A cross-sectional study of muscle strength and mass in 45- to 78-yr-old men and women

FRONTERA, WALTER R., VIRGINIA A. HUGHES, KARYN J. LUTZ, AND WILLIAM J. EVANS
Human Physiology Laboratory, US Department of Agriculture—Human Nutrition Research Center on Aging, Tufts University, Boston, Massachusetts 02111

The increased prevalence of disability in the elderly population (22) has been associated with disorders of the musculoskeletal system, including weakness and muscle atrophy from disuse. A reduction in muscle strength with advancing age has been demonstrated in several studies (2, 8, 25, 29, 37) and is likely the result of a quantitative loss of muscle mass (7, 26, 28, 34) and/or a specific decrease in the ability of aging muscles to generate tension (8, 37). However, the contribution of the two mechanisms to age-related muscle weakness has not been established.

Bruce et al. (8) showed that the ratio of muscle maximum voluntary force to muscle cross-sectional area for the elderly subjects was 78% that for the young adults and suggested that muscle atrophy is not the only cause of the weakness of old age. Vandervoort and McComas (36) reported that the decreases with age in ankle plantar and dorsiflexor muscle strength were larger than the reductions in muscle cross-sectional area. Therefore calculated ratios of torque per unit area were significantly lower in the elderly subjects. Because distal muscles were used in these studies and the rate of strength decline during aging is different between distal and proximal muscle groups and upper and lower extremities (23, 30, 33), these results should not be generalized to muscles such as the elbow and knee flexors and extensors.

A comparison of muscle strength between young and older subjects should include a measurement of the amount of muscle tissue available to generate force. However, most of the available in vivo methods to estimate muscle mass are prone to considerable error (14). Normalization of muscle force with in vivo determinations of cross-sectional area (CSA) might be appropriate in parallel-fiber skeletal muscles (e.g., the adductor pollicis) but underestimates physiologically effective muscle size in pennate muscles, such as the quadriceps and the triceps. The intra- and intermuscular fat stores of elderly people are considerable (7, 21), resulting in an overestimation of muscle CSA and therefore an underestimation of the strength-to-muscle size ratio. This study uses whole body estimates of muscle and fat-free mass to evaluate age- and gender-related differences in muscle strength.

Gender related differences have been studied in relation to the decline in muscle strength with advancing age. Differences between men and women in absolute strength in various muscle groups have been reported by several authors (4, 12, 29, 31, 36). However, when corrected for differences in body weight (11, 29), height and lean body weight (31), and muscle area (4, 36), these differences decrease and/or disappear. It is interesting to note that the decline in the CSA of the quadriceps muscle has been found to be less than the reduction in voluntary quadriceps strength in elderly men (38) but not in elderly women (37). This finding suggests that the importance of a diminished muscle mass to the age-related decline in muscle strength could be related to the sex of the individual.

Finally, the frequent use of isokinetic dynamometers in rehabilitation clinics attended by an increasingly older population emphasizes the need to understand the normal variations in isokinetic strength with aging and their relationship to changes in muscle mass. The objectives of the present study were 1) to measure the strength of the knee and elbow extensor and flexor muscle groups in normal 45- to 78-yr-old male and female subjects; 2) to examine the relationship between changes in muscle strength, age, and body composition; and 3) to describe
these changes in relation to sex, muscle location (upper vs. lower extremity), and function (extension vs. flexion).

METHODS

Subjects. Two hundred healthy noninstitutionalized men and women from the Greater Boston Area between the ages of 45 and 78 yr volunteered for the study in response to newspaper advertisements. They had no history, symptoms, or signs of any neuromuscular condition or organic disease that could impair skeletal muscle function or influence body composition. All volunteers received a complete explanation of the purpose and procedures of the investigation and gave their consent. The study was approved by the Human Investigation Review Committee of Tufts University-New England Medical Center.

Muscle strength. Dynamic concentric muscle strength of the dominant (dominance was self-reported) and nondominant knee and elbow extensor (KE and EE) and flexor (KF and EF) muscle groups was measured with a Cybex II isokinetic dynamometer (Lumex, Ronkonkoma, NY). During the testing of the knee joint, the lever arm was attached to the tibia, and its axis of rotation was aligned with the anatomic axis of rotation of the knee joint. To stabilize the hip joint and the trunk, the volunteers were seated in a chair with support for the back and were restrained with straps at the level of the chest, pelvis, and thigh. The hip joint was at an angle between 90 and 100° of flexion during testing.

