EFFECTS OF AGING AND RESISTANCE EXERCISE ON DETERMINANTS OF MUSCLE STRENGTH

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ABSTRACT

Although the loss of muscle strength with aging is multifactorial, the primary factor is the loss of muscle mass. A preferential loss of Type II (fast-twitch) muscle fibers which produce more force than Type I fibers is also observed. The loss of muscle mass may be related to a reduction in the rate of muscle protein synthesis in the old versus the young. Changes in muscle quality and the ability to activate muscle appear to play a minor role in the loss of strength with age. However, co-activation of antagonist muscle groups does appear to reduce muscle force generating capacity in the elderly. Strength gains in response to resistance exercise training in the elderly, although substantial, may be less than in young individuals. Increases in muscle mass appear to be similar in elderly and young individuals as does the muscle protein synthetic response to resistance exercise. Muscle co-activation appears to be substantially and similarly reduced (improved) in young and elderly individuals as a result of resistance training.

INTRODUCTION

Muscle force generating capacity declines in sedentary individuals as they age. It has been reported by Larsson et al. (1) that muscle strength is maintained between the ages of 30-50 but after the age of 50 until 70 there is approximately a 30% drop in muscle strength. Similar reductions in muscle force generating capacity with age have been reported by others (2-4). A large proportion of this decline in strength is due to a reduction in the size and or number of type II or fast twitch muscle fibers (5). The age-related loss in muscle mass has been termed *sarcopenia* (6). Loss in muscle mass, to a large degree, accounts for the age-associated decreases in basal metabolic rate, muscle strength, and activity levels, which in turn, is the cause of the decreased energy requirements of the elderly (7, 8). However, loss of muscle mass may not be the only cause of decreased strength. Reduced muscle agonist activation (9) and increased antagonist co-activation (10-12) as well as reduced muscle quality (13) may play a role. The decline in muscle strength is associated with decreased functional ability (14) and an increased incidence of falls (15) in the elderly. Tzankoff and Norris (16) reported a strong relationship between the reduction in muscle mass and the reduction in resting oxygen consumption. This lower energy expenditure may contribute to an imbalance between energy intake and energy expenditure and an accumulation of body fat. Resistance exercise training has been shown to

increase strength, muscle mass and resting energy expenditure in the elderly and improve performance of functional tasks (17, 18).

This review will examine data regarding the causes for the loss in muscle strength with increasing age and the mechanisms by which muscle strength is increased with resistance exercise training in the elderly.

The Reduction in Muscle Mass is the Primary Reason for Reduced Muscle Strength in the Elderly

Clearly, the most important factor in the loss of force generating capacity with increasing age is the reduction in muscle cross-sectional area (CSA). Recently, Akima et al. (19) reported a strong negative relationship between peak torque and age in men and women age 20-84. In addition when all ages were included, these individuals reported a strong correlation between quadriceps CSA and maximum knee extension torque (0.827 for men and 0.657 for women). Thus, 68% of the variation in torque could be explained by CSA in men and 43% of the variation in torque could be explained by CSA in women. In addition, in women, Young et al. (20) reported that muscle CSA explained 44% of the differences in quadriceps strength in elderly subjects and 28% in young. In old men, these investigators reported that quadriceps size explained 59% of the variation in strength while in young men quadriceps size only explained 2.3% of the variation in muscle strength. Based on these data, and those of others, there appears to be a strong relationship between muscle CSA and muscle torque production.

Muscle Fiber Size Changes with Age

The number and size of Type II muscle fibers are extremely important to muscle force production. For example, it is known that for a given fiber size, Type II fibers produce more force than Type I fibers (21). Further, at the whole muscle level, Type II fiber percentage is positively related to increased maximal torque production (22-24). Lexell et al. (5) has reported that in the vastus lateralis muscle, increasing age leads to a greater reduction in number and size of type II fibers than type I fibers. Thus, because of the greater torque production for Type II fibers observed at both the single fiber and whole muscle level, the reduction in Type II fiber number and fiber size would appear to play an important role in the loss of force producing capabilities with age. Indeed, this has been reported by Hakkinen et al. (12).

Muscle Protein Synthesis in Young and Old

Muscle mass is primarily determined by the balance between muscle protein synthesis and degradation. There is a paucity of data regarding muscle protein degradation with aging but muscle protein synthesis and aging has received considerable attention.

