Explosive heavy-resistance training in old and very old adults: changes in rapid muscle force, strength and power

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Age-related decline in muscle power predicts falls, motor impairments and disability. Recent guidelines suggested that training programs should be tailored to maximize muscle power. This study investigated the effects of 12 weeks of explosive-type heavy-resistance training (75–80% of 1 repetition maximum) in old (60–65 years, TG60) and very old (80–89 years, TG80) community-dwelling women. Training was performed with maximal intentional acceleration of the training load during the concentric movement phase. Maximal isometric voluntary muscle strength (MVC), rapid force capacity, assessed as rate of force development (RFD), and impulse, maximal muscle power during a countermovement jump (CMJ) and during unilateral leg extension task (LEP) were evaluated. RFD, impulse and MVC increased by 51%, 42% and 28% in TG80, and by 21%, 18% and 18% in TG60, respectively. CMJ jump height increased by 18% in TG80 and 12% in TG60, respectively, while jump peak power increased in TG60 (5%). Finally, LEP increased 28% in TG80 and 12% in TG60. These findings demonstrate that explosive-type heavy-resistance training seems to be safe and well tolerated in healthy women even in the eighth decade of life and elicits adaptive neuromuscular changes in selected physiological variables that are commonly associated with the risk of falls and disability in aged individuals.

Muscle power, which is the product of contractile force and movement velocity, is a stronger predictor of functional motor performance, incidence of falling and self-reported functional status than maximal muscle strength in community-dwelling old adults (Foldvari et al., 2000; Skelton et al., 2002). Furthermore, lower limb muscle power declines at a faster rate than maximum muscle strength with aging (Skelton et al., 1994; Izquierdo et al., 1999b), and elderly women consistently show lower power levels than elderly men (Bassey et al., 1992; Skelton et al., 1994; Caserotti et al., 2001).

Therefore, recent recommendations aimed at reducing the risk of physical dependency in community-dwelling older adults have suggested that strength training programs should be designed to maximize muscle power rather than muscle strength (Bassey et al., 1992; Evans, 2000; Porter, 2006).

The development of high muscle power output involves the integration of two fundamental properties of the contractile system: (i) the ability to produce high muscle force, which is related to the number of active sarcomeres in parallel, and (ii) the ability to develop high contraction velocity, which is related to the number of active sarcomeres in series (Edgerton et al., 1986; Kraemer & Newton, 2000). Thus, maximal muscle power depends on the muscle morphology (e.g. physiological muscle cross-sectional area, muscle fiber pennation angle, muscle fiber length, fiber-type composition) and neuromuscular activation properties (discussed below), and it is therefore closely linked to maximal muscle strength (Kraemer & Newton, 2000). In addition, a key role in maximal muscle power development is played by the contractile rate of force development (RFD), which is defined as the ability to produce muscle force rapidly (Kraemer & Newton, 2000; Aagaard et al., 2002). RFD determines the magnitude of acceleration in the initial phase of a movement and ultimately influences the velocity of the movement (Kraemer & Newton, 2000; Aagaard et al., 2002) and therefore a high RFD is important in short-lasting and fast movements, especially in situations with limited joint range of motion. RFD is dependent on muscle morphology (e.g. muscle cross-sectional area) while also affected by neuromuscular function (e.g. motor unit firing frequency, agonist–antagonist muscle coactivation) (Kraemer & Newton, 2000; Aagaard
et al., 2002, for a review, see Aagaard, 2003). Relevantly, in older individuals a reduced RFD has previously been reported to correlate with reduced capacity to maintain postural control (Izquierdo et al., 1999b) and a reduced rate of EMG increase, which is the neural equivalent of RFD, has been associated with poor balance recovery after tripping (Pijnappels et al., 2005). Thus, training aimed at inducing both muscle hypertrophy and enhanced neural function preferentially should be used in the elderly.

Heavy-resistance strength training protocols are effective in eliciting muscle hypertrophy according to the dose–response relationship that dictates greater hypertrophy at heavy loadings (>75% 1 repetition maximum (1 RM)) (Kraemer & Newton, 2000; Fry, 2004). Indeed, elderly subjects also demonstrate increases in muscle cross-sectional area, maximal muscle strength and maximal muscle power output in response to heavy-resistance strength training (80% 1 RM) (Ferri et al., 2003). Similarly, heavy-resistance training leads to enhanced neural function in young (Aagaard et al., 2002), old (Hakkinen et al., 1998) and very old individuals (Harridge et al., 1999), although not consistently demonstrated (Hakkinen et al., 1985). In contrast, it has been speculated that maximal muscle power may be improved in sedentary subjects with low initial levels of muscle strength regardless of the type of strength training performed (Kraemer & Newton, 2000). Thus, explosive-type strength training (i.e. with maximal intentional acceleration of the load) may be particularly relevant when substantial muscle strength is reached (Kraemer & Newton, 2000).