The EE and EF muscle groups were tested with the volunteers in a supine position and restrained with a strap at the level of the pelvis. The arm was positioned in 45° of abduction. The volunteers were instructed to keep the wrist locked in neutral position throughout the movement. The rotational axis of the lever arm was aligned with the axis of rotation of the elbow just distal to the lateral epicondyle of the humerus. The test was started with the elbow in full flexion. The volunteers were not permitted to raise the shoulder or arm off the testing table backrest or elbow pad.

Calibration of the machine was performed using standard weights placed on the lever arm. On the testing day, after a period of standardized warm-up and familiarization, the subjects were verbally encouraged to exert maximal muscular force. The subjects performed five maximal voluntary contractions at 60°/s. They were also asked to perform 25 maximal contractions at 240°/s for the knee and at 180°/s for the elbow. It was determined before the study that not all subjects were able to generate torque with their elbow flexors and extensors at 240°/s. The highest or peak torque was recorded and taken as representing slow- and fast-speed isokinetic strength.

All subjects were tested on two occasions 7–10 days apart. The higher value of the two tests was used for analysis. Average values were significantly higher ($P < 0.001$) in the second test. An increase of 9.5–17.7 and 10.5–20.6% was measured in the knee and elbow, respectively.

Body composition. Body density was determined by hydrostatic weighing (17) with a Sauter scale (model K120, Mettler Instruments). Residual lung volume was estimated from age and height (5). Body fat was calculated from total body density with the equation of Siri (32). Fat-free mass (FFM) was calculated by subtracting fat tissue mass from total body mass. A subgroup of the 200 subjects ($n = 141$) was instructed to follow a creatine and creatinine-free diet for 5 days. Two 24-hr urine specimens were collected during the last 2 days of the dietary period. Urinary creatinine was measured on a Cobas Fara II centrifugal analyzer with a commercially available kit based on the method of Larsen (24), as modified by Roche Diagnostic Systems Technical Procedure 44905, 1985 (Montclair, NJ). Muscle mass (MM) was calculated by assuming an equivalence of 18.5 kg of muscle per gram of urinary creatinine (19).

Statistical analysis. Means ± SD were calculated for all variables. A two-way analysis of variance (ANOVA) was used to determine the effects of age, gender, and the age-gender interaction. When a statistically significant $F$ value was obtained, a one-way ANOVA was used to examine the age effect in each gender. Regression analysis was performed to examine the association between variables of interest. Statistical significance was accepted at an alpha level $<0.05$.

RESULTS

Subject characteristics. The number of subjects in each group, mean age, weight, height, and FFM are shown in Table 1. Mean muscle mass (MM) data for the subgroup of 141 subjects are also included in Table 1. There were no significant differences between this subgroup ($n = 141$) and the rest of the population ($n = 59$) for the variables shown in Table 1.

Significantly lower FFM ($P = 0.001$) and MM ($P = 0.002$) were observed in the older groups. On average, men were taller and heavier, with greater FFM and MM than women ($P < 0.001$).

Muscle strength. Absolute and corrected muscle strength values are presented in Tables 2–5. Because no significant differences were seen between the dominant and nondominant sides, only the results of the dominant side (87% of the subjects were right-handed) are presented. There were no significant differences in absolute strength and strength corrected for FFM in all muscle groups between the total population ($n = 200$) and the subgroup ($n = 141$) with MM data. No age-gender interaction was found in any of the muscle groups.

