

Maximum Voluntary Activation in Nonfatigued and Fatigued Muscle of Young and Elderly Individuals

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Background and Purpose. Researchers studying central activation of muscles in elderly subjects (≥ 65 years of age) have investigated activation in only the nonfatigued state. This study examined the ability of young and elderly people to activate their quadriceps femoris muscles voluntarily under both fatigued and nonfatigued conditions to determine the effect of central activation failure on age-related loss of force. **Subjects and Methods.** Twenty young subjects (11 men, 9 women; mean age=22.67 years, SD=4.14, range=18–32 years) and 17 elderly subjects (8 men, 9 women; mean age=71.5 years, SD=5.85, range=65–84 years) participated in this study. Subjects were seated on a dynamometer and stabilized. Central activation was quantified, based on the change in force produced by a 100-Hz, 12-pulse electrical train that was delivered during a 3- to 5-second isometric maximum voluntary contraction (MVC) of the quadriceps femoris muscle. Next, subjects performed 25 MVCs (a 5-second contraction with 2 seconds of rest) to fatigue the muscle. During the last MVC, central activation was measured again. **Results.** In the nonfatigued state, elderly subjects had lower central activation than younger subjects. In the fatigued state, this difference became larger. **Discussion and Conclusion.** Central activation of the quadriceps femoris muscle in elderly subjects was reduced in both the fatigued and nonfatigued states when compared with young subjects. Some part of age-related weakness, therefore, may be attributed to failure of central activation in both the fatigued and nonfatigued states. [Stackhouse SK, Stevens JE, Lee SCK, et al. Maximum voluntary activation in nonfatigued and fatigued muscle of young and elderly individuals. *Phys Ther.* 2001;81:1102–1109.]

Key Words: *Aging, Central activation, Maximum voluntary contraction, Skeletal muscle.*

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Volitional activation of skeletal muscle requires proper functioning of both the central nervous system and peripheral neuromuscular pathways. The central nervous system processes involve the activation of the motor portions of the cerebral cortex and motoneuron pool in the ventral gray matter of the spinal cord.¹ Peripheral activation begins with the transmission of the action potential along the peripheral motor nerve axon, continues across the neuromuscular junction to the muscle membrane and the transverse tubular system, and ends with crossbridge formation between the myosin heads and actin filaments. Failure anywhere along the central or peripheral pathways can result in fatigue (ie, decreases in force production).²⁻⁶ *Fatigue* is defined as any reduction in the force-generating capacity of a muscle

due to recent activation and can be attributed to peripheral or central nervous system failure.^{3,7,8} A decline in central activation due to vigorous exercise is often defined as *central fatigue* or *central activation failure*.^{3,8}

Two techniques have been developed to measure deficits in a subject's volitional ability to activate a muscle maximally. The twitch-interpolation technique involves delivering single electrical pulses to a muscle when the subject is at rest and while the subject attempts to produce a maximum voluntary contraction (MVC). The degree of central activation is expressed as:

$$1 - \frac{\text{twitch force during the contraction}}{\text{twitch force at rest}} \times 100$$

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In the second method, the burst superimposition technique, a high-frequency train of electrical pulses is delivered to the contracting muscle. Kent-Braun and Le Blanc⁴ outlined a way to express the level of central activation using the burst superimposition technique by calculating a central activation ratio (CAR). The CAR is the ratio of the voluntary force to the total force (including any force increment from the burst superimposition). A CAR of 1.0 indicates complete activation, whereas a CAR of less than 1.0 indicates central activation failure or inhibition. Recently, the burst superimposition technique has been shown to improve detection of central activation failure (compared with the twitch-interpolation technique) during maximal and submaximal muscle contractions.^{4,9,10}

