This study explored the age-related deterioration in stretch-shortening cycle (SSC) muscle power and concurrent force–velocity properties in women and men across the adult life span.

A total of 315 participants (women: $n = 188$; men: $n = 127$) aged 18–81 years performed maximal counter-movement jumps on an instrumented force plate.

Maximal SSC leg extension power expressed per kg body mass ($P_{peak}$) was greater in men than in women across the adult age span ($P < 0.001$); however, this gender difference was progressively reduced with increasing age, because men showed an ~50% faster rate of decline in SSC power than women ($P < 0.001$). Velocity at peak power ($V_{Ppeak}$) was greater in men than in women ($P < 0.001$) but declined at a greater rate in men than in women ($P = 0.002$). Vertical ground reaction force at peak power ($F_{Ppeak}$) was higher in men than in women in younger adults only ($P < 0.001$) and the age-related decline was steeper in men than in women ($P < 0.001$).

Men demonstrated a steeper rate of decline in $P_{peak}$ than women with progressive aging. This novel finding emerged as a result of greater age-related losses in men for both force and velocity. Consequently, maximal SSC power production was observed to converge between genders when approaching old age.

It is well established that human ageing is characterized by a progressive decline in the function of the physiological system (Young, 1997; Vandervoort, 2002; Aagaard et al., 2010; Narici & Maffulli, 2010). Specifically, evidence of impaired neuromuscular function has been observed in old age (Young, 1997; Vandervoort, 2002; Aagaard et al., 2010; Narici & Maffulli, 2010), which is accompanied by an age-related decline in muscle mass (sarcopenia) and a change in muscle architecture (Rosenberg, 1997; Iannuzzi-Sucich et al., 2002; Narici & Maffulli, 2010). Consequently, the contractile force–velocity properties of human skeletal muscle become compromised with increasing age as manifested by substantial reductions in maximal muscle strength, rate of force development (RFD), and muscle power (Young & Skelton, 1994; Pearson et al., 2002; Trappe et al., 2003; Petrella et al., 2005; McNeil et al., 2007; Thom et al., 2007; Toji & Kaneko, 2007; Raj et al., 2010). Peak muscle power is considered a predictor of functional performance and an important factor for the risk of falling (Basey, 1992; Skelton et al., 1994; Bean et al., 2002), and both animal and human study findings support that lower limb muscles are more affected by age-related changes than proximal upper limb muscles (Lexell et al., 1988; Hashizume & Kanda, 1995; Klein et al., 2003; Aagaard et al., 2010).

A certain minimum magnitude of lower limb muscle strength and power is required for independently performing a number of daily activities (ADL) such as stair-climbing and rising from a chair (Holsgaard Larsen et al., 2007). Furthermore, a successful execution of more reactive motor tasks, such as fall avoidance maneuvers, depends strongly on the muscle capacity to generate high maximal muscle power (Metter et al., 1997; Caserotti et al., 2001). Consequently, reduced muscle power has been suggested to play a key role in the decline in functional capacity seen with musculoskeletal ageing (Basey, 1992; Michaelis et al., 2008) and is considered functionally more relevant than maximal muscle strength per se (Basey, 1992).

From the age of 65 years, the rate of decline in maximal muscle power is more pronounced (3.5% per annum) than that of maximal muscle strength (1.5–2%) (Skelton et al., 1994). Similar trends have been reported over a greater age span (40–90 years), albeit of a smaller relative magnitude (1.3% vs 0.6% decline in power vs
strength, respectively) (Pearson et al., 2002). Power is defined as the rate of external work or energy production, and can be calculated as the product between propulsive force and resulting movement speed (Caserotti et al., 2001; Thorlund et al., 2008). Gender differences in these determining factors of muscle power [i.e., force (Yamauchi et al., 2010) and velocity (Caserotti et al., 2001)] seem to exist between aging women and men (Caserotti et al., 2001; Petrella et al., 2005; Yamauchi et al., 2010) although not previously examined across the adult life span.