In elderly women with self-reported disability explosive-type strength training performed at 70% 1 RM, using pneumatic training loads resulted in superior improvements in muscle power compared with traditional strength training at 70% 1 RM (Fielding et al., 2002). In addition, gains in maximal muscle strength were greater when explosive-type training using heavy loads (80% 1 RM) was compared with moderate-intensity training (50% 1 RM) using pneumatic resistance exercises in healthy 69-year-old adults (de Vos et al., 2005). Thus, a superior adaptation in mechanical muscle function (e.g. muscle power, strength, RFD) may be achieved with explosive-type strength training as compared with traditional-type training. To improve muscle power optimally, it has been advocated that it is most favorable to use training load intensities that maximize muscle power. Macaluso and De Vito (2003) reported a load intensity of 60% maximal isometric voluntary contraction as the optimal load to produce the largest lower limbs’ muscle power in older women. When optimal load for power development was assessed according to the 1 RM method, one study reported that the greatest lower limbs muscle power was achieved using a load intensity of 70% 1 RM in elderly males (Izquierdo et al., 1999a). Notably, isolated knee extension training at heavy loads (8 RM) has been reported to induce gains in maximum power that were greater than training at lower loads (16 RM, 24 RM), indicating that training at a higher intensity (70–80% 1 RM) compared with a lower intensity (40–60% 1 RM) is more beneficial for power development during unrestricted movements (i.e. non-isokinetic movements) (Aagaard et al., 1994).

Thus, designing a strength-training program using heavy loadings (75–80% 1 RM) with maximal intentional acceleration of the load (explosive type) may result in an optimal combination of both muscle hypertrophy and neural adaptation, and may thereby elicit superior gains in explosive force and muscle power capacity, respectively. If this is the case, such training regimes would be highly beneficial for old and particularly very old individuals due to the marked reduction in muscle mass (i.e. sarcopenia) and impaired neural function and reduced mechanical motor performance observed at old age.

Although the effects of explosive-type strength training using low, moderate or heavy training loads have been investigated in older adults (Earles et al., 2001; Fielding et al., 2002; de Vos et al., 2005; Henwood & Taaffe, 2005), it has never been examined whether this training modality is tolerable in very old healthy individuals (≥80 years). In addition, no study so far has compared the adaptive training response between old and very old people.

The aims of this study were to investigate: (i) the effect of a low-frequency explosive-type heavy-resistance strength training in two age groups (60–65 and 80–89 years) of old individuals on maximal muscle power, strength and explosive force characteristics, and (ii) whether a differential age-related responsiveness in mechanical muscle function exists with this training type.

**Methods**

Sixty-five healthy home-dwelling women who were moderately physically active (maximum once a week multicomponent physical training), and without any strength training background, volunteered to participate in this randomized-controlled trial. The specific age groups were chosen because they represent elderly subjects approaching the steep decline in neuromuscular function (age group 60: mean age 62.7 ± 2.2 SD), and subjects who presumably display more accelerated impairments in neuromuscular function (age group 80: mean age 81.8 ± 2.7 SD). Subjects were recruited through local senior centers, social clubs and by word of mouth. All subjects gave written informed consent and underwent a medical screening aimed at excluding any neuromuscular and orthopedic problem that could interfere with the study. In addition, subjects reported no difficulties in perform-
ing daily motor tasks as evaluated by questionnaire and objective assessment (data not reported). None of the subjects was on hormonal replacement therapy or medication, which could interfere with the study, as evaluated by a medical doctor.

Subjects from each age group were randomized into a training group (TG) (TG60, n = 20; TG80, n = 12) and a control group (CG) (CG60, n = 20; CG80, n = 13) using stratification according to muscle power score obtained in the leg extensor power rig. The control group did not engage in physical training during the entire period of the experiment and maintained the lifestyle before enrolling in the experiment. The protocol was approved by the local ethical committee.

