Specific strength and voluntary muscle activation in young and elderly women and men

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Kent-Braun, Jane A., and Alexander V. Ng. Specific strength and voluntary muscle activation in young and elderly women and men. *J. Appl. Physiol.* 87(1): 22–29, 1999.—The extents to which decreased muscle size or activation are responsible for the decrease in strength commonly observed with aging remain unclear. Our purpose was to compare muscle isometric strength [maximum voluntary contraction (MVC)], cross-sectional area (CSA), specific strength (MVC/CSA), and voluntary activation in the ankle dorsiflexor muscles of 24 young (32 ± 1 yr) and 24 elderly (72 ± 1 yr) healthy men and women of similar physical activity level. Three measures of voluntary muscle activation were used: the central activation ratio [MVC/(MVC + superimposed force)], the maximal rate of voluntary isometric force development, and foot tap speed. Men had higher MVC and CSA than did women. Young men had higher MVC compared with elderly men [262 ± 19 (SE) vs. 197 ± 22 N, respectively], whereas MVC was similar in young and elderly women (136 ± 15 vs. 149 ± 16 N, respectively). CSA was greater in young compared with elderly subjects. There was no age-related impairment of specific strength, central activation ratio, or the rate of voluntary force development. Foot tap speed was reduced in elderly (34 ± 1 taps/10 s) compared with young subjects (47 ± 1 taps/10 s). These results suggest that isometric specific strength and the ability to fully and rapidly activate the dorsiflexor muscles during a single isometric contraction were unimpaired by aging. However, there was an age-related deficit in the ability to perform rapid repetitive dynamic contractions.

physical activity; magnetic resonance imaging; aging; gender; estrogen

IN GENERAL, human skeletal muscle function decays with age. Primary among the changes is a loss of muscle strength, which has largely been attributed to a loss of muscle mass (4). However, it has been suggested that the loss of muscle strength in aging may exceed that of muscle mass, resulting in a decrease in specific tension (force per unit muscle) in the elderly. Although a number of investigators have reported decreased specific strength (maximum voluntary force per unit muscle) in aging (7, 26, 29), this has not been a universal finding (12, 13, 25). Some of the variability in these results may have to do with the methods used for estimating muscle size or with the range in health and activity status of the subjects (20).

Inadequate voluntary activation of muscle can result in a decrease in strength that is independent of the effect of muscle atrophy. Furthermore, habitual physical activity level can influence both strength and activation. Thus reductions in either activation or activity level could result in decreased specific strength. The extent to which reductions in muscle mass or size, changes in voluntary muscle activation, and differences in habitual physical activity level are responsible for the decrease in strength in the elderly remains unclear. The purpose of the present study was to determine whether there were differences in ankle muscle strength [maximum voluntary contraction (MVC)], fat-free muscle cross-sectional area (CSA), specific strength (MVC/CSA), and voluntary muscle activation in healthy young and elderly men and women of similar physical activity level.

METHODS

Subjects. Twelve men and 12 women aged 25–44 yr formed the young group, and 12 men and 12 women aged 65–83 yr formed the elderly group. All subjects were recruited from the community and were selected to be nonsmoking and healthy (e.g., no cardiovascular, metabolic, or immunologic disorders) on the basis of a standardized interview. Subjects were also selected to be relatively sedentary, defined here as no more than one to two regular exercise sessions per week (e.g., walking, hiking, tennis) for the previous 3 mo. By recruiting relatively sedentary subjects, we hoped to limit the influence of physical activity on our measures. Because the effects of estrogen replacement therapy (ERT) on muscle function in postmenopausal women are unclear, an effort was made to recruit a similar number of ERT and non-ERT women for the elderly group. Before participation in the study, signed informed consent was obtained from all subjects as approved by the Committee on Human Research at the University of California, San Francisco.

Physical activity measurements. After all the subjects were screened by interview for usual activity habits, their average daily physical activity was estimated by using both a 7-day-recall questionnaire (27) and a three-dimensional accelerometer (Tritrac R3D, Professional Products, Madison, WI). These methods have been reported in more detail previously (24). The 7-day-recall questionnaire is an interview-based questionnaire that estimates caloric expenditure by query regarding physical activity levels over the previous 7 days. The accelerometer is a battery-operated unit that measures acceleration along the *x*-, *y*-, and *z*-axes. The net vector magnitude of the three axes can be used as a representative measure of motion or activity. Subjects were instructed in the use of the accelerometer and wore it around the waist for 7 days. The monitor was then returned to the laboratory, and the data were downloaded to a computer. The vector magnitude data were averaged over the 7-day period and reported as average daily activity (arbitrary units/day). The 7-day-recall questionnaire was administered when the activity monitor was returned so that the measurement period was the same for both instru-

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ments. The same investigator administered the 7-day recall questionnaire to all subjects.