Recently, Volpi et al. (26) reported that mixed muscle protein synthesis was similar in older and younger individuals when measured in the fasted state. In

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contrast, Hasten et al. (27) reported mixed muscle and myosin heavy chain synthesis rates were lower in old than young when examined in the fasted state. Welle et al. reported that the myofibrillar protein synthesis rate was significantly lower in older than younger subjects in the postabsorptive state (28%) (28) and in the postprandial state (28% lower) (29). Additionally, in another study, Welle et al. (30) reported that the myofibrillar protein synthesis rate was 33% lower in older individuals than younger individuals in the fasted condition. Further, Balagopal et al. (31) reported a reduced myosin heavy chain protein synthesis rate in the elderly in the fasted condition. However, Volpi et al. (32) also measured the mixed muscle protein synthetic in old and young in response to 40 g of amino acids in the same proportion as that found in beef and 40 g of carbohydrate. They found that the mixed muscle protein synthesis rate increased 118% ($P=0.005$) in the young and only 12.9 % in the elderly (non-significant). Thus, the majority of the data suggest that the resting muscle protein synthesis rate is significantly lower in older when compared to younger individuals.

High intensity resistance training is clearly anabolic in both young and older individuals. Data from our laboratory (33) demonstrated a 10 to 15 percent decrease in nitrogen (N) excretion at the initiation of training that persists for 12 weeks. That is, progressive resistance training improved N-balance, thus older subjects performing resistance training have a lower mean protein requirement than do sedentary subjects. This effect was seen at a protein intake of 0.8 and 1.6 g protein $\cdot$ kg⁻¹ $\cdot$ d⁻¹, indicating that the effect of resistance training on protein retention may not be related to dietary protein intake. These results are somewhat at variance to our previous research (34) demonstrating that regularly performed aerobic exercise causes an increase in the mean protein requirement of middle-aged and young endurance athletes (mean of 0.93 g $\cdot$ kg⁻¹ $\cdot$ d⁻¹). This difference likely results from increased oxidation of amino acids during aerobic exercise that may not be present during resistance training.

Strawford et al (35) also demonstrated similar effects of resistance exercise training on nitrogen balance in patients with HIV-related weight loss. The investigators examined the effects of an anabolic steroid (oxandrolone, 20 mg/d and placebo) and high intensity resistance exercise training in 24 eugonadal men with HIV-associated weight loss (mean, 9% body weight loss). Both groups showed significant nitrogen retention and increases in LBM, weight, and strength. The mean gains were significantly greater in the oxandrolone group than in the placebo group in nitrogen balance, accrual of FFM, and strength. Results were similar whether or not patients were taking protease inhibitors. These results confirm the positive effects of resistance exercise on nitrogen retention and protein requirements.

These studies, taken as a whole demonstrate the powerful effects of resistance exercise training on protein nutrition. The anabolic effects have important implications in the treatment of many wasting diseases and conditions such as cancer, HIV infection, aging, chronic renal failure, and undernutrition seen in many very old

men and women. By effectively lowering dietary protein needs (33), resistance exercise can limit further losses of skeletal muscle mass while simultaneously increasing muscle strength and functional capacity.

Single Fiber Contractile Function and Age

Krivickas et al. (36) reported that in men, aging seems to result in a slowing of maximal shortening velocity in type II a fibers w/out a change in Type I fibers. However, in women maximal shortening velocity decreases in Type I rather than Type II a fibers.

Muscle Quality and Aging

In a recent study of 2,627 men women age 70-79 years Goodpaster et al. (13) reported that muscle quality, as measured by the attenuation of skeletal muscle using CT analysis, was significantly related to muscle torque production at 60 degrees/sec. However, the impact of this finding with regard to muscle function is debatable because the partial R^2 for muscle quality was 1.6% for men for women was 3%. The change in muscle attenuation is thought to represent the infiltration of muscle with fat. Thigh muscle cross-sectional area had the greatest impact on torque production of any factor studied (they did not study neurologic factors) with a partial R^2 of 30.4% for men and 25.0% for women. Although no data on young individuals was presented, it would appear that muscle quality, as measured by the attenuation of skeletal muscle, does not play a major role in the reduction of strength with aging.

Effects of Age on Muscle Activation

The ability of the muscles to produce force is first initiated in the nervous system. The two neurologic factors that cause muscle induced force production are modulation of motor unit recruitment, and the rate of motor unit firing. Collectively, this is called central activation. Activation typically is measured by superimposing an electrical stimulus on to a muscle that is performing a maximal voluntary contraction (MVC). The muscle force produced from the electrical stimulus is considered maximal or 100%. If the maximal force production via electrical stimulation is greater than force produced via voluntary muscle contraction this is considered evidence of central activation failure.

The effect of age on muscle activation has not been extensively studied but there are unreplicated data on many muscle groups. For the tibialis anterior (37, 38), quadriceps (39), adductor pollicis (40), triceps surae (41) there appears to be no impairment of muscle activation in old vs. young. For the biceps brachii, Yue et al. (9) have reported that muscle activation was significantly less in the elderly than the young. Thus, in most muscle groups studied it does not appear that central activation failure is a consequence of increasing age.