Factors such as fatigue and age may affect the ability to voluntarily activate a muscle maximally. Controversy exists over whether central fatigue plays a major role in the loss of force associated with fatigue, and several researchers have attempted to address this conflict by evaluating central activation failure immediately following a voluntary fatigue protocol. In the study by Kent-Braun and Le Blanc,⁴ a subset of subjects was selected to participate in a fatigue test. The exercise protocol consisted of a 4-minute sustained MVC during which force fell to $24\% \pm 3.8\%$ of the initial MVC. A single supramaximal electrical pulse and a doublet (2 closely spaced pulses) superimposed on the last 30 seconds of the MVC detected 2% and 1% central activation failure, respectively. A superimposed, 50-Hz, 500-millisecond train of electrical pulses, however, produced 11% activation failure. Thus, a superimposed train was determined to be more sensitive in detecting inhibition in fatigued muscle than a twitch or a doublet. Gandevia and colleagues³ reported a similar drop in voluntary activation for the biceps brachii muscle after a 3-minute sustained MVC. Bigland-Ritchie et al¹¹ examined central fatigue of the quadriceps femoris muscle during sustained MVCs by comparing the decline in MVC force with the decline in electrically elicited force. Because the MVC force fell more rapidly than did the electrically elicited force in 5 out of 9 subjects, Bigland-Ritchie and colleagues believed that central fatigue accounted for a large portion of the force loss.

Similarly, fatigue protocols that use intermittent contractions also produce central activation failure.^{6,7,12} During 45 minutes of repetitive isometric contractions of the elbow flexors (6 seconds in duration, 4 seconds of rest) at 30% of nonfatigued maximal voluntary torque, Lloyd et al¹² observed a decline in central activation from 99% in the nonfatigued state to 87% in the fatigued state using the twitch interpolation technique. Newham and colleagues⁶ also obtained central activation failure isometrically ($36.4\% \pm 3.1\%$) after the human quadriceps

femoris muscle was fatigued by using 85°/s intermittent isokinetic contractions. Although intermittent contractions allow unrestricted blood flow and reactive hyperemia to occur and produce slower rates of force decline compared with sustained contractions, central activation failure can still occur.⁷

Age is another variable that may play a crucial role in a person's ability to generate a maximum contraction. In 5 recent studies, no differences in central activation were found between young and elderly subjects (≥ 65 years of age),¹³⁻¹⁷ and 3 studies showed small differences in central activation.^{4,18,19} In studies where there were differences in central activation between young and elderly subsets, the burst superimposition technique was used to detect central activation failure. However, only one study¹⁷ that used the burst superimposition technique did not demonstrate a difference in central activation between young and elderly people.

Although researchers have used study protocols¹⁷⁻¹⁹ to examine the ability of elderly people to activate muscles maximally, none have focused on the extent to which fatigue affects their ability to centrally activate muscles. We, therefore, examined the ability of young and elderly individuals to activate their quadriceps femoris muscles voluntarily under both fatigued and nonfatigued conditions to determine the effect of central activation failure on age-related loss of force.

Method

Subjects

Thirty-seven subjects with no history of vascular, orthopedic, or neurological dysfunction voluntarily participated in this study. The young population consisted of 11 men and 9 women (mean age=22.67 years, SD=4.14, range=18-32), and 8 men and 9 women (mean age=71.5 years, SD=5.85, range=65-84) comprised the elderly population. Each subject signed an informed consent form prior to data collection.

Experimental Setup

All testing was done with the subjects seated on a computer-controlled dynamometer (Kin-Com 500 H, software version 4.03).^{*} Their right leg, thigh, pelvis, and shoulders were stabilized with Velcro[†] straps. Hips and knees were flexed to 90 degrees, and the subjects were instructed to keep their arms folded across their chest. Two 7.6- × 12.7-cm self-adhesive electrodes[‡] were placed on the motor points of the vastus medialis and proximal rectus femoris portions of the quadriceps

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‡ CONMED Corp, 310 Broad St, Utica, NY 13501.

muscle. The quadriceps femoris muscle was stimulated using a Grass S8800 stimulator with a Grass model SIU8T stimulus isolation unit.[§] The stimulator was driven by a personal computer using custom-written software (Lab-View 4.0.1)^{||} to control the timing for each stimulation train. Force data were digitized online at 200 samples per second and analyzed with custom-written software.