Muscle force measurements. Isometric dorsiflexion strength and electrically stimulated tetanic force (TF; 50 Hz, 1 s) were determined for all subjects. These methods have been described in detail previously (16). All testing took place with the subject seated and legs extended. The right leg was studied unless there was a contraindication to do so (e.g., obvious weakness with manual muscle testing, foot pain, arthritis, bunions). The maximum leg circumference (cm) of all subjects was measured with a tape measure and recorded. The leg was stabilized with a knee brace, and the ankle angle was fixed at 120° plantar flexion. Force was measured by a transducer mounted under the footplate. The transducer signal was amplified (TECA electromyograph TE-4, White Plains, NY) and coupled to an IBM 486 personal computer. Force data were collected by using Labview software (National Instruments, Austin, TX) and subsequently transferred to a spreadsheet for analysis. All force data were acquired at a sampling rate of 500 Hz. Three MVCs were obtained and measured as the peak force (N) obtained during a voluntary 3- to 5-s maximal dorsiflexion. One minute of rest separated each MVC measurement, and all subjects received verbal encouragement during this procedure. Specific strength was calculated as the MVC/CSA ratio (N/cm^2). Specific strength was also examined by plotting the relationship between MVC and CSA for both groups. To examine the intrinsic force-generating capacity of the muscle, a supramaximal stimulus (0.1 ms) was delivered to the relaxed muscle via surface electrodes at the peroneal nerve.

As described previously (16–19, 28) the stimulating electrode was placed over the nerve, ~1 cm distal to the fibular head. The recording electrodes were placed over the belly of the tibialis anterior, the reference electrode was secured on the medial malleolus, and the ground plate was placed on the calf. Supramaximality of stimulation was ensured by using an intensity 10–15% higher than that eliciting the peak amplitude of the compound muscle action potential (CMAP). To assess the excitability of the neuromuscular junction and muscle membrane, the CMAP data were acquired at 2,500 Hz and analyzed as peak-to-peak amplitude (mV). The average of three CMAPs (acquired with 1 min of rest between measurements) was recorded. The highest force value attained during the 50-Hz stimulus train was recorded as the TF, and specific tension was calculated as TF/CSA (N/cm^2). This measure of specific tension is considered an estimate, because only the tibialis anterior muscle (primary dorsiflexor) has a parallel fiber arrangement, and precise quantitation of specific tension requires knowledge of the angle of pennation for all muscles involved.

Magnetic resonance imaging (MRI) measurements. As performed previously (17), proton MRI was used to quantitate the fat-free CSA of the anterior compartment of the lower leg. After a scout image was obtained, 33 transverse slices were acquired in an interleaved fashion (slice thickness = 4 mm, echo time = 14 ms, repetition time = 510 ms, flip angle = 70°, field of view = 210 mm^2, 256 × 256 matrix). The slice in which anterior compartment CSA was largest was then analyzed for fat-free area. A software program written in Matlab (MathWorks, Natick, MA) was used to *1*) generate a signal-intensity histogram from a region of muscle and subcutaneous fat, *2*) set a signal-intensity threshold for noncontractile tissue on the basis of the histogram, and *3*) outline the muscles of the anterior compartment (illustrated in Fig. 1). The within-subject variability for the selection of the signal-intensity threshold was 5.0%. The signal from fat (i.e., noncontractile tissue) was subsequently subtracted from the

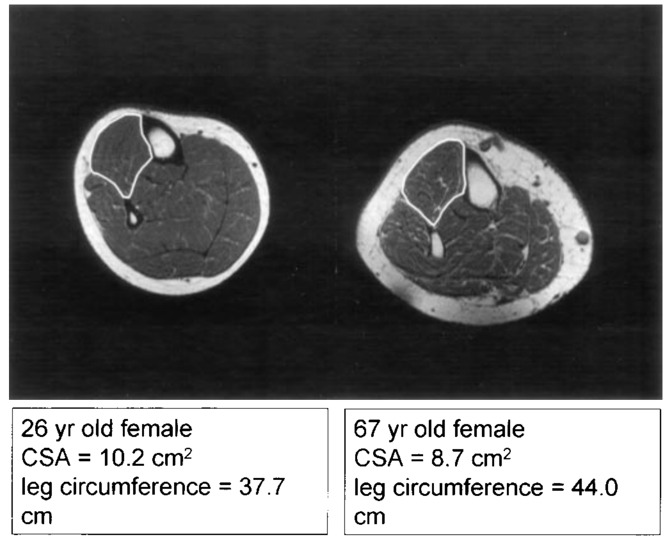

Fig. 1. Magnetic resonance images of lower leg of a young (*left*) and elderly (*right*) woman, with anterior compartment outlined. Muscle is dark, adipose tissue is light. Note greater subcutaneous and intramuscular fat content in elderly subject. CSA, cross-sectional area.

anterior compartment region of interest. Each image was analyzed three times, and average CSA (cm^2) was recorded. For the image analysis, the investigator was blinded as to the identity of the subject.

