

Maximal strength and power characteristics in isometric and dynamic actions of the upper and lower extremities in middle-aged and older men

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ABSTRACT

Muscle cross-sectional area of the quadriceps femoris (CSA_{QF}), maximal isometric strength (handgrip test and unilateral knee extension/flexion), the shape of isometric force–time curves, and power–load curves during concentric and stretch–shortening cycle (SSC) actions with loads ranging from 15 to 70% of one repetition maximum half-squat ($1RM_{HS}$) and bench-press ($1RM_{BP}$) were examined in 26 middle-aged men in the 40-year-old (M40) (mean age 42, range 35–46) and 21 elderly men in the 65-year-old age group (M65) (mean age 65, range 60–74). Maximal bilateral concentric ($1RM_{HS}$ and $1RM_{BP}$), unilateral knee extension (isometric; MIF_{KE} and concentric; $1RM_{KE}$) strength and muscle CSA in M65 were lower ($P < 0.001$) than in M40. The individual values of the CSA_{QF} correlated with the individual values of maximal concentric $1RM_{HS}$, $1RM_{KE}$ and MIF_{KE} in M65, while the corresponding correlations were lower in M40. The maximal MIF_{KE} value per CSA of $4.54 \pm 0.7 \text{ N m cm}^{-2}$ in M40 was greater ($P < 0.05$ – 0.01) than that of $4.02 \pm 0.7 \text{ N m cm}^{-2}$ recorded in M65. The maximal rate of force development of the knee extensors and flexors in M65 was lower ($P < 0.01$ – 0.001) and the heights in squat and counter-movement jumps as much as 27–29% lower ($P < 0.001$) than those recorded in M40. M65 showed lower ($P < 0.001$) concentric power values for both upper and lower extremity performances than those recorded for M40. Maximal power output was maximized at the 30–45% loads for the upper extremity and at the 60–70% loads for the lower extremity extensors in both age groups. Muscle activation of the antagonists was significantly higher ($P < 0.01$ – 0.001) during the isometric and dynamic knee extension actions in M65 than in M40. The present results support a general concept that parallel declines in muscle mass and maximal strength take place with increasing age, although loss of strength may vary in both lower and upper extremity muscles in relation to the type of action and that ageing may also lead to a decrease in voluntary neural drive to the muscles. Explosive strength and power seem to decrease with increasing age even more than maximal isometric strength in both actions but power was maximized at the 30–45% loads for the upper and at the 60–70% loads for the lower extremity action in both age groups. High antagonist muscle activity may limit the full movement efficiency depending on the type of muscle action, testing conditions and the velocity and/or the time duration of the action, especially in the elderly.

Keywords ageing, agonist–antagonist activation, force–time curve, force–velocity, muscle power, muscle strength.

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Ageing is known to be associated with decreased maximal strength and explosive force production, especially at the onset of the sixth decade (Vandervoort & McComas 1986, Narici *et al.* 1991, Häkkinen *et al.*

1995, 1996, 1998). In healthy men ranging 65–89 years, age-related decreases in quadriceps and handgrip maximal strength may take place to about 1.5% per year, although age-related decrease in maximal eccentric

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strength is known to be smaller than that recorded for concentric or isometric strength actions (Poulin *et al.* 1992, Porter *et al.* 1995). The corresponding age-related changes in power of the lower limb extensors may be as great as 3.5% per year (Skelton *et al.* 1994, Young 1997). It has been suggested that age-related changes in muscular performance may vary among the upper and lower extremity muscles in relation to differences in age-related declines in the quantity and/or intensity of daily physical activities throughout the life span (Enoka *et al.* 1992, Häkkinen 1994, Mälkiä *et al.* 1994, Kamen *et al.* 1995, Winegard *et al.* 1996). Age-related decreases in strength and power are associated with declines in muscle mass thought to be mediated by a reduction in the size and/or a loss of individual muscle fibres, especially of fast twitch fibres (Lexell *et al.* 1983, 1988). Moreover, maximal voluntary activation of the agonist muscles and/or changes in the degree of agonist/antagonist co-activation (Häkkinen *et al.* 1998) may also differ in relation to age depending on the type of muscle action, the complexity of the motion and the time or velocity characteristics of the action.

It is well known that in the classical concentric force–velocity curve the amount of muscle tension decreases with the increase in velocity reaching the maximal tension near the isometric, i.e. zero velocity condition. Under these circumstances maximum power output has been defined to occur approximately at 30% of the maximal isometric force and/or between 30 and 45% of the one repetition maximum (1RM) (Kaneko *et al.* 1983, Duchateau & Hainaut 1984, Faulkner *et al.* 1986, Mastropaolo 1992, Moritani 1993, Newton *et al.* 1996, 1997, Mayhew *et al.* 1997, Toji *et al.* 1997, Moss *et al.* 1997). Natural dynamic human locomotion is characterized by stretch–shortening cycle (SSC) actions, in which an eccentric muscle action precedes a concentric muscle action. It is well known that the force outcome in the maximal SSC actions is greater than force produced during a concentric muscle action alone (Asmussen & Bonde-Petersen 1974, Komi & Bosco 1978, Bosco & Komi 1982, Komi 1984). This is true also in ageing subjects, although some studies have reported that mechanical performance enhancement after prestretching is somewhat diminished with ageing (Bosco & Komi 1980), while some others have shown no age-related differences in performance enhancement with SSC (Svantesson & Grimby 1995).

Although previous studies have examined the relationship between maximal power output and load in isolated bundle of muscles fibres (Hill 1938) or in explosive movements involving upper or lower body muscle groups such as vertical jumping (Bosco & Komi 1980) or bench-press throws (Newton *et al.* 1997), there is a paucity of research on examining to what extent maximal strength and power characteristics may vary

between the upper and lower extremity muscles with increasing age. It is likely that the load–velocity and load–power relationship may vary among the different muscles groups in relation to its fibre type distribution, different use in daily physical activities and/or biomechanical characteristics of the open and close upper/lower kinetic chains. Therefore, it should be within scientific and practical interests to examine to what extent the increases of load may influence the power output in the upper and lower extremity muscles and whether it may vary to some extent between different age groups.