Age effect. At 60°/s the oldest subjects had a significantly lower absolute strength in all muscles. This difference was still evident after correction for FFM in the KE and EF in both sexes and in the KE of male subjects. Strength per kilogram of FFM did not differ between age groups in the KE of female subjects and the EE of both sexes. At this angular velocity, the correction of strength for MM eliminated the significant differences between age groups in all muscles. The percent difference between the youngest and the oldest group was smaller when corrected strength values were compared. The difference in absolute strength ranged from 18.8 to 21.1% in the various muscle groups (because there was no age-gender interaction, values for male and female subjects
TABLE 1. General subject characteristics

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>Age, yr</th>
<th>Weight, kg</th>
<th>Height, cm</th>
<th>FFM, kg</th>
<th>MM, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men</td>
<td>I</td>
<td>24</td>
<td>50.5±2.8</td>
<td>80.8±13.7</td>
<td>176.3±7.4</td>
<td>60.2±6.9</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>28</td>
<td>60.1±3.0</td>
<td>76.4±10.1</td>
<td>177.0±6.7</td>
<td>57.0±6.4</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>34</td>
<td>68.5±2.8</td>
<td>79.0±9.1</td>
<td>174.4±7.5</td>
<td>55.4±5.3</td>
</tr>
<tr>
<td>Women</td>
<td>I</td>
<td>24</td>
<td>50.2±2.6</td>
<td>61.6±10.0</td>
<td>163.8±5.9</td>
<td>40.5±5.3</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>52</td>
<td>60.1±2.8</td>
<td>66.6±11.2</td>
<td>162.0±5.9</td>
<td>38.3±4.4</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>34</td>
<td>69.0±3.8</td>
<td>63.4±10.6</td>
<td>158.4±5.0</td>
<td>36.2±4.9</td>
</tr>
</tbody>
</table>

Values are means ± SD; n, no. of subjects in each group. FFM, fat-free mass determined by hydrostatic weighing; MM, muscle mass estimated from urinary creatinine excretion in 141 subjects (nos. per group in parentheses). * Age effect in the absence of age-gender interaction; † gender effect in the absence of age-gender interaction.

were combined). When strength was expressed per kilogram of MM, the difference ranged from 3.6 to 10.0%.

At the faster speed, older subjects had a significantly lower absolute muscle strength in all muscle groups. Correction for FFM and MM eliminated this difference in all muscle groups except KE. The percent difference in absolute strength between the youngest and the oldest groups ranged from 18.7 to 23.0% in the various muscle groups and from 3.8 to 14.2% when strength was expressed per kilogram MM.

The KF-to-KE absolute muscle strength ratios averaged 55.8 and 54.0% in men and women, respectively, when tested at 60°/s and 62.2 and 61.4% at 240°/s. The strength of the extensors and flexors in the upper extremities was more balanced. The EF-to-EE ratios averaged 103.7 and 90.7% in men and women, respectively, at the slow speed and 102.1 and 87.8% when testing was conducted at 180°/s. These ratios were similar in all age groups.

When tested at 60°/s, the slope of the curve showing the decline in strength with aging in the KE and KF muscle groups was significantly different (P < 0.02) from that of the EE and EF groups in both men and women.

Gender effect. Men were significantly stronger at both angular velocities and in all four muscle groups tested. This gender effect was independent of the age group. These differences persisted in all muscle groups after correction for FFM.

At the slower speed, strength per kilogram of MM remained significantly (P < 0.001) higher in men in the EF only. At the faster speed, the KE and KF muscle strength per kilogram of MM were similar in men and women. On the other hand, the EF and EE muscle groups remained significantly (P = 0.001) stronger in men, even after adjustment for MM. In women tested at the slower speed, KE absolute peak torque and torque corrected for FFM and for MM were for each of three age groups 60.6, 91.9, and 97%, respectively, those of men (Table 6). Corresponding values for the KF were 58.7, 89.9, and 95.9%. In the upper extremities the values for the EE were 53.6, 82.7, and 84.2%, and those for the EF were 46.9, 72.2, and 73.2%, respectively. The calculated percentages for the peak torque at the faster speed were similar in all age groups.

