Stair-Ascent Performance in Elderly Women: Effect of Explosive Strength Training

Anders Holsgaard-Larsen, Paolo Caserotti, Lis Puggaard, and Per Aagaard

Explosive-type strength training may alter kinetics and neuromuscular activity during stair ascent in elderly women. This may improve functional ability. Nineteen women (69.7 ± 3.4 yr) were randomly allocated to strength training (TG; twice per wk, 12 wk) or a control group (CG). Stair ascent was assessed at self-chosen (AFV), standardized (ASV), and maximal velocity (AMV) pre- and posttraining. Ground-reaction force (GRF) and EMG quantified kinetics and neuromuscular activity. After training, TG increased AMV and AFV velocity by 8% (p = .02) and 17% (p = .007), respectively (TG vs. CG; p < .05). This was accompanied by elevated rectus femoris EMG (from 21% to 48%, p < .047). At AFV, TG increased GRF first peak force 4% (p = .047), and CG increased second peak force 5% (p = .036). Muscle coactivation remained unaltered in both groups. Explosive-type strength training led to enhanced stair-climbing performance at maximal and self-chosen speed, reflecting an improved functional ability.

Keywords: antagonist muscle coactivation, muscle power, functional performance, exercise

Stair negotiation is an important functional movement task that requires considerable amounts of muscle strength and power (Hortobagyi, Mizelle, Beam, & DeVita, 2003; Larsen, Puggaard, Hamalainen, & Aagaard, 2008; Larsen, Sorensen, Puggaard, & Aagaard, 2008) and is considered one of the most hazardous activities for the elderly in the home (Roys, 2001). With increasing age, muscle power and strength progressively decrease (Skelton, Greig, Davies, & Young, 1994), and stair ascent becomes more demanding because of the relatively higher load imposed on the leg-extensor muscles (Hortobagyi et al., 2003). In addition, it was recently reported that older women used 67% of their maximal stair-climbing speed when climbing stairs at self-selected (habitual) velocity, compared with only 47% for younger women (Larsen, Puggaard, et al., 2008), supporting the idea that the overall functional reserve capacity of stair ascent is progressively reduced with increasing age (Larsen, Puggaard, et al., 2008). It was postulated that adequate strength and...
power generation at the knee and ankle joints is necessary for safe stair negotiation (Cavanagh, Mulfinger, & Owens, 1997; Larsen, Sorensen, et al., 2008). Furthermore, maximum leg-muscle power and isokinetic strength were reported to be strong determinants of stair-negotiation performance in elderly individuals (Bassey, Fiatarone, Oneill, Kelly, Evans, & Lipsitz, 1992; Larsen, Sorensen, et al., 2008).

Multidimensional and strength exercise interventions in elderly individuals have been effective in improving stair-ascent performance (Bean et al., 2002; Beyer et al., 2007; Capodaglio, Edda, Facioli, & Saibene, 2007; Fiatarone et al., 1994; Skelton, Young, Greig, & Malbut, 1995; Suetta et al., 2008) and combined stair ascent and descent (Capodaglio et al., 2007) but not during descent-only protocols (Mian, Thom, Narici, & Baltzopoulos, 2007). However, none of the aforementioned studies performed a kinetic analysis (i.e., ground-reaction-force [GRF] analysis) to investigate biomechanical aspects related to the adaptive change in stair-ascent function. In addition, biomechanical GRF analysis enables a more complete understanding of the mechanisms responsible for the training-induced modulation in stair-climbing performance in elderly individuals.

Elevated agonist–antagonist muscle coactivation recently was observed during stair ascent and descent in elderly compared with young subjects (Larsen, Puggaard, et al., 2008). Increased muscle coactivation in elderly subjects during locomotion is most commonly ascribed as a compensatory mechanism to increase joint stiffness and thereby enhance lower limb stability (DeVita & Hortobagyi, 2000). However, elevated antagonist-muscle coactivation may limit the full potential of net joint torque production and range of motion, especially in dynamic motor tasks (Baratta et al., 1988; Hakkinen et al., 1998; Izquierdo, Ibanez, et al., 1999). In the current study we expected that training-induced gains in maximal leg-muscle force and power would enable trained individuals to readopt a neuromuscular motor program during stair climbing that was more similar to that seen in younger and more able-bodied individuals (Larsen, Puggaard, et al., 2008).

Increased neuromuscular activity for the agonist muscles and reduced antagonist-muscle coactivation during isolated single-joint maximal voluntary contractions (MVCs) were previously observed in elderly subjects after 6 months of heavy-resistance strength training (Hakkinen et al., 1998). Nevertheless, it is not clear whether and to what extent the reduced amount of antagonist coactivation observed after strength and power training in elderly subjects can be transferred to more complex multijoint functional performances (i.e., stair climbing). To our knowledge, no study has investigated the effect of a strength-training intervention on the kinetic profile and neuromuscular activity during stair ascent in elderly individuals.