Human locomotion involves multi-joint movements and consists of coupled eccentric–concentric muscle actions known as stretch-shortening cycle (SSC) activities (Komi & Bosco, 1978; Bosco et al., 1982; Svantesson et al., 1994). Thus, it seems relevant to investigate mechanical muscle function using multi-joint weight-bearing SSC movements, such as countermovement jump (CMJ), to evaluate potential age and gender differences in maximal muscle power production (Bosco & Komi, 1980; Caserotti et al., 2001, 2008b; Bojsen-Moller et al., 2005; Holsgaard Larsen et al., 2007), rather than solely evaluating maximal muscle power using isolated concentric-only muscle contractions (Basey, 1992; Skelton et al., 1994). Because the CMJ involves (a) coupled eccentric–concentric muscle actions and (b) simultaneous and coordinated flexion–extension movements in the hip, knee, and ankle joints, and (c) incorporates the production of propulsive ground reaction forces, this test modality may better imitate typical activities of daily living such as stair-climbing (Larsen et al., 2009), sit to stand, and gait (Caserotti et al., 2008b) than single-joint muscle power tests. The CMJ maneuver has previously been used to assess maximal SSC muscle power in both old and young adults (Caserotti et al., 2001, 2008a; Bojsen-Moller et al., 2005; Holsgaard Larsen et al., 2007; Jakobsen et al., 2012) and the mechanical output of the musculoskeletal system (propulsive force, power, etc.) appears to be highly reproducible during CMJ testing, including elderly subjects (Holsgaard Larsen et al., 2007). However, only a limited number of studies have evaluated human skeletal muscle power and its force–velocity components during functional multi-joint movements (Bosco & Komi, 1980; De Vito et al., 1998; Macaluso & De Vito, 2003; Yamauchi et al., 2010; Jakobsen et al., 2012). Even fewer studies have examined potential age-related differences in SSC muscle power and related force–velocity properties across the adult life span (Runge et al., 2004; Yamauchi et al., 2010).

Given that skeletal muscle power is dependent on muscle force production and contraction velocity, and that maximal muscle power plays an important role for functional activities of daily living (ADL) such as walking and stair walking, it seems crucial to improve our understanding of contributing factors responsible for the loss in maximal muscle power observed with aging. Furthermore, for elderly individuals to sustain locomotive ADL functions and sustain an independent lifestyle, it is of importance to detect early deteriorations in function and muscle power in order to initiate early preventive strategies. Therefore, an improved understanding and awareness of the impact that natural ageing has on SSC muscle power and its constituting force–velocity components may potentially yield useful tools in the risk assessment of the ageing individual.

The aim of the present study was therefore to study the influence of aging and gender on the magnitude of maximal SSC muscle power production during coupled eccentric–concentric muscle contractions across the full-adult age range.

It was hypothesized that women would produce lower SSC muscle power than men and that gender differences in the rate of decline in SSC muscle power would be observed with increasing age when examined over a wide age range (~20 to 80 years of age).

Materials and methods

Study design

Three different age groups (18–34, 35–55, and 65–81) were recruited and the main inclusion criterion was that subjects should be able to successfully perform a maximal vertical jump. Exclusion criteria were: any severe musculoskeletal injuries or problems affecting physical performance; any detectable neurological, cardiopulmonary, or cognitive problems; or arthroplastic surgery in the lower extremity. Testing was conducted at two separate research facilities by the same two test leaders at the respective laboratories. All test procedures followed the same standardized protocol.

The study was approved by the Regional Ethical Review Board, Gothenburg, Sweden, and all experimental subjects gave their written informed consent to the conditions of the study.

