

ORIGINAL ARTICLE

WILEY

Neuromuscular adaptations after 12 weeks of light- vs. heavy-load power-oriented resistance training in older adults

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Funding information

Ministerio de Economía y Competitividad; Universidad de Castilla-La Mancha

This study aimed to determine the specific adaptations provoked by power-oriented resistance training using light (LL-PT, 40% 1-RM) vs. heavy (HL-PT, 80% 1-RM) loads in older adults. Using a randomized within-subject study design, 45 older adults (>65 years) completed an 8-week control period (CTR) followed by 12 weeks of unilateral LL-PT vs. HL-PT on a leg press. The 1-RM, theoretical force at zero velocity (F_0), maximal unloaded velocity (V_0), and maximal muscle power (P_{\max}) were determined through a force-velocity relationship test. Isometrically, the rate of force development (RFD) and the corresponding muscle excitation of the knee extensor muscles were assessed. In addition, muscle cross-sectional area (CSA) and architecture of two quadriceps muscles were determined. Changes after CTR, LL-PT and HL-PT were compared using linear mixed models. HL-PT provoked greater improvements in 1-RM and F_0 (effect size (ES) = 0.55–0.68; $p < 0.001$) than those observed after LL-PT (ES = 0.27–0.47; $p \leq 0.001$) (post hoc treatment effect, $p \leq 0.057$). By contrast, ES of changes in V_0 was greater in LL-PT compared to HL-PT (ES = 0.71, $p < 0.001$ vs. ES = 0.39, $p < 0.001$), but this difference was not statistically significant. Both power training interventions elicited a moderate increase in P_{\max} (ES = 0.65–0.69, $p < 0.001$). Only LL-PT improved early RFD (ie, ≤ 100 ms) and muscle excitation (ES = 0.36–0.60, $p < 0.05$). Increased CSA were noted after both power training programs (ES = 0.13–0.35, $p < 0.035$), whereas pennation angle increased only after HL-PT (ES = 0.37, $p = 0.004$). In conclusion, HL-PT seems to be more effective in improving the capability to generate large forces, whereas LL-PT appears to trigger greater gains in movement velocity in older adults. However, both interventions promoted similar increases in muscle power as well as muscle hypertrophy.

KEYWORDS

aging, explosive, force, high, intensity, low, strength, velocity

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1 | INTRODUCTION

The aging process is associated with progressive losses of muscle strength and power, which are mainly explained by changes of the neuromuscular system.¹ One of the most effective countermeasures against this age-related functional decline is resistance training.² Current resistance exercise recommendations for older adults suggest including power-oriented exercises (ie, concentric movements performed as fast as possible) into training programs, since muscle power is most critical to physical performance in daily tasks.²⁻⁴ Moreover, muscle power declines at a faster rate than both muscle mass and strength, making it the main target of resistance training in older adults.^{5,6}

In power-oriented resistance training, commonly called power training, subjects aim to perform concentric contractions as fast as possible, in order to maximize mechanical power output and the demands on the neuromuscular system.^{7,8} As previous studies have shown, power training is more effective in improving muscle power and physical function of older adults than traditional resistance training.⁸⁻¹⁰ Furthermore, a recent meta-analysis has demonstrated the benefits of power training in improving the muscle mass of older adults.¹¹ Since mechanical power is the product of force and velocity, it can be increased through both gains in strength and movement velocity. For example, gains in muscle power can be obtained through plyometric exercise^{12,13} (high-velocity demands) and maximal strength training (high-force demands)¹⁴ in older adults, although different mechanisms may underlie the functional gains. While plyometric exercise is assumed to increase fascicle length and the effectiveness of the stretch-shortening cycle (favoring high-velocity adaptations),^{12,13} maximal strength training typically augments muscle size and neural drive (favoring high-force adaptations).¹⁴ For this reason, several studies have attempted to determine the optimal training loads (ie, intensities) to maximize power development in older adults.¹⁵⁻¹⁷ A respective systematic review suggested that a wide range of intensities—from light-moderate ($\leq 50\%$ 1-RM) to heavy ($\geq 80\%$ 1-RM) loads—may be used to improve muscle power and physical function.¹⁸ However, the low number of studies directly comparing the effect of power training using different loads precluded the authors of this study from performing a meta-analysis, thus limiting its significance. Furthermore, it should be noted that earlier studies mostly failed to equate the prescribed volume load (ie, the number of repetitions \times external load) of the implemented power training programs, which complicates the comparison of training effects.¹⁹ In consequence, it is still unknown whether completing progressive systematic resistance training targeting the high-force

or high-velocity end of the force-velocity spectrum would be preferable to increase muscle power. This knowledge might help to optimize the prescription of power training programs for older adults.²⁰

Therefore, the present study aimed to evaluate the effects of volume load-equated light- vs. heavy-load power training on (1) the force-velocity relationship and maximal dynamic strength, (2) maximal isometric force and rate of force development and (3) muscle size and architecture in the lower limbs of older adults. According to the specificity principle of exercise training, we hypothesized that heavier loads would provoke larger increases in the high-force, low-velocity portion of the force-velocity profile whereas lighter loads would be more beneficial in improving performance in low-force, high-velocity contractions. On the other hand, both power training interventions would improve rate of force development since in both cases the repetitions are performed at maximal intended velocity, which would maximize neural drive adaptations, a major determinant of rapid force performance.²¹ Finally, maximal isometric force might increase in connection with the expected hypertrophy response,¹¹ which could be similar in both interventions due to the equal volume load.¹⁹

2 | MATERIALS AND METHODS

2.1 | Study design

The present investigation addressed the objective I of a randomized controlled trial previously described and registered in clinicaltrials.gov (ID: NCT03724461, October 30th, 2018).²² The study was performed as a within-person randomized controlled trial with repeated measures and included an 8-week control period (CTR) followed by 12 weeks of power training targeting the lower limbs. By using a control period (ie, a longitudinal study design) rather than a parallel control group we aimed to minimize bias related to biological variability and learning effects during testing, thus increasing statistical power.²³ For the training period, participants were randomized to one of the three following study arms: (i) one leg performed light-load power training (LL-PT) and the contralateral leg did not perform any exercise; (ii) one leg performed heavy-load power training (HL-PT) and the contralateral leg did not perform any exercise; and (iii) one leg performed LL-PT and the contralateral performed HL-PT (Figure 1). Within each group, the treatment assigned to each leg was randomized. Detailed information about the study design has been previously provided in a respective methods paper.²² Briefly, the rationale for this three-arm unilateral training design was based on the advantages