It is recommended that strength-training programs emphasize gains in muscle power rather than strength to maximize functional capacity in aging individuals (Caserotti, Aagaard, Buttrup Larsen, & Puggaard, 2008; Izquierdo, Hakkinen, et al., 2001). Interventions involving explosive-type heavy-resistance training (i.e., with maximal intentional acceleration of the load) have demonstrated substantial increases in maximal muscle power in old and very old individuals (63–86 years; Caserotti et al., 2008; de Vos et al., 2005; Hakkinen et al., 2002; Marsh, Miller, Rejeski, Hutton, & Kritchevsky, 2009; Suetta et al., 2004). Thus, explosive-type heavy-resistance training may be a particularly useful training regimen in elderly subjects to improve performance of motor tasks such as stair ascent (Hortobagyi et al., 2003; Larsen, Sorensen, et al., 2008).
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The aim of the current study was to test the hypothesis that explosive-type strength training would lead to increased functional capacity during stair climbing in elderly women (i.e., increase stair-ascent velocity) and to investigate potential underlying mechanisms related to concurrent changes in kinetic GRF profile and antagonist-muscle coactivation.

Methods

Participants
Thirty-two community-dwelling elderly women without any strength-training background volunteered to participate in this randomized controlled trial. Subjects were included if they participated at most once a week in structured multicomponent training that included no specific strength-training exercises. Subjects who engaged in any kind of strength training including multicomponent training were not included in the study. Subjects were recruited through local newspaper advertisement and senior centers and by word of mouth. All gave written informed consent and underwent a screening by a medical doctor to exclude neuromuscular, orthopedic, or cardiovascular problems that could interfere with the study. In addition, subjects reported no difficulties in performing daily motor tasks as evaluated by questionnaire. Nine subjects were excluded based on the exclusion criteria (mainly because of uncontrolled hypertension). Twenty-three subjects (age 69.7 ± 3.4 years, M ± SD) subsequently were randomized in a stratified manner into a training group (TG; n = 12) or a control group (CG; n = 11) according to maximal leg-muscle power measured during a countermovement jump. Stratification was performed to ensure that the two groups had similar muscle-power capacity at baseline, because the intervention was designed to improve muscle power. In addition, a physical activity questionnaire was used to compare physical activity level (type, intensity, frequency, and volume) at baseline for the two subject groups (Caserotti et al., 2008; Larsen, Puggard, et al., 2008; Larsen, Sorensen, et al., 2008). TG subjects performed explosive-type heavy-resistance strength training twice a week for 12 weeks. CG subjects did not engage in physical training during the entire period of the experiment and were asked to simply maintain their lifestyles as before enrolling in the experiment. The conditions and methods of the study were approved by the local ethics committee.

Body height was measured by a conventional metric scale, and body weight, lean body mass, and fat mass were estimated by a body-composition analyzer (Tanita Body Composition Analyzer, TBF-3000, Tokyo, Japan; Heitmann, 1990).

Data Collection and Analysis
The protocol included, in the following order, (1) EMG electrodes placed for muscle-activity measurements, (2) a 5-min standardized warm-up session on a bicycle ergometer, (3) MVC-strength assessments, (4) stair-climbing familiarization, and (5) a standardized stair-climbing protocol.

Surface EMG signals were obtained from five muscles (vastus lateralis, vastus medialis, rectus femoris, biceps femoris, and semitendinosus) of the left leg during all stair-ascent trials and were subsequently normalized to the maximal EMG-signal amplitude recorded during MVC. EMG signals were recorded at 1,000 Hz using
Ag/AgCl surface electrodes (Blue Sensor, N-00-s, Ballerup, Denmark) with a 2.5-cm interelectrode distance and a measuring area of 95 mm². The skin was shaved and cleaned with alcohol to reduce electrode–skin impedance before the electrodes were positioned bipolarly (Hermens et al., 1999). EMG electrodes were connected directly to small custom-built preamplifiers taped onto the skin. The EMG signals were led through shielded wires into the main amplifier (amplification gain 400, signal-to-noise ratio >80 dB) containing an analog high-pass filter (10 Hz) and a low-pass filter (500 Hz), and then into a 32-channel 12-bit A/D converter (Data Translation Inc., Type DT3010) connected to a personal computer. All EMG and GRF signals were recorded synchronously. After placement of the EMG electrodes a 5-min standardized warm-up session on a bicycle ergometer was performed before the MVC recordings of the left leg. To obtain a measure of maximum EMG-signal amplitude, the maximal EMG activity was defined as the highest (peak) filtered EMG-signal amplitude recorded in three consecutive MVC trials. A similar experimental approach has been used previously (Larsen, Puggaard, et al., 2008; Zebis et al., 2008). Isometric quadriceps and hamstring MVCs were performed in a sitting position while the subject performed maximal static knee-extensor and -flexor contractions, respectively. The foot was secured on a rigid foot plate (extensor MVCs) or manually fixated by the test leader (flexor MVCs). The hip was flexed approximately 90°, and the knee angle was 120° extension. Strong verbal encouragement was given with every contraction to promote maximal effort. The MVC measurements were followed by a specific warm-up and familiarization on the stairs, including ascending and descending the flight of stairs (nine steps) twice. A separate complete familiarization session was performed 1–3 days before the actual test session.