Measurements

Weight, lean body mass and fat mass were measured by a conventional bioimpedance leg-to-leg method (Heitmann, 1990). The within-subjects coefficient of variation for lean body mass and fat mass was previously reported to be 1.4% and 3.2%, respectively (Kjaer & Puggaard, 1999).

Lower limb explosive muscle power

Explosive lower limb muscle power was assessed during (i) a single-legged multijoint motor task (leg extensor power rig) (Bassey et al., 1992) and (ii) a weight-bearing multijoint motor task (counterjumping test CMJ) performed on an instrumented force plate (Caserotti et al., 2001).

Power rig

Subjects were seated in the power-rig chair and pushed away the footplate connected to a flywheel as hard and fast as possible (Bassey & Short, 1990). Eight to 10 trials were performed for each leg while visual feedback was provided in a PC screen after each trial. The best values for the right and left leg extenders were summed (LEP). The within-subjects coefficient of variation (CV) for the dominant leg on four different measurement days was 7.1%.

CMJ

After several submaximal trials, four maximal standardized CMJ separated by 1.5-min interval were performed on a force platform (Kistler, 9281 B) (Caserotti et al., 2001; Holsgaard et al., 2007). Subjects were instructed to perform a rapid downward movement to about 90° of knee flexion immediately followed by an upward movement with the hands on the hips while intending to jump as high as possible. The trial with maximal jump height (JH) calculated by the kinetic take-off impulse was selected for further analysis. Instantaneous jump power was continuously calculated as the product of vertical ground reaction force (Fz) and center of mass velocity. The mean (Pmean) and peak (Ppeak) concentric power were calculated and Ppeak was subsequently decomposed into force and velocity components at peak power (Fpeak and Vpeak, respectively) (Caserotti et al., 2001). In addition, maximal concentric velocity (Vmax) and take-off velocity (Vsoft) were determined (data not reported) and the ratio in percent between Vsoft and Vmax (Vratio) was calculated (data reported). This ratio provides information on how much of the maximal velocity developed during the concentric phase of the movement was maintained until the instant of take-off and thereby transformed into JH. A high test–retest repeatability was recently demonstrated for the various CMJ test parameters in elderly subjects (within-subjects CV for JH 7.1%, Ppeak 2.9%, Pmean 5.1%, Fpeak 8.9% and Vpeak 2.9%) (Holsgaard et al., 2007).

Maximal muscle strength

Maximal muscle strength was measured during maximal isometric voluntary contraction (MVC). Subjects were seated in a custom-built unilateral leg press device (knee and ankle angles of 120 and 90°, respectively) while performing static leg press as hard and fast as possible with their dominant leg against a fixed footplate instrumented with piezoelectric force transducers (Kistler 9367/8 B). The force signals were digitally sampled at 1 kHz while on-line visual feedback was provided to the subject. The contractile RFD and impulse were determined in the trial with the highest resultant peak force (Aagaard et al., 2002). RFD was calculated as the mean tangential slope of the force–time curve in the initial 200 ms of contraction (RFD = Δforce/Δtime, RFD200 = F200/0.200 s), while impulse was calculated as the area under the force–time curve (Aagaard et al., 2002). Contractile impulse was assessed because it represents the total force–time integral in a given time period, and consequently reflects the velocity that the limb segment would achieve at that specific time instant if allowed to move (Aagaard et al., 2002). The 0–200 ms time interval was chosen for analysis because it reflects explosive force characteristics (RFD) both in the very initial phase (0–50 ms) and the later phase (0–200 ms) of the muscle contraction, and has been reported to discriminate between young and old adults in a time limited motor task, i.e. reversing a fall (Pijnappels et al., 2005). Five trials were performed with 2-min rest intervals and MVC was accepted if, within the five trials, the two highest recordings differed <5%. Otherwise, additional trials were performed ad libitum until this criterion was fulfilled. The within-subjects CV on four different measurement days was 5.1%.