Experimental Sessions

All subjects participated in one testing session. After an explanation of the experimental design, subjects performed a 3- to 5-second maximum voluntary isometric contraction of the quadriceps femoris muscle. A 100-Hz, 12-pulse electrical train was delivered to the contracting muscle. The intensity of the Grass S8800 stimulator was set at 135 V, and the SIU8T unit was set to deliver the maximum voltage. All stimulation pulses were 600 microseconds in duration. Subjects were given both verbal encouragement and visual feedback to help to ensure that a maximal effort was being put forth. Verbal encouragement consisted of loudly exhorting a subject (“Kick hard! Go! Go! Go! Kick! Kick! Kick!”) for the entire duration of the contraction.

If CARs were less than 0.95, subjects were encouraged to kick harder, and, after a 5-minute rest period, the procedure was repeated. Each subject was given 3 attempts to reach a CAR of greater than or equal to 0.95. The highest CAR was recorded from all attempts of the initial MVC for each subject, and the force value was used to set a visual target on the monitor for the fatigue test. After a 5-minute rest from the last MVC, the fatigue test was initiated. Subjects performed a series of 25 maximum voluntary isometric contractions. Each contraction was maintained for 5 seconds and was followed by a 2-second rest. During the fatigue test, subjects were again given strong verbal encouragement and visual feedback to help them attain maximal efforts. On the 25th contraction, a 100-Hz, 12-pulse electrical train was superimposed on the subject’s maximal effort to test the CAR in the fatigued state.

Data Management

Calculating the mean peak force before the burst in the young and elderly subjects allowed us to compare MVC forces before fatigue. The CAR was calculated by dividing the maximum voluntary force produced prior to the delivery of the stimulation train by the force produced by the combination of the electrical and voluntary activation. A CAR of 1 was taken to mean 100% voluntary activation. Central activation ratios of less than 1 indicated incomplete activation. To investigate the amount

of fatigue that was produced by the fatigue test, peak forces for the young and elderly subjects during the fatigue sequence were normalized to the peak force in the first contraction of the sequence. *Fatigue*, in this study, was defined as any reduction in force generation that exceeded 10% from the 1st to 24th contraction of the fatigue sequence. The data obtained for any subjects who did not reduce their peak force by $\geq 10\%$ were eliminated from the analysis.

Data Analysis

Independent *t* tests were used to compare both the peak forces of the MVC before the burst and the mean normalized forces over the last 3 contractions of the fatigue test between the young and elderly subjects. We used a 2-way, mixed-design analysis of variance (ANOVA) to look for main effects of age and fatigue state on the CAR. Paired *post hoc t* tests were used to determine whether fatigued CARs differed from nonfatigued CARs for each age group. Independent *post hoc t* tests were used to determine whether elderly people differed from young people in their ability to activate a muscle maximally for each fatigue state.

Results

Of the 37 subjects tested, data from only 34 subjects were analyzed. One elderly female subject produced large fluctuations in force during successive contractions of the fatigue protocol and demonstrated a decline in peak force of only 2% from the first to last contraction; therefore, her data were eliminated. In addition, 2 young subjects (1 man, 1 woman) who had fatigued CARs more than 3 standard deviations less than the mean were also excluded from analysis because we believe that these subjects were not truly trying to produce a maximal contraction (Fig. 1).

As a group, young subjects generated higher force levels than the elderly subjects. The mean peak force was 980.65 N (SD=352.73, range=414–1,535) for the young subjects and 582.27 N (SD=184.26, range=180–925) for the elderly subjects ($t=4.19, P<.001$). During the initial 8 contractions of the fatigue test, the elderly subjects showed a larger decrease in normalized peak force than the young subjects. By the end of the fatigue test, however, the young and elderly groups produced similar declines in normalized peak force (Fig. 2). The mean normalized force over the last 3 contractions was 0.50 ± 0.14 for the young subjects and 0.55 ± 0.15 for the elderly subjects ($t=1.00, P=.32$).