Subjects were instructed to ascend a custom-built staircase in order of least-to-most demanding task at freely chosen velocity (AFV), standardized velocity (stride frequency [heel-to-heel strike of the same foot] of 35 strides/min; ASV), and maximal velocity (AMV). Strong verbal encouragement was given to each subject during AMV to motivate a maximal performance. Trials were repeated if visible hesitation, misplaced footing, use of handrails, or stumbles were observed. All trials were performed without the use of a handrail. To standardize the protocol, participants performed stair ascent without shoes. In addition, the stairs were covered with an antislippery surface coating. Details of the analysis have been reported previously (Larsen, Puggaard, et al., 2008; Stacoff, Diezi, Luder, Stussi, & Kramers-De Quervain, 2005; Stüssi & Debrunner, 1980). In brief, two-dimensional (sagittal-plane) GRF signal was recorded at 1,000 Hz from a forceplate (Kistler 9281 B, Winterthur, Switzerland) that was integrated in a custom-built staircase (nine steps). The current study intended to describe various biomechanical variables related to the steady-state phase of stair ascent (Andriacchi, Andersson, Fermier, Stern, & Galante, 1980; Stacoff et al., 2005). Consequently, the forceplate was placed halfway between bottom and top of the staircase (at the fifth step), and it was completely isolated from the rest of the staircase structure to avoid vibration artifacts. Furthermore, two strain gauges connected to a custom-made amplifier were integrated in the third and forth steps. These signals were exclusively used to define the instant of foot contact and foot takeoff, to calculate stride frequency (strides/min). Hence, they were determined as an on–off signal and the magnitude was not determined. The staircase was designed with a rise of 16 cm, a depth of 23 cm, and a step width of 60 cm. GRF signal was low-pass filtered using a fourth-
order zero-lag Butterworth filter with a 25-Hz cutoff frequency and normalized relative to body weight (% BW; Figure 1). The following variables were defined: $F_{z2}$ = the first peak force, present in the phase of weight acceptance; $F_{z3}$ = the minimum force, present during midstance and representing absorption of energy; $F_{z4}$ = the second peak force, present in the push-off phase before takeoff; loading slope = the loading rate at touchdown, calculated as the linear gradient from onset force to 80% of $F_{z2}$; and unloading slope = the negative rate at takeoff, calculated as the linear negative gradient from 80% $F_{z4}$ to takeoff (Stüssi & Debrunner, 1980). In addition, the mean vertical force production during the entire stance phase was calculated ($F_{\text{mean,stance}}$), along with the mean vertical force production in the loading phase ($F_{\text{mean,load}}$), from onset of force to $F_{z2}$ and in the unloading phase ($F_{\text{mean,unload}}$) from $F_{z4}$ to foot takeoff. Furthermore, stride frequency (strides/min) and duty factor (duration of the stance phase as a fraction of total stride duration) were calculated (Larsen, Puggaard, et al., 2008).

During post hoc analysis all EMG signals were digitally high-pass filtered (5-Hz cutoff frequency), subsequently rectified, and finally low-pass filtered (10-Hz cutoff frequency) and plotted as a function of time. All filters used were fourth-order zero-lag Butterworth filters. As initially described by Winter (1990) and recently used by others (Larsen, Puggaard, et al., 2008; Vinther et al., 2006), the magnitude of agonist–antagonist muscle coactivation was quantified by calculating the magnitude of relative signal overlapping (“intersecting” EMG-signal areas) for the two EMG signals $EMG_{a}$ and $EMG_{b}$ ($\int \min\{EMG_{a}, EMG_{b}\}dt$) relative to the “unified” EMG-signal area ($\int \max\{EMG_{a}, EMG_{b}\}dt$) in a given time interval $[t_1, t_2]$.

Antagonist coactivation = $\int \min\{EMG_{a}, EMG_{b}\}dt/\int \max\{EMG_{a}, EMG_{b}\}dt$

Muscle coactivation was calculated for the entire stance phase, loading phase, and unloading phase for the thigh.

**Figure 1** — Illustration of the kinetic variables of the biphasic (M-shaped) ground-reaction-force pattern typically observed during the stance phase. Kinetic parameters: $F_{z2}$ = first vertical peak force; $F_{z3}$ = minimum vertical force; $F_{z4}$ = second vertical peak force; loading slope = $F_z$ loading rate during weight acceptance (loading phase: onset of force to $F_{z2}$); unloading slope = $F_z$ unloading rate during foot takeoff (unloading phase: $F_{z4}$ to takeoff); $F_{\text{mean,stance}}$ = mean $F_z$ force in the entire stance phase; $F_{\text{mean,load}}$ = mean $F_z$ force in the loading phase; $F_{\text{mean,unload}}$ = mean $F_z$ force in the unloading phase.
Maximal concentric quadriceps and hamstring contraction strength were obtained to evaluate the effectiveness of the intervention paradigm (explosive-type strength training) to induce improvements in isolated muscle mechanical function. Isolated quadriceps and hamstring strength were assessed by isokinetic dynamometry (KinCom 500H, Chattanooga Corp., Hixson, TN). The maximal gravity-corrected knee-extensor and -flexor torques were obtained during fast (180°/s) concentric contraction of the quadriceps and hamstring muscles, respectively. Range of motion was 90–20° (0° = full knee extension). Online visual feedback of the exerted force (torque) was provided to the subjects on a computer screen, and multiple trials were performed (45-s pause) until the subjects were unable to further improve the peak-torque value. Details of the measurement procedures have been described elsewhere (Holsgaard Larsen, Caserotti, Puggaard, & Aagaard, 2007).