Resistance training protocol

Training consisted of a 12-week progressive explosive-type heavy-resistance strength training program twice a week with at least 2 days between training sessions. Training was performed exclusively for the lower limbs (bilateral knee extension, horizontal leg press, hamstring curls, calf rise and inclined leg press) using isoinertial resistance training equipment (Cybex, Medway, MA, USA). This equipment allows for unrestricted acceleration of the training load and thereby enables to achieve variable velocity throughout the entire range of motion. Four sets were performed for each exercise with training loads of 75–80% 1 RM (8–10 repetitions per set) (Baechle et al., 2000). Training load was estimated using a four to eight repetition method to avoid excessive overloading. Thus, subjects were asked to perform each exercise with a load that was estimated by an expert trainer to allow maximum four to eight repetitions. Then, a training load of 75–80% 1 RM corresponding to eight to 10 repetitions per set was obtained according to Baechle et al. (2000). An explosive movement pattern (i.e. maximal intentional load acceleration) was used during the concentric contraction while the eccentric phase of each exercise was performed using and slow-to-moderate speed. Visual inspection concerning the exercise technique and movement explosiveness and verbal encouragement were continuously given by professional trainers during the training sessions. All sessions started with 10 min of standardized warming up, and the first set of each exercise was always performed with half of the training load subsequently used for the explosive training (approximately 35–40% 1 RM loading). Throughout the study training loads were adjusted every 2
weeks using the four to eight repetition method. During the first four training sessions, subjects used a 50% 1 RM load (15–20 repetitions each set) with controlled velocity.

Statistical analysis
Pre- vs post- intervention data were evaluated by the Wilcoxon signed-rank tests within groups. Changes between training vs control groups (e.g. ΔTG60 vs CG60) were evaluated by Mann–Whitney tests. Age-related responses to training (TG60 vs TG80) were investigated by linear regression analyses adjusted for baseline absolute values and by Mann–Whitney tests for relative values. The association between variables was assessed by Spearman’s r correlation analysis. *P values for within-group changes after the intervention period.

Results
Thirty-four subjects from group 60 (TG60 = 17; CG60 = 17) and 22 subjects from group 80 (TG80 = 10; CG80 = 12) completed the study. One subject dropped out from TG60 due to cardiovascular disease, and one from CG60 due to fear of injury after the first testing session. The remaining four subjects stopped due to lack of time and loss of interest. Two subjects dropped out from TG80: one due to exacerbation of preexisting osteoarthritis and one due to stroke which was unrelated to the training. One subject dropped out from CG80 due to foot pain problems unrelated to the study.

Physical anthropometric characteristics
The anthropometric characteristics of all the subjects are reported in Table 1. Body height remained unchanged after the training period for all groups. Body weight decreased significantly for TG60 after training by 3% (*P = 0.009) and showed a strong trend of a decrease for TG80 (*P = 0.059). No changes were reported for CG60 and CG80. Fat mass decreased for TG60 by 4%, whereas no changes were observed from the baseline for any other groups.

Mechanical muscle output parameters are reported for the training and control groups pre- and post- intervention in Tables 2 and 3.

MVC, RFD and impulse
Significant between-groups differences for TG80 vs CG80 were observed after the training period for MVC, RFD and impulse. The pre-to-post mean net changes in between-groups difference for MVC, RFD and impulse were 3.6 N/kg (95% CI 1.5:5.7), 20.9 N/kg (95% CI 12.8:28.9) and 0.4 N/kg (95% CI 0.3:0.6), respectively (Table 2). Similarly, significant between groups difference occurred for TG60 vs CG60 after the training period for MVC, RFD and impulse with a mean net change of 4.3 N/kg (95% CI 2.7:5.9), 11.8 N/kg (95% CI 2.7:21.2) and 0.3 N/kg (95% CI 0.02:0.5), respectively (Table 3). Although MVC, RFD and impulse differed at the baseline between TG80 and CG60 (deficits at baseline of TG80 relative to CG60 of 22, 44, 38% in MVC, RFD and impulse, respectively, *P<0.05), this difference disappeared after the intervention period (Fig. 1).

Countermovement jump
JH exhibited a between-groups difference (TG80 vs CG80) after the intervention period of 1.6 cm (95% CI 0.3:2.8) with a concomitant significant mean net difference of 1.7 W/kg in $P_{\text{peak}}$ (95% CI 0.1:3.2) (Table 2). $F_{\text{ppeak}}$ and $V_{\text{ppeak}}$ were unchanged, while $P_{\text{mean}}$ showed a between-groups difference of 1.8 W/kg (95% CI 0.2:3.3) and a $V_{\text{ratio}}$ of 6% (95% CI 0.2:10.8) (Table 2). Similarly, the mean net changes in between-groups difference for TG60 vs CG60 were 1.4 cm (95% CI 0.6:2.1) for JH, 2.5 W/kg (95% CI 1.2:3.8) for $P_{\text{peak}}$ and 0.07 m/s (95% CI 0.02:0.1) for $V_{\text{ppeak}}$ (Table 3). In contrast, the $F_{\text{ppeak}}$ remained unchanged with training while $P_{\text{mean}}$ exhibited a
Explosive-type strength training in aging