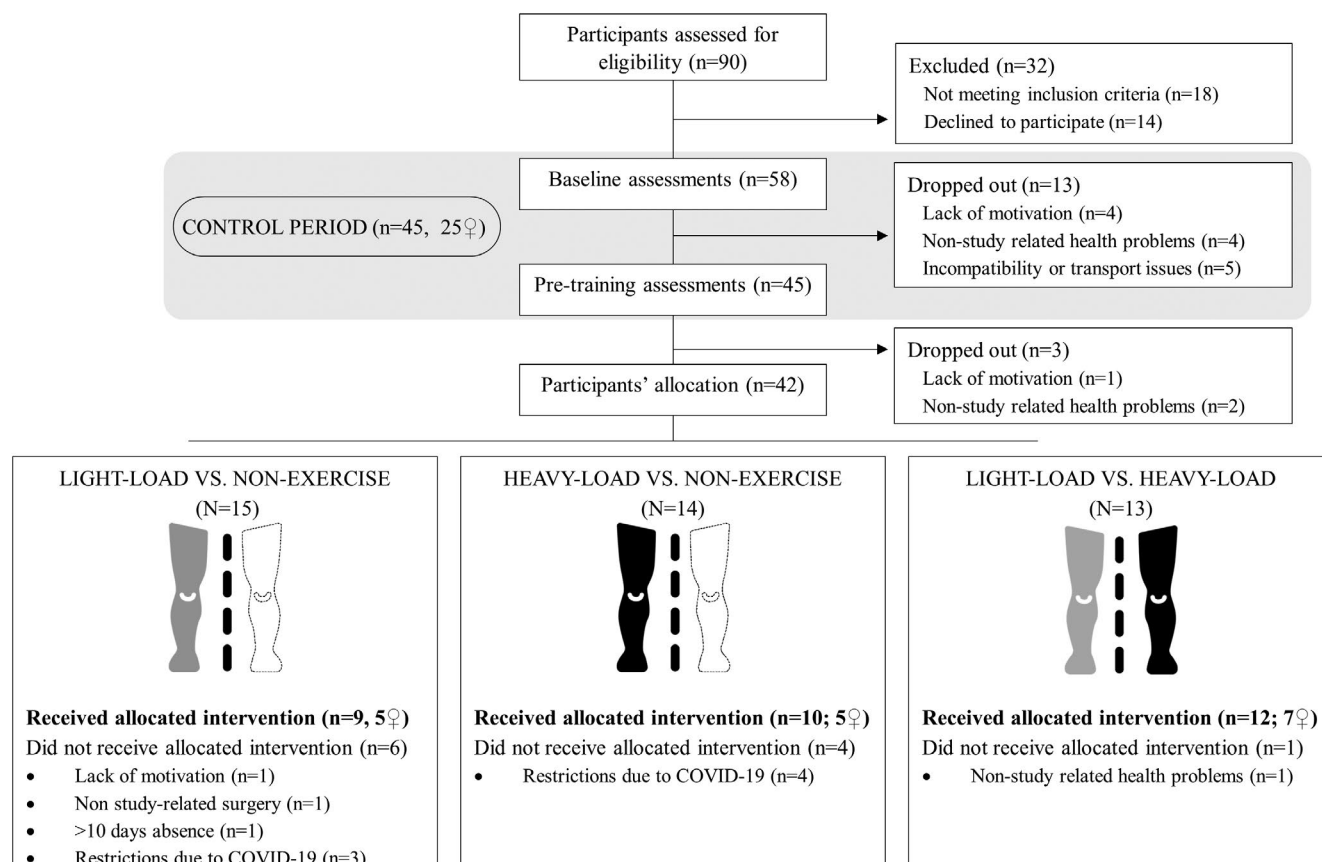


FIGURE 1 Participant selection, allocation and dropouts

that unilateral exercise models confer in terms of reducing inter-individual variability and increasing statistical power,²⁴ and also on the possibility to investigate cross-education effects, which is the objective II of the above-mentioned project. Accordingly, the data acquired in the non-exercised contralateral legs are not directly pertinent to the scope of this report and, therefore, not presented.

2.2 | Participants

Older adults (≥ 65 years old) were recruited through advertisements and community newsletters. Those who accepted to participate were examined by a geriatrician and screened for the following exclusion criteria: frailty or low-level of physical function (ie, SPPB score ≤ 7 points), history of regular resistance exercise training in the last 3 years or undergone knee arthroplasty. A flow chart showing the process of participant selection and allocation, as well as the reasons for dropouts, is shown in Figure 1. Finally, 45 participants (ie, 90 legs) completed the CTR period, and 31 participants (ie, 62 legs) completed the power training period. Further details concerning the *a priori* sample size calculation, participant recruitment and exclusion criteria are provided in the original study protocol.²² All subjects

were informed about the potential risk and benefits associated with participation in this study before giving written informed consent. The study was performed in accordance with the Helsinki Declaration and approved by the Clinical Research Ethics Committee of the Complejo Hospitalario de Toledo (Spain).

2.3 | Interventions

Detailed descriptions of all interventions are provided in the original study protocol.²² To summarize, the participants were asked to maintain their lifestyle during the CTR period, particularly regarding physical activity, diet and to inform study administrators about any changes in their medication. Regarding the exercise interventions, unilateral power training targeting the lower limbs was performed on a horizontal leg press device (Selection MD, Technogym, Italy) twice a week, for 12 weeks with a minimum of 48 hours between sessions. LL-PT consisted of 6 sets of 12 repetitions with a load equivalent to 40% 1-RM, whereas HL-PT consisted of 6 sets of 6 repetitions with a load equivalent to 80% 1-RM. Thus, both power training programs had the same volume load (ie, number of repetitions \times external load relative to 1-RM). Participants were requested to perform

the concentric phase of each repetition as fast as possible, independently of the load used. A 2-min passive recovery was allowed between sets. The 1-RM was re-assessed every 4 weeks to adjust training load and ensure progressive overload. After completing the 12 weeks of training, a subsequent training program for the contralateral leg was offered to those participants who only trained one of their lower limbs (ie, study arm i and ii) and whose lower limb muscle power asymmetry was greater than 15%; that is, a level of asymmetry that exceeds the normal physiological range.²⁵ For a better characterization of training programs, the principal mechanical characteristics (load, time under tension, range of movement, work, velocity, acceleration, force, power as well as the relative loss of velocity, force and power within each exercise set) of LL-PT and HL-PT were tested during the third training session.

2.4 | Procedures

Comprehensive and detailed information about procedures has been previously depicted in the respective methods paper.²⁶ The following outcomes were evaluated at three different time points: week 0 (W0) corresponding to the beginning of CTR, week 8 (W8) corresponding to the end of CTR and the beginning of the intervention period, and week 20 (W20) corresponding to the end of the intervention period. The participants completed two familiarization sessions before W0, and the final evaluation (ie, W20) was conducted at least 72 h after the last exercise session to ensure that participants were fully recovered.

To measure neuromuscular performance (ie, muscle function), the 1-RM and force-velocity (F-V) relationship were measured unilaterally through a progressive load test (including at least 4 loads ranging from 40% of body mass to 1-RM), previously validated,²⁷ performed on the horizontal leg press device instrumented with a linear position transducer (Linear encoder, Chronojump Bosco System, Spain; 1019 Hz) and a force plate (Type 9286BA, Kistler, Switzerland; 1000 Hz). A linear model was fitted to F-V data collected above 45% of the theoretical maximal isometric force (F_0), which together with maximal unloaded velocity (V_0) were obtained from the force and velocity intercepts, respectively.²² Accordingly, both the slope of the F-V relationship (S_{FV}) and maximal muscle power (P_{max}) were determined. Moreover, since the validity of V_0 values obtained from linear models has recently been questioned,²⁸ the velocity exerted at 50% of F_0 (ie, the optimal velocity (V_{opt}) or the velocity coinciding with P_{max}) was also calculated. In addition, the velocity and power values at 85% of the individual body weight were calculated ($V_{0.85BW}$ and $P_{0.85BW}$, respectively) as proxies of unilateral physical function. This value (0.85 body weight) was chosen based on previous