Resistance Training

Training consisted of a 12-week progressive explosive-type heavy-resistance strength-training program twice a week for a total of 24 sessions, with at least 2 days between successive 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 isokinetic resistance-training equipment (Cybex, Medway, MA). Four sets were performed for each exercise, with training loads of 75–80% 1-repetition maximum (8–10 repetitions per set; Mazzeo et al., 1998). During the first two training sessions, subjects used lower loading intensity (50% 1-repetition maximum, 15–20 repetitions per set) with controlled velocity to emphasize proper exercise technique. An explosive-type movement pattern (i.e., maximal intentional load acceleration) was used during the concentric contraction phase, and the eccentric phase of each exercise was performed at a slow to moderate speed (Caserotti et al., 2008; Marsh et al., 2009; Suetta et al., 2004). All training was supervised, and exercise technique, movement explosiveness, and intensity were continuously monitored and adjusted by professional trainers during each training session.

Statistical Analyses

Results are expressed as $M \pm SD$. Pre- to postintervention changes were evaluated using a Wilcoxon signed rank test (within group) or Mann–Whitney test (between groups). Level of significance was set at $p < .05$.

Results

Maximal Muscle Strength and Anthropometrics

Nineteen subjects (10 from TG and 9 from CG) completed the study. No differences in baseline anthropometric measures or physical activity (type, intensity, frequency, and volume) were observed between TG and CG. Dropouts were unrelated to the conditions of the study (two were for personal reasons, one for illness, and one, no reason given). The compliance to training was 92% (accomplished training sessions
in percentage of total planned sessions; 24 sessions in total), with an individual minimum of 83%.

Maximal concentric quadriceps and hamstring contraction strength increased in TG (+11%, \( p = .025 \), and +27%, \( p < .008 \), for quadriceps and hamstring, respectively). All anthropometric measures remained unchanged subsequent to training (Table 1). No changes were observed for the CG (Table 2).

### Table 1  Anthropometrics Pre- and Postintervention for Training Group and Control Group

<table>
<thead>
<tr>
<th></th>
<th>Mass (kg)</th>
<th>Body-mass index</th>
<th>Fat-free mass (kg)</th>
<th>Fat mass (kg)</th>
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<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
<td>Post</td>
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<tr>
<td>Training group</td>
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<tr>
<td>( M )</td>
<td>70.4</td>
<td>70.0</td>
<td>27.2</td>
<td>27.0</td>
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<tr>
<td>( SD )</td>
<td>9.7</td>
<td>9.8</td>
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<td>3.7</td>
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<tr>
<td>Control group</td>
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<tr>
<td>( M )</td>
<td>72.8</td>
<td>71.9</td>
<td>26.8</td>
<td>26.5</td>
</tr>
<tr>
<td>( SD )</td>
<td>11.9</td>
<td>11.4</td>
<td>3.7</td>
<td>3.6</td>
</tr>
</tbody>
</table>

### Table 2  Maximal Isokinetic Quadriceps and Hamstring Strength Pre- and Postintervention for Training Group and Control Group

<table>
<thead>
<tr>
<th></th>
<th>Quadriceps (Nm/body weight)</th>
<th>Hamstring (Nm/body weight)</th>
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<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
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<tr>
<td>Training group</td>
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<td></td>
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<tr>
<td>( M )</td>
<td>0.91</td>
<td>1.00*</td>
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<tr>
<td>( SD )</td>
<td>0.16</td>
<td>0.24</td>
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<tr>
<td>Control group</td>
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<td></td>
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<tr>
<td>( M )</td>
<td>0.95</td>
<td>0.97</td>
</tr>
<tr>
<td>( SD )</td>
<td>0.16</td>
<td>0.14</td>
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</table>

*Note. Nm = Newton meter.*

*\( p < .05 \) and **\( p < .01 \), significant difference pre- versus postintervention (within group). \( $p < .05 \), significant difference for delta values (between groups).*
GRF-Curve Analysis

Typical M-shaped GRF curves were obtained during AFV and ASV (see Figure 2). At AMV, GRF curves were produced with monophasic peaks only (Figure 2). Consequently, $Fz_3$ and $Fz_4$ were not calculated and $Fz_2$ was defined as the single maximum peak of the GRF signal. The duty factor did not change (pre–post) in any subject group for any test modes examined.