Table 2. Changes in muscle mechanical variables for the age group 80

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>ΔTG80</th>
<th>Mean ± SD</th>
<th>ΔCG80</th>
<th>Δgroups</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TG80 pre</td>
<td>TG80 post</td>
<td>%</td>
<td>P value*</td>
<td>CG80 pre</td>
</tr>
<tr>
<td>MVC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak force (N/kg)</td>
<td>17.8 ± 3.5</td>
<td>22.8 ± 2.6</td>
<td>28.1±</td>
<td>0.005</td>
<td>18.2 ± 4.4</td>
</tr>
<tr>
<td>RF200 (N/kg)</td>
<td>37.4 ± 9.4</td>
<td>56.3 ± 9.1</td>
<td>50.5±</td>
<td>0.055</td>
<td>39.8 ± 15.7</td>
</tr>
<tr>
<td>Impulse 200 (N/kg)</td>
<td>0.93 ± 0.2</td>
<td>1.32 ± 0.2</td>
<td>41.9±</td>
<td>0.005</td>
<td>1.01 ± 0.4</td>
</tr>
<tr>
<td>Countermovement jump</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Jump height (cm)</td>
<td>6.1 ± 2.4</td>
<td>7.32 ± 2.4</td>
<td>31.0±</td>
<td>0.048</td>
<td>5.6 ± 1.5</td>
</tr>
<tr>
<td>Peak power (W/kg)</td>
<td>18.9 ± 3.5</td>
<td>20.0 ± 4.3</td>
<td>9.3±</td>
<td>0.051</td>
<td>18.3 ± 2.3</td>
</tr>
<tr>
<td>Force at peak power (N/kg)</td>
<td>15.1 ± 3.4</td>
<td>16.1 ± 3.2</td>
<td>7.0±</td>
<td>0.009</td>
<td>14.8 ± 1.1</td>
</tr>
<tr>
<td>Velocity at peak power (m/s)</td>
<td>1.25 ± 0.2</td>
<td>1.38 ± 0.2</td>
<td>1.2±</td>
<td>0.03</td>
<td>1.15 ± 0.1</td>
</tr>
<tr>
<td>Mean power (W/kg)</td>
<td>10.8 ± 1.9</td>
<td>11.8 ± 2.1</td>
<td>1.0±</td>
<td>0.139</td>
<td>10.5 ± 1.5</td>
</tr>
<tr>
<td>V_ratio (V_t-off/V_max) (%)</td>
<td>86.1 ± 2.8</td>
<td>79.8 ± 2.8</td>
<td>21.3±</td>
<td>0.036</td>
<td>76.5 ± 5.2</td>
</tr>
<tr>
<td>Power rig</td>
<td>2.89 ± 0.7</td>
<td>3.7 ± 1.0</td>
<td>28.1±</td>
<td>0.037</td>
<td>2.90 ± 1.0</td>
</tr>
</tbody>
</table>

* P values for within-group changes after the intervention period.
1 P values for between-group changes after the intervention period (ΔTG80 vs ΔCG80).
2 P values for relative between-training groups changes, ΔTG80 (%) vs ΔTG60 (%).

TG80, training group; CG80, control group; pre and post, before and after strength training values, respectively; TG80Δ and G80Δ, changes in percent after training for training and control groups, respectively.