DISCUSSION

Age effect. The decline in muscle strength associated with advancing adult age could result from a quantitative...
loss of contractile protein (loss of muscle fibers due to muscular and/or neural alterations), a decrease in the ability of skeletal muscle to generate tension due to localized changes (e.g., a change in fiber length or angle), a reduction in the capacity of the central nervous system to activate otherwise normal motor units, or any combination of these mechanisms. Our results strongly suggest that a significant component of the age-related muscle weakness is a loss of muscle mass. Grimby and Saltin (18) argued that a major reason for the marked loss of strength in elderly people is a quantitative and not a qualitative change resulting from the loss of muscle fibers. This theory was confirmed later by Lexell et al. (26), who counted the number of fibers in autopsied vastus lateralis muscle and reported an average reduction in muscle area of 40% and in total number of fibers of 38% from 20 to 80 yr. Although fiber hypotrophy was also present, the lower number of fibers could almost completely account for the smaller muscle size. It is not possible with our data to determine whether the loss of muscle mass was due to a reduction of motor neurons resulting in loss of all the muscle fibers of a motor unit or a decrease in the number of muscle fibers in the presence of a constant number of functioning motor neurons. Others have shown, however, that the number of motor units decreases with aging (9).

The second explanation, an alteration in muscle fiber length and/or angle, remains a reasonable hypothesis but cannot be tested with our data. With the present techniques it is virtually impossible to measure these variables in living humans (14). The third possibility, a failure in the activation of the complete motor neuron pool during a maximal voluntary contraction, is not supported by the findings of Vandervoort and McComas (36). Most of their subjects did not show an increase in force output in response to a superimposed electrical stimulus during a maximal voluntary effort.

In the present study, absolute isokinetic strength of the KE and KF muscle groups was 20.0 and 22.0% lower in elderly men and 17.6 and 15.5% lower in elderly women, respectively, than in the younger groups of the same sex. Strength values and the differences between age groups found in the present study are consistent with other studies of isokinetic muscle strength in older men and women. Larsson et al. (25) found that the quadriceps isokinetic strength measured at 60°/s was 28.1% lower in men with an average age of 70 yr than in a younger group (average = 43.1 yr). Borges (6) found that

### Table 3. Isokinetic muscle strength of the knee flexors of the dominant side

<table>
<thead>
<tr>
<th>Age Range, yr</th>
<th>60°/s N·m</th>
<th>N·m·FFM⁻¹</th>
<th>N·m·MM⁻¹</th>
<th>240°/s N·m</th>
<th>N·m·FFM⁻¹</th>
<th>N·m·MM⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45–54</td>
<td>100±21</td>
<td>1.7±0.3</td>
<td>3.6±0.7</td>
<td>61±16</td>
<td>1.0±0.2</td>
<td>2.2±0.6</td>
</tr>
<tr>
<td>55–64</td>
<td>94±20</td>
<td>1.6±0.3</td>
<td>3.6±0.5</td>
<td>57±15</td>
<td>1.0±0.2</td>
<td>2.1±0.5</td>
</tr>
<tr>
<td>65–78</td>
<td>78±19</td>
<td>1.4±0.3</td>
<td>3.0±0.8</td>
<td>50±15</td>
<td>0.9±0.3</td>
<td>1.9±0.6</td>
</tr>
<tr>
<td>Women</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45–54</td>
<td>58±14</td>
<td>1.4±0.2</td>
<td>3.3±0.7</td>
<td>36±10</td>
<td>0.9±0.2</td>
<td>2.0±0.5</td>
</tr>
<tr>
<td>55–64</td>
<td>52±10</td>
<td>1.4±0.2</td>
<td>3.1±0.7</td>
<td>33±7</td>
<td>0.9±0.2</td>
<td>2.0±0.5</td>
</tr>
<tr>
<td>65–78</td>
<td>49±10</td>
<td>1.4±0.3</td>
<td>3.3±0.7</td>
<td>29±8</td>
<td>0.8±0.2</td>
<td>1.9±0.5</td>
</tr>
</tbody>
</table>

Values are means ± SD. * Age effect in the absence of age-gender interaction; † gender effect in the absence of age-gender interaction; ‡ significant age-gender interaction in 2-way ANOVA; 1-way ANOVA: men P = 0.007, women P = 0.481.