evidence on unilateral force demands registered in older adults while performing a functional task.²⁹ Besides, the maximal isometric force (MIF) and the rate of force development (RFD) in the first 50, 100 and 200 ms (RFD50, RFD100 and RFD200, respectively) after the onset of the contraction were evaluated through maximal voluntary isometric contractions (MVIC) of the knee extensors performed on a custom-built rigid chair (Telju Fitness, Spain) instrumented with a strain gauge (Linear Force-SmartLead, Noraxon, USA; 1500 Hz, resolution = 0.07 N).²² For this purpose, the participants were seated with knee and hip angles of 90° and 120°, respectively (180° full extension). The tested lower leg was connected to the strain gauge through an ankle brace fixed just above the malleoli and a steel cable with minimal compliance. The participants were instructed to extend their knee as fast and strong as possible and hold the contraction for 3 s after the cue “ready, set, go!”. Moreover, strong verbal encouragement and visual feedback were given to ensure maximal efforts. Countermovement prior to contraction onset was not allowed and checked by an experienced evaluator through force signal inspection. Participants were also instructed to avoid any movements, involving the trunk or hip. The best three of five valid trials (separated by 60 s) were averaged and considered for analysis. Surface electromyography signals (EMG) of the quadriceps (vastus lateralis, vastus medialis and rectus femoris muscles) and biceps femoris (long head) muscles were acquired during MVICs (DTS EMG sensors & Desktop DTS, Noraxon, USA). The SENIAM recommendations were followed when placing bipolar electrodes.³⁰ Force and EMG signals were synchronously captured and processed within the same software (Myoresearch 3.10, Noraxon, USA). EMG signals were amplified and filtered with a band-pass filter between 10 and 500 Hz (common mode rejection ratio <100 dB, input impedance <100 M Ω and gain = 500) and then smoothed (100 RMS) and normalized to the muscle-specific maximum value registered during MVICs. Finally, the integrated area under the EMG signal (iEMG) during the first 50, 100, and 200 ms of contraction (QiEMG50, QiEMG100 and QiEMG200, respectively) was determined together with the corresponding biceps femoris co-activation.^{22,31} An automated threshold method was used to detect the onsets of muscle excitation and force production as the instant when each signal exceeded a level corresponding to the mean plus 3 SD of their respective baseline noise. Finally, muscle morphology was evaluated through ultrasound-based measurements over the mid-thigh portion (50% of femur length) of each leg (MyLab 25, Esaote Biomedica, Italy; 50 mm, 10–15 MHz linear-array probe).²² The cross-sectional area of the rectus femoris and the vastus lateralis (RF_{CSA} and VL_{CSA}) were determined at the same site, using the extended field of view feature of the scanner to detect changes in muscle size.

Images were analyzed with Fiji, an open-source software for biomedical image analysis.³² Then, images of the vastus lateralis were acquired in the fascicle plane at an individually determined optimal location (characterized by parallel aponeuroses and consistency of the fascicle orientation) to analyze muscle architecture. An automated software was used to compute the dominant fascicle pennation angle (VL_{PA}) and length (VL_{FL}).³³ To maximize accuracy and reliability, minimal pressure and abundant transmission gel were applied during the examination. All images were captured and analyzed by the same experienced operator. Demonstrative ultrasound images from a representative subject are shown in Figure 2. Moreover, the position of the EMG electrodes and ultrasound probe was recorded onto a transparent acetate sheet placed on the surface of the thigh to achieve consistency in measurement sites across testing days. Inter-session (7 days) coefficients of variation for MIF, and RFD at 50, 100, and 200 ms were 4.7, 27.1, 21.0, and 12.4%, respectively. Coefficients of variation for RF_{CSA} , VL_{CSA} , VL_{PA} , and VL_{FL} were 5, 3.8, 6.2 and 10%, respectively.

2.5 | Statistical analysis

Data are presented as means \pm standard deviation. Normality was assessed by the Shapiro-Wilk's test and data were log-transformed in case of non-normal distribution. The outcomes were registered as the absolute changes noted during

the 8-week control period (ie, W8 minus W0) and the 12-week power training period (ie, W20 minus W8). Linear mixed-effect model analyses were conducted to evaluate the main effects of treatment: CTR, LL-PT and HL-PT. Of note, linear mixed-effect models are generally recognized for their ability to handle missing data (eg, legs that only completed the CTR period) and their adequacy to analyze partially correlated data (eg, two legs of the same participant contributing to two different treatment groups).³⁴ In addition, linear mixed-effect models combine both, within-subject and between-subject comparisons as required by the provided data. For comparison, treatment (LL-PT vs. HL-PT vs. CTR) was included as a fixed factor, participants as a random factor and baseline values and time (ie, duration of the period) as covariates. The models considered the maximum likelihood estimation and the best-fitting covariance structure. The latter was determined using the chi-square likelihood ratio test, being the variance components the most frequently preferred covariance structure.³⁵ Pairwise Bonferroni-adjusted comparisons were performed to explore significant differences between treatments. Cohen's *d* effect sizes were calculated and classified as trivial (0.20), small (0.20–0.49), moderate (0.50–0.79), and large (>0.8).³⁶ Finally, a sensitivity analysis was conducted to assess the possible effect produced by the different study arms on the results derived from the different treatments following the same above-mentioned procedures. All statistical analyses were performed using SPSS Statistics 24 (IBM Corp, Armonk, NY), and the level of significance was set at $\alpha = 0.05$.

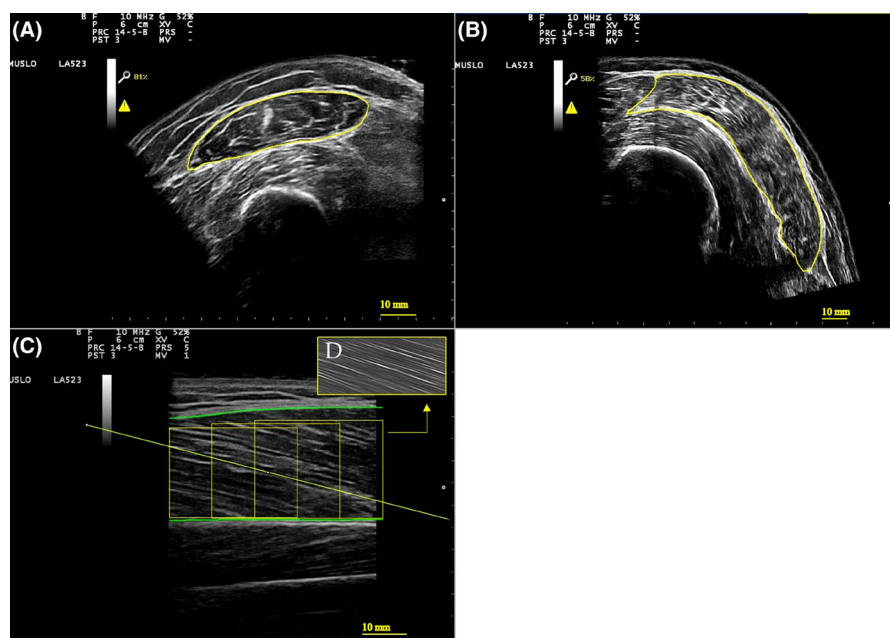


FIGURE 2 Ultrasound images obtained from the rectus femoris and vastus lateralis muscles of a representative subject. The cross-sectional area of the rectus femoris (A) and vastus lateralis (B) muscle corresponds to the area enclosed by the yellow line. The semi-automated analysis of vastus lateralis muscle architecture is presented in panel C. This tool highlights aponeuroses (green lines) and identify fascicles (D) within three different regions of interest (overlapping yellow rectangles) to obtain the dominant fascicle orientation and estimate fascicle length (larger oblique line)

3 | RESULTS

3.1 | Participants' characteristics

By the end of this study, the total number of participants (women) were 45 (25), 9 (5), 10 (5), and 12 (7) for CTR, study arm I (LL-PT vs non-exercise), II (HL-PT vs. non-exercise), and III (LL-PT vs. HL-PT), respectively (Figure 1). The age (mean, range: 70.6, 64.0–83.0 years), body mass index (28.9, 20.2–48.0 kg·m⁻²), body fat percentage (36.7, 14.7–48.6%) and appendicular skeletal muscle mass (7.4, 4.7–10.7 kg·m⁻²) were not significantly different between study arms (all $p > 0.05$). Moreover, all participants exhibited good levels of physical function (11.9, 11–12 SPPB points), handgrip strength (31, 18.9–49.4) and sit-to-stand relative muscle power (4.3, 2.6–6.5), with no differences between study arms (all $p > 0.05$).