Table 3. Changes in muscle mechanical variables for the age group 60

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>ΔTG60</th>
<th>Mean ± SD</th>
<th>ΔCG80</th>
<th>Δgroups</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TG60 pre</td>
<td>TG60 post</td>
<td>%</td>
<td>P value*</td>
<td>CG60 pre</td>
</tr>
<tr>
<td>MVC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak force (N/kg)</td>
<td>24.6 ± 6.9</td>
<td>29.9 ± 7.4</td>
<td>21.5</td>
<td>0.0001</td>
<td>22.9 ± 6.9</td>
</tr>
<tr>
<td>RF200 (N/kg)</td>
<td>63.1 ± 15.9</td>
<td>74.5 ± 14.8</td>
<td>18.1</td>
<td>0.003</td>
<td>66.1 ± 24.1</td>
</tr>
<tr>
<td>Impulse 200 (N/kg)</td>
<td>1.47 ± 0.4</td>
<td>1.74 ± 0.4</td>
<td>18.4</td>
<td>0.009</td>
<td>1.49 ± 0.5</td>
</tr>
<tr>
<td>Countermovement jump</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jump height (cm)</td>
<td>2.89 ± 2.4</td>
<td>12.2 ± 2.9</td>
<td>1.2±</td>
<td>0.002</td>
<td>11.7 ± 3.7</td>
</tr>
<tr>
<td>Peak power (W/kg)</td>
<td>24.0 ± 2.8</td>
<td>25.3 ± 3.0</td>
<td>1.3±</td>
<td>0.301</td>
<td>26.1 ± 4.7</td>
</tr>
<tr>
<td>Force at peak power (N/kg)</td>
<td>15.5 ± 0.9</td>
<td>15.7 ± 0.7</td>
<td>1.3±</td>
<td>0.001</td>
<td>16.6 ± 1.8</td>
</tr>
<tr>
<td>Velocity at peak power (m/s)</td>
<td>1.55 ± 0.2</td>
<td>1.61 ± 0.2</td>
<td>3.9±</td>
<td>0.001</td>
<td>1.56 ± 0.2</td>
</tr>
<tr>
<td>Mean power (W/kg)</td>
<td>13.9 ± 2.0</td>
<td>14.5 ± 2.1</td>
<td>1.2±</td>
<td>0.088</td>
<td>14.8 ± 3.0</td>
</tr>
<tr>
<td>V_ratio (V_t-off/V_max) (%)</td>
<td>86.1 ± 4.4</td>
<td>79.0 ± 3.5</td>
<td>1.1±</td>
<td>0.215</td>
<td>85.6 ± 4.8</td>
</tr>
<tr>
<td>Power rig</td>
<td>4.60 ± 1.3</td>
<td>5.17 ± 1.1</td>
<td>12.4</td>
<td>0.009</td>
<td>4.65 ± 1.3</td>
</tr>
</tbody>
</table>

* P values for within-group changes after the intervention period.
1 P values for between-group changes after the intervention period (ΔTG60 vs ΔCG60).

TG60, training group; CG60, control group; pre and post, before and after strength training values, respectively; TG60Δ and G60Δ, changes in percent after training for training and control groups, respectively.

mean net change after the intervention period of 1.3 W/kg (95% CI 0.2:2.3) and a V_ratio of 0.6% (95% CI -1.1:2.2) (Table 3). The deficit between TG80 and CG60 observed at baseline in JH, P_peak, P_mean, V_peak and V_ratio remained present after the intervention period, although significantly reduced (Fig. 1).

Leg extensor power rig

LEP exhibited a between-group difference for TG80 vs CG80 after the intervention period of 0.7 W/kg (95% CI 0.1:1.5) (Table 1), whereas the between group difference of TG60 vs CG60 showed a strong trend for significant change (P = 0.055) (Table 2). The deficit between TG80 and CG60 observed at baseline (39%, P < 0.05) persisted after training (22%, P = 0.052), although it significantly reduced (Fig. 1).

Correlation between RFD and mechanical muscle power at baseline

A positive correlation between isometric leg press RFD and LEP (r = 0.79, P < 0.05) and RFD and CMJ muscle power (r = 0.51, P < 0.05) was observed at baseline.
Relationship between training-induced changes

A positive correlation between changes from pre to post were observed in TG60 for LEP and MVC \((r = 0.55, \ P < 0.05)\), LEP and RFD \((r = 0.67, \ P < 0.05)\), \(P_{\text{peak}}\) and JH \((r = 0.64, \ P < 0.05)\) and \(V_{\text{ratio}}\) and JH \((r = 0.77, \ P < 0.05)\). TG80 showed a positive correlation between changes from pre to post in \(V_{\text{ratio}}\) and JH \((r = 0.74, \ P < 0.05)\) and in \(V_{p\text{peak}}\) and JH \((r = 0.86, \ P < 0.05)\).

Age-related training responses

Linear regression analysis performed on absolute units and adjusted for baseline values indicated similar training-related responses for both age groups (TG60 and TG80), although TG80 demonstrated greater relative increases (increase in %) with training for MVC, RFD impulse, JH and mean power in the power rig assessment (Table 2).