Stair Ascent at AFV

After the strength-training intervention, stair-ascent velocity at AFV increased by 17% ($p = .007$; pre–post difference) for TG, and a between-groups difference was also found ($p = .045$; Table 3). The elevated stair-ascent speed was accompanied by increased loading slopes (+21%, $p = .014$) and unloading slopes (+21%, $p = .005$; Table 3). In addition, $Fz_2$ increased after strength training (+4%, $p < .047$). CG displayed only a higher $Fz_4$ (+5%, $p = .036$) at posttest (Figure 3[a]). Neuro-muscular activity increased (+21%) for the rectus femoris muscle ($p = .039$) in TG (Figure 3[b]), and muscle coactivation remained unchanged after strength training (Figure 3[c]). No EMG changes were observed in CG.

![Figure 2](image)

**Figure 2** — Typical examples (from 1 subject) of vertical ground-reaction-force (GRF) signals recorded during the stance phase of stair ascent at freely selected velocity (gray line), standardized velocity (black line), and maximal velocity (dashed line).
Table 3  Time Parameters for Ascending at Freely Chosen (AFV), Standardized (ASV), and Maximal Velocity (AMV) Pre- and Postintervention for Training Group and Control Group

<table>
<thead>
<tr>
<th></th>
<th>Stride frequency (strides/min)</th>
<th>Duty factor (%)</th>
<th>Loading slope (N · s⁻¹ · % body weight⁻¹)</th>
<th>Unloading slope (N · s⁻¹ · % body weight⁻¹)</th>
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<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
<td>Post</td>
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<tr>
<td>AFV</td>
<td></td>
<td></td>
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<tr>
<td>Training group</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>44.9</td>
<td>52.8**$</td>
<td>65.8</td>
<td>64.8</td>
</tr>
<tr>
<td>SD</td>
<td>6.8</td>
<td>6.8</td>
<td>4.1</td>
<td>2.5</td>
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<tr>
<td>Control group</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>44.3</td>
<td>44.1</td>
<td>67.8</td>
<td>66.9</td>
</tr>
<tr>
<td>SD</td>
<td>7.8</td>
<td>7.3</td>
<td>4.7</td>
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<tr>
<td>ASV</td>
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<tr>
<td>Training group</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>35.6</td>
<td>36.0</td>
<td>67.7</td>
<td>36.0</td>
</tr>
<tr>
<td>SD</td>
<td>2.2</td>
<td>3.0</td>
<td>5.0</td>
<td>66.8</td>
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<tr>
<td>Control group</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>35.5</td>
<td>35.5</td>
<td>66.4</td>
<td>67.2</td>
</tr>
<tr>
<td>SD</td>
<td>1.7</td>
<td>1.8</td>
<td>6.6</td>
<td>5.0</td>
</tr>
<tr>
<td>AMV</td>
<td></td>
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<tr>
<td>Training group</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>M</td>
<td>79.8</td>
<td>85.9*$</td>
<td>60.5</td>
<td>60.9</td>
</tr>
<tr>
<td>SD</td>
<td>16.3</td>
<td>15.9</td>
<td>6.4</td>
<td>3.6</td>
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<tr>
<td>Control group</td>
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<td></td>
</tr>
<tr>
<td>M</td>
<td>72.6</td>
<td>68.1</td>
<td>61.0</td>
<td>59.8</td>
</tr>
<tr>
<td>SD</td>
<td>18.4</td>
<td>11.3</td>
<td>4.4</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Note. Stride frequency is measured for left to left leg. Duty factor calculated as the fractional part of the stance phase in relation to the total stride duration.

* $p < .05, ** p < .01, significant difference pre- versus postintervention (within group). $p < .05, significant difference for delta values (between groups).
Figure 3(a–c) — Vertical ground-reaction force ($Fz$), EMG variables, and agonist–antagonist muscle coactivation pre- and post-strength-training intervention (TG) and in untrained controls (CG) for ascending at freely chosen velocity (AFV). Gray bars = pretraining; striped bars = posttraining. (a) First vertical peak force ($Fz_2$), minimum force ($Fz_3$), second peak force ($Fz_4$), mean force in the entire stance phase, mean force in the loading phase, and mean force in the unloading phase. (b) Mean EMG activity in the entire stance phase as a fraction of maximal EMG for the vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), biceps femoris (BF), and semitendinosus (ST) muscles. (c) Antagonist muscle coactivation for the thigh muscles (VL + VM + RF vs. BF + ST) divided into entire stance phase, loading phase, and unloading phase. *$p < .05$, significant difference pre- versus postintervention (within group).
Figure 3(d–f) — Vertical ground-reaction force ($F_z$), EMG variables, and agonist–antagonist muscle coactivation pre- and post-strength-training intervention (TG) and in untrained controls (CG) for ascending at freely chosen velocity (AFV). Gray bars = pretraining; striped bars = posttraining. (d) First vertical peak force ($F_{z2}$), minimum force ($F_{z3}$), second peak force ($F_{z4}$), mean force in the entire stance phase, mean force in the loading phase, and mean force in the unloading phase. (e) Mean EMG activity in the entire stance phase as a fraction of maximal EMG for the vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), biceps femoris (BF), and semitendinosus (ST) muscles. (f) Antagonist muscle coactivation for the thigh muscles (VL + VM + RF vs. BF + ST) divided into entire stance phase, loading phase, and unloading phase. *$p < .05$, significant difference pre- versus postintervention (within group). $p < .05$, significant difference for Delta values (between groups).
**Figure 3(g–i)** — Vertical ground-reaction force ($F_z$), EMG variables, and agonist–antagonist muscle coactivation pre- and post-strength-training intervention (TG) and in untrained controls (CG) for ascending at freely chosen velocity (AFV). Gray bars = pretraining; striped bars = posttraining. (g) Vertical peak force ($F_{z2}$), mean force in the entire stance phase, mean force in the loading phase, and mean force in the unloading phase. (h) Mean EMG activity in the entire stance phase as a fraction of maximal EMG for the vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), biceps femoris (BF), and semitendinosus (ST) muscles. (i) Antagonist muscle coactivation for the thigh muscles (VL + VM + RF vs. BF + ST) divided into entire stance phase, loading phase, and unloading phase. *$p < .05$, significant difference pre- versus postintervention (within group).
Stair Ascent at ASV