3.2 | Training mechanical characteristics

The mechanical characteristics of LL-PT and HL-PT as assessed during a standard training session are shown in Table 1. Briefly, greater total mechanical work and higher power values were achieved during LL-PT compared to HL-PT. Both training protocols provoked small relative velocity losses (average value for all exercise sets: ~5%), but relative power losses were larger in LL-PT than in HL-PT (~11% vs. ~6%, respectively). These results are comparable to earlier findings by our group obtained in a similar sample.³⁷

3.3 | 1-RM and F-V on the horizontal leg press

The baseline values and changes in leg press 1-RM and F-V relationship characteristics by time and treatment condition are shown in Table 2. Moderate increases in 1-RM were found after LL-PT ($p < 0.001$, ES = 0.47) and HL-PT ($p < 0.001$, ES = 0.68), but not after CTR ($p = 0.904$, ES = 0.00; comparison of treatment effects: $F = 67.112$, $p < 0.001$, post hoc: both LL-PT and HL-PT > CTR, $p < 0.001$). When comparing the two training interventions, the gains in 1-RM were significantly greater after HL-PT compared to LL-PT (post hoc: $p = 0.039$).

Similarly, small to moderate increases in F_0 were found after LL-PT ($p = 0.001$, ES = 0.27) and HL-PT ($p < 0.001$, ES = 0.55), respectively. No significant changes in F_0 were determined after CTR ($p = 0.846$, ES = 0.01). There was a main effect of treatment for F_0 ($F = 18.717$, $p < 0.001$), showing that the changes provoked by LL-PT and HL-PT were significantly greater than those seen after CTR (post

hoc: both, $p \leq 0.05$). Between training interventions, there was a trend toward greater gains in F_0 changes after HL-PT (post hoc: $p = 0.056$). The gains in V_0 , by contrast, were greater after LL-PT ($p < 0.001$, ES = 0.71) compared to HL-PT ($p = 0.004$, ES = 0.39), respectively. No changes in V_0 were found after CTR ($p = 0.739$, ES = -0.02). There was a significant main effect of treatment for V_0 ($F = 12.940$, $p < 0.001$) and the post hoc analyses revealed that changes in V_0 after both LL-PT and HL-PT were significantly larger than those seen after CTR (both, $p < 0.022$). Likewise, an increase in V_{opt} were found after LL-PT ($p < 0.001$, ES = 0.73) and HL-PT ($p = 0.003$, ES = 0.39), whereas no changes were noted after CTR ($p = 0.722$, ES = -0.03). There was a significant main effect of treatment for V_0 ($F = 16.379$, $p < 0.001$) and the post hoc analyses revealed that changes in V_{opt} after both LL-PT and HL-PT were significantly larger than those seen after CTR (both, $p < 0.009$). S_{FV} values increased after LL-PT ($p = 0.021$, ES = 0.33) (ie, the slope became less negative, which is indicative of gains in V_0), decreased non-significantly after HL-PT ($p = 0.133$, ES = -0.22) and remained constant after CTR ($p = 0.957$, ES = 0.00). The corresponding effect of treatment was significant ($F = 3.791$, $p = 0.026$) with post hoc tests showing a trend toward statistical differences between LL-PT and HL-PT ($p = 0.097$). These changes in the participants' F-V profiles are shown in Figure 3.

With regard to P_{max} , large to moderate improvements were registered after LL-PT ($p \leq 0.001$, ES = 0.79) and HL-PT ($p < 0.001$, ES = 0.65), while no changes were seen after CTR ($p = 0.752$, ES = 0.02). Changes in P_{max} were significantly greater in both LL-PT and HL-PT as compared to CTR ($F = 26.663$, $p < 0.001$; post hoc: both, $p < 0.001$).

The velocity ($V_{0.85BW}$) and power ($P_{0.85BW}$) produced at a load corresponding to 85% of body weight increased after both LL-PT and HL-PT (all, $p < 0.001$, ES = 0.54–0.77), whereas no changes were observed after CTR (both, $p \geq 0.223$, ES = 0.06–0.05). Differences between the training conditions and CTR were significant for both $V_{0.85BM}$ ($F = 30.213$, $p < 0.001$, post hoc $p < 0.001$) and $P_{0.85BW}$ ($F = 29.279$, $p < 0.001$, post hoc $p < 0.001$) (Figure 4A,B, respectively). Finally, the sensitivity analysis showed no difference in the effects provoked by each training intensity regardless of the treatment conducted on the contralateral leg ($F = 0.015$ –0.797, $p \geq 0.382$).

3.4 | Maximal isometric force and rate of force development of knee extensors

The baseline values and changes of parameters obtained from the isometric knee extensor strength tests by time and treatment condition are shown in Table 3. No significant changes in MIF were found after CTR ($p = 0.729$,

TABLE 1 Mechanical characteristics of light-load and heavy-load power training

	LL-PT	HL-PT		
	Mean (SD)	Mean (SD)	ES	<i>p</i>
Load (kg)	25.8 (8.2)	55.3 (16.9)	2.21	0.005
Relative load (% 1RM)	36.3 (2.8)	77.2 (4.1)	11.73	0.005
TUT (s) ^a	8.25 (1.78)	5.37 (0.76)	2.10	0.005
ROM (mm)	261 (23)	217 (28)	1.71	0.007
Work (J) ^a	1542 (427)	797 (157)	2.31	0.005
Velocity (m·s ⁻¹)	0.38 (0.06)	0.24 (0.03)	2.89	0.005
Acceleration (m·s ⁻²)	0.91 (0.5)	0.06 (0.2)	2.50	0.007
Force (N)	497 (147)	625 (166)	0.82	0.005
Power (W)	187 (71)	153 (37)	0.60	0.028
Relative velocity loss (%)	5.4 (0.0)	5.6 (0.0)	0.07	0.721
Relative force loss (%)	6.5 (0.0)	2.4 (0.0)	1.23	0.007
Relative power loss (%)	10.8 (0.0)	6.3 (0.0)	1.06	0.047

Note: These data correspond to a standard session of each power training program in those participants that trained both legs at the corresponding load intensity.

Abbreviations: ES, effect size; HL-PT, heavy-load power training; LL-PT, light-load power training; ROM, range of movement; TUT, time under tension.

^aTotal per set.

ES = 0.02), LL-PT ($p = 0.077$, ES = 0.15) or HL-PT ($p = 0.241$, ES = 0.10), with differences between treatments being non-significant ($F = 1.201$, $p = 0.304$).

The LL-PT induced significant positive changes in RFD50 ($p = 0.002$, ES = 0.60), RFD100 ($p = 0.020$, ES = 0.31) and RFD200 ($p = 0.049$, ES = 0.26), whereas only a trend toward increased RFD50 values was found after HL-PT ($p = 0.056$, ES = 0.36). No changes in RFD values were registered after CTR (all $p > 0.05$). Comparisons of changes in RFD values between treatments failed to reach statistical significance (all $F \leq 2.807$, $p \geq 0.064$), although a trend toward greater increases in RFD50 in LL-PT compared to CTR was noted ($p = 0.075$).