Discussion

The major finding of the present study was that 12 weeks of low-frequency (twice a week) explosive-type heavy-resistance strength training induced substantial improvements in maximal isometric strength, isometric explosive force characteristics and muscle power in both old (TG60) and very old elderly women (TG80). Notably, both age groups responded similarly to the training protocol by showing comparable absolute gains in maximal isometric muscle strength, explosive force characteristics (RFD, impulse) and muscle power (LEP) (Fig. 2, Table 1). This corresponded to greater relative increases (increase in %) in the very old individuals for MVC, RFD impulse, JH and mean power (power rig). The increases in MVC and explosive force characteristics for TG80 were of such a magnitude that the deficit reported at baseline relative to the age group 60 (CG60) disappeared (i.e. statistically non-significant) after training.

This is the first study to examine explosive-type heavy-resistance (75–80% 1 RM) strength training in old vs very old individuals. Interestingly, the largest improvements were seen in RFD, impulse, MVC and LEP (by 51, 42, 28 and 28%, respectively, in TG80, and by 18, 18, 22 and 12%, respectively, in TG60). The larger relative increases observed in TG80 (RFD, impulse) may reflect the greater age-related deficit in neuromuscular function in the very old participants at the onset of the study (Table 1, Fig. 1). With increasing age, a progressive selective atrophy of fast-twitch muscle fibers (Lexell et al., 1988) and reduced rate coding (Vailancourt et al., 2003) and a decline in maximal unloaded fiber shortening speed (Krivicks et al., 2001) have been reported, which would potentially impair rapid force and power production more than MVC per se.
Although muscle morphology was not investigated in the present study, it is likely that the oldest individuals (TG80) exhibited more type II muscle fiber atrophy than the younger subjects (TG60) (Macaluso & DeVito, 2004). However, heavy-resistance strength training can effectively induce type II fiber hypertrophy even in very old women (80+ years) concomitant with increases in neuromuscular activation (Hakkinen et al., 2001). The strength training performed in the present study using heavy-resistance loadings (75–80% 1RM) allowed participants to develop large muscle forces concomitant with a prolonged duration of muscle activation, which has been suggested to be crucial to induce muscle hypertrophy (Hakkinen et al., 2001). Thus, the greater relative increase in RFD and impulse observed in TG80 compared with TG60 may have been caused by enhanced neuromuscular activation and/or reduced antagonist coactivation as well as a greater muscle hypertrophy response, especially for the type II muscle fibers.

Interestingly, muscle power has been recognized previously as a predictor of risk of disability, rate of falls and injuries in old adults (Bassey et al., 1992; Foldvari et al., 2000; Skelton et al., 2002; Pijnappels et al., 2005). The findings of the present study indicate that in situations requiring rapid and powerful force generation, the trained elderly (TG80 and TG60) may have increased the ability to initiate a movement with a high RFD and hence may potentially exert increased acceleration and greater speed throughout the movement as also supported by the observed gain in maximal muscle power.

In both age groups, the mean and peak muscle power recorded during the CMJ exhibited a substantially smaller improvement with training (4–6%) than LEP (12–28%) (Tables 1 and 2, Figs. 2 and 3). This discrepancy may be explained by the biomechanical design of the power rig. The short distance (16.5 cm) that the leg is allowed to travel (Bassey et al., 1992) and the relatively low external resistance (flywheel) that the subject must accelerate make time a key factor for assessing mechanical muscle power with the power rig. Thus, a high production of muscle power becomes highly dependent on the ability to accelerate the footplate forcefully and explosively from the absolute initial phase of the push (i.e. exerting a high RFD). Subjects with a low RFD may not be able to fully reach their maximal muscle power capability with the power rig due to the time constraint and limited joint range of motion. In contrast, the larger external resistance and longer time available during CMJ testing likely render mechanical muscle power less dependent on the RFD capability. This notion is confirmed in the present study by a positive correlation between RFD and LEP ($r = 0.79$, $P < 0.05$) and between RFD and CMJ muscle power ($r = 0.51$, $P < 0.05$) at baseline. Similarly, the larger age-related deficit at baseline (TG80 vs TG60) in LEP (43%) and CMJ mean jump
power (23%) (Fig. 1) also is likely related to reduced RFD capacity in the oldest group. The training-related increase in RFD and impulse in TG80 (51, 42%) was accompanied by an increase in LEP (28%) and an improvement in CMJ peak power (6%) (Table 1). Pre training JH showed the largest difference between the two age groups (47%), while a 28% difference was seen in peak jump power (Fig. 1), while a strong correlation between these two variables was observed at baseline ($r = 0.94$, $P < 0.05$).