Although muscle activation impairment does not seem to occur in most muscle groups as a result of age, there are other signs of impaired nervous system input to muscle as a result of age (10-12, 38). For example, Klein et al. (10) reported increased muscle coactivation (5%) of antagonist muscles for both the elbow flexors and extensors in the elderly. In addition, greater coactivation of the knee flexors when contractions of the

knee extensors are occurring has been reported in the elderly vs. middle aged individuals by Hakkinen et al. (12) and Izquierdo et al. (11). Further, Kent-Braun et al. (38) reported that aging reduced foot tapping speed. Clinically, foot tapping speed is used to determine upper motor neuron function. These investigators suggested that the reduction in foot tapping speed with age represents an impaired ability to rapidly regulate motor unit discharge rates or motor unit recruitment, but they suggested that lower motor unit loss or joint stiffness may play a role. Future studies should be conducted to see if these changes in coactivation with age and a reduced ability to produce rapid and repetitive movements occur in other muscle groups.

Strength Response to Resistance Training in the Elderly vs. the Young

Moritani and deVries (42) reported that eight weeks of strength training did not result in a significant difference in strength gains between old (22.3% increase) and young (29.5% increase) individuals. However, one could argue that the number of subjects was low ($n=5$ per group) and that significant differences were not observed because of a lack of statistical power. Lemmer et al. (43) reported that the change in 1 RM was greater in young than old individuals following 9 weeks of intense resistance training. Hakkinen et al. (12) reported no significant difference in strength increase in young and old following 10 weeks of progressive resistance training. In Table 1 the strength training induced increases in 1RM in the elderly for selected studies are presented.

Muscle Hypertrophy Response to Resistance Training in the Elderly vs. the Young

In an early study, Moritani and de Vries (42) reported that eight weeks of resistance training resulted in a significant 9.1% increase in muscle cross-sectional area in young subjects but to a non-significant 1.5% increase in CSA in old subjects. Welle et al. (44) previously reported that older individuals (> 60 years old) have a reduced muscle hypertrophic response to three months of resistance training than younger individuals (22-31 years old). However, a more recent study using a more intense training

but shorter duration (9 weeks) reported that muscle hypertrophy was not attenuated by age (45). Campbell et al. (33) showed no significant increase in muscle size in elderly men and women after 3 months of high intensity resistance training using CT analysis. One methodological difference between the studies of Welle et al. (44) and Ivey et al. (45) is that Welle et al. (44) used a single MRI slice of each muscle group trained and Ivey et al. (45) calculated muscle volume from many scans of each limb. Ivey et al. (45) reported that the change in muscle size following a training program using single mid-thigh MRI slice explained only 50% of the variance in volume change while the measurement of the change in every other slice from knee to hip explained 98% of the variance in total muscle volume change. However, Bamman et al. (46) reported that anatomical CSA for the triceps surae muscle group (single slice CT or MRI scan) and physiological CSA (which takes into account muscle volume, angle of muscle pennation, and fiber length for each individual muscle) was superior to muscle volume measurements in predicting strength. Hakkinen et al. (12) reported that the resistance training (10 weeks) induced increase in quadriceps femoris muscle cross-sectional area was not significantly different between young and old individuals. Thus, the majority of the data suggest that the increase in hypertrophy in response to resistance training is not different between young and old.

Muscle Fiber Size Changes with Resistance Training in the Aged

Both major muscle fiber types (I, II) increase in size as a result of resistance training in the elderly (12, 47-50). Although, both type I and type II fibers increase in size in response to resistance training it would appear that the increase in type II fiber size would be relatively more important, as type II fibers produce more force per unit area than type I fibers, and due to the fact that there is a reduction in type II fiber area/number with aging.

Effect of Resistance Training on Muscle Protein Synthesis

Hasten et al. (27) reported that the increase in myosin heavy chain (MHC) synthesis rate increased 144%

Table 1: Strength Adaptations of Elderly Individuals to Selected Resistance Training Regimens.