Concomitantly, small but significant positive adaptations in QiEMG50 were observed after LL-PT ($p = 0.046$, ES = 0.36), but not after HL-PT or CTR (all $p \geq 0.512$, ES = 0.07–0.04). No changes in QiEMG100 and QiEMG200 were observed (all $p \geq 0.376$; ES = 0.00–0.16). Besides, no differences between treatments were found for QiEMG, irrespective of the time intervals in which it was measured ($F \leq 1.139$, $p \geq 0.323$). Finally, biceps femoris co-activation during the first 200 ms remained unchanged ($p \geq 0.699$, ES ≤ 0.29) and no treatment effect was found ($F = 0.111$, $p = 0.894$) (data are not shown). Finally, the changes observed after HL-PT and LL-PT were independent of the intervention conducted on the contralateral leg, as revealed the sensitivity analysis ($F = 0.001$ – 0.430 , $p \geq 0.519$).

3.5 | Mid-thigh muscle mass and architecture

Trivial to moderate and moderate increments in RF_{CSA} and VL_{CSA}, respectively, were found after LL-PT and HL-PT (all $p \leq 0.035$, ES = 0.13–0.35), whereas no changes were observed after CTR ($p \geq 0.343$, ES = −0.03 to 0.00) (Figure 5A,B). The effect of treatment was statistically significant for both RF_{CSA} ($F = 12.860$, $p < 0.001$) and VL_{CSA} ($F = 26.005$, $p < 0.001$), with post hoc analyses revealing that all changes except RF_{CSA} after LL-PT ($p = 0.068$) were greater after either training intervention than those seen after CTR (all $p < 0.001$). Regarding muscle architecture, HL-PT provoked moderate increases in VL_{PA} ($p = 0.004$, ES = 0.37), whereas no changes were observed after LL-PT ($p = 0.908$, ES = −0.02) and CTR ($p = 0.191$, ES = 0.08) (Figure 5C). An overall trend toward significant differences between treatments ($F = 2.676$, $p = 0.073$) was not confirmed by post hoc analyses (all $p \geq 0.131$). Neither significant changes ($p > 0.199$) nor effects of treatment ($F = 1.189$, $p = 0.308$) were found for VL_{FL} (Figure 5D). Finally, the sensitivity analysis showed that the changes observed in VL_{CSA} after HL-PT were higher when the contralateral leg was not trained ($F = 5.793$; $p = 0.025$). The remaining effects provoked by each training intervention were independent of the intervention conducted on the contralateral leg ($F = 0.012$ – 2.900 , $p \geq 0.105$).

TABLE 2 Baseline values and changes in leg press one-repetition maximum and force-velocity relationship characteristics

		Baseline	Change (Δ)	Time effect			Treatment effect	
		Mean (SD)	Mean (SD)	ES	CI 95%	<i>p</i>	<i>p</i>	post hoc
1-RM (kg)	CTR	73.1 (25.1)	0.1 (6.5)	0.00	−0.05 to 0.06	0.904	≤0.001	
	LL	71.2 (20.8)	11.7 (7.6)	0.47	0.35 to 0.59	≤0.001		LL>CTR*
	HL	70.7 (22.4)	16.8 (7.3)	0.68	0.56 to 0.79	≤0.001		HL>CTR*, LL*
F_0 (N)	CTR	945 (298)	3.1 (111)	0.01	−0.07 to 0.09	0.846	≤0.001	
	LL	949 (266)	80.8 (116)	0.27	0.11 to 0.44	≤0.001		LL>CTR*
	HL	928 (262)	163.5 (137)	0.55	0.39 to 0.72	≤0.001		HL>CTR*, LL ^a
V_0 (m·s ^{−1})	CTR	0.75 (0.29)	−0.01 (0.14)	−0.02	−0.16 to 0.11	0.739	≤0.001	
	LL	0.69 (0.31)	0.22 (0.31)	0.71	0.43 to 0.98	≤0.001		LL>CTR*
	HL	0.81 (0.33)	0.12 (0.25)	0.39	0.12 to 0.66	0.004		HL>CTR*
V_{opt} (m·s ^{−1})	CTR	0.38 (0.15)	−0.01 (0.07)	−0.03	−0.17 to 0.12	0.722	≤0.001	
	LL	0.34 (0.16)	0.11 (0.15)	0.73	0.46 to 0.99	≤0.001		LL>CTR*
	HL	0.40 (0.16)	0.06 (0.13)	0.39	0.13 to 0.65	0.003		HL>CTR*
S_{FV} [N(m ^{−1} ·s ^{−1}) ^{−1}]	CTR	−1422 (698)	−9 (497)	0.00	−0.15 to 0.14	0.957	0.026	
	LL	−1559 (593)	256 (610)	0.33	0.05 to 0.62	0.021		LL>HL ^a
	HL	−1279 (529)	−157 (492)	−0.21	−0.50 to 0.07	0.133		
P_{max} (W)	CTR	176 (82)	0 (26)	0.02	−0.09 to 0.13	0.752	≤0.001	
	LL	164 (81)	66 (70)	0.79	0.57 to 1.02	≤0.001		LL>CTR*
	HL	189 (97)	57 (67)	0.65	0.43 to 0.87	≤0.001		HL>CTR*

Abbreviations: 1-RM, one-repetition maximum; CI, confidence interval; CTR, control period (note that CTR represents a control period rather than a parallel group); ES, effect size; F_0 , force intercept; HL, heavy-load power-oriented resistance training; LL, light-load power-oriented resistance training; P_{max} , maximum muscle power; S_{FV} , slope of the force-velocity relationship; V_0 , velocity intercept; V_{opt} , optimal velocity or velocity produced at maximum power.

* $p < 0.05$; ^a $p < 0.10$.

4 | DISCUSSION

The main findings of this investigation were: (i) LL-PT induced positive changes in early RFD and muscle excitation levels and tended to provoke greater gains in movement velocity than HL-PT; (ii) HL-PT induced greater adaptations in 1-RM and V_{LPA} , and tended to benefit force development against heavy loads more than LL-PT; (iii) both LL-PT and HL-PT led to similar gains in P_{max} , functional power and velocity, and mid-thigh muscle size.

To our knowledge, this is the first study to compare heavy- vs. light-load power training in terms of the changes in the F-V relationship in older adults. In our study, the training adaptations were found to be load-specific, with HL-PT being superior to LL-PT in promoting gains in F_0 (+17.8 vs. +8.6%) and 1-RM (+24.0 vs. +16.5%). In line with our results, De Vos et al.¹⁵ found a dose-response relationship in the 1-RM gains provoked by 12 weeks of heavy- (80% 1-RM), moderate- (50% 1-RM) and light- (20% 1-RM) load power training 1-RM (mean gains: 20%, 16% and 13%, respectively) in

well-functioning older adults. By contrast, other studies that looked into the training responses of power training interventions in mobility-limited older adults (ie, SPPB score <9 points)¹⁷ or for shorter durations (ie, 6 weeks)¹⁶ reported that the power gains in the high-force portion of the F-V relationship were similar independently of the load used.