JH is determined by the kinetic take-off impulse generated by the sum of muscle torques developed at each joint. The sequential activation of hip, knee and ankle muscles and the optimal joint to joint muscle torque transfer determine the final take-off velocity and thereby the JH (Bobbert & van Soest, 2001). The discrepancy in the difference between JH and peak power for the two age groups (60 vs 80) (deficit; Fig. 1) can be explained by the lower $V_{ratio}$ in the oldest group compared with the younger groups.

A reduced $V_{ratio}$ was observed in the oldest individuals (TG60, CG60), showing that a reduced percentage of the maximal velocity was conserved during the concentric phase of the movement (Tables 2 and 3) hence producing a reduced JH according to the potential capability. The results showed that the age-related difference for JH was greater than that of peak power. Lower ankle extensor muscles propulsion during the final push-off phase of the jump and/or less effective muscle torque transfer to the ankle joint may have contributed to the larger difference in JH compared with peak power between the two age groups (Fig. 1) (Bobbert & van Soest, 2001). In accordance, ankle plantar flexors’ muscle power strongly predicted the ability to perform functional motor tasks in aged individuals (Suzuki et al., 2001). Increased ankle extensors push-off action and/or more efficient proximal to distal muscle torque transfer may therefore have contributed to the greater relative JH improvement in TG80 (18%) after training, despite similar absolute enhancement having occurred in both groups for peak jump power (Bobbert & van Soest, 2001) (Table 2). This notion was supported by the significant increase in $V_{ratio}$ in TG80 after training and by the positive correlation between changes from pre to post for $V_{ratio}$ and JH ($r = 0.74$, $P < 0.05$), indicating a better use of maximal capability (i.e. maximal concentric velocity) to perform a higher jump. Although no significant increase was reported for TG60 in $V_{ratio}$ after training, a positive correlation between changes from pre to post for $V_{ratio}$ and JH ($r = 0.77$, $P < 0.05$) was observed, which may explain the differential increase in percent between JH (+10%) and $P_{peak}$ (5%).

It has been reported that training with heavier loads shifted the resistance that maximize muscle power leftwards on the force-velocity curve, indicating enhanced power production at heavier loads.
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(Duchateau & Hainaut, 1984). Hortobagyi et al. (Hortobagyi et al., 2003) observed that the mechanical demand to perform a given weight-bearing motor task (e.g. rising from a chair) for elderly individuals was close to their maximal capability, indicating that elderly subjects often operate on the left side of the force-velocity curve during daily motor tasks. Thus, a training protocol able to maximize muscle power with heavier loads is likely to be beneficial for older adults who often operate close to their maximum capability (at a high % of 1 RM). The present study demonstrated that an explosive heavy-resistance strength training protocol may effectively counterbalance this potential mismatch between mechanical muscle function and functional demand.

**Perspectives**

Although no subject reported any neuromuscular problem, explosive-type resistance training may potentially be injurious for populations different from the one examined in the present study. The present subjects were healthy, community dwelling and were screened by medical professional, and the training sessions were carefully controlled and supervised by professional training experts. The present regime of explosive-type resistance training appeared to be highly effective in eliciting increases in maximal isometric strength, explosive force characteristics and muscle power. These changes occurred with a low training frequency (twice a week) and a short duration (12 weeks). Notably, the explosive-type training modality was well tolerated by the present individuals and led to significant enhancement in neuromuscular performance even in the eighth decade of life. These results are functionally relevant as reduced muscle power and explosive force capacity have been associated previously with impaired functional performances and an enhanced risk of falls (Skelton et al., 2002). The present results suggest that following explosive-type resistance training, elderly individuals are better capable of developing muscle force rapidly for example during unexpected postural perturbation. Thereby, they may potentially have an increased ability to prevent a fall compared with untrained age-matched individuals.

Importantly, although international guidelines for physical activity for older adults suggest a training frequency of three to five times a week, it is often a problem to motivate individuals to take part in such vigorous training programs. The present data demonstrated that healthy elderly can effectively benefit from participating in low-frequency training programs at least when explosive muscle actions are involved.

Future studies could incorporate other types of explosive resistance training (e.g. also using lower training loads) and different training frequency (>twice a week) to further evaluate the effect of training load intensity and frequency–response relationship in the oldest population.

**Key words:** elderly, aging, strength training, power, countermovement jump.

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