Raw force traces from a typical young subject and a typical elderly subject during determination of their CAR in the fatigued and nonfatigued states are presented in Figure 3. These raw force traces reflect the results from the group data (see below). During the

[§] Grass Instruments, Div of Astro-Med Inc, 600 E Greenwich Ave, West Warwick, RI 02893.

^{||} National Instruments, 6504 Bridge Point Pkwy, Austin, TX 78730.

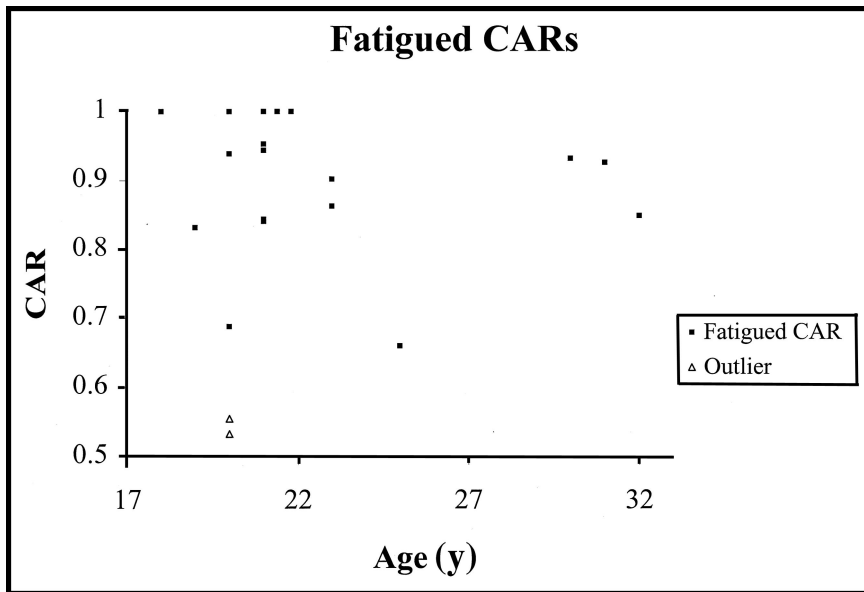


Figure 1. Fatigued central activation ratios (CARs) of the young subjects showing the 2 outliers that were more than 3 standard deviations less than the mean CAR (0.90).

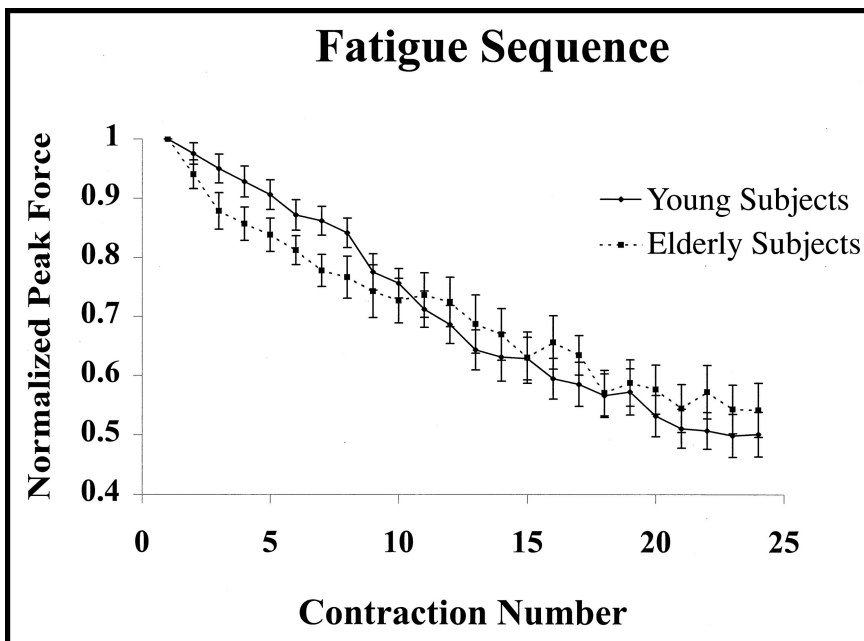


Figure 2. Mean normalized forces for each contraction of the fatigue test of the young and elderly subjects. There were no differences in mean normalized force between the young and elderly groups over the last 3 contractions (0.50 and 0.55, respectively).

