High-Velocity Resistance Training Increases Skeletal Muscle Peak Power in Older Women

Roger A. Fielding, PhD,* Nathan K. LeBrasseur, MSPT,* Anthony Cuoco, MS,* Jonathan Bean, MD, MS,† Kelly Mizer, BS,* and Maria A. Fiatarone Singh, MD‡

OBJECTIVES: Peak power declines more precipitously than strength with advancing age and is a reliable measure of impairment and a strong predictor of functional performance. We tested the hypothesis that a high-velocity resistance-training program (HI) would increase muscle power more than a traditional low-velocity resistance-training program (LO).

DESIGN: Randomized controlled trial.

SETTING: University-based human physiology laboratory.

PARTICIPANTS: Thirty women with self-reported disability (aged 73 ± 1, body mass index 30.1 ± 1.1 kg/m²).

INTERVENTION: We conducted a randomized trial comparing changes in skeletal muscle power and strength after 16 weeks of HI or LO. Training was performed three times per week, and subjects completed three sets (8–10 repetitions) of leg press (LP) and knee extension (KE) exercises at 70% of the one-repetition maximum (1RM).

MEASUREMENTS: One-repetition maximum (1RM) and peak power for KE and LP.

RESULTS: LP and KE relative training force and total work were similar between groups (P > .05). However, HI generated significantly higher power during training sessions than LO for LP (3.7-fold greater, P < .001) and KE (2.1-fold greater, P < .001). Although LP and KE 1RM muscle strength increased similarly in both groups as a result of the training (P < .001), LP peak power increased significantly more in HI than in LO (267 W vs 139 W, P < .001). Furthermore, HI resulted in a significantly greater improvement in LP power at 40%, 50%, 60%, 70%, 80%, and 90% of the 1RM than did LO (P < .05).

CONCLUSIONS: HI improved 1RM strength similarly and was more effective in improving peak power than was traditional LO in older women. Improvements in lower extremity peak power may exert a greater influence on age-associated reductions in physical functioning than other exercise interventions. J Am Geriatr Soc 50:655–662, 2002.

Key words: exercise; aging; power training

Skeletal muscle strength, or the maximum capacity to generate force, declines with advancing age after the fifth decade of life. A progressive loss in muscle mass, or sarcopenia, due to reductions in the number and size of muscle fibers, contractile velocity, and muscle quality (declines in single-fiber diameter, peak force, and maximum shortening velocity), appears to contribute to this phenomenon. Peak skeletal muscle power, the product of the force and velocity of muscle shortening, declines earlier and more precipitously than strength with advancing age. Mechanisms accounting for this precipitous decline may include loss of type II motor units, reductions in nerve conduction velocity, and intrinsic changes in skeletal muscle force and power-generating capacity with aging. Although considerable efforts have been made to understand the etiology, associations, and reversibility of the age-related decline in strength, not until recently has there been an interest in alterations in skeletal muscle peak power.

Power is a reliable measure of muscle performance in younger and older individuals. The significance of impairments in muscle power has been demonstrated in studies confirming the positive association between muscle power and functional mobility tasks and the identification of peak muscle power as a strong physiological predictor of functional limitations and disability in older people.

Several studies have demonstrated that, given a training stimulus of appropriate intensity (70–90% of the one-repetition maximum (1RM)), gains in muscle strength and size in older healthy and frail individuals are comparable with the gains observed in young individuals (for review see 10). However, despite demonstrating over a 100% in-
crease in strength, Fiatarone et al. observed only a 28% increase in stair climbing power in response to a progressive resistance-training intervention. Similarly, with more-modest increases in strength, Skelton et al. failed to observe a significant increase in leg extensor peak power (18%) after 12 weeks of progressive resistance training in older women. Recently Joszi et al. also noted modest improvements in knee extensor strength (17–35%) and power (14–29%) in response to 12 weeks of progressive resistance training in healthy older men and women. A recent study using a high-velocity resistance-training program (HI) has reported similar gains in strength (22%) and peak power (22%) in older healthy men and women. These results suggest that progressive resistance training results in small improvements in peak power. Resistance-training interventions that specifically target the development of high muscle power during movement are likely required to produce significant changes in peak power in older adults.