The purpose of the study was to examine differences in: (1) maximal strength, (2) the shapes of isometric force–time curves and (3) power–load curves during concentric and stretch–shortening cycle actions of the lower and upper extremities between middle-aged and older men.

METHODS

Subjects

Fifty-six male subjects volunteered for the study. Prior to participation in the study all potential candidates underwent physical examination. Nine of them who were found to have cardiovascular risks and/or neuromuscular disorders were excluded as subjects. From the screening we obtained a sample of 47 male subjects. They were divided into two different groups according to age: 26 middle-aged men in the 40-year-old age group (M40) (mean age 42, range 35–46) and 21 elderly men in the 65-year-old age group (M65) (mean age 65, range 60–74). The physical characteristics of the subject groups are presented in Table 1. All subjects were healthy and habitually physically active. Minnesota Leisure Time Physical Activity Questionnaires (LTPA) were used to quantify a 4-week physical activity energy cost in both age groups (Reiff *et al.* 1967, Ainsworth *et al.* 1993). Most of them performed recreational physical activities such as walking, biking, cross-country hiking and to a lesser extent swimming and soccer. However, none of the subjects had any background in regular strength training or competitive sports of any kind. None had been involved in any structured physical fitness program within the last 3 months. In the elderly group all lived at home and were able to perform activities of daily life independently. No medication was being taken by the subjects which would have been expected to affect physical performance. Each subject signed a written informed consent form prior to participation in the study.

Testing procedures

The subjects were carefully familiarized with the testing procedure of voluntary force production of the upper

Table 1 Physical characteristics of middle-aged (40 years, M40) and elderly (65 years, M65) men

Variable	M40 (<i>n</i> = 26)	M65 (<i>n</i> = 21)	Significance of differences
Age (years)			
Mean	42	65	
SD	2.9	4.1	
Body height (cm)			
Mean	173.7	165.3	M40/M65**
SD	6.3	4.6	
Body mass (kg)			
Mean	84	78	M40/M65**
SD	9.6	9.3	
Body fat (%)			
Mean	22.6	22.7	
SD	3.9	4.3	
Energy cost (MET-min d ⁻¹)			
Mean	1392	893	M40/M65*
SD	920	404	

P* < 0.05; *P* < 0.01.

and lower extremity muscles during several submaximal and maximal actions a few days before the measurements. In addition, also several warm-up contractions were recorded prior to the actual maximal test actions. Testing was conducted over two sessions separated by 5 days.

During the first testing occasion each subject was tested for his one concentric repetition maximum (1RM) from a half-squat position (1RM_{HS}). The shoulders were in contact with a bar positioned so that the knee starting angle was 90°. On command the subject performed a concentric leg extension (as fast as possible) starting from a flexed position of 90° to reach the full extension of 180° against the resistance determined by the weight plates added to both ends of the bar. The trunk was kept as straight as possible and no bouncing was allowed at the bottom position of the half-squat. A security belt was used by all subjects. All the tests were performed in a squatting apparatus in which the barbell was attached to both ends with linear bearings on two vertical bars allowing only vertical movements. Four to five separate attempts were performed until the subject was unable to extend the legs to the required position. The last acceptable extension with the highest possible load was determined as 1RM.

The load–velocity and load–power relationship of the leg extensor muscles were also tested concentrically in a half-squat position using the loads of 0 (no additional weight on the shoulders), 15, 30, 45, 60, and 70% of 1RM. In this case the subjects were instructed to move the load as fast as possible. Two testing actions

were recorded and the best reading (with the best velocity) was taken for further analyses.

Dynamic explosive force was measured by asking the subject to perform a maximal vertical squat jump (on the contact platform) (SJ; from a starting position of a knee flexion of 90°), and a counter-movement jump (CMJ; with a preparatory movement from the extended leg position down to the 90° knee flexion followed by a subsequent concentric action) with no load (SJ₀ and CMJ₀) and with the 30% load of 1RM (SJ_{30%} and CMJ_{30%}). These tests have been utilized with good success for examination of explosive force production in elderly men and women by Bosco & Komi (1980) and Häkkinen *et al.* (1997, 1998). In SJ and CMJ the height was calculated from the flight time. Three maximal jumps were recorded in both cases and the best reading was used for further analysis.

Maximal isometric strength of the forearm muscles (handgrip test; MIF_{HAN}) was measured from the right hand. The subject was sitting on a chair in an erect position with the 90° hip, knee and elbow flexion position. A hand dynamometer (Newtest OY, Finland) was fixed on the right arm of the chair and adjusted at the most comfortable distance as decided by the subject. Three maximal attempts were recorded and the maximum reading was used for further analysis.

In the second test session each subject was tested for his maximal bilateral concentric 1RM bench-press (1RM_{BP}). In the 1RM concentric performance the bar was positioned 1 cm above the subject's chest supported by the bottom stops of the measurement device. The subject was instructed to perform from the starting position a purely concentric action maintaining the shoulders in a 90° abducted position to ensure consistency of the shoulder and elbow joints throughout the testing movement (Newton *et al.* 1997). Three to four trials were performed until the subject was unable to reach the full extension position of the arms. The last acceptable extension with the highest possible load was determined as 1RM.

The velocity and power during the concentric actions were recorded with the loads of 0 (no load), 30, 45, 60 and 70% of the maximal 1RM. In this case the subjects were instructed to perform each test action as fast as possible. Additionally, an SSC action was performed without extra load (with a stick; SSC_{0%}). The subject was instructed to lower the stick at a self-selected velocity during the eccentric phase without contacting the chest and immediately to perform a purely concentric action as fast as possible. Two testing actions were recorded and the best reading (with the best velocity) was taken for the subsequent statistical analysis.