fatigued and nonfatigued state CAR tests, the electrical burst produced a larger increment in force and, therefore, a lower CAR for the elderly subject than for the young subject.

ing fatigue is severely compromised by inadequate central activation.

The CARs in the nonfatigued state in this study were similar to other reports of central activation for young and elderly subjects using the burst superimposition

Sixteen of 18 young subjects and 9 of 16 elderly subjects were able to achieve CARs of at least 0.95 in the nonfatigued state. The average CARs were 0.98 ± 0.03 and 0.94 ± 0.07 for the young and elderly subjects, respectively (Fig. 4). After the fatigue test, only 6 young subjects and 3 elderly subjects achieved CARs greater than 0.95, and the mean CARs were 0.90 ± 0.10 for the young subjects and 0.74 ± 0.19 for the elderly subjects. A 2-way ANOVA showed main effects for both age and fatigue state (age: $F=10.68$, $P<.01$; fatigue state: $F= 38.34$, $P<.001$). An interaction between age and fatigue state was also observed ($F=7.23$, $P<.05$). *Post hoc* testing revealed that fatigue lowered the CARs for both the young and elderly subjects (young subjects: $t=3.459$, $P<.01$; elderly subjects: $t=4.962$, $P<.001$) (Fig. 4). In addition, a small difference in CARs between young and old subjects was found in the nonfatigued state ($t=2.121$, $P<.05$), and a larger difference was found in the fatigued state ($t=3.178$, $P<.01$).

Discussion

Central activation of the quadriceps femoris muscle in the elderly subjects was diminished in both the fatigued and nonfatigued states when compared with the young subjects. Some part of age-related weakness, therefore, may be attributed to failure of central activation. In the nonfatigued state, there was a small difference in the CAR between the young and elderly subjects (0.98 and 0.94, respectively). In contrast, the CARs in the fatigued state showed a larger difference between young and elderly subjects (0.90 and 0.74, respectively) despite the same relative amount of fatigue in both groups (about 50% and 45%, respectively). This large difference in fatigued CARs indicates that the force-generating ability of elderly people dur-