Therefore, the aim of the present study was to compare the physiological outcomes of a high-force HI with a conventional high-force low-velocity resistance-training program (LO) in older women with self-reported functional limitations. Women with self-reported limitations in functioning were specifically targeted in this study because of their lower peak power and increased risk of falls and functional dependency compared with age-matched men and women with no functional limitations. We hypothesized that a HI would result in significantly greater increases in peak muscle power of the lower extremities than a LO and in similar improvements in muscle strength (1RM).

METHODS

Study Design

This study was a randomized 16-week trial comparing the physiological outcomes of a HI to a LO in older women with preexisting functional limitations. Research subjects were randomly assigned to the study arms after acceptance into the study and after baseline testing.

Study Population

Subjects were recruited from the Boston area through advertisements in local senior citizen publications, visits to senior residences, and through the Harvard Research Cooperative on Aging volunteer database. Potential subjects were initially screened by telephone or in person. To be eligible for the study, subjects needed to be aged 65 and older, community dwelling, and capable of walking with or without use of an assistive device and to report two or more deficits on the physical function subscale of the Medical Outcomes Study Short Form. Eligible subjects completed a medical history questionnaire and underwent a physical examination and medical screening by the study physician. Subjects were excluded from participation if they had acute or terminal illness, myocardial infarction in the past 6 months, unstable cardiovascular disease or other medical condition as assessed during the screening history and physical examination, upper or lower extremity fracture in the past 6 months, upper or lower extremity amputation, cognitive impairment according to the Folstein Mini-Mental State Examination (MMSE) (score <23), current participation in regular exercise sessions (>1×/week), or unwillingness to be randomized into either intervention or to complete the study requirements. Subjects meeting these criteria and given medical clearance by the study physician and written approval from their primary care physician were determined eligible for participation. All subjects gave written informed consent. The Boston University Institutional Review Board approved this study.

Subject Characteristics

Body mass was recorded on a standard platform scale at baseline, 8 weeks, and 16 weeks to the nearest 0.1 kg with the subject in similar clothing each time. Height was measured to the nearest 0.5 cm with a scale stadiometer. Body mass index was calculated by dividing body mass in kilograms by height in meters squared. Psychosocial variables, including measures of cognition, depressive symptoms, and physical activity, were also recorded at baseline, because these factors may be important covariates when examining the response to exercise training. The Geriatric Depression Scale was administered to assess depression. Habitual occupational, household, and leisure physical activity was estimated using the Physical Activity Scale for the Elderly. Global cognitive function was assessed by the MMSE. Number of medical diagnoses and daily medications were assessed via medical history questionnaires and the physical examination. History of falling was determined by questionnaire. Baseline habitual gait velocity was measured using an Ultra timer (DCPB Electronics, Glasgow, Scotland).

High-Velocity Resistance-Training Program

Subjects randomized to the HI trained three times per week for 16 weeks. All of the training sessions and evaluation sessions were conducted in the human physiology laboratory under the direct supervision of one of the exercise trainers. During each session, subjects performed three sets of eight repetitions of bilateral leg press (LP) and individual left and right knee extension (KE) using Keiser pneumatic resistance training equipment (Keiser Sports Health Equipment Inc., Fresno, CA). Subjects were instructed to complete the concentric phase of each repetition as fast as possible, maintain full extension for 1 second, and perform the eccentric phase of each repetition over 2 seconds. Exercise intensity was set at 70% of the subject’s 1RM. The resistance was adjusted biweekly by repeating 1RM measures (see below). After each set, average power and total work performed were calculated as described below and recorded. During training and assessment, the recumbent LP apparatus was adjusted to provide support to the spinal column. In the starting position, the seat was positioned to place the knee and hip joints at 90° of flexion. Subjects were instructed to extend both legs fully but short of locking the knee joint. Similarly, subjects were positioned in the seated KE apparatus with the spine supported by an adjustable seat back. The articulation of the femur with the tibia was aligned with the axis of rotation of the lever arm, and the lever arm was adjusted to place the knee at 90° of flexion. The lower leg pad rested on the anterior tibia and was positioned just superior to the malleolus of the tested extremity. Exercise sessions were preceded by supervised lower extremity stretching exercises of the hip, knee, and ankle musculature.
Low-Velocity Resistance-Training Intervention