Dynamic concentric and SSC throwing actions were also measured by asking the subject to perform a

maximal concentric (CT_{30%}) and SSC (SSCT_{30%}) throwing action with the 30% load of 1RM upwards for as high as possible. In the concentric action the starting position was similar to that described in the paragraphs above. In this SSC occasion the subject was instructed to lower the bar at a self-selected velocity without bouncing on the chest and immediately thereafter throw it upwards for maximum height. The subject was not allowed to raise the shoulders off the bench and stop between the eccentric and concentric phases of the SSC throws.

A David Rehab 2200 dynamometer (David Fitness and Medical Ltd., Vantaa, Finland) was used to measure maximal isometric torque (MIF; N m) and rate of force development (RDF; N m s⁻¹) of the knee extensor (KE) and flexor muscles (KFLE). The subject was in a seated position so that the hip and knee angles were 110° and 90°, respectively. On verbal command the subject performed a maximum isometric knee extension or flexion for the right leg. A minimum of three maximal actions were recorded for the extension and flexion action, and the best maximum was taken for further analysis. Maximal unilateral concentric 1RM was also assessed with the David 2200. In this test the subject performed a concentric knee extension from a flexed position of 70° to reach a required extension of a minimum 170° (full extension 180°) against the resistance determined by the loads chosen on the weight stacks. In testing the maximal load, separate 1RM (repetition maximum) contractions were performed. After each repetition, the load was increased until the subject was unable to extend the leg to the required position. The last acceptable extension with the highest possible load was determined as 1RM.

Electromyographic (EMG) activity during the unilateral isometric and dynamic right knee extension and flexion was recorded from the agonist muscles of the vastus lateralis (VL) and vastus medialis (VM) and from the antagonist muscle of biceps femoris (BF; long head). Bipolar surface EMG recording (diameter 10 mm, Dormo-Stress, Barcelona, Spain) was employed. The EMG signals were amplified (Mega electronics, Kuopio, Finland) by a multiplication factor of 500 using high and low cut-off frequencies of 25 and 500 Hz. The preamplifiers were situated on the head of the cable and fixed directly on the skin with the ground electrode. The EMG was full-wave rectified, integrated (iEMG in $\mu\text{V s}^{-1}$) and time normalized for 1 s in the maximal peak force phase (1000–1500 ms) to calculate maximal iEMG (Häkkinen *et al.* 1986) in the isometric and 1RM dynamic actions.

In all tests of neuromuscular performance, strong verbal encouragement was given for each subject to motivate them to perform each test as fast and as

maximally as possible. The time period of rest in all tests conditions was always 1.5 min.

During the upper and lower extremity test actions bar displacement, maximal average velocity (m s⁻¹) and power (W) were recorded by linking a shuttle to the end part of the bar locked to an infrared sensor. The accuracy of the electronic device reached the 10- μs time resolution with an optical transducer interruption each of 3 mm displacement (Bosco *et al.* 1995). The velocity (V ; m s⁻¹) was calculated at each instantaneous displacement (Δd) of 3 mm by using the following equation.

$$V = \Delta d \cdot \Delta t^{-1} \quad [1]$$

where Δt is the time (s) to perform the instantaneous range of displacement (3 mm) with a resolution of 10 μs . The calculation of instantaneous power was then calculated by multiplying the velocity over each displacement period by force derived from the product of mass of the load and acceleration owing to gravity (Bosco *et al.* 1995). Average velocity and power were calculated through all the ranges of motion utilized to perform a complete repetition. Power curves are plotted using average power over the whole range of movement as a most representative mechanical parameter associated to a contraction cycle of each muscle group.

The cross-sectional area (CSA) of the quadriceps femoris (QF) muscle group (rectus femoris, vastus lateralis, vastus medialis and vastus intermedialis; CSA_{QF}) was measured with a compound ultrasonic scanner (Toshiba SSA-250) and a 5 MHz convex transducer. The CSA was measured at the lower third portion between the greater trochanter and lateral joint line of the knee. Two consecutive measurements were taken from the right thigh and then averaged for further analyses. The CSA was then calculated from the image by the computerised system of the apparatus. The percentage of fat in the body was estimated for the measurements of skinfold thickness (Jackson & Pollock 1977, Jackson *et al.* 1978).

Statistical methods

Standard statistical methods were used for the calculation of the means and standard deviations (SD), standard errors (SE) and Pearson product moment correlation coefficient. The results for the average power and velocity were compared using probability adjusted *t*-test. The velocity and power at each load were compared using a one-way analysis of variance (ANOVA), using Scheffe post hoc comparison to determine differences within loads. The $P < 0.05$ criterion was used for establishing statistical significance.

RESULTS

The maximal bilateral concentric 1RM_{HS} and 1RM_{BP} (mean ± SD) of 117.5 ± 3.9 and 59.5 ± 2 kg in M40 were greater ($P < 0.001$ – 0.01) than those of 101 ± 5 and 47 ± 2.4 kg recorded for M65 (Fig. 1a). The maximal unilateral concentric 1RM_{KE} of 75 ± 10 kg was greater ($P < 0.001$) than that of 55 ± 10 kg recorded for M65. The maximal unilateral isometric force (right leg) of the knee extensor and flexor muscles differed also between the groups so that the values in M40 were greater ($P < 0.01$) than in M65 (Fig. 1b). Maximal isometric force of the forearm muscles (handgrip test) of 534 ± 56 N in M40 were greater ($P < 0.001$) than that of 445 ± 70 N recorded for M65.

The mean (±SD) value of 48.2 ± 1.3 cm² for the CSA of the QF in M40 was greater ($P < 0.01$) than that of 42.1 ± 2.2 cm² in M65. (Fig. 2). The maximal 1RM_{KE} and MIF_{KE} values per CSA of 1.57 ± 0.2 kg cm⁻² and 4.54 ± 0.7 Nm cm⁻² in M40 were greater ($P < 0.05$ – 0.01) than those of 1.35 ± 0.2 kg cm⁻² and 4.02 ± 0.7 Nm cm⁻² recorded in M65, respectively.