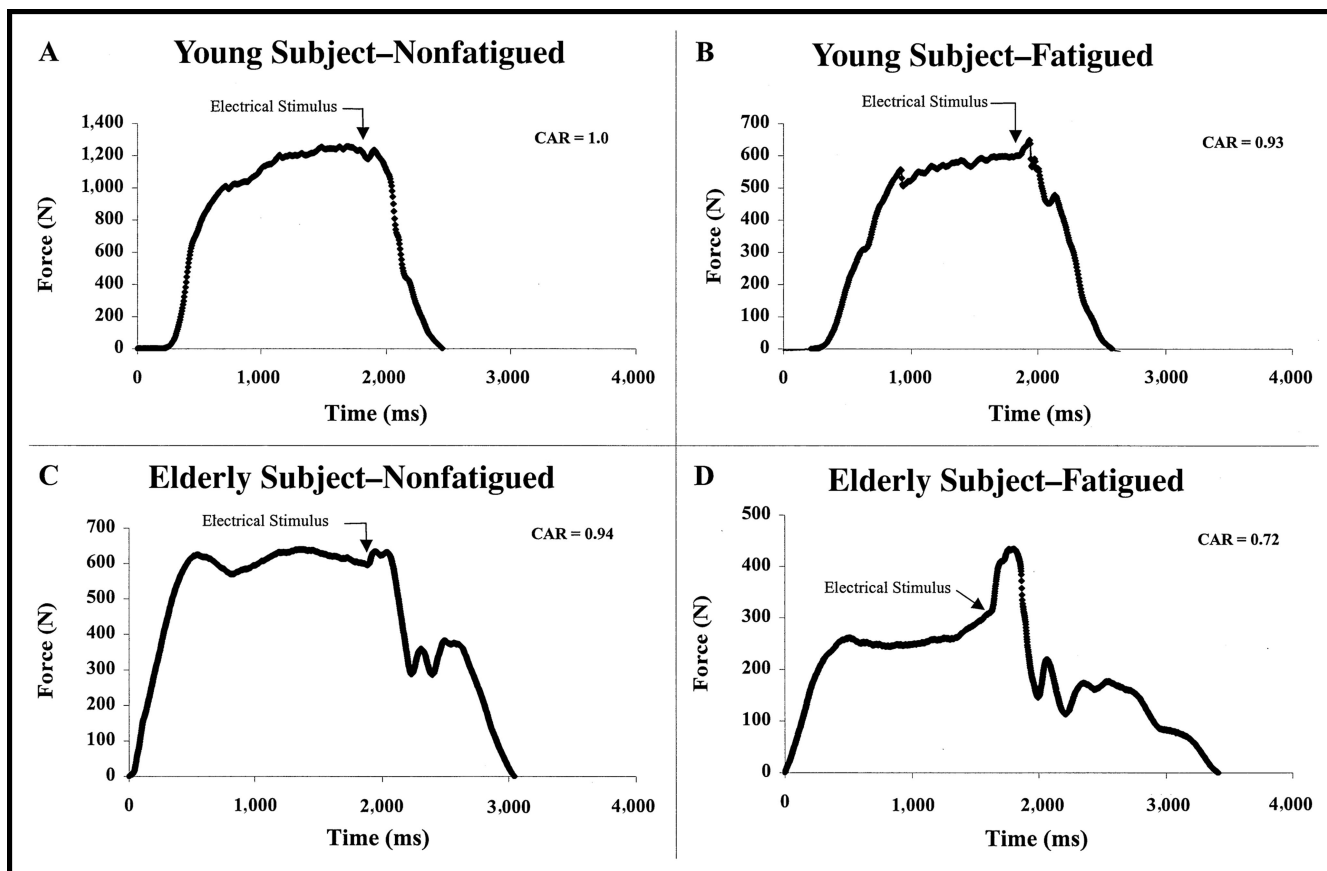


Figure 3.

Typical raw force traces from a young subject and an elderly subject during the burst superimposition test. In the nonfatigued state, the young subject was able to produce full activation (central activation ratio [CAR]=1.0) (A), and, in the fatigued state, the same subject maintained a high level of activation (CAR=0.926) (B). In contrast, the elderly subject produced a high level of activation (CAR=0.939) in the nonfatigued state (C) and demonstrated substantial central fatigue (CAR=0.722) during fatigue (D).

technique. De Serres and Enoka¹⁹ reported activation levels for the biceps brachii muscle of 97.8% and 95% for young and elderly subjects, respectively. Similarly, Yue and colleagues¹⁸ reported biceps brachii muscle activation levels of 96.8% for young subjects and 93.7% for elderly subjects. Both of these studies revealed small differences in central activation of the biceps brachii muscle between young and elderly subjects. Prior investigations of age-related changes in central activation of the quadriceps femoris muscle did not use the burst superimposition technique. For example, a recent study by Roos and colleagues¹⁶ showed no difference in quadriceps femoris muscle activation level between young and elderly subjects (93.6% and 95.5%, respectively) when tested with the twitch-interpolation technique. However, we believe that their results should be questioned in light of the evidence demonstrating the superiority of detecting central activation failure when using the burst superimposition technique.^{4,9,10}

Our results on central activation in the nonfatigued state parallel those of Yue and colleagues¹⁸ and De Serres and Enoka,¹⁹ who used the burst superimposition technique.