Subjects randomized to LO also trained three times per week for 16 weeks, performing three sets of eight repetitions of bilateral LP and individual left and right KE at 70% of the 1RM. All of the training and evaluation sessions were conducted in the human physiology laboratory under the direct supervision of one of the exercise trainers. Resistance was adjusted biweekly by measuring the 1RM as described below. Subjects were instructed to complete the concentric phase, maintain full extension, and perform the eccentric phase of each repetition over 2, 1, and 2 seconds, respectively. After each set, average power and total work performed were calculated as described below and recorded. Exercise sessions were preceded by stretching exercises of the hip, knee, and ankle musculature.

Outcome Measures

**Muscle Strength**

Muscle strength of the lower extremities was quantitatively assessed by 1RM measures of bilateral LP and individual left and right KE. The 1RM is defined as the maximum load that can be moved one time only throughout the full range of motion (ROM) while maintaining proper form. The 1RM measurements were conducted using the same seated LP and recumbent leg press pneumatic resistance machines customized with software and digital displays used for the training intervention. An ultrasonic system measuring position, and therefore relative motion, aided examiners in establishing a subject's full ROM by observing the excursion of a lighted bar on the output screen during performance of the measure with minimal resistance. Subjects performed the concentric phase, maintained full extension, and performed the eccentric phase of each repetition over 2, 1, and 2 seconds, respectively. The examiner progressively increased the resistance for each repetition until the subject could no longer move the lever arm one time through the full ROM. Baseline LP and KE 1RM measures were performed twice, with the second evaluation occurring 3 to 7 days after the initial evaluation. The best of the two baseline measures of strength was used as the baseline 1RM. The correlation of repeated 1RM testing of LP and KE in this population was intraclass correlation coefficient (ICC) = 0.75 and ICC = 0.77, respectively. On average, peak power for the LP and KE increased 11.9% and 7.8%, respectively, between baseline evaluations. Peak muscle power measures were repeated at Weeks 2, 4, 6, 8, 10, 12, and 16, in coordination with the 1RM measures.

**Peak Muscle Power**

After measurement of the 1RM, assessment of bilateral LP and individual left and right KE peak muscle power was performed using the same pneumatic resistance machines used for training and 1RM testing. Performance of power tests using the pneumatic resistance machines as summarized below has previously been described and validated by our laboratory. Power (W) was assessed at eight relative intensities (40%, 50%, 60%, 70%, 80%, and 90%) of the 1RM. Beginning with 40%, subjects performed the lift at each established percentage of her 1RM as fast as possible through her full ROM. At each force setting, subjects performed one maximal effort with a 30- to 45-second rest between repetitions. The software engineered for the testing equipment calculated work and power during the concentric phase of each repetition by sampling the system pressure (equivalent to force (piston area is constant)) and position 400 times a second. Data collected between the start and stop positions of the concentric phase of the repetition were used to compute work (J). Data collected between 5% and 95% of the concentric phase were used to calculate power (W) to eliminate noisy data generated at the start and end of the motion. After each repetition, work and power data were stored and then displayed on the output screen. The highest power achieved was recorded as the peak power. Baseline LP and KE peak muscle power measures were performed twice, with the second evaluation occurring 3 to 7 days after the initial evaluation. The best of the two baseline measures was used as the baseline peak muscle power. The correlation of repeated peak muscle power testing of LP and KE in this population was ICC = 0.87 and ICC = 0.75, respectively. On average, peak power for the LP and KE increased 11.9% and 7.8%, respectively, between baseline evaluations. Peak muscle power measures were repeated at Weeks 2, 4, 6, 8, 10, 12, and 16, in coordination with the 1RM measures.