### Table 4. Isokinetic muscle strength of the elbow extensors of the dominant side

<table>
<thead>
<tr>
<th>Age Range, yr</th>
<th>60°/s N·m</th>
<th>N·m·FFM⁻¹</th>
<th>N·m·MM⁻¹</th>
<th>180°/s N·m</th>
<th>N·m·FFM⁻¹</th>
<th>N·m·MM⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45–54</td>
<td>50±15</td>
<td>0.8±0.2</td>
<td>1.3±0.6</td>
<td>37±9</td>
<td>0.6±0.1</td>
<td>1.3±0.3</td>
</tr>
<tr>
<td>55–64</td>
<td>46±11</td>
<td>0.8±0.2</td>
<td>1.3±0.4</td>
<td>33±10</td>
<td>0.6±0.1</td>
<td>1.2±0.3</td>
</tr>
<tr>
<td>65–78</td>
<td>40±10</td>
<td>0.7±0.2</td>
<td>1.2±0.5</td>
<td>29±10</td>
<td>0.5±0.2</td>
<td>1.2±0.4</td>
</tr>
<tr>
<td>Women</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45–54</td>
<td>27±11</td>
<td>0.7±0.2</td>
<td>1.6±0.5</td>
<td>18±19</td>
<td>0.4±0.2</td>
<td>1.0±0.5</td>
</tr>
<tr>
<td>55–64</td>
<td>25±8</td>
<td>0.6±0.2</td>
<td>1.5±0.6</td>
<td>16±6</td>
<td>0.4±0.1</td>
<td>1.0±0.5</td>
</tr>
<tr>
<td>65–78</td>
<td>21±6</td>
<td>0.6±0.2</td>
<td>1.6±0.6</td>
<td>15±5</td>
<td>0.4±0.2</td>
<td>1.0±0.4</td>
</tr>
</tbody>
</table>

Values are means ± SD.
the isokinetic strength of the KE measured at 90°/s was 23.1 and 19.7% lower in the 70-yr-old men and women, respectively, than in the 50-yr-old group. In that study, strength values of the KF were 20.4 and 25.0% lower in the older men and women, respectively.

Loss of static muscle strength with age has been studied (23, 35) in EE and EF muscle groups, indicating a 30% difference in EF isometric strength between 40- to 49- and 60- to 69-yr-old men. Kamon and Goldfuss (23) reported a 16 and 7% difference in the isometric strength of EF in male and female subjects, respectively, when the 19- to 31- were compared with 32- to 67-yr-old workers. In the present study, isokinetic strength of the KE and EF muscle groups was 20.0 and 20.8% lower, respectively, in older men and 22.2 and 16.7% lower in older women.

We found an average difference in MM of 13.4% between the oldest and youngest groups. These findings are in agreement with at least two cross-sectional studies that have also used urinary creatinine excretion to estimate MM. Tzankoff and Norris (34) studied 959 healthy subjects aged 20-97 yr and saw a reduction of ~33% of the total MM over a 50-yr period. Fleg and Lakatta (15) examined 83 men (28-87 yr) and 101 women (22-82 yr) and found that the loss of MM between 30 and 70 yr was 23.4% for men and 22.0% for women.

The loss of muscle strength in the proximal muscles of the lower extremities is greater than that of the upper extremities, presumably due to a decreasing use of lower compared with upper limb muscles in the elderly groups (2, 23, 30, 33, 35). It has also been postulated that the use of faster and more forceful contractions in the upper than in the lower extremities might delay the fast-twitch muscle fiber atrophy known to occur with aging (3, 18). Chemical analysis of the total intramuscular fat content of the biceps brachii (16) did not show a significant increase in older subjects, in contrast to the findings in thigh and leg muscles (16), suggesting that the decline in MM is slower in the upper extremities. Our results do suggest a differential loss of strength between upper and lower extremity muscles, with a faster decline in the strength of the KE and KF than in the EE and EF muscle groups with advancing age. This age effect was independent of gender.