Although the difference in the CAR between young and elderly subjects in the nonfatigued state is small (0.04) and may seem clinically irrelevant, recent work from our laboratory indicates that the relationship between CAR and percentage of MVC is curvilinear (Fig. 5).²⁰ As a person approaches 75% and 100% of voluntary effort, the change in CAR becomes progressively smaller. Thus, a small change in the CAR could mean a substantial change in force.

No other investigators have reported the effects of fatigue and age on the ability to activate a muscle fully while using either the twitch-interpolation or burst superimposition methods. The young subjects in our study had a mean CAR of 0.90 at the end of the fatigue sequence. Kent-Braun and Le Blanc⁴ reported a similar mean CAR (0.89) using a burst superimposition after a sustained MVC of the tibialis anterior muscle in 9 young subjects. Newham and colleagues⁶ also reported lower isometric activation levels (63.6%) using the burst superimposition technique after fatigue with maximal, intermittent, 85°/s isokinetic contractions.

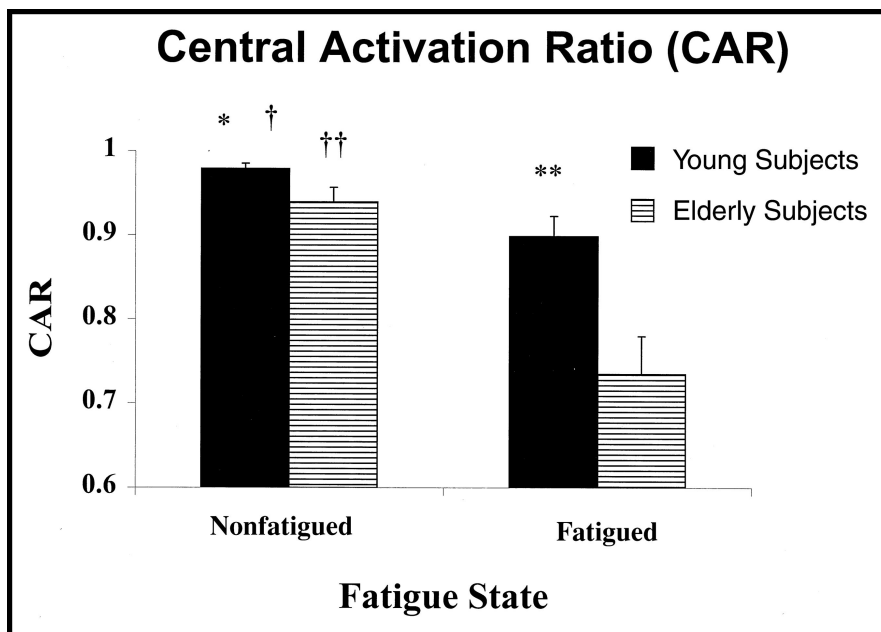


Figure 4. Mean central activation ratios (CARs) for both young and elderly subjects across fatigue states. For comparisons between young and elderly subjects (independent *post hoc t* tests) within the nonfatigued and fatigued states: * indicates $t=2.121$, $df=32$, $P\leq.05$, and ** indicates $t=3.178$, $df=32$, $P\leq.01$. For comparisons between nonfatigued and fatigued states within an age group (paired *post hoc t* tests): † indicates $t=3.459$, $df=17$, $P\leq.01$, and †† indicates $t=4.962$, $df=17$, $P\leq.001$.