Measures of voluntary muscle activation. Three measures of voluntary muscle activation were used in this study. In total, these measures require rapid and complete motor unit recruitment and discharge-rate modulation and therefore provide information concerning central motor drive. The three measures were the central activation ratio (CAR), the maximum rate of voluntary force development, and foot tap speed (19). These procedures have been reported in more detail previously (16, 19). To quantitate the completeness of voluntary activation of the muscle, we determined the CAR for each subject. This involved superimposing a train of stimuli (50 Hz, 500 ms) during the third MVC performed by the subject (16). The CAR is defined as the proportion of total muscle force obtained that was due to voluntary force production, and it is calculated as follows: CAR = MVC/(MVC + superimposed force). In the case where there was no increase in force during the electrical stimulation, CAR = 1.0 and voluntary activation was considered complete. Because a superimposed twitch stimulus is often used to assess central activation (2), we also performed this measure during the second MVC. The superimposed train technique is one of the available methods used to test isometric activation of skeletal muscle (2, 9, 29). However, because a train of stimuli will indirectly assess both rate and recruitment, because TF more closely approximates the force-generating capacity of the muscle than does twitch force, and because we observe activation impairment more frequently by using the tetanic stimulus, we chose to use this technique as our primary measure of the completeness of muscle activation during an isometric MVC.

To quantitate the maximum rate of voluntary force development, the subjects were instructed to perform a single rapid isometric dorsiflexion to 40% MVC. This contraction requires the ability to rapidly mount high discharge rates and to modulate motor unit recruitment appropriately (8, 22). A 40% MVC contraction was used to assess activation during a submaximal contraction, which is relevant to activities of daily living and not likely to result in fatigue in this muscle. Subjects were told to perform the contraction as fast as possible. They received verbal feedback from the investigators, who monitored force on the computer screen. Several trials were typically necessary for the subjects to learn how to perform this procedure consistently. After learning was accomplished, four contractions were performed 1 min apart. The trial that was closest to 40% MVC was analyzed for the maximal rate of voluntary force development. To control for the slowing of contraction speed that occurs due to changes in fiber type composition with aging (7, 29), the voluntary rate data were normalized to each individual's maximum rate of force development measured during a separate 50-Hz tetanic contraction. In this way, any differences observed between the two groups could be inferred to arise from "central" slowing. The maximum rate of force development was also calculated for the MVC.

Rapid foot tapping requires rapid modulation of both motor unit recruitment and discharge rates (23). The speed of rapid tapping was measured as the number of taps performed in 10 s. Foot taps were performed while the subjects were seated in a chair with knees and hips at 90° of flexion. Subjects were instructed to maintain the heel on the floor and to tap the floor with the ball of the foot as quickly as possible for 10 s. The same investigator counted the foot taps for all subjects. This measure was made before the subject was loaded into the exercise apparatus.

Statistical analyses. The data were analyzed by using a two-factor ANOVA, with age and gender as factors. All significant age-by-gender interactions are reported. Linear regression analyses were performed to determine the relationships between muscle size (CSA) and both MVC and TF. Exploratory post hoc comparisons between elderly women taking estrogen and those not taking estrogen were performed by using unpaired *t*-tests. Statistical analyses were performed by using SYSTAT software (SYSTAT, Evanston, IL). For all analyses, differences were considered significant when $P < 0.05$. All data are presented as means ± SE.

RESULTS

Subjects. The age of the young group was 32 ± 1 yr (range 26–44 yr) and that of the elderly group was 72 ± 1 yr (range 65–83 yr). There was no significant difference between young and elderly groups in weight (80 ± 5 vs. 69 ± 3 kg, respectively). The men were taller than the women (176 ± 2 vs. 165 ± 2 cm, men vs. women, $P < 0.001$); this difference was consistent in both age groups, and there was no overall difference between young and elderly groups in height. In the elderly group, six of the women were on ERT and six were not. All of the older women were a minimum of 10 yr postmenopause.