The main finding of the present study was that correction of absolute isokinetic muscle strength values for FFM and MM significantly reduced and/or completely eliminated age-related differences. Furthermore, this observation was independent of muscle location (upper and lower extremities) as well as function (extension and flexion). In relative terms, the percent difference in strength between the youngest and the oldest male and female subjects was smaller when corrected for MM. In women, differences in strength were completely elimi-
nated and, in a particular case, the EF tested at 60°/s, the oldest group was stronger than the younger groups. Other investigators have also reported that old and young women have similar strength per unit area of the KE (37). On the other hand, our findings are in contrast with the results of Davies et al. (13), Bruce et al. (8), and Vandervoort and McComas (36), who reported that differences in isometric strength between young and older adults remained, even when a correction was made for estimated muscle CSA and results were expressed in terms of specific tension (N/cm²). However, it should be noted that the reduction in specific tension is due in part to the difficulty of actually measuring muscle CSA from simple anthropometric tests (8, 13) or ultrasound images (36). If the age-related replacement or infiltration by fat of muscle tissue is not taken into consideration (7, 21), even with the use of modern imaging techniques, the effective muscle CSA in elderly subjects will be overestimated and the specific tension underestimated. Lexell et al. (26) have calculated that, in male vastus lateralis muscle of younger (20 yr) individuals, ~70% of the muscle area was composed of muscle fibers, whereas for the older individuals (80 yr) this value was ~50%, the remainder including fat, connective tissue, and blood vessels.

**Gender effect.** The expected gender-related differences in absolute muscle strength and body composition were found in the present study. Women had 59.8 and 68.7% the strength of men in the lower extremities when they were tested at the slow and faster speeds, respectively. The differences were more marked in the EE and EF muscle groups, where women had between 50.2 and 46.1% the strength of men.

Our data are consistent with published reports (1, 6, 27, 33). For example, Sperling (33) found that 70-yr-old women had in elbow extension ~48% and in elbow flexion ~60% the static strength of healthy 70-yr-old men. Aniansson et al. (1) studied older subjects and reported an average KE isokinetic peak torque for women that was 55% that of men. Murray et al. (27) found in the KE that 20- to 86-yr-old women averaged 74% the strength of men the same age. More recently, Borges (6) found women in different age groups to have ~65.7 and 53% the isokinetic peak torque of men in the KE and KF, respectively.

It has been suggested that gender-related variations in strength are due largely to differences in body size and/or composition (11, 29, 31, 33). Expression of muscle strength values per kilogram of body weight has been shown to eliminate upper and lower extremity strength differences between the sexes (11, 29). Relative to lean body weight, young women have greater lower-body strength (leg press) but less upper-body (bench press) strength than men (20). Vandervoort and McComas (36) reported lower (60-70%) strength values in young and old female subjects relative to age-matched male subjects, but the ratios of torque per muscle unit area did not show a gender difference. Bassey et al. (4) showed a significantly lower ratio of strength per kilogram of body weight in old women but no difference when the strength was expressed per unit area of muscle plus bone calculated from circumference and skinfolds. These findings suggest that gender-related differences in strength are more quantitative than qualitative in nature.

Calf muscle CSAs in older women are ~75% those of older men (36). Cohn et al. (10) have shown that female subjects between 40 and 79 yr have ~40-55% the MM of males, the percentage being lower in the older (60-69 and 70-79) two groups. In the three age groups studied in this investigation, women had 66, 63, and 59% the MM of men, respectively. The lower percentage in the oldest groups suggests that the loss of MM may occur at a relatively faster rate in women. It has been reported that, in female subjects, the amount of interstitial fat in thigh muscles is larger and the increase with age occurs at a faster rate (16). These data are consistent with the larger difference in MM between the oldest and the youngest women compared with men in our population.

The differences between men and women, like the age-related changes, were diminished or completely eliminated when muscle strength was expressed per kilogram of MM. This was true of the KE and KF peak torque values; however, in the upper extremities, the EF peak torque remained significantly lower even after adjustment for MM, suggesting that the loss of MM was not the only reason for the decline in strength in this muscle group.

**Conclusion.** The data presented in this study show a substantial difference in muscle strength with advancing age. Additionally, our results suggest that these differences are most likely caused by changes in MM and not by altered muscle function. These data are representative of healthy elderly individuals and therefore may not be generalizable to the entire population of older people. However, because the subjects in the present study were free from disease, the results represent true age-related changes.

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Address for reprint requests: W. R. Frontera, Center for Sports Health and Exercise Sciences, Albuquerque Olimpico, P.O. Box 2004, Salinas, PR 00751.

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**REFERENCES**


AGING, MUSCLE STRENGTH, AND MASS