The individual values of the CSA_{QF} correlated with the individual values of the maximal concentric 1RM_{HS} and 1RM_{KE} and isometric MIF_{KE} in M65 ($r = 0.60$,

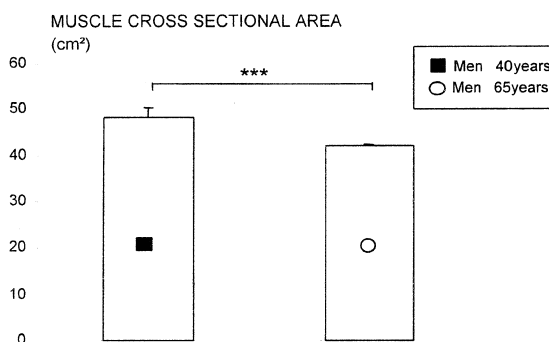


Figure 2 Mean (±SE) cross-sectional area of the quadriceps femoris muscle for the right leg in middle-aged (40 years) and elderly (65 years) men (** $P < 0.001$).

$r = 0.65$ and $r = 0.59$; $P < 0.01$), while the corresponding correlation coefficient was lower in M40 ($r = 0.32$, $r = 0.27$ and $r = 0.09$; n.s.). These individual values for the 1RM actions in both groups are plotted together (M40 + M65; $r = 0.54$ and $r = 0.57$; $P < 0.01$) in Fig. 3. No significant correlations were found between the CSA and various dynamic explosive actions of the lower extremities in the younger group (Table 2). When these relationships were examined for

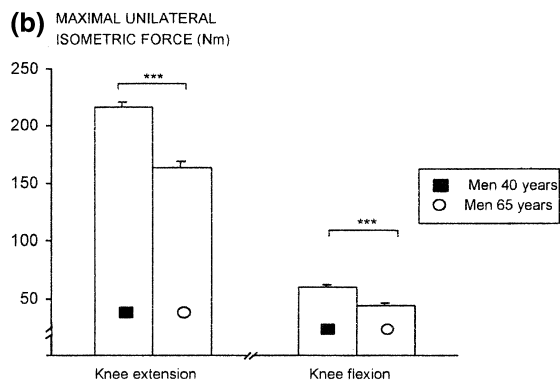
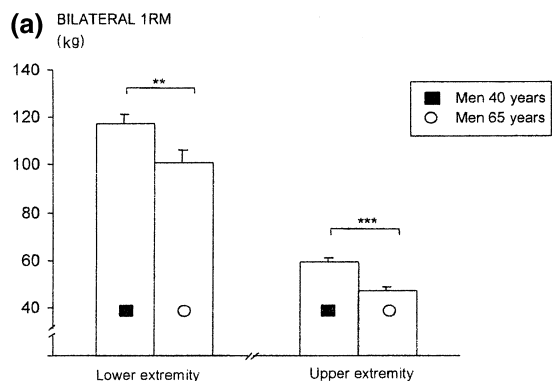


Figure 1 Mean (±SE) Maximal bilateral concentric 1RM half-squat and bench-press and maximal unilateral isometric knee extension and flexion force in middle-aged (40 years) and elderly (65 years) men (** $P < 0.01$).

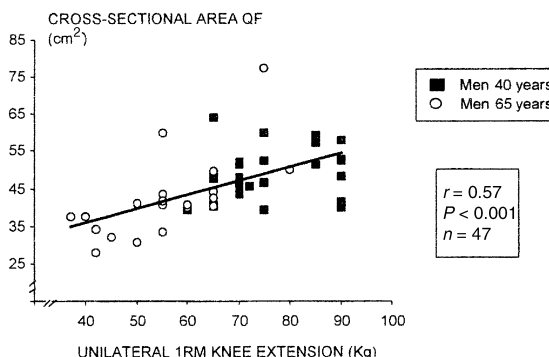
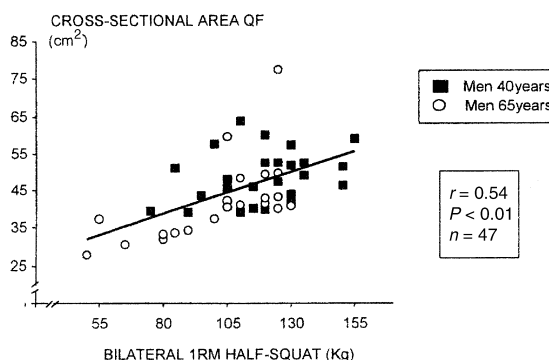


Figure 3 The relationship between the cross-sectional area of the quadriceps femoris muscle (right leg) and maximal bilateral concentric 1RM half-squat and maximal unilateral 1RM knee extension (right leg) in a total group of middle-aged (40 years) and elderly (65 years) men.

Table 2 Correlation coefficients between various indices of explosive and maximal concentric force production and muscle mass of the upper and lower extremity muscles in M40, M65 and for a combined group of M40 + M65

	SJ _{0%}	CMJ _{0%}	SJ _{30%}	CMJ _{30%}	V _{low60%}	V _{low70%}	RFD _{KE}	1RM _{HS}	1RM _{KE}	MIF _{KE}
M40										
1RM _{HS}	0.4*	0.54**	0.17	0.18	0.04	0.07	0.13	–	–	–
1RM _{KE}	0.2	0.39*	0.14	0.20	0.32	0.27	0.26	0.37	–	–
MIF _{KE}	0.23	0.26	0.14	0.10	0.46*	0.2	0.52**	0.38	0.71**	–
CSA _{QF}	–0.13	0.06	–0.09	–0.17	–0.32	–0.06	–0.12	0.32	0.27	0.09
M65										
1RM _{HS}	0.54**	0.59**	0.43*	0.55**	0.42*	0.35	0.34	–	–	–
1RM _{KE}	0.55**	0.58**	0.74**	0.74**	0.74**	0.55**	0.55**	0.63**	–	–
MIF _{KE}	0.06	0.03	0.12	0.36	0.42	0.36	0.47*	0.54**	0.66**	–
CSA _{QF}	0.43*	0.39	0.34	0.54**	0.5*	0.41*	0.58**	0.60**	0.65**	0.59**
M40 + M65										
1RM _{HS}	0.57**	0.63**	0.42**	0.46**	0.36**	0.24	0.31*	–	–	–
1RM _{KE}	0.65**	0.72**	0.58**	0.65**	0.65**	0.57**	0.58**	0.59**	–	–
MIF _{KE}	0.47**	0.50**	0.41**	0.47**	0.56**	0.42**	0.58**	0.52**	0.81**	–
CSA _{QF}	0.39**	0.40**	0.31*	0.35*	0.32*	0.27	0.29*	0.55**	0.57**	0.42**

* $P < 0.05$; ** $P < 0.01$.