Physical activity. Physical activity level was similar in both the young and elderly groups, whether measured by activity monitor (164,153 ± 14,471 vs. 137,757 ± 12,314 units/day, respectively; $P = 0.17$) or estimated by questionnaire (37 ± 1 vs. 36 ± 1 kcal·kg^{-1}·day^{-1}, respectively; $P = 0.37$). These analyses were based on activity monitor measurements obtained from 21 young and 21 elderly subjects. Reasons for data loss included loss of monitor ($n = 1$), monitor failure ($n = 3$), and subject noncompliance ($n = 2$). The 7-day-recall data were obtained from 22 young and all 24 elderly subjects

Strength, CSA, and specific strength. The individual isometric strength data are illustrated in Fig. 2. Women were weaker and had lower TF values than did men ($P < 0.001$). The young men were significantly stronger than the elderly men and women and the young women. There was no difference in MVC between the young and elderly women (Table 1). There was no age-related difference in TF ($P = 0.10$), although it appeared that the elderly women had lower TF than did the young women (Table 1). TF data were unavailable for seven elderly and two young subjects because of discomfort from the stimulation ($n = 2$), equipment failure ($n = 5$), lack of force plateau ($n = 1$), or submaximal stimulation ($n = 1$).

Figure 1 shows the magnetic resonance images from two female subjects, one young and one elderly. The anterior compartment, which contains the tibialis anterior muscle, has been outlined in each image. Note the apparently greater amount of both subcutaneous and intramuscular fat (light tone) in the elderly compared with the young woman. Although the elderly woman had a larger total leg circumference, when subcutaneous and intramuscular fat contents were accounted for, muscle CSA was smaller in this subject. Individual

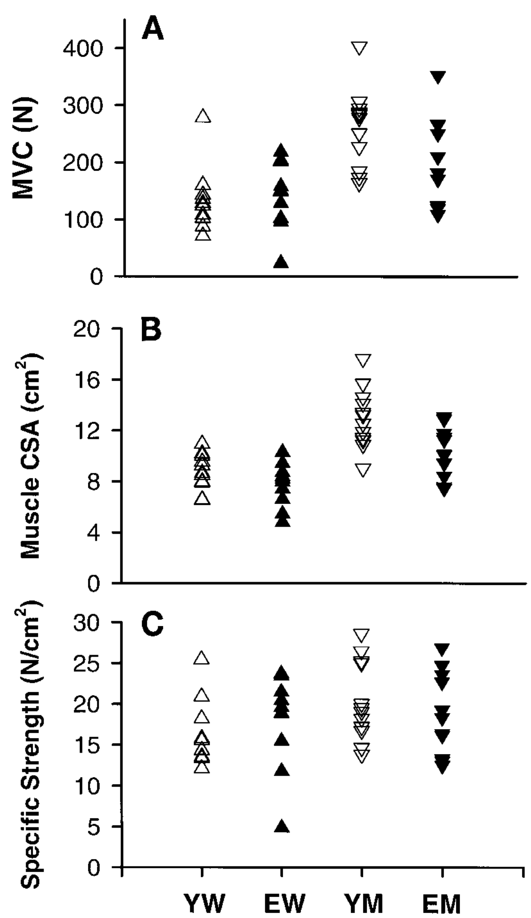

Fig. 2. Individual data for dorsiflexor muscle isometric strength [maximal voluntary contraction (MVC); *A*], fat-free muscle CSA (*B*), and specific strength (MVC/CSA; *C*) in young and elderly women (YW and EW, respectively) and men (YM and EM, respectively). There was no effect of age or gender on dorsiflexor muscle specific strength.

Table 1. *Dorsiflexor isometric force, CMAP, cross-sectional area, and specific strength*

	Young Women	Elderly Women	Young Men	Elderly Men
MVC, N	136 ± 15 (12)	149 ± 16 (12)	262 ± 19*‡ (12)	197 ± 22* (12)
TF, N	145 ± 18 (10)	91 ± 13 (9)	179 ± 15* (12)	169 ± 31* (8)
CMAP, mV	8.8 ± 0.5 (12)	8.3 ± 1.0 (12)	9.0 ± 0.4 (12)	8.2 ± 0.7 (12)
CSA, cm^2	8.7 ± 0.4† (11)	7.7 ± 0.5 (10)	13.0 ± 0.7*† (12)	10.3 ± 0.6* (12)
MVC/CSA, N/cm^2	16.1 ± 1.2 (11)	17.8 ± 1.8 (10)	20.4 ± 1.4 (12)	18.8 ± 1.4 (12)

Values are means ± SE for no. of subjects in parentheses. Ankle dorsiflexor muscle maximum voluntary contraction (MVC), tetanic force (TF), compound muscle action potential amplitude (CMAP), fat-free cross-sectional area (CSA), and specific strength (MVC/CSA) for young and elderly women and men are shown. *MVC, TF, and CSA were greater in men compared with women, $P < 0.05$. †CSA was greater in young compared with elderly subjects, $P < 0.05$. ‡Young men were stronger than the other 3 groups, $P < 0.05$. There were no main effects on CMAP or specific strength.