As implicated by the protocol (a constant stride frequency of 35/min) stair-ascent speed remained unchanged during ASV (Table 3). However, mean delta values differed after the training period between CG and TG for $F_{z2}$ ($p < .033$), and a significant but small increase was observed for $F_{\text{mean stance}}$ (+2%, $p < .036$) in CG (Figure 3[d]). For CG a reduced (pre–post) neuromuscular activity (lowered normalized EMG amplitude) was observed in biceps femoris (−34%, $p < .044$) and semitendinosus (−40%, $p < .013$; Figure 3[e]). Furthermore, a between-groups difference (pre–post delta) was observed for semitendinosus (TG –14% vs. CG –40%, $p = .036$). Muscle coactivation remained unaltered in the posttests for both groups (Figure 3[f]).

Stair Ascent at AMV

After the intervention period maximal stair-ascent velocity (strides/min) increased by 8% ($p = .022$) for TG, with pre–post changes differing between TG and CG ($p = .045$; Table 3). No changes were observed for any of the GRF variables (Figure 3[g]). EMG activity increased for the rectus femoris muscle (+48%, $p < .047$) for TG (Figure 3[h]). No differences in muscle coactivation were observed pre- to posttraining (Figure 3[i]).

Discussion

The current study is the first to investigate the effect of explosive-type strength training on kinetic variables (GRF) and neuromuscular activity during stair ascent in elderly women. We observed that explosive-type strength training in elderly women led to improved stair-climbing velocity during both maximal (AMV) and self-selected speed (AFV), which reflects an improved functional capacity. These adaptive changes were accompanied by an altered GRF profile (increased $F_{z2}$, loading slope, and unloading slope) during AFV and elevated neuromuscular activity in the biarticular component of the quadriceps muscle during AMV and AFV. We assessed biomechanical GRF profile and antagonist-muscle coactivation to examine the mechanisms by which training-induced improvements in isolated mechanical muscle function were translated into enhanced locomotor capacity during stair ascent in old age. This information may further help identify effective prophylactic intervention regimens such as explosive-type strength training in aging individuals.

In the current study, stair-ascent velocity during AFV increased by 17% after training. This was accompanied by a slight increase (+4%) in $F_{z2}$ and a 21% increase in loading slope and unloading slope. The observed increases in loading and unloading slope indicate a higher intensity in the weight-transfer phase (Nigg & Skeleryk, 1988), most likely to match the higher stride frequency after training. Conversely, the 8% increase in stride frequency during AMV was not accompanied by a change in GRF profile. When we analyzed the curvature and the corresponding GRF data for each individual, it was apparent that the lack of statistically significant GRF changes during AMV may have resulted from individually opposing adaptation strategies, which during the process of group averaging caused a cancellation effect and a resulting lack of detectable changes. Thus, the increase in AMV velocity for
some subjects occurred as a result of increased loading slope or increased $F_{z2}$, whereas for others it was the result of increased $F_{\text{mean,stance}}$ or increased unloading slope. Consequently, it was not possible to demonstrate consistent changes in the group mean GRF pattern during stair climbing at maximum speed. In addition, a monophasic GRF pattern characterized by an absence of the $F_{z3}$ and $F_{z4}$ deflection points was observed during AMV, which may have contributed to reduced analysis sensitivity in this condition. In contrast, the distinct biphasic GRF pattern observed during AFV is likely to have increased the sensitivity to detect systematic changes in GRF characteristics, as reflected by the observed changes in $F_{z2}$, loading slope, and unloading slope.

