee extension and flexion.

2) Older women cannot even move the resistance at which the young women achieve maximum power during a leg-press action, which is a functional gesture, after optimisation of load. Their lower levels of power, which appear to be more affected by ageing than isometric strength, are due to lower levels of both force and velocity at which maximum power is measured.

3) Changes in force and in the time-domain characteristics of the surface electromyogram measured on the biceps-brachii muscle during constant-force sustained-isometric contractions at high intensity and short duration are different in young and older women in response to the same short-term resistance-training programme. Older women respond with a lower increase in strength than the young women, although the two groups show the same temporal pattern. "Early" RMS, an indicator of the initial state of muscle activation, increases in the young subjects, whilst it is the "late" RMS, which describes changes in sEMG amplitude during the latter part of a sustained-isometric contraction, that increases in the older subjects, thus revealing a different training-induced adaptation in the neural strategies to keep a constant level of force during a short-sustained isometric contraction at high intensity. No changes in the frequency content of the sEMG, expressed as MDF, occur in both groups, thus suggesting that no changes in the quality of the recruited MUs take place.

4) Three modalities of resistance-training, carried out for 16 weeks on a cycle-ergometer at either high-resistance and low-speed, low-resistance and high-speed, or a combination of both, are equally effective in improving power, strength and selected functional abilities in a healthy population of 65-74 year-old women. Even fit older women still have a margin for improvement in muscle function. The improvements in most of the functional parameters reach significance after 8 weeks of training with no further changes in the following 8 weeks, with the exception of maximum walking speed and the maximum resistance to complete two pedal revolutions.

Certainly there is scope for a continuation of the experimental work, which include the following areas:

1) Many of the factors contributing to the loss of strength and power in older women, some of which have been measured in the experimental studies of this thesis and others reported in the literature, may have to be investigated simultaneously on the same population, in order to quantify the relative contribution of each single factor. These measurements include: strength and power, under both voluntary and electrically elicited contraction, muscle architecture, percentage coactivation of antagonist muscles, hystochemical analysis of biopsies, estimation of number and size of MUs, and hormonal factors. Controlling all of these factors in one study may be impractical, but would be the only possibility for resolving unanswered questions.

2) Neural mechanisms and adaptations to training, which have been investigated in the experimental studies of this thesis by bipolar sEMG, may have to be further explored by using more complex techniques, such as electrode arrays with the simultaneous measure of intramuscular EMG. An electrode array (Merletti et al., 2001) would allow measurement of muscle fibre action potential conduction velocity, which has been described as the main determinant of the sEMG power spectrum. The direct measure of conduction velocity may be more sensitive to changes in the quality of muscle fibres due to ageing or training. Intramuscular EMG would allow the study of the behaviour and adaptations of single MUs, and also rule out interference of skin and subcutaneous tissue.

3) It has been suggested in the final experimental study of this thesis that the increase in strength following resistance training may depend on the mechanical work

performed, regardless of the speed of execution, whilst the increase in power may relate to power generated during the training sessions. This deserves further investigation in which more accurate measures of mechanical work and power, both internal and external, are performed.

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