CSA data are shown in Fig. 2*B*. Fat-free CSA of the ankle dorsiflexor muscles was smaller in women than in men and in the elderly compared with young subjects (Table 1).

The relationship between MVC and CSA for both groups is illustrated in Figure 3. As expected, there was a significant linear relationship ($P < 0.001$) between these two variables for both the young ($r = 0.77$) and elderly groups ($r = 0.81$). Individual specific strength (MVC/CSA) data are shown in Fig. 2*C*, and group data are provided in Table 1. Overall, there were no age or gender effects on specific strength, although there was a tendency for the men to have a higher specific strength compared with the women ($P = 0.08$). Because, as a group, the young women in this study exhibited significant central activation failure (see *Measures of voluntary muscle activation*), the MVC, CSA, and specific strength data were also analyzed for only those subjects who had CAR = 1.0 (Table 2). Again, MVC and CSA were greater in men compared with women, and CSA was greater in young compared with elderly subjects. There was no difference in specific strength in this subset of subjects.

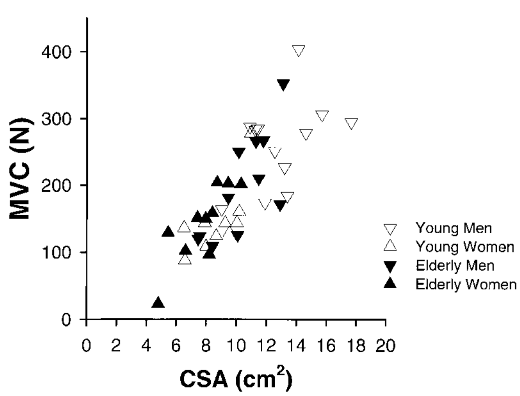

Fig. 3. Muscle strength (MVC) vs. fat-free CSA in young and elderly women and men. There was a significant linear relationship ($P < 0.001$) between MVC and CSA for both young ($n = 22$, $r = 0.77$) and elderly ($n = 22$, $r = 0.81$) groups.

Table 2. *Dorsiflexor strength, cross-sectional area, and specific strength in subjects with complete voluntary muscle activation*

	Young Women (5)	Elderly Women (8)	Young Men (11)	Elderly Men (11)
MVC, N	158 ± 31	146 ± 22	265 ± 21*	196 ± 24*
CSA, cm^2	9.0 ± 0.5†	7.9 ± 0.7	13.0 ± 0.7*†	10.2 ± 0.6*
MVC/CSA, N/cm^2	17.1 ± 2.3	17.8 ± 2.3	20.7 ± 1.5	18.9 ± 1.5

Values are means ± SE for subset of subjects (from Table 1) exhibiting control activation ratio = 1.0 and for whom CSA measurements were available; nos. of subjects are in parentheses. *MVC and CSA were greater in men compared with women; $P < 0.05$. †CSA was greater in young compared with elderly subjects, $P < 0.05$. There were no main effects on specific strength.

The relationship between TF and CSA (not shown) was also linear: young, $r = 0.51$, $P < 0.02$; and elderly, $r = 0.86$, $P < 0.001$. There were no age or gender effects on specific tension (TF/CSA: young men = 14.0 ± 1.1, young women = 16.6 ± 1.7, elderly men = 15.6 ± 2.1, elderly women = 11.8 ± 2.1 N/cm^2).

There were no differences in CMAP amplitude between any of the groups (Table 1). Furthermore, there was no relationship between CMAP amplitude and muscle CSA ($r = -0.02$).

Measures of voluntary muscle activation. Individual data for the three measures of voluntary activation are presented in Fig. 4. There was no difference in CAR between the young and elderly groups (0.96 ± 0.02 and 0.99 ± 0.01, respectively, $P = 0.18$). There was a trend toward a lower CAR in women compared with men ($P = 0.05$), which post hoc analysis revealed to be due to the lower CAR in young women (0.92 ± 0.03) compared with young men (1.00 ± 0.01). Overall, there were 10 cases of incomplete activation by using the superimposed train stimulus, and 0 cases by using a superimposed twitch stimulus. Of the 10 cases, 3 were elderly subjects and 7 were young.

Similarly, although the rates of TF development were slower in the elderly (0.42 ± 0.02%/ms) compared with young subjects (0.48 ± 0.02%/ms), there were no differences in the normalized rate of voluntary force development during the 40% MVC contraction (young = 1.76 ± 0.08; elderly = 1.95 ± 0.12; $P = 0.34$). Similarly, there was no difference between young and elderly in the normalized maximum rate of force developed during the MVC (data not shown). Peak force developed during the 40% MVC contraction was similar in both groups (young = 40.4 ± 0.5% MVC, elderly = 40.2 ± 1.1% MVC).