Subjects

Recruitment procedures

In this multicenter, study participants were recruited using different means of approach. Persons living in the Gothenburg area 18 years and older were invited to participate by recruiting at the local university campus, University of Gothenburg, Sweden. A total of 135 persons accepted to participate and 131 (97%) met the inclusion criteria. Women and men aged 35–55 years residing in Odense, Denmark, were randomly selected through the Danish National Civil Registration System as a matched control group for another study (Thorlund, 2010). Finally, women and men aged between 65 and 80 years and living in Gothenburg were randomly selected from the Swedish National Registry and were invited to participate in the study. Of the 500 participants, 200 (40%) accepted to participate and 154 (31%) of these met the inclusion criteria. In total, 315 participants were recruited. The subjects were divided in three different age groups: young (Y) (18–34 years, \( n = 107 \)), middle aged (M) (35–55 years, \( n = 54 \)), and old (O) (65–81 years, \( n = 154 \)). Each group was further divided by gender: women (W) (\( n = 188 \), 19–81 years) and men (M) (\( n = 127 \), 18–80 years).

Experimental procedures

All participants visited the research laboratory one time, either at the University of Gothenburg (all Swedish participants) or at the
University of Southern Denmark (all Danish participants). Prior to testing, all subjects performed a 5- to 7-min general warm-up on a Monark ergometer cycle. Shortly after the warm-up (1–2 min), the subjects performed the actual test after receiving verbal and visual instructions. All participants wore the same type of athletic shoes provided by the research laboratory.

**Anthropometry assessments**

Body height was measured to the nearest centimeter (cm) and body mass (kg) was measured using a digital scale with participants lightly dressed (Table 1).

**Assessment of SSC muscle power**

Maximal leg extension power was determined during a standardized SSC movement performed as a maximal bilateral CMJ as described in detail previously (Caserotti et al., 2001; Bojsen-Moller et al., 2005; Holsgaard Larsen et al., 2007; Thorlund et al., 2008; Jakobsen et al., 2012). The subjects were instructed to perform a fast downward movement to about 90° knee flexion starting from an upright standing position to be immediately followed by a fast upward movement, and to jump as high as possible. To minimize the influence of the arms, the subjects kept their hands on their hips (Lees et al., 2004). In brief, vertical ground reaction force (\(F_z\)) was measured by a force plate (AMTI OR6-5-1, 51 × 46 × 8 cm, Watertown, Massachusetts, USA, and Kistler 9281 B, Kistler Instruments, Winterthur, Switzerland) in accordance with previous procedures (Caserotti et al., 2001; Bojsen-Moller et al., 2005; Holsgaard Larsen et al., 2007; Thorlund et al., 2008).

Starting from an upright standing position, subjects were instructed to perform a fast downward movement (eccentric phase) with their hands on their hips immediately followed by a fast upward movement (concentric phase), and to jump as high as possible (Lees et al., 2004; Holsgaard Larsen et al., 2007). The jump was visually demonstrated to the subject who subsequently performed three to five submaximal jumps for practice. After a short rest period, the subject executed three maximal jumps on the force plate with approximately 1-min rest periods between successive trials. The jump with the highest jump height was selected for further analysis (Lees et al., 2004). CMJ testing of maximal SSC power of the leg extensors has previously been validated in study populations covering a wide age range (Rittweger et al., 2004) as well as in old individuals separately (Holsgaard Larsen et al., 2007).