	C _{0%}	SSCT _{0%}	CT _{30%}	SSCT _{30%}	V _{upp30%}	V _{upp40%}
M40						
1RM _{BP}	0.17	0.33	0.07	0.12	0.14	0.15
M65						
1RM _{BP}	0.43*	0.24	–0.2	0.004	0.50*	0.23
M40 + M65						
1RM _{BP}	0.4**	0.41**	–0.12	–0.07	0.47**	0.32*

* $P < 0.05$; ** $P < 0.01$.

SJ_{0%}: squat jump with 0% load; CMJ_{0%}: counter-movement jump with 0% load; SJ_{30%}: squat jump with 30% load; CMJ_{30%}: counter-movement jump with 30% load; V_{low60%}: average concentric velocity lower extremity at 60% load; V_{low70%}: average concentric velocity lower extremity at 70% load; 1RM_{HS}: one concentric repetition maximum from a half-squat position; 1RM_{KE}: one concentric repetition maximum of the knee extensor muscles; MIF_{KE}: maximal isometric torque of the knee extensor muscles; CSA_{QF}: cross-sectional area of the quadriceps femoris muscle group; C_{0%}: average concentric velocity upper extremity at 0% load; SSCT_{0%}: average stretch–shortening cycle velocity upper extremity at 0% load; CT_{30%}: dynamic concentric throwing height upper extremity with 30% load; SSCT_{30%}: dynamic stretch–shortening cycle throwing height upper extremity with 30% load; V_{upp30%}: average concentric velocity upper extremity at 30% load; and V_{upp40%}: average concentric velocity upper extremity at 40% load.

the older group, the CSA_{QF} correlated significantly ($P < 0.05$ – 0.01) with the explosive concentric (SJ₀ with CSA_{QF}, CMJ_{30%} with CSA_{QF} and V_{low60} with CSA_{QF} in M65; $r = 0.43$, $r = 0.54$ and $r = 0.50$, respectively) and explosive isometric (RFD_{KE} with CSA_{QF} in M65; $r = 0.58$) performances of the lower extremity.

The jumping height in the SJ and CMJ differed between the groups such that both values were 27.1 and 29.1% greater ($P < 0.001$) in M40 than in M65 (Fig. 4). The values in the SJ_{30%} and CMJ_{30%} also were 26.7 and 28.3% greater ($P < 0.001$ – 0.01) in M40 than in M65. The distance of throwing in the CT_{30%} and SSCT_{30%} in the bench-press action differed between the groups such that both values were greater ($P < 0.01$) in M40 (18.3 ± 1 and 16.7 ± 1 cm) than those recorded for M65 (13.2 ± 1 and 11.6 ± 1 cm).

The shapes of the average bilateral concentric half-squat and bench-press velocity–time and power–time curves in absolute values differed also between the groups. Average concentric velocity decreased with increasing loads in both groups, but the velocities at the same relative loads were in M40 higher than in M65 in both lower ($P < 0.01$ at 30, 45, 60 and 100% loads) and upper extremity actions ($P < 0.05$ at 0 and 30% loads). Maximal power output of the lower extremities was produced at the loads of 60% (486 ± 20 W) and 70% (391 ± 28 W) for M40 and M65, respectively (Fig. 5). In the upper extremity performances the highest average power output was reached at the loads of 30% (237 ± 11 W) and 45% (293 ± 11 W) for M65 and M40, respectively (Fig. 5). The shape of the average unilateral isometric force–time curve of the knee extensor and flexor muscles differed also between the

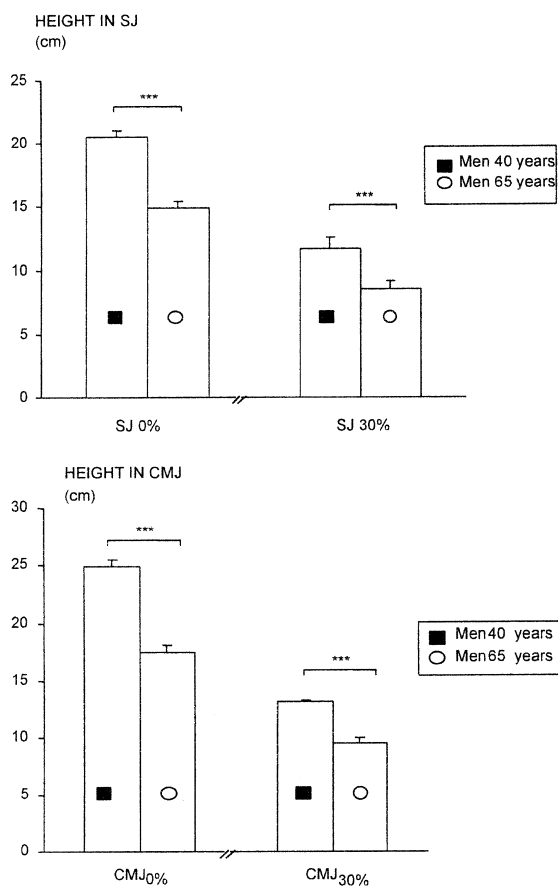


Figure 4 Mean (\pm SE) dynamic explosive force of height in squat jump (SJ) and counter-movement jump (CMJ) with 0% and 30% load of 1RM in middle-aged (40 years) and elderly (65 years) men (*** $P < 0.001$).

groups. Maximal RFDs of 801 ± 321 and 280 ± 84 in M40 were greater ($P < 0.01$ – 0.001) than those of 601 ± 235 and 209 ± 51 recorded for the knee extension and flexion actions in M65, respectively.