Regarding the low-force/high-velocity region of the F-V spectrum, both load conditions elicited significant improvements in V_0 , but larger effects were noted after LL-PT. This is partly in accordance with a previous study³⁸ that found superior velocity-related adaptations after 12 weeks of high-speed power training (ie, intensities corresponding to 40% 1-RM, movement execution as fast as possible) than traditional slow-speed resistance training (ie, 80% 1-RM, 2 s during concentric phase) in well-functioning older adults. As compared to this study, our subjects were also requested to perform repetitions as fast as possible when working against heavy resistances. This approach appears to yield better outcomes in HL-PT.^{9,10} The fact that the adaptations

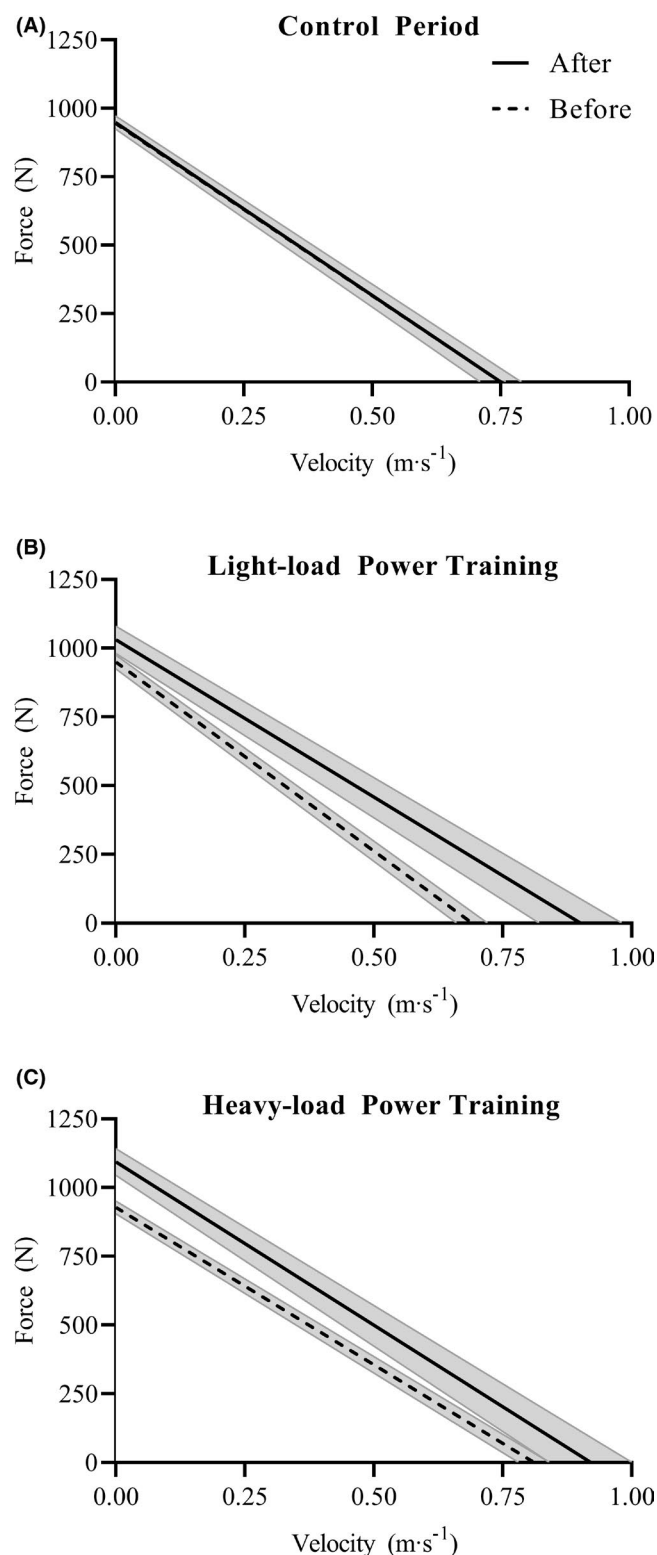


FIGURE 3 Force-velocity relationships. Data obtained before (dashed lines) and after (solid lines) the control period (CTR, $n = 89$), light-load (LL-PT, $n = 21$) and heavy-load (HL-PT, $n = 22$) power-oriented resistance training are shown in panels A, B and C, respectively. Note that CTR represents a control period rather than a parallel group. The lines represent mean values and the gray areas the corresponding 95% confidence intervals (mean goodness of fit: $R^2 = 0.98 \pm 0.02$)

to training load-is also reflected by the changes in S_{FV} , which tended to differ between HL-PT and LL-PT (Table 2). Despite the evident rightward displacement of the F-V relationship after both training conditions, HL-PT led to a steeper trajectory of F-V line (ie, more F_0 -oriented adaptations) whereas it was flattened after LL-PT (ie, more V_0 -oriented adaptations) (Table 2, Figure 3). The resultant increases in P_{max} , however, did not differ significantly after LL-PT and HL-PT ($\sim +40\%$ and $+28\%$, respectively). It may be concluded that the improvement in P_{max} noted after LL-PT was mostly the result of an improved capacity to produce force at high movement velocities, whereas gains at both the velocity- and force-end of the F-V spectrum appear to contribute almost equally to the P_{max} adaptations seen after HL-PT. While velocity-specific adaptations after power training have been previously reported in older adults,^{16,38} this is the first study to directly show load-specific changes in the F-V relationship. The differences in training responses notwithstanding, it is important to note that both LL-PT and HL-PT may be beneficial to improve physical function. While direct measurements of functional capacity (eg, through walking or sit-to-stand tests) reflect the performance of both legs and were, therefore, not considered in the present study, movement velocity ($V_{0.85BW}$) and power production ($P_{0.85BW}$) were assessed at loads that are representative of force demands in locomotion (ie, at 85% of body weight). These parameters increased to an extent safely beyond the respective thresholds of clinically meaningful improvements (10% and 7%, respectively).³⁹

In terms of contraction explosiveness, moderate to small effects, on early RFD (ie, ≤ 100 ms) were observed only after LL-PT, accompanied by a small, yet significant increase in the level of quadriceps femoris excitation (QiEMG50). This result suggests that increased neural drive contributes to the improvement of rapid force production in LL-PT.²¹ While several parameters, such as tendon mechanical properties, muscle fiber type and muscle morphology,⁴⁰ may equally influence RFD, the improvement in the neural drive is worth mentioning since older adults typically struggle to activate their quadriceps muscles to the same extent in LL-PT as in HL-PT.³⁷ Interestingly, despite existing solid evidence about the effectiveness of heavy traditional resistance training and power training to improve RFD in older adults,⁴¹ no improvements were seen after HL-PT, and RFD100 and RFD200 were not affected by either intervention. It is possible that this lack of improvement is due to the different exercises performed for training and testing (leg press vs. knee extension, respectively).^{42,43} It is worth noting that performance and muscle excitation adaptations observed were load-specific, although they could have been partly