**Statistical Analysis**

Data were analyzed using the Super ANOVA software package (Abacus Concepts, Berkeley, CA). All data were first examined visually and statistically for normality of distribution. All values are reported as means ± standard error. Mean differences between variables at baseline were assessed using unpaired t tests. Variables were assessed using analysis of variance and covariance for repeated measures to analyze the effect of time, treatment, and time-by-treatment interactions for all primary outcome variables. Specific mean differences were assessed using linear contrasts. Univariate regression analyses were performed to assess relationships between variables. Test/retest reliability of LP and KE repeated measurements were assessed using the ICC. Significance was set at P < .05.

**RESULTS**

Recruitment and Adherence to Training Intervention

One hundred sixty-two women responded to recruitment efforts, and, of those, 114 completed a telephone screening; 86 (53%) met the study inclusion criteria, 28 did not meet study inclusion criteria, and 38 met the criteria but could not commit to the study requirements. Eligible subjects (48) were invited to a screening assessment and physical examination. After this visit, eight were no longer eligible because of medical exclusions, and 10 were eligible but could not commit to study requirements. Therefore 30 subjects, 19% of the original respondents, were eligible and were randomized to the HI or LO study arm. Three of 15 subjects randomized to HI and two of 15 subjects randomized to LO dropped out during the training intervention. Two subjects in each group discontinued secondary to exacerbation of preexisting osteoarthritis, and one subject in the HI group withdrew secondary to recurrence of chronic plantar fasciitis. Only one of these subjects was withdrawn from the study after consultation with the study physician, the remainder withdrew on their own. No
other adverse events were reported. HI and LO subjects completing the study demonstrated excellent adherence, attending 95% and 94% of the 48 scheduled sessions, respectively.

Subject Characteristics
Descriptive characteristics are presented in Table 1. HI and LO consisted of 15 women each, with a mean age of 73.2 ± 1.2 and 72.1 ± 1.3, respectively. The racial distribution of the participants was as follows: 86% Caucasian, 7% African American, 7% Asian, and 7% of other ethnic origin. Body mass was not significantly different between groups at baseline (P = .60) or at completion of the 16-week intervention (P = .56). Of the psychosocial variables, measures of habitual physical activity (P = .54), number of medical diagnoses (P = .17), medications (0.10), habitual gait velocity (0.24), and cognitive function (P = .79) were not different between groups. However, the depression scale (P = .05) and number of falls per year (P = .05) were different. Because of these baseline differences, analysis of covariance models for time effects and time-group interactions were adjusted for baseline depression, number of medications per day, number of falls per year, and habitual activity and were used to analyze the primary outcomes.

Training Intensity
To compare the intensity at which subjects were training throughout the duration of the study, training data were analyzed on representative training days that were conducted two sessions after the 1RM and peak power measures performed at baseline and weeks 4, 8, and 12. Results for all three sets of each exercise were averaged and are presented in Table 2. As can be seen in Table 2, the relative training force was maintained at or near the desired goal of 70% of the 1RM in both groups throughout the course of the study. In addition, LP and KE absolute training force (N) and total work (J) performed were similar between groups. However, as intended, power output (W) during training was significantly higher in HI than in LO in both LP (3.7-fold) and KE (2.1-fold) (P < .001 and P < .001, respectively).

Outcome Measures
Muscle Strength
There were no differences in muscle strength between groups at baseline for LP (P = .65) or KE (0.99). Muscle strength increased progressively throughout the intervention for LP (P < .001) and KE (P < .001) in both the HI and LO groups. Compared with baseline, LP 1RM increased 305 N (35%) and 269 N (33%) in HI and LO, respectively (Figure 1a), with no significant difference between groups (P = .52), and KE 1RM increased 25 N (45%) and 22 N (41%) in HI and LO, respectively, with no difference between groups (P = .22) (Figure 1b).