In the older group maximal strength of the upper and lower extremity correlated significantly ($P < 0.05$ – 0.01) with various explosive concentric and SSC values (Table 2). Also in the older group explosive concentric and SSC jumping performances correlated significantly (from $r = 0.47$ to 0.66 ; $P < 0.05$ – 0.01) with the average concentric velocity at the loads of 60 and 70% (Table 3). In the upper extremity the respective correlation (between the explosive concentric and SSC throwing performances and the average concentric velocity) in the elderly group were somewhat lower (from n.s. to $P < 0.05$), but in the younger group the respective correlation coefficients reached the statistical significant levels (from $r = 0.39$ to 0.52 ; $P < 0.05$ – 0.01) (Table 3).

The antagonist muscle activation during the isometric and dynamic knee extension actions were greater ($P < 0.01$ – 0.001) in M65 than in M40 (Fig. 6).

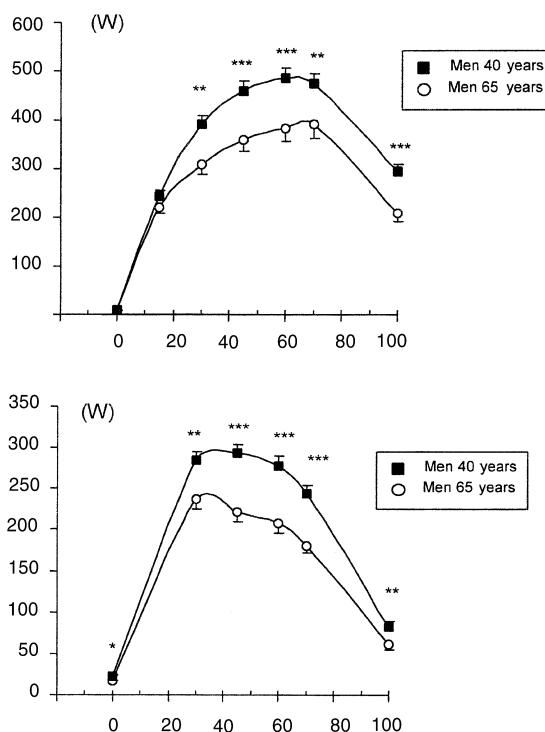


Figure 5 Average power–load curve in the concentric half-squat and bench-press actions in middle-aged (40 years) and elderly (65 years) men (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$).

DISCUSSION

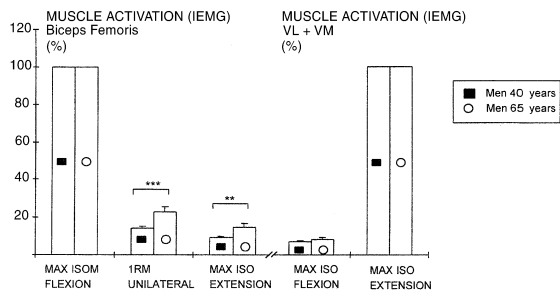
The differences between M65 and M40 observed in both maximal strength and muscle CSA of the leg extensors were well in agreement with previous studies that have shown almost parallel declines in muscle mass and strength with increasing age (Larsson 1978, Heikkinen *et al.* 1984, Young *et al.* 1984, Rice *et al.* 1989, Frontera *et al.* 1991, Häkkinen & Häkkinen 1991, Narici *et al.* 1991, Doherty *et al.* 1993, Häkkinen & Pakarinen 1993, Häkkinen *et al.* 1995, 1996, 1998). An age-related difference of 13% in muscle mass in the lower extremity was almost the same as the difference of 14% recorded for maximal concentric 1RM_{HS} strength, while the differences in the maximal unilateral concentric (1RM_{KE}) and isometric (MIF_{KE-KFLE}) knee extension and flexion ranged 24–26% between M40 and M65, respectively. The individual values of CSA of the QF correlated significantly with the individual values of maximal unilateral and bilateral strength and to some extent with those of explosive and power production in the elderly. Accordingly, in the upper extremity muscles the maximal bilateral concentric 1RM_{BP} and maximal isometric handgrip force (MIF_{HAN}) in M65 were 21 and 17% lower than in M40, respectively.

The age-related decrease in maximal strength has been attributed to a loss of muscle mass mediated by

Table 3 Correlation coefficients between various indices of explosive concentric and stretch–shortening cycle actions of the upper and lower extremity muscles in M40, M65 and for a combined group of M40 + M65. For definitions see Table 2

	M40					M65					M40 + M65				
	$V_{low60\%}$	$V_{low70\%}$	SJ _{0%}	SCMJ _{0%}	SJ _{30%}	$V_{low60\%}$	$V_{low70\%}$	SJ _{0%}	SCMJ _{0%}	SJ _{30%}	$V_{low60\%}$	$V_{low70\%}$	SJ _{0%}	SCMJ _{0%}	SJ _{30%}
SJ _{0%}	0.42*	0.23	–	–	–	0.47*	0.55**	–	–	–	0.57**	0.44**	–	–	–
CMJ _{0%}	0.37	0.27	0.87**	–	–	0.54**	0.47*	0.93**	–	–	0.59**	0.40**	0.94**	–	–
SJ _{30%}	0.33	0.26	0.41*	0.61**	–	0.50*	0.66**	0.82**	0.76**	–	0.53**	0.49**	0.75**	0.78**	–
CMJ _{30%}	0.27	0.11	0.51**	0.65**	0.83**	0.54**	0.62**	0.81**	0.75**	0.82	0.51	0.37**	0.76**	0.79**	0.87**
RFD _{KE}	0.26	0.15	0.28	0.26	0.48**	0.32	0.23	0.28	0.25	0.13	0.38**	0.27	0.41**	0.40**	0.42**