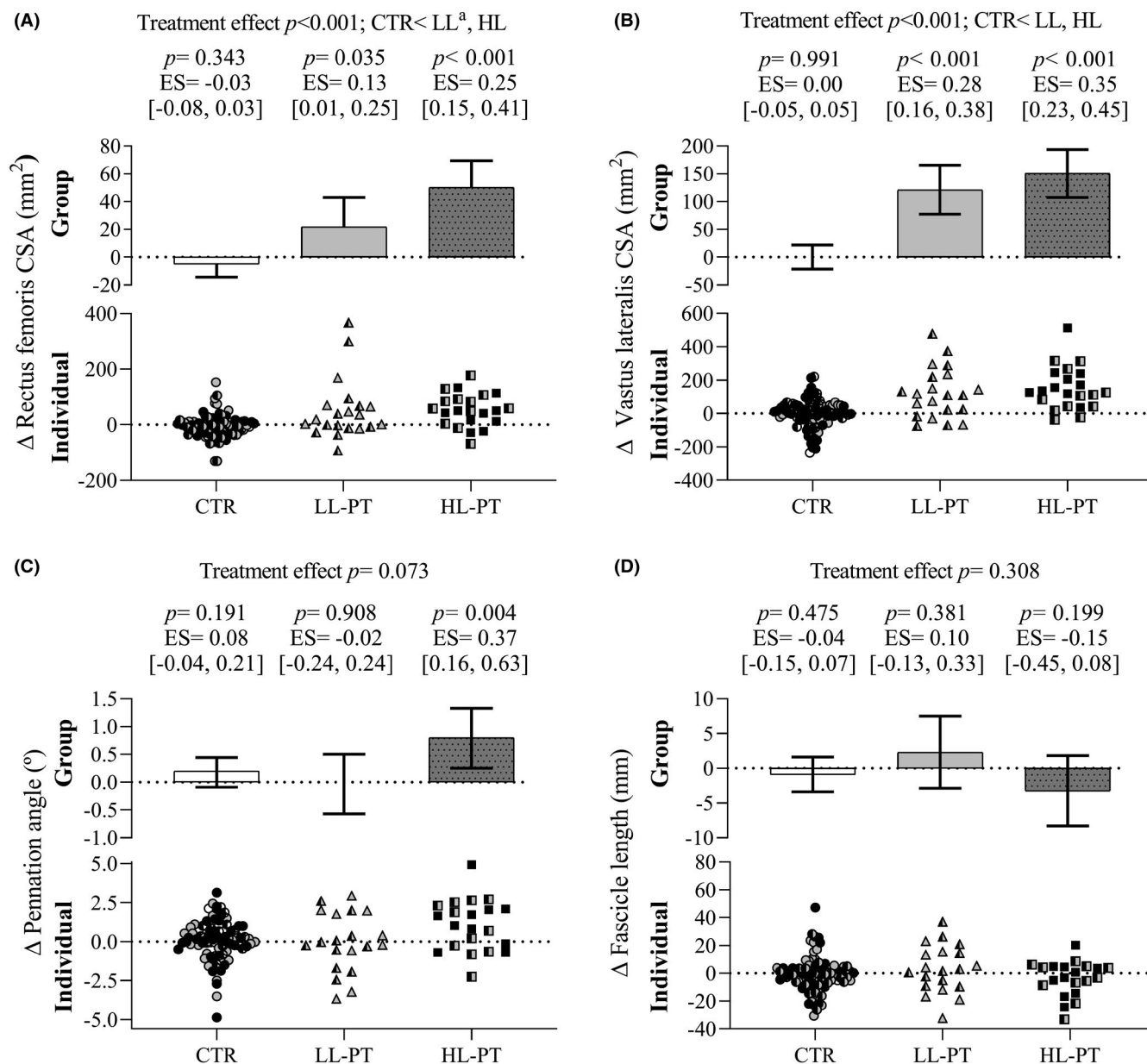


FIGURE 4 Leg press movement velocity and power output. Changes (Δ) in movement velocity (A) and power output (B) at forces equivalent to 85% of body weight (0.85 BW) noted after the control period (CTR, $n = 89$), light-load (LL-PT, $n = 21$) and heavy-load (HL-PT, $n = 22$) power-oriented resistance training. Symbols, bars and error bars show individual data, adjusted means and 95% confidence intervals (CI; error bars), respectively, for each treatment. Circles, triangles, and squares correspond to CTR, LL-PT and HL-PT, respectively. Symbols are filled according to the study arm I (gray), II (black) and III (black and gray). Note that CTR represents a control period rather than a parallel group. The results of statistical tests of between-group differences in treatment effects are indicated on the top of each panel. Within-group comparisons (time effects) with effect sizes and 95% confidence intervals of changes are shown separately for each treatment

influenced by potential cross-education derived from those participants completing HL-PT and LL-PT (ie, study arm III). This suggests that different training targets could be developed simultaneously between legs, which will be explored in detail in a separate paper (under review).

Regarding muscle morphology adaptations, power training has recently been shown to be as effective in increasing muscle size of older adults as traditional resistance training.¹¹ However, the intensity at which power

training should be performed to maximize muscle hypertrophy has not been thoroughly investigated so far. In our study, both LL-PT and HL-PT induced noticeable muscle hypertrophy (on average +7% and +9%, respectively) in the rectus femoris and vastus lateralis muscles. This degree of muscle growth is comparable to that typically seen after traditional resistance training. Indeed, a systematic review reported that in older adults the average gains in appendicular muscle size ranged between 9–11%, independently

TABLE 3 Knee-extensor isometric neuromuscular performance

		Baseline	Change (Δ)	Time effect			Treatment effect	
		Mean (SD)	Mean (SD)	ES	CI 95%	<i>p</i>	<i>p</i>	post hoc
MIF (N)	CTR	381 (118)	1.4 (47.6)	0.02	−0.07 to 0.10	0.729	0.304	
	LL	404 (103)	16.5 (57.8)	0.15	−0.02 to 0.32	0.077		
	HL	388 (122)	14.4 (38.7)	0.10	−0.07 to 0.27	0.241		
RFD50 (N·s ^{−1})	CTR	555 (310)	41 (275)	0.12	−0.06 to 0.31	0.189	0.064	LL>CTR ^a
	LL	633 (461)	164 (335)	0.60	0.15 to 0.97	0.002		
	HL	496 (284)	121 (271)	0.36	−0.01 to 0.74	0.056		
RFD100 (N·s ^{−1})	CTR	1155 (624)	−10 (408)	−0.01	−0.14 to 0.12	0.852	0.100	
	LL	1177 (637)	191 (413)	0.31	0.04 to 0.57	0.020		
	HL	1157 (762)	45 (418)	0.06	−0.17 to 0.32	0.682		
RFD200 (N·s ^{−1})	CTR	1131 (454)	−25 (271)	−0.04	−0.17 to 0.08	0.509	0.107	
	LL	1154 (456)	116 (341)	0.26	0.00 to 0.52	0.049		
	HL	1083 (499)	67 (321)	0.10	−0.15 to 0.36	0.451		
QiEMG50 (%MVIC·s)	CTR	4.9 (1.6)	0.1 (1.5)	0.07	−0.11 to 0.25	0.451	0.323	
	LL	4.8 (1.5)	0.6 (1.7)	0.36	0.00 to 0.72	0.046		
	HL	4.5 (1.3)	0.1 (1.4)	0.04	−0.39 to 0.41	0.820		
QiEMG100 (%MVIC·s)	CTR	8.5 (2.5)	0.1 (2.4)	0.06	−0.12 to 0.24	0.512	0.849	
	LL	8.3 (2.7)	0.4 (2.4)	0.16	−0.18 to 0.52	0.376		
	HL	7.8 (2.2)	0.2 (2.2)	0.03	−0.39 to 0.39	0.889		
QiEMG200 (%MVIC·s)	CTR	16.0 (4.2)	0.1 (3.8)	0.03	−0.14 to 0.21	0.725	0.984	
	LL	15.7 (5.3)	0.0 (4.3)	0.00	−0.29 to 0.35	0.988		
	HL	14.8 (3.3)	0.3 (3.3)	0.02	−0.43 to 0.39	0.903		

Abbreviations: CI, confidence interval. ES, effect size. CTR, control period (note that CTR represents a control period rather than a parallel group). LL, light-load power-oriented resistance training. HL, heavy-load power-oriented resistance training. MIF, maximal isometric force. RFD, rate of force development. QiEMG, integrated electromyographic signal of the quadriceps.