In the current study we hypothesized that explosive-type strength training would lead to improved stair-climbing capacity in elderly individuals, manifested by an increased maximum stair-ascent velocity. This hypothesis was confirmed by the current data when stair climbing was performed at maximum and self-selected velocity. Furthermore, it might have been reasonable to expect that the training-induced gain in maximum stair-climbing capacity would lead to an increased functional reserve capacity; that is, stair climbing at self-selected speed would represent a lower fraction of the maximum capacity after the period of training. However, this expectation was not met by the current data—habitual stair-climbing speed increased more than maximum speed. Functional reserve capacity is an abstract concept because subjects can always perform a given motor task using a lower or higher self-selected speed, and therefore it can vary considerably. As a result of their enhanced muscle strength and power, therefore, trained subjects (TG group) may have tended to “overperform” during the trial of self-chosen stair-climbing speed in the postintervention tests, besides feeling more comfortable in walking up stairs at a faster self-chosen speed. Regardless, the fact that after training subjects chose to perform self-chosen stair ascent closer to their maximum capacity can be interpreted as an improvement in functional stair-climbing ability (feeling stronger and safer after training).

Because power is calculated as the product of force and speed, the elevated stair-ascent speed along with the finding of unaltered or increased GRF values implicitly reflects an elevated mechanical power production during stair ascent at maximum and freely chosen speed. Thus, the current training-induced gains (8–17%) in stair-climbing velocity reflect corresponding changes in vertical power production on the body’s center of mass. In line with the current study, Bean et al. (2002) reported 12% improvement in stair-climbing power in mobility-limited older people after functional power training including weighted ascending and descending stairs. In addition, a multidimensional training intervention that included moderate resistance and balance exercise also led to improved maximal stair-climbing speed in elderly women (70–90 years) with a history of accidental falls (Beyer et al., 2007). Furthermore, improvements in stair-ascent power were observed in long-term-care residents (Fiatarone et al., 1994) and elderly elective-hip-replacement patients (Suetta et al., 2008) after a progressive resistance-training protocol. In contrast, stair-ascent velocity did not improve in hip-replacement patients assigned to conventional rehabilitation, not even when supplemented with electrical percutaneous muscle stimulation (Suetta et al., 2008). The current study was not designed to compare the effects of different training regimens on stair-ascent performance. Furthermore, to our knowledge, no study has directly
compared the effects of traditional strength training with those of explosive-type strength training on stair climbing. Based on the current results and the previously published literature (Bean et al., 2002; Beyer et al., 2007; Fiatarone et al., 1994; Suetta et al., 2008) it is not possible to conclude whether explosive-type strength training is superior to other types of progressive strength training. Consequently, this important aspect should be examined in future studies.

Contrary to expectations, CG demonstrated ~30–40% reduced (pre–post) neuromuscular activity in the hamstring muscles (biceps femoris and semitendinosus) at standard stair-climbing speed (ASV). This decrease was mainly caused by a large posttraining decrease in normalized EMG amplitude in 2 subjects; the other subjects showed no or only minor decrease in hamstring EMG activity. It is possible that at the baseline tests these 2 subjects were unable to perform true MVC flexor efforts, resulting in suppressed peak EMG amplitudes, in turn giving rise to excessively large normalized hamstring EMG signals. Furthermore, the standardized stair-climbing speed may have been difficult to perform for some of the fittest subjects because it had to reflect the velocity of the slowest (least fit) subject included in the study. Thus, to be forced to reduce stair-climbing speed substantially below self-selected velocity may have introduced substantial longitudinal variability in the motor pattern of the fittest subjects.

It has been proposed that elevated muscle coactivation helps stiffen the leg to compensate for impaired neuromotor functions (Hortobagyi & DeVita, 2000). Elevated biceps femoris and tibialis anterior coactivation have previously been reported at touchdown during a single isolated step down from a platform set at 20% body height (Hortobagyi & DeVita, 2000) in older (mean age 69) versus younger women (mean age 21). In addition, a significantly greater coactivation in the gait cycle (i.e., increased time in percent of simultaneous antagonistic-muscle activation) has been observed in the thigh of older (mean age 73 years) than younger (mean age 27 years) adults during level walking on a motor-driven treadmill (Mian, Thom, Ardigo, Narici, & Minetti, 2006). Elevated antagonist-muscle coactivation has previously been reported for older subjects during stair ascent and descent at standardized velocity (stride frequency = 40/min), but only for the quotient of vastus lateralis versus biceps femoris measured during the entire stance phase (Hortobagyi et al., 2003). Furthermore, it has recently been demonstrated that during stair ascent or descent muscle coactivation for the thigh is ~15% greater (range 10–20%) in healthy community-dwelling elderly (mean age 72 years) than younger individuals (mean age 26 years; Larsen, Puggaard, et al., 2008). Assuming constancy in agonist-muscle activity, a decrease in antagonist-muscle coactivation seems desirable, because the resulting knee-flexor moment (negative work) would decrease. However, a decrease in antagonist-muscle coactivation might not be optimal for the integrity of the joint. Indeed, during simple motor tasks (isometric and dynamic leg extension) reduced antagonist-muscle coactivation in elderly subjects was observed after progressive long-term (6-month) heavy-resistance training combined with explosive types of exercises (Hakkinen, Alen, Kallinen, Newton, & Kraemer, 2000; Hakkinen et al., 1998; Hakkinen, Kraemer, Newton, & Alen, 2001), although not consistently demonstrated in all training studies (Aagaard et al., 2000; Hortobagyi et al., 1996; Morse et al., 2005). Furthermore, antagonist-muscle coactivation decreased by ~13% after a short-term intervention of explosive resistance training (Laroche, Roy, Knight, & Dickie, 2008). However, in that study
all training was performed using the same isokinetic device as was used during the test sessions (Laroche et al., 2008). Thus, specific neural adaptation related to the given motor task (i.e., learning effect) might be the main reason for the reported reduction in muscle coactivation.