	M40					M65					M40 + M65				
	$V_{upp30\%}$	$V_{upp45\%}$	$C_{0\%}$	SSC _{0%}	CT _{30%}	$V_{upp30\%}$	$V_{upp45\%}$	$C_{0\%}$	SSC _{0%}	CT _{30%}	$V_{upp30\%}$	$V_{upp45\%}$	$C_{0\%}$	SSC _{0%}	CT _{30%}
$C_{0\%}$	0.39*	0.24	–	–	–	0.07	0.43*	–	–	–	0.37**	0.35*	–	–	–
SSC _{0%}	0.39*	0.17	0.67**	–	–	–0.09	0.05	0.46*	–	–	0.34**	0.17	0.66**	–	–
CT _{30%}	0.5*	0.52**	0.08	0.11	–	0.36	0.56*	–0.1	0.17	–	0.52**	0.51**	0.12	0.23	–
SSCT _{30%}	0.39*	0.51**	0.27	0.12	0.82**	0.46*	0.25	0.22	0.20	0.71**	0.48**	0.45**	0.32*	0.24	0.74**

* $P < 0.05$; ** $P < 0.01$.**Figure 6** Mean (\pm SE) integrated electromyographic activity (IEMG in relative [%] values) for the (1) biceps femoris (right leg) during the maximal isometric knee flexion maximal concentric 1RM knee extension and maximal voluntary isometric knee extension and for the (2) sum of vastus lateralis and vastus medialis (right leg) during the maximal isometric knee flexion in middle-age (40 years) and elderly (65 years) men (** $P < 0.01$; *** $P < 0.001$).

both a loss and a decrease in the size of individual muscle fibres (Larsson 1978, Aniansson *et al.* 1981, Lexell *et al.* 1983, 1988, Essen-Gustavsson & Borges 1986, Porter *et al.* 1995) associated perhaps in part with age-related alterations in hormone balance (e.g. Häkkinen & Pakarinen 1993). In accordance with previous studies M65 showed a 35% lower energy cost than M40 associated usually with age-related declines in the quantity and intensity of daily physical activity (e.g. Mälkiä *et al.* 1994). Furthermore, when the individual values of maximal strength were related to the individual values of CSA of the QF, the force (kg and $N m^{-1}$) per CSA in M65 was significantly lower than in M40. These findings in line with previous studies indicate that in addition to a decrease in muscle mass, a decline in maximal strength in ageing may be accompanied in part by a decrease in voluntary neural drive to muscles (Häkkinen *et al.* 1995, 1996, 1998) and/or with

qualitative characteristics of the muscle tissue itself (Häkkinen & Häkkinen 1991).

Some previous studies (Grimby & Saltin 1983, McDonagh *et al.* 1984, Viitasalo *et al.* 1985, Frontera *et al.* 1991, Lynch *et al.* 1999) have found that the loss of muscle strength appears to develop more rapidly in the lower than in the upper extremity muscles. Our data showed that the difference between the two age groups was somewhat greater in the 1RM squat lift action compared with the 1RM bench-press action. However, it should be noted that several of the previous studies have utilized 'unnatural' movements such as isokinetic and isometric testing actions and isolated specific muscles group such as knee, trunk and elbow extensor/flexors. The present data also showed that the difference in the unilateral knee extension strength (both isometric and concentric) between the two age groups was somewhat greater compared with the difference in maximal hand grip strength. The results may therefore be slightly different, when more complex movements such as concentric leg extensor (hip, knee and ankle extensor) and arm extensor (elbow and shoulder extensor) performances are utilized as shown also by the present data. It is likely as suggested in previous studies (Häkkinen *et al.* 1998, Izquierdo *et al.* 1999) that different tests designed to estimate the capacity for explosive/maximal strength muscle performances in isokinetic/concentric and/or isometric type of actions in the lower or upper extremity may indicate distinct qualities of muscle functions.

The present older men also showed a lowered ability of both upper and lower extremity muscles to develop maximal power output compared with the present middle-aged subjects. The difference in rapid isometric force production and power between the older and

younger group was similar or even slightly greater than the age-related differences observed in maximal strength of the same muscle groups. The differences in maximal dynamic concentric power was about the same for both upper and lower extremity performances: M65 showing lower power values than recorded for M40. The SJ and CMJ heights were 27–29% lower in M65 compared with those recorded for M40. In general, the present data are in line with previous findings, as the magnitude of age-related declines in explosive strength and power appears to be even greater than that of maximal strength whether determined using dynamic actions (Bosco & Komi 1980, Bassey *et al.* 1992) or as a slowing of the maximal rate of isometric force production (Clarkson *et al.* 1981, Vandervoort & McComas 1986, Häkkinen *et al.* 1995, 1996, 1998). The present findings support the suggestion that selective atrophy and/or a loss of FT fibres and a possible decrease in the capacity for rapid neural activation of the muscles may explain the great age-related decreases in explosive neuromuscular performances.

The magnitude of age-related decreases in strength and power may vary, for example, between the upper or lower extremity muscle groups in relation to the type, quantity and quality of daily physical activities involved in. In the present study maximal power output was maximized at the 30–45% loads for the upper extremity and at the 60–70% loads for the lower extremity extensor muscles in both age groups. In agreement with previous studies (Kaneko *et al.* 1983, Duchateau & Hainaut 1984, Faulkner *et al.* 1986, Mastropaolo 1992, Moritani 1993, Newton *et al.* 1996, 1997, Mayhew *et al.* 1997, Toji *et al.* 1997, Moss *et al.* 1997) maximum power of the arm extensor muscle was maximized at $\approx 30\%$ of maximum isometric force or maximum concentric strength ($1RM_{BP}$). However, the present data showed that during the performances involving the leg extensor muscles as $1RM_{HS}$ maximal mechanical power may be reached with the loads ranging 60–70% of the 1RM. A possible explanation for the differences observed in percentage of the maximal concentric 1RM in which maximal power output was maximized in lower (60–70%) in comparison with that of 30% that occur in the upper extremity muscles may be associated to the extremity-related differences in maximal strength, muscle cross-sectional area, fibre type distribution (Grimby *et al.* 1981), muscle mechanics (i.e. length and muscle pennation angle) of the upper and lower limbs together with functional differences according to the joint position (Gülch 1994) and type of physical activity involved in (e.g. weightlifting vs. jumping).