^a*p* = 0.075.

of whether training interventions were performed with heavy or light loads.¹⁹ The fact that, in our study, the hypertrophic response was similar in both loading conditions is interesting, since the total amount of mechanical work performed—which is considered to be a major determinant of resistance training-induced hypertrophy in older adults¹⁹—was significantly larger in LL-PT (Table 1). One possible explanation for this observation is that stretch-shortening cycles may facilitate the execution of repetitions more in LL-PT as compared to HL-PT,⁴⁴ which would limit the anabolic response to exercise.^{45,46} In terms of changes in muscle architecture, VL_{PA} was significantly increased only after HL-PT (+7.5%), which agrees with the larger changes in force production (ie, *F*₀ and 1-RM) observed after this intervention.^{47,48} VL_{FL}, by contrast, was not significantly affected by either form of power training. In contrast, a previous study involving light-load plyometric exercise (using a trampoline training device) in older adults has shown meaningful increases in VL_{FL} and VL_{PA}

(+8 and +7%, respectively).¹³ The discrepancies between studies may derive from differences in the training device used and some methodological limitations in determining this measure in our study (with large portions of fascicle length lying outside the available field-of-view) potentially introducing bias.⁴⁹ While it is possible that LL-PT (which resembles plyometric exercise to a certain extent) would benefit the effectiveness of the stretch-shortening cycle, it remains to be explored whether LL-PT or HL-PT would have greater adaptive potential in this regard.

Some limitations should be considered when interpreting the present findings. The experimental F-V data were fitted using linear models. These may be less sensitive in detecting adaptations induced at the low-force/high-velocity portion of the F-V than hyperbolic models.⁵⁰ Moreover, physical performance was not directly assessed since typically measured outcomes such as gait speed or sit-to-stand performance are affected by both legs; however, we determined the changes in unilateral power and movement

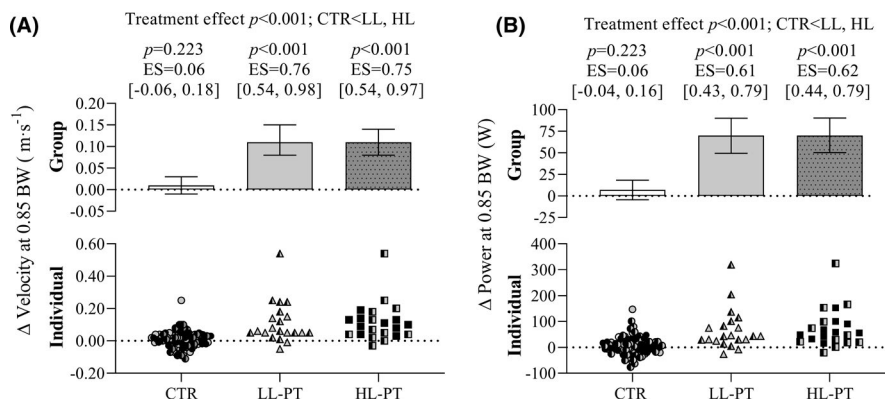


FIGURE 5 Muscle size and architecture. Changes (Δ) in rectus femoris (A) and vastus lateralis cross-sectional area (B) as well as vastus lateralis fascicle pennation angle (C) and fascicle length (D) noted after the control period (CTR), light-load (LL-PT) and heavy-load (HL-PT) power-oriented resistance training. The sample sizes of each group were CTR = 88, 87, 86, 86; LL: 19, 21, 29, 20; and HL-PT = 21, 22, 20, 21 for panels A, B, C and D, respectively. Symbols, bars and error bars show individual data, adjusted means and 95% confidence intervals (CI; error bars), respectively, for each treatment. Circles, triangles, and squares correspond to CTR, LL-PT and HL-PT, respectively. Symbols are filled according to the study arm I (gray), II (black) and III (black and gray). Note that CTR represents a control period rather than a parallel group. The results of statistical tests of between-group differences in treatment effects are indicated on the top of each panel. Within-group comparisons (time effects) with effect sizes and 95% confidence intervals of changes are shown separately for each treatment. Note that the post hoc comparison of rectus femoris cross-sectional area between CTR and LL failed to reach statistical significance (^a, $p = 0.068$)

velocity at a relative intensity (ie, 85% of body weight) that is representative of the force demands encountered in locomotion and other tasks of daily living. Thus, these measures may serve as proxies of the functional adaptations provoked by the power training programs. The MIF and RFD measurements were intentionally performed using a custom-built chair for knee extension rather than the leg press used for training, as the knee extension device was more rigid and, thus, better suited for the evaluation of explosive strength.⁴⁰ At the same time, we acknowledge that, ideally, training and testing should be performed on the same devices. Ultrasound scans were obtained in two of the four heads of the quadriceps femoris muscle and at a single level of femoral length only. This was due to time constraints in data acquisition and poor reliability of measurements obtained off-center. Considering the possibility of regional hypertrophy⁵¹ and the demonstrated intra- and intermuscular variability of quadriceps architecture,⁵² our results reflecting the changes in muscle size and architecture should be interpreted with caution. Finally, the influence of possible cross-education in those subjects training both legs at different intensities (ie, subjects in study arm III) cannot be completely discarded, although the sensitivity analyses revealed the consistency of the results for each of the different treatments (ie, training intensities) regardless of the study arm.

In conclusion, power training provokes significant improvements in muscle strength, power and size in older adults independently of the load used. Importantly, power training across of wide range of loads appears to improve the power output when working against resistances that

are typical for the force demands encountered in locomotion and further activities of daily living. Nevertheless, the adaptations of central characteristics of the force-velocity profiles differed between loads, suggesting that HL-PT may preferentially stimulate force-related muscle power adaptations whereas LL-PT might be more suitable for developing the velocity component of muscle power, according to the larger effect size observed.

5 | PERSPECTIVES

Power training is considered a cornerstone in resistance training programs for older adults given its greater potential to improve functional performance in comparison to traditional resistance training.⁵³ Although it is known that a wide range of intensities may be used to develop muscle power and functional performance in older adults,¹⁸ the influence of training with different loads on the F-V relationship is still poorly understood in this population. The results of our study demonstrate that in power training in older adults both light and heavy loads may be used to induce improvements in muscle function and muscle hypertrophy. However, HL-PT is more appropriate to develop high-force capabilities, while LL-PT appears to be superior in promoting gains in movement velocity and, thus, the performance in explosive tasks. Therefore, HL-PT should be prescribed to older people with force deficits, whereas LL-PT should be recommended to older people presenting with performance deficits at

the high-velocity, low-force end of the F-V spectrum.²⁰ Such individualized prescription may maximize the benefits of power training and help counteract the age-related decline in functional ability.

ACKNOWLEDGMENTS

This work was supported by the Ministerio de Economía y Competitividad of the Government of Spain (DEP2015-69386-R and BES-2016-077199) (MINECO/FEDER, EU). IBF received a PhD grant from the University of Castilla-La Mancha “Contratos predoctorales para la formación de personal investigador en el marco del Plan Propio de I+D+i, cofinanciados por el Fondo Social Europeo” (2018-CPUCLM-7636). The authors thank Dr. Pedro Alcaraz, head of the Research Center for High Performance Sport at Catholic University San Antonio, Murcia, Spain for helping us resolve technical problems with the force plate used in this study.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.


DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Rodriguez-Lopez C, Alcazar J, Sanchez-Martin C, et al. Neuromuscular adaptations after 12 weeks of light- vs. heavy-load power-oriented resistance training in older adults. *Scand J Med Sci Sports.* 2022;32:324-337. <https://doi.org/10.1111/sms.14073>