Peak Muscle Power
Peak power occurred at similar percentages of 1RM for both muscle groups (LP median = 75%; KE median = 75%). There were no differences between groups at baseline for LP (P = .28) or KE (0.92) peak muscle power. At baseline, peak power of the LP was significantly related to habitual gait speed (LP: r² = 0.32, P < .001). Peak muscle power improved significantly from baseline for LP (P < .002) and KE (P < .001) in HI and LO. For LP, HI demonstrated significantly greater increases in peak power than LO (267 W (97%) vs 139 W (45%)) (P < .007) over the 16-week intervention (Figure 2a). Peak power in HI at 4 weeks increased 53% from baseline and continued to increase throughout the intervention. In LO, significant increases in peak power were not observed until 8 weeks (25%), af-

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>HI n = 15</th>
<th>LO n = 15</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, years</td>
<td>73.2 ± 1.2</td>
<td>72.1 ± 1.3</td>
<td>.53</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>157.6 ± 1.5</td>
<td>157.2 ± 1.4</td>
<td>.82</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>74.7 ± 3.4</td>
<td>71.2 ± 5.6</td>
<td>.60</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>30.0 ± 1.2</td>
<td>28.7 ± 8.2</td>
<td>.59</td>
</tr>
<tr>
<td>Medical Outcomes Survey Short Form-36</td>
<td>72.3 ± 5.2</td>
<td>71.0 ± 5.3</td>
<td>.98</td>
</tr>
<tr>
<td>Physical Function Subscale¹ (0–100)*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical Activity Scale for Elderly²⁰</td>
<td>107 ± 16.9</td>
<td>122 ± 18.2</td>
<td>.54</td>
</tr>
<tr>
<td>Habitual gait speed (m/s)</td>
<td>1.15 ± 0.04</td>
<td>1.06 ± 0.06</td>
<td>.24</td>
</tr>
<tr>
<td>Falls in past year (no.)</td>
<td>1.0 ± 0.3</td>
<td>0.3 ± 0.2</td>
<td>.05</td>
</tr>
<tr>
<td>Folstein Mini-Mental State Examination score¹⁸ (0–30)</td>
<td>29.0 ± 0.4</td>
<td>29.0 ± 0.4</td>
<td>.79</td>
</tr>
<tr>
<td>Geriatric Depression Scale score¹⁹ (0–30)†</td>
<td>5.9 ± 1.0</td>
<td>3.2 ± 0.8</td>
<td>.05</td>
</tr>
<tr>
<td>Medical diagnoses (no.)</td>
<td>2.0 ± 0.4</td>
<td>2.8 ± 0.4</td>
<td>.17</td>
</tr>
<tr>
<td>Medications per day (no.)</td>
<td>2.5 ± 0.5</td>
<td>3.9 ± 0.7</td>
<td>.10</td>
</tr>
</tbody>
</table>

*<24 = cognitive impairment.
†>9 = depression of increasing severity.
HI = high velocity resistance training; LO = low velocity resistance training.
ter which LO also increased peak power progressively throughout the intervention. Improvements in KE peak power were not significantly different between HI (30 W (33%)) and LO (22 W (25%)) \((P = .183)\) after training (Figure 2b).

In addition, the HI intervention at 70% of the 1RM resulted in a significantly greater improvement in LP power at 40%, 50%, 60%, 70%, 80%, and 90% of the 1RM compared with LO \((P < .05)\) (Figure 3). This finding was not observed in the KE power measures at varying percentages of the 1RM \((P = .822)\) (data not shown).