In the current study, the observed increase in stair-climbing performance after strength training could be related to a decrease in antagonist-muscle coactivation, reflecting the fact that the strength-trained individuals had readopted a neuromuscular motor program during stair climbing that was more similar to that seen in young individuals (Larsen, Puggaard, et al., 2008). In disfavor of this notion, however, agonist–antagonist muscle coactivation remained unaffected after the training. Elevated muscle coactivation has been suggested to provide a compensatory mechanism to increase joint stiffness and enhance lower limb stability in aging subjects (DeVita & Hortobagyi, 2000). Thus, our finding of persistently elevated antagonist-muscle coactivation during stair climbing in the trained elderly subjects may represent an inherent safety mechanism that helps ensure an optimal postural control with increasing age. In addition, the multijoint motor-task nature of stair climbing involves simultaneous activation of the hip, knee, and ankle joints. A temporal modulation in muscle activity (especially for biarticular muscles) from one joint to another is evident depending on the different phases of the stance phase (Lyons, Perry, Gronley, Barnes, & Antonelli, 1983). In the current study we report data on muscle coactivation for the thigh muscles alone. However, we assessed antagonist-muscle coactivation and analyzed (data not shown) the ankle muscles, as well (soleus and gastrocnemius lateralis vs. tibialis anterior). No significant alterations were observed in any of these parameters in either TG or CG. Antagonist-muscle coactivation is a central component of the nervous system’s control of natural movement (Darainy & Ostry, 2008) and is probably not reduced in elderly people as a result of short-term explosive resistance training per se but needs to also incorporate specific task-oriented training that mimics the motor tasks of daily living.

The current study involved a trial at standardized velocity (ASV), that is, using a fixed stride frequency and step length (step length dictated by the dimension of the stairs). Although changes in GRF in ASV and AMV are difficult to directly attribute to changes in motor-control strategies (because they are largely an epiphenomenon of increased speed), a potential change in GRF or neuromuscular activity during ASV would reveal a truly altered motor strategy after training. However, no changes in GRF variables or neuromuscular activity were observed at ASV pre- versus post-training in TG. Consequently, the lack of altered motor strategy at standardized stair-climbing speed after training during stair climbing at maximal and self-selected speed indicate that the adaptive change in motor strategy is closely linked to the modified behavior (higher velocity) and does not represent an alteration in how the motor output was organized (unaltered strategy). The observed rise in rectus femoris EMG activity during stair climbing at self-selected and maximal speed likely indicates that the elevated stride frequency was mainly produced by means of a more forceful knee-extension or hip-flexor action. The finding of unaltered levels of antagonist coactivation after training may suggest that the training regimen was not adequate or specific enough to alter antagonist-muscle coactivation during stair ascent. Alternatively, the GRF pattern during ASV and the overall level of antagonist-muscle coactivation may have already been optimally tuned for our healthy elderly subjects before training.
Some potential limitations and methodological decisions of the current study may be noted: (a) The sample size was relatively small. Nonetheless, it was possible to demonstrate a significant increase in muscle strength and stair-climbing velocity during AFV and AMV. (b) The current study examined a group of relatively well-functioning elderly women. The outcome might have been different if elderly subjects with lesser walking ability or subjects with more advanced neuromuscular age-related impairments were examined. (c) In addition, the current study’s data were obtained only in elderly women. Thus, the results and conclusions should not be considered general between genders without great precaution. (d) The subjects wore no shoes during stair ascent, which could have altered motor performance. (e) Agonist–antagonist muscle coactivation assessed in the quadriceps versus hamstring muscles (here quantified as EMG-signal overlap) may be difficult to interpret because of the dual role of the biarticular hamstring muscles acting as both knee flexors and hip extensors, as well as the reverse role (concurrent knee extensor and hip flexor) played by the biarticular rectus femoris muscle.

Conclusions

Improvements in maximal and freely chosen-stair climbing velocity were observed in healthy elderly women after a period of explosive-type strength training. The improvements in performance outcome were accompanied by changes in kinetic profile (GRF pattern) and neuromuscular activity along with unaltered thigh-muscle coactivation. Biomechanical GRF analysis augments our understanding of stair-ascent motor tasks in the elderly and may help identify effective prophylactic intervention regimens such as explosive-type strength training in aging individuals. It was demonstrated that explosive-type strength training led to enhanced stair-climbing performance in healthy elderly women, reflecting an important improvement in functional ability for this population.

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