Study	Gender	Age (yr)	Duration (wks)	Frequency (days/wk)	Training % of 1RM	% Increase in Strength
Hakkinen et al. (12)	10 men	61 $\pm$ 4	10	3	8-10RM, 3-5RM, 15RM	15.6%
Moritani and deVries (42)	5 men	69.6	8	3	66% 1RM	22.3
Balagopal et al. (56)	?	71 $\pm$ 1	12	3	80% 1RM	37.4
Hagerman et al. (57)	Men	63.7	16	2	85-90% 1RM	68.7
Jubrias et al. (58)	17 men; 23 women	69.2	24	3	60-70% 1RM for 4 wks, 70-85% 1 RM for remainder	64
Flynn et (59)	Women	67-84	10	3	80% 1RM	82%
Welle et al. (30)	4 men; 4 women	62-72	12	3	80% 3RM	?
Fiatarone et al. (60)	37 men; 63 Women	87.1	10	3	80% 1RM	113%
Lemmer et al. (43)	Men and Women	65-75	9	3	5RM	27%
Brown et al. (61)	Men	60-70	12	3	70-90% 1RM	48%
Trappe et al. (54)	Women	74 $\pm$ 2	12	3	80% 1RM	56%
Trappe et al. (48)	Men	74 $\pm$ 2	12	3	80% 1RM	50%
Campbell et al. (62)	8 men; 4 women	56-80	12	3	80% of 1RM	55.2
Harridge et al. (63)	8 men; 3 women	85-97	12	3	80% of 1RM	134%
Yarasheski et al. (52)	8 women; 4 men	76-92	12	3	65-100% of 1RM	24.7
Griewe et al. (64)	4 men; 4 women	82 $\pm$ 1	12	3	85-100% of initial 1RM	23.5
Frontera et al. (1988)(50)	12 men	60-72	12	3	80% 1RM	107.4

whereas the mixed muscle protein synthesis rate increased 166% in response to two weeks of resistance exercise training. The response was similar for 78-84 year olds and 23-32 year olds. Yarasheski et al. (51) reported that two weeks of resistance training increased mixed muscle protein synthesis by 153% in elderly subjects. Yarasheski et al. (52) also reported that mixed muscle protein synthesis was increased ($P < 0.01$) in response to 3 months of resistance training in individuals over the age of 75. Further, Welle et al. (30) reported that after three months of resistance training there was no change in the myofibrillar protein synthesis rate in either young or old groups. One mechanism for an increased rate of muscle protein synthesis could be increased muscle IGF-1 levels observed in elderly men and women as a result of resistance exercise training (53). The majority of data suggest that there is an increase in muscle protein synthesis in response to resistance training in the elderly and that the increase is similar to that of young people.

Single Fiber Contractile Function, Exercise, and Age

Trappe et al. (48, 54) have extensively studied the single fiber physiological response to resistance exercise in elderly men and women. It should be noted that these single fiber measurements are conducted in absence of nervous system input. The increase in whole muscle strength in response to the resistance training protocol was 50% in men and 56% in women. They reported that in men a 45% increase in the fiber area of myosin heavy chain (MHC) I fibers and a 28% increase in the MHC II a fiber area. However, in women, there was a 24% increase in the size of MHC I fibers and no increase in MHC II a single fibers. In men and women there was a substantial increase in the isometric force of both MHC I and MHC II a fibers with the increase being greater in men than in women and for MHC I than MHC II a fibers. For men there was a 75, and 45% increase in MHC I and MHC II a fiber unloaded shortening velocity but no increase in unloaded shortening velocity of either fiber type for women. In men and women the peak power increased in both MHC I and MHC II fiber types with the increase being greater for MHC I than MHC II and the increase being greater for men than women. Thus, from these data it appears that in the elderly, the adaptations in the MHC type I fiber are greater than MHC type II fiber and that the adaptations at the single cell level are greater in men than women. This is despite similar increases in whole muscle strength. One possible interpretation that requires scientific inquiry is that the neurological adaptations (increased motor unit firing rates or recruitment and/or decreased antagonist co-activation) are greater in women than in men.

Effects of Resistance Training on Muscle Activation

Generally speaking, since muscle activation is maximal, in most muscle groups in the elderly, an increase in activation cannot occur even with resistance training. However, there are changes in muscle coactivation. Carolan and Cafarelli (55) reported a 21.8% reduction of co-activation of the biceps femoris during vastus lateralis MVC as a result of 8 weeks of isometric knee extensor training. However, this was in young individu-

als. Hakkinen et al. (12) reported a 12.5 % reduction in co-activation in ~70 year old men and a 22.6% decrease in co-activation in ~70 year old women as a result of 6 months of heavy resistance training combined with explosive exercise. Thus it appears that a reduction in co-activation plays a significant role in the increased force production in the direction of intended movement in resistance trained elderly.

CONCLUSION

The factor exerting the most influence on muscle force production is its cross-sectional area. Muscle quality (force production/unit cross-sectional area) appears to play a minor role in force producing capabilities. Resistance training clearly can increase muscle cross-sectional area in the elderly and the extent of this increase in muscle size appears to be similar in older and younger individuals. Agonist muscle activation does not appear to be limiting factor to muscle force production in the elderly however antagonist muscle co-activation does appear to play a significant role. Resistance training in addition to its direct effect on muscle agonist force production can lessen the effects of antagonist muscle co-activation. In summary, resistance training appears to be a very efficacious alternative in lessening the deleterious effects of sarcopenia.

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