To examine the contribution of muscle strength to the variance in peak power, linear regression analyses were performed. At baseline, in both groups combined, LP 1RM strength accounted for 70% of the variance in LP peak power \((P < .001)\). Similarly, KE 1RM strength accounted for 65% of the variance in KE peak power \((P < .001)\). After the 16-week training intervention, LP 1RM maximal strength accounted for 62% of the variance in LP peak power \((P < .001)\), and KE 1RM maximal strength accounted for 68% of the variance in KE peak power \((P < .001)\). However, when HI and LO were examined separately at 16 weeks, only 24% of the variance in LP peak power in the HI group was explained by LP 1RM strength \((P = .104)\), whereas 78% of the variance in LP peak power of the LO group was explained by LP 1RM strength \((P < .001)\). The KE data demonstrate a similar although less dramatic effect after training, with 51% of the variance in KE peak power explained by 1RM strength in the HI group \((P < .009)\) and 77% of the variance in KE peak power of the LO group explained by KE 1RM strength \((P < .001)\).

**DISCUSSION**

The primary finding of the present study was that HI can increase peak power more dramatically than LO, particularly of the leg extensors, in older women with self-reported functional limitations. The present study confirms and extends a recent study by Earles et al., which reported similar increases in lower extremity power after HI in healthy older men and women.\(^{14}\)

Peak power output, or the maximum capacity to perform work per unit of time, of the lower extremity muscle groups has been associated with reduced function\(^{8}\) and increased levels of disability in older individuals. Specifically, in a recent study of community-dwelling women aged 70 to 95, lower extremity power was independently correlated with self-reported functional status when examined along with physical activity, neuropsychological status, medical diagnoses, and other physiological measures including strength.\(^{7}\) Similarly, in a recent study of older women with limitations in function, ankle peak power was an independent predictor of chair rise and stair climb performance.\(^{9}\)

The HI resulted in nearly a twofold increase in LP peak power and a nonsignificant 32% increase in KE peak power. These improvements in peak power after the HI were 84% greater for LP and 34% greater for KE than for LO. The time course of the increase in peak power for LP and KE in HI was remarkably similar, with both muscle groups demonstrating a rapid early rise by 4 weeks (53% and 15%, respectively) and an additional, more-gradual increase thereafter (15% per month and 6% per month, respectively). Other studies suggest that such early rises in peak power may be related to adaptations in the recruitment or activation of motor units in response to power training. Recently, Van Cutsem et al. reported an enhanced speed of voluntary contraction after 12 weeks of HI at a relatively low training force (30–40% of maximal voluntary contraction) in younger individuals.\(^{22}\) These data suggest that early changes in motor unit recruitment and activation contribute to the increased velocity of contraction observed early during dynamic training. Although not specifically measured, similar changes in motor unit activation and enhanced firing rates may have been responsible for the observed early increases in peak power in our HI. In addition, mechanisms underlying the improve-
ments in peak power observed in the present study may include specific increases in the cross-sectional area of type II muscle fiber and increases in specific force and shortening velocity of single muscle fibers. Recently, Earles et al., using a similar intervention, reported that movement velocity during the LP test increased approximately 60% in healthy older men and women, suggesting that improvements in velocity are an important component of the increased power with power training.

Along with the rapid increase in peak power, the improvements in LP power spanned a range (40–90% of the 1RM) of external resistances. This apparent lack of speci-
The results of this study demonstrate that HI can increase lower extremity muscle power in older women with self-reported functional limitations. The improvements in lower extremity muscle power are greater in HI than in LO, despite similar increases in muscle strength. These results illustrate that age-related reductions in peak lower extremity power can be ameliorated with an appropriate exercise intervention. Future studies should examine the mechanisms underlying the increase in peak power with HI, optimize the training techniques employed to improve peak power across multiple muscle groups, and assess the role of HI in improving function and reducing disability in older individuals.
ACKNOWLEDGMENTS

We would like to thank Nadine Kassis, Sharon Cyberry, and Damien Callahan for their technical assistance, and acknowledge Dennis Keiser and Keiser Sports Health Equipment Inc. for the use of their equipment.

REFERENCES