Age-related decrease in maximal eccentric strength is known to be smaller than that recorded for concentric or isometric strength actions (Poulin *et al.* 1992, Porter

et al. 1995). The preservation of higher efficiency in eccentric actions in the ageing population could be related in part to changes in mechanochemical, neuromuscular activation, contractile velocity and connective tissue factors that occur with advancing age (Poulin *et al.* 1992, Lexell 1993, Porter *et al.* 1995). In the high velocity SSC performance in which an eccentric muscle action precedes a concentric muscle action, the force outcome will be greater than in a pure concentric muscle action alone (Asmussen & Bonde-Petersen 1974, Komi & Bosco 1978, Bosco & Komi 1982). The present differences in dynamic concentric and SSC explosive jump actions support this suggestion, as the height in SJ, $SJ_{30\%}$ in both groups were 16 to 10% lower ($P < 0.001$) than in CMJ and $CMJ_{30\%}$, respectively. However, the SSC efficiency in the upper limb throws was lower, as the distance in $SSCT_{30\%}$ was 9 and 12% lower compared with $CT_{30\%}$ in M40 and M65, respectively. It is difficult to determine to what extent the latter observation could be explained by a lack of neuromuscular skill to perform the present upper limb SSC exercise in a proper manner and/or by functional and structural factors related to the utilization of elasticity (Bosco & Komi 1980, Komi 1984, Svantesson & Grimby 1995, Bobbert *et al.* 1996). Therefore, further research is needed to clarify the performance capacity of SSC actions in the upper extremity actions.

Age-related decreases in muscle strength and, especially the ability of the leg extensor muscles to develop force rapidly have important consequences with the successful performances of several tasks of daily life such as climbing stairs, walking or even the prevention of falls and/or trips (Danneskiold-Samsøe *et al.* 1984, Bassey *et al.* 1992, Young & Skelton 1994, Young 1997). In agreement with previous studies (Häkkinen *et al.* 1997, 1998, Izquierdo *et al.* 1999) the present data also suggest that in middle-aged men high maximal force may not be necessarily related with high explosive force production capacity, while in older men a low level of maximal strength seems to be associated also with a lower ability to develop force rapidly (Table 2). This seemed to be the case not only for the lower extremity action but to some extent also for the present upper extremity action. However, different tests designed to estimate explosive force production capacity in dynamic vs. isometric conditions may indicate distinct qualities of muscle functions (Murphy *et al.* 1994, Abernethy *et al.* 1995). Under these conditions differences in mechanical, neuromuscular activation, and movement pattern aspects may explain the findings of the unrelated tests scores (Baker *et al.* 1994, Wilson *et al.* 1995).

It was within our interest to examine also possible age- and type of muscle action related differences in the antagonist muscle activation during unilateral dynamic

and isometric knee extension and flexion actions. The determination of the antagonist activation around the knee joint during different types of actions is an important factor which contributes to knee joint stabilization and movement efficiency (Eloranta & Komi 1981, Baratta *et al.* 1988). The EMG data presented in Fig. 6 showed that the activation of the antagonist muscles (biceps femoris or vastus lateralis/vastus medialis) during the corresponding isometric and dynamic agonist actions (knee extension or knee flexion) ranged in both groups between 9 and 22% of the corresponding maximal activity. However, during the present unilateral dynamic action the co-activation was significantly higher than during the isometric actions. These results are in agreement with previous findings that have shown differences in hamstring co-activation levels depending on the muscle, type of muscle action and testing conditions, the velocity and/or the time duration of the action in both middle-aged and elderly men (Eloranta & Komi 1981, Baratta *et al.* 1988, Häkkinen *et al.* 1998). It must also be pointed out that in line with our previous results obtained during bilateral leg extension actions (Häkkinen *et al.* 1998) higher antagonist muscle activity was also recorded in the elderly group compared with the middle-aged group in the present unilateral actions (Fig. 6). High antagonist co-activation may limit the full potential of the agonist muscular function, especially in dynamic types of movements.

In summary, the present findings confirm well the general concept that parallel declines in muscle mass and maximal strength take place with increasing age. However, the lower force/CSA ratio of the leg extensors observed in the elderly group compared with that of the middle-aged group further suggests that ageing may also lead to a decrease in voluntary neural drive to the muscles. Age-related loss of muscle strength may vary in both lower and upper extremity muscles in relation to the type of action. Explosive strength and power output decreased with increasing age even more than maximal strength of the same muscle groups. However, power was maximized at the 30–45% loads for the upper extremity and at the 60–70% loads for the lower extremity extensor muscles in both age groups. High antagonist muscle activity may in part limit the full movement efficiency depending on the type of muscle action, testing conditions and the velocity and/or the time duration of the action, especially in the elderly. This type of information may also be useful to create optimal strength and/or power training programs for people at different ages and/or different sports requirements.

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Abbreviations: one repetition maximum half-squat (1RM_{HS}), one repetition maximum bench-press (1RM_{BP}), biceps femoris (BF), counter-movement jump (CMJ), maximal concentric throwing action (CT), muscle cross-sectional area [CSA] of the quadriceps femoris muscle group [QF] (CSA_{QF}), electromyography (EMG), integrated electromyographic activity (IEMG), 40-year-old age group (M40), 65-year-old age group (M65), maximal isometric strength handgrip test [HAN] (MIF_{HAN}), maximal isometric torque knee extension [KE] (MIF_{KE}), maximal isometric torque knee flexion [KFLE] (MIF_{KFLE}), rate of force development (RFD), stretch–shortening cycle (SSC), squat-jump (SJ), stretch–shortening cycle throwing action (SSCT), vastus lateralis (VL), vastus medialis (VM).