In contrast to the CAR and maximum rate of voluntary force development measures, there was a significant age effect on foot tap speed such that tapping was slower in the elderly (34 ± 1 taps/10 s) compared with the young (47 ± 1 taps/10 s; $P < 0.001$). There was no gender effect on this measure.

ERT. In the elderly group, six of the women had been taking ERT (7+ yr), and six had not taken ERT.

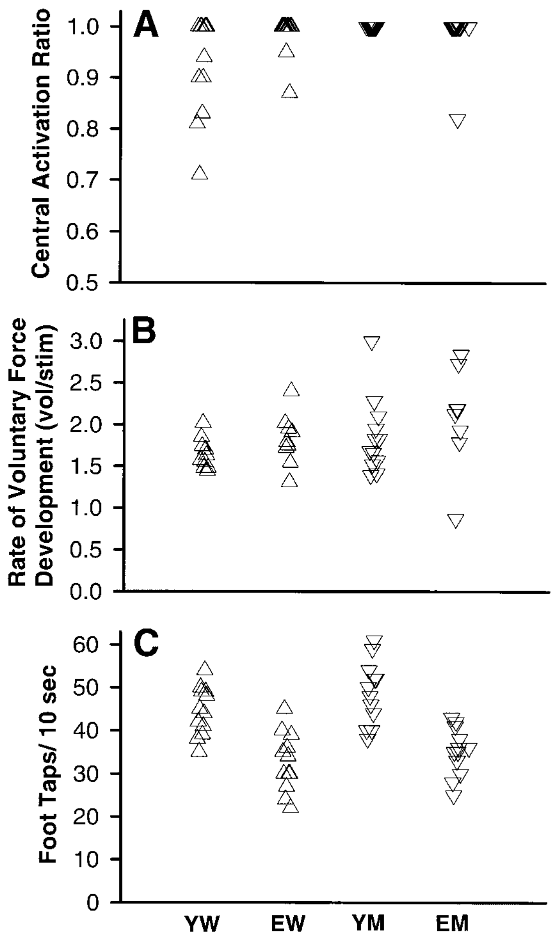

Fig. 4. Individual data for measures of voluntary muscle activation in YW, EW, YM, and EM. *A*: central activation ratio. *B*: maximal rate of voluntary force development. *C*: speed of rapid foot tapping. Only foot tap speed was significantly reduced in elderly compared with young subjects ($P < 0.001$). To enhance visibility in areas of overlap (e.g., central activation ratio = 1.0), all data points are open and have been distributed along *x*-axis. See text for other details.

Complete data were acquired on five women from each group. Exploratory analyses of the data indicated that ERT and non-ERT women had similar CAR (1.0 ± 0.0 and 0.96 ± 0.3, respectively) and no significant difference in MVC (ERT = 162 ± 20 N, non-ERT = 122 ± 30 N). The ERT group did have a larger muscle CSA (8.9 ± 0.4 cm^2) compared with the non-ERT group (6.6 ± 0.7 cm^2; $P = 0.02$), although there was no difference in specific strength (ERT = 18.1 + 1.7 N/cm^2, non-ERT = 17.6 + 3.5 N/cm^2). There was a tendency for ERT to have higher foot tap speed (ERT = 37 ± 4 taps/10 s, non-ERT = 29 ± 2 taps/10 s, $P = 0.09$).

DISCUSSION

The major findings of this study were that, in healthy young and elderly volunteers of similar physical activity level, *1*) dorsiflexor muscle specific strength (MVC/CSA) was unaffected by aging; and *2*) although the elderly subjects were as capable as the young subjects of complete and rapid muscle activation during a single voluntary isometric contraction, they were impaired in their ability to perform rapid repetitive foot tapping. These results suggest that, in the ankle dorsiflexor muscles, rapid repetitive movements may be more susceptible to impairment with aging than are single forceful isometric contractions.

Strength, CSA, and specific strength. As expected, men were stronger and had greater fat-free muscle CSA than did women. Although elderly men were weaker than young men, strength (MVC) was similar in young and elderly women (Table 1). This pattern is consistent with recent longitudinal data reported by Metter et al. (21), which indicated greater loss of upper extremity muscle power and isometric stength in elderly men compared with women. The observation of greater loss of strength in men may be due to their larger initial values, with a subsequently greater dynamic range. In the present study, MVC was higher in young men compared with the other three groups, who all exhibited similar strength (Table 1). This pattern was also observed by Young et al. (32) in their studies of specific strength in aging. The possibility that testosterone plays a role in differentiating the strength of young men from the others seems plausible.