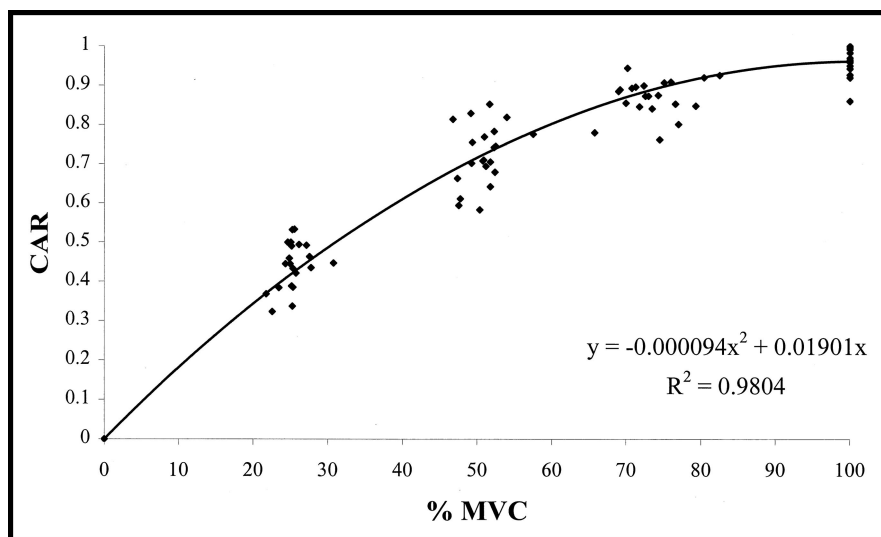


Figure 5. Central activation ratio (CAR) data plotted as a function of the percentage of maximum voluntary contraction (% MVC). The relationship is curvilinear and best fit by a second-order polynomial. These data were adapted with permission of John Wiley & Sons Inc from Stackhouse SK, Dean JC, Lee SC, Binder-MacLeod SA. Measurement of central activation failure of the quadriceps femoris in healthy adults. *Muscle Nerve*. 2000;23:1706-1712. Copyright 2000.

The mean CAR of the elderly subjects dropped from 0.94 in the nonfatigued state to 0.74 in the fatigued state even though visual force feedback and strong verbal encouragement were given during all contractions. Despite the differences in central activation between the

young and elderly subjects, both groups were fatigued by the same relative amount (approximately 50%). We did not expect this finding, because deficits in central activation result from a reduction in motor unit recruitment or a lowering of motor unit firing rates, and, therefore, a larger central activation deficit should translate into a greater relative loss of force in elderly people. One possible explanation for these findings is that elderly people have quadriceps femoris muscles with slower rates of force development and relaxation than young subjects,¹⁶ which could allow lower motor unit firing rates in elderly people to produce full fusion of force at lower frequencies. Although this has not been substantiated for the quadriceps femoris muscle in the nonfatigued state,¹⁶ it still may be a possible explanation for the larger reduction in the CAR seen immediately following fatiguing contractions.

Clinical Implications

Muscles are known to undergo age-related changes, such as specific fiber-type atrophy, changes in myosin heavy-chain isoforms, and loss of motor units.²¹⁻²³ Despite the changes in muscle due to age, at least one authority proposes exercise guidelines for strengthening that are no different for young people than for elderly people (2-3 sets of 8-12 repetitions at 80% of a 1-repetition maximum).²⁴ The results from our study show that central activation is altered, especially during fatigue resulting from repeated MVCs, in an elderly population. In addition, when visually inspecting the fatigue sequence, elderly subjects appear to us to have a more rapid drop in normalized peak force than young subjects. The CAR data, coupled with the observation of a more rapid decline in normalized peak force, may be relevant for

designing optimal strength training programs for elderly people. Due to greater difficulties in achieving maximum activation, it may be necessary to provide elderly people with closer supervision throughout exercise programs to ensure that they perform each repetition

correctly (without substitution or incomplete range of motion), to adjust rest times between contractions or sets to maintain higher levels of central activation throughout an exercise, or to use neuromuscular electrical stimulation as an alternative to provide more consistent muscle activation during strength training.

Conclusion

The quadriceps femoris muscles of elderly subjects demonstrated greater central activation failure during MVCs in the nonfatigued state than the quadriceps femoris muscles of young subjects, and this increase in central activation failure became greater with fatigue. Therefore, some part of age-related loss of force can be attributed to deficits in central activation in both the fatigued and nonfatigued states of the quadriceps femoris muscle. The results from our study could have implications for the optimization of strength training programs. Studies are needed, however, to assess whether ways to promote greater central activation during strength training will translate into larger strength gains in elderly people.

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