As documented by Clarkson et al. (6), the explosiveness of the contraction is vital in obtaining a truly maximal MVC in the elderly (6). In studies of strength in the elderly, measures not performed this way may lead to overestimations of muscle weakness with aging. The MVCs obtained in this study were performed by the subjects as rapidly and forcefully as possible, thus avoiding an underestimation of muscle strength in the elderly. This may, in part, explain the lack of difference in strength between the young and elderly women in our study, which differs from some (e.g., 12, 29) but not all (1) previous reports.

Dorsiflexor muscle fat-free CSA was lower in the elderly compared with the young subjects and in the women compared with men. The reduction of muscle size with aging is consistent with previous reports (11, 12, 15, 25, 32, 33). It is of interest that CSA was reduced with age despite our studying subjects of similar habitual physical activity level. Both the young and elderly groups had activities slightly lower than that previously observed in a different group of healthy young subjects (24), indicating that they were relatively sedentary subjects. Few data are available regarding in vivo estimates of dorsiflexor muscle fat-free CSA. However, our present results compare well with control data from our previous study of muscle function in multiple sclerosis subjects (17).

In the present study, specific strength was similar in the young and elderly groups, although there was a tendency for men to have a higher specific strength than women. The question of age-related changes in specific strength is central to the question of whether there is a quantitative or qualitative change in skeletal muscle function with age. The literature regarding specific strength in aging humans is conflicting, with some investigators reporting decreased specific strength in the elderly and others observing no change. The lack of difference in specific strength in the present study is consistent with some previous studies of isometric (12, 13, 25, 32) and dynamic (11) contractions. Overend et al. (25) used computed tomography to account for noncontractile tissue in their quantitation of muscle CSA and found no difference in quadriceps isometric specific strength between young and elderly men. They did, however, find that isokinetic strength per CSA was reduced in the older men at speeds of 120°/s. Frontera et al. (11) and Jubrias et al. (15) had similar findings in that differences in specific strength were most apparent in the elderly at higher contraction speeds.

In contrast to the results of the above studies, others have reported reduced specific strength during isometric (4, 7, 26, 29, 33) and dynamic (15, 25) contractions in the elderly. However, methodological concerns arise from some of these studies. In several cases, conclusions were based solely on regression analysis of the force vs. CSA relationship, and data regarding MVC, CSA and the MVC/CSA ratio were not always provided, thereby making interpretation difficult. Additionally, in some studies the method of measuring CSA did not account for intramuscular noncontractile tissue content; thus CSA may have been overestimated in the older subjects. Jubrias et al. (15) recently reported a twofold increase in quadriceps muscle fat content in elderly compared with young subjects, demonstrating the importance of accounting for this component of muscle CSA in studies of aging skeletal muscle.

The difference in the results of previous studies concerning specific strength may be due to the difference between isometric and dynamic contractions and may be amplified at higher contraction speeds. It is possible that central (motor drive) and peripheral (loss of motor units) changes in the elderly have a greater effect on dynamic power than on isometric strength. The influence of age on specific strength may also vary depending on the muscle group.

TF was lower in women compared with men, and there was a tendency toward decreased TF in the elderly compared with young subjects ($P = 0.10$). The lack of a significant reduction in TF in the elderly is in contrast to a previous study of the dorsiflexor muscles, in which MVC and TF were reduced in elderly compared with young subjects (30). In the present study, there was a tendency for TF to be lower in the elderly women compared with young women, which was somewhat surprising given that there was no difference between these groups in MVC. However, as discussed in *Voluntary muscle activation*, the lack of difference in MVC between these two groups may have been due to activation failure in the young women, which would have lowered their MVC. In contrast to the women, the men showed a lack of difference in TF where one might have been expected given the higher MVC of young compared with elderly men. We have no particular explanation for this result. There was no difference in the amplitude of the CMAP in these groups (Table 1); thus we cannot attribute these results to a difference in excitability between the groups. Inadvertent stimulation of the plantar flexors is a limitation to peripheral nerve stimulation of the dorsiflexors. For this reason, measures of TF should be considered secondary to those of MVC in healthy subjects.

Similar to the specific strength results, our data indicate that there was no significant decrease in specific tension (TF/CSA) with age, although there was a tendency for it to be lower in the elderly. Again, this tendency was likely a result of the low TF in the elderly women, as well as the smaller sample size in the elderly group overall. Davies et al. (7) reported decreased specific tension, in this case measured as the slope of tetanic tension vs. CSA, in the triceps surae of elderly compared with young men and women. However, the authors of this earlier study suggested that CSA may have been overestimated in their older subjects (7).

Voluntary muscle activation. The results of this study indicate that the ability to fully activate the dorsiflexor muscles during a maximal contraction and the maximal speed of voluntary force development during a single submaximal contraction were relatively unimpaired in elderly compared with young subjects. These data suggest no significant impairment on the part of the elderly subjects when performing a single, maximal voluntary isometric contraction in a distal muscle group. In contrast, the performance of repeated, rapid movements (foot tapping) was significantly slowed in the elderly subjects.

The observation of essentially complete voluntary muscle activation (CAR) in the elderly supports the reports of other investigators in a variety of muscle groups (3, 9, 29), including the dorsiflexors (29). Both the significant linear relationship between muscle strength and size (Fig. 3) and the lack of difference between young and elderly subjects in specific strength (MVC/CSA) are consistent with the observation of full voluntary activation during a single isometric MVC. Thus there appears to be no impairment with aging in the ability to mount sufficiently high discharge rates and recruit all motor units during an isometric MVC of the dorsiflexor muscles.

Interestingly, CAR was lower in young women compared with young men. Six of the 12 young women had CAR < 1.0 (range $= 0.71–0.94$). It is not clear why these young women showed activation impairment on this measure, which most likely contributed to the lack of difference in MVC between young and elderly women (Table 1). In our previous studies using this measure, we have observed no systematic failure on the part of younger women to completely activate their dorsiflexor muscles (18, 19); however, this result suggests a need for further investigation.

There was no difference between young and elderly subjects in their ability to rapidly generate force during a single submaximal or maximal voluntary isometric contraction. Performance of a rapid contraction requires the ability to generate high discharge rates (8, 23, 31). However, changes in either central or peripheral function could result in slowing of voluntary contraction speed. In the present study we have controlled for the observed peripheral changes (i.e., slowed TF development and relaxation) by normalizing the speed of the voluntary contraction to that of the stimulated tetanic contraction. Normalizing the speed of the voluntary contraction in this way reduces the contribution from any age-related changes in muscle fiber types or contractile properties, thereby allowing assessment of central changes. Presumably, one could also normalize to the rate of force developed during a single twitch stimulus; however, the variability of the twitch (10) makes this a less-attractive option.

Hakkinen and colleagues (14) reported an age-related slowing of the maximum rate of absolute force developed during isometric quadriceps contractions in men; however, maximum force was lower in the older men. In a study by Hakkinen and Hakkinen (12), slower relative rates of quadriceps force development and relaxation were observed in elderly compared with young women. In contrast, Clarkson et al. (6) also observed slower absolute knee extension force development in elderly compared with younger men, but this difference disappeared when the rate was normalized to maximum strength.

The speed of rapid repetitive movements is a clinical tool used for assessing upper motoneuron function (19, 31). Functionally, the ability to perform repeated rapid movements may be more important in activities of daily living than the ability to perform a single isometric contraction. The slowing of foot tap speed in the elderly subjects suggests that the ability to rapidly modulate discharge rate and motor unit recruitment may be impaired with aging. The potential influence of age-related lower motoneuron loss on the slowing of foot tap speed cannot be determined in this study. However, foot tap speed slows to 21–24 taps/10 s in patients with upper motoneuron disorders, including multiple sclerosis (28) and amyotrophic lateral sclerosis (19). Similarly, changes in ankle joint stiffness may also influence this measure. Thus, although some contribution from lower motor unit loss or increased joint stiffness may be a factor in the slowing of movement speed with aging, there is likely an important effect of central changes on this slowing with age.

ERT. The effects of ERT on muscle function in postmenopausal women have not been thoroughly investigated. There may be some preservation of strength in women on ERT compared with those not on ERT (5), but this has not always been observed (15). Our preliminary data on a small number of subjects from this study suggest that muscle CSA was greater in ERT compared with non-ERT women, although neither MVC nor specific strength was significantly affected by estrogen status. This latter result is in contrast to the report of Phillips et al. (26), who found a more rapid decrease in adductor pollicis MVC/CSA in women not on ERT. Muscle strength and CSA data were not reported in that study. In ERT vs. non-ERT women, changes in the pattern of activation were similar to that observed between young and elderly subjects, with no difference in CAR or the maximum rate of voluntary force development but with a trend toward slower foot tap speed in non-ERT compared with ERT women ($P = 0.05$). With the increasing prevalence of ERT use in postmenopausal women, it is important to determine more fully the possible ameliorating effects of this therapy on muscle function.

Conclusions. The results of this study suggest that, when physical activity level and muscle size were accurately accounted for, isometric specific strength was unaffected by aging. In addition, while the ability to fully and rapidly activate the dorsiflexor muscles during a single isometric contraction was unaffected by aging, there was an age-related deficit in the ability to perform rapid repetitive dynamic contractions. Thus consideration must be given to the type of muscle contractions performed when changes in muscle function with age and their relevance to activities of daily living are assessed.

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