**Data sampling and analysis**

The force plate was connected to an amplifier and the vertical ground reaction force signal (\(F_z\)) was fed through the amplifier to a 12-bit A/D converter (A/D Interactive Utility) into a personal computer at a 1000-Hz sampling rate. The \(F_z\) signal was later analysed as explained in detail elsewhere (Caserotti et al., 2001; Bojsen-Moller et al., 2005; Thorlund et al., 2008; Jakobsen et al., 2012). In brief, the vertical velocity (\(V\)) of the body center of mass (BCM) was found by time integration of the instantaneous acceleration signal (\(F(z/m-g)\) dt, where \(m=\) body mass, \(g=9.81\) m/s²). Subsequently, the vertical position of the center of mass (CMpos) was obtained by time integration of the velocity signal (\(V\) dt). Throughout the entire movement, instantaneous power (\(W\)) exerted on the BCM was calculated as the product of vertical ground reaction force (\(F\)) and BCM velocity (\(V\)) (Holsgaard Larsen et al., 2007; Thorlund et al., 2008; Jakobsen et al., 2012). All jumps were analysed separately for the eccentric phase (EccP, downward movement of BCM), with negative BCM velocity, and the subsequent concentric phase (ConP: upward propulsive BCM movement), characterized by positive BCM velocity. Every CMJ trial performed was analysed for maximal jump height (\(JH\)) by calculating the vertical velocity of BCM at the instant of takeoff based on the takeoff impulse (\(MV\)) of the subject (\(JH=V_{\text{takeoff}}/2g\)) (Caserotti et al., 2001). Furthermore, the duration of the propulsive takeoff phase (\(T_{\text{Con}}\)) was determined. Peak vertical force was identified in the eccentric movement phase (\(F_{\text{peak-Ecc}}\)) and the concentric phase (\(F_{\text{peak-Con}}\), respectively. Peak power (\(P_{\text{peak}}\)) exerted on the BCM was identified in the concentric phase together with its constituting components, namely vertical BCM velocity and vertical ground reaction force at the instant of peak power, respectively (\(P_{\text{peak}}, F_{\text{peak}}\)). Furthermore, total work produced on BCM in the concentric phase was determined (\(Work_{-Con}\)). To quantify the ballistic nature of the jumping movement, the rate of force development (\(RFD=dF/dt\)) was calculated in the 100 ms time interval starting from the onset of BCM deceleration in the eccentric movement phase (i.e., instant where \(F\) exceeded body mass) (Holsgaard Larsen et al., 2007; Thorlund et al., 2008).

CMJ parameters were selected based on results from previous studies that have demonstrated their importance for mechanical muscle performance during SSC testing in both young and old individuals (Caserotti et al., 2001; Bojsen-Moller et al., 2005; Holsgaard Larsen et al., 2007; Thorlund et al., 2008; Jakobsen et al., 2012). Acceptable-to-excellent test–retest reproducibility (\(r=0.73–0.95, CV_{\text{within subject}}=3–8\%\)) has been reported in healthy elderly adults (72.3 ± 6.6 years) for the CMJ analysis parameters examined in the present study (Holsgaard Larsen et al., 2007).

**Statistical analysis**

Data are expressed as group means ± standard deviation unless otherwise stated. Differences between women and men within their respective age group (\(Y\), \(M\), and \(O\)) were evaluated using non-paired Student t-tests. A one-way between-groups analysis of variance (ANOVA) was used to compare the CMJ characteristics of the age groups. Significance level was set at \(P<0.05\).

| Characteristics | Young | | Middle aged | | Old |
|-----------------|-------|----------------|----------------|----------------|
|                 | Women | Men | Women | Men | Women | Men |
| Age (years)     | 24 (4) | 26 (5)* | 41 (5) | 44 (7) | 72 (5) | 72 (5) |
| Height (cm)     | 169 (7) | 179 (6)** | 166 (7) | 180 (8)** | 163 (5) | 178 (7)** |
| Weight (kg)     | 63.2 (7.7) | 78.3 (8.6)** | 65.3 (8.2) | 87.4 (14.6)** | 68.2 (10.9) | 82.9 (11.9)** |
| Body mass index | 22.2 (2.2) | 24.3 (2.2)** | 23.6 (2.5) | 27.0 (4.2)** | 25.5 (3.8) | 26.2 (3.0) |
| Jump height (cm) | 20.8 (4.2) | 31.6 (6.2)** | 19.8 (3.9) | 25.0 (4.0)** | 8.2 (3.2) | 12.7 (4.9)** |

*P*-values show difference between women (\(w\)) and men (\(m\)): * < 0.05, ** < 0.01, *** < 0.001; statistically significant differences between age groups.

†Young w/m vs old w/m (\(P < 0.05\)).

‡Old w/m vs middle-aged w/m (\(P < 0.05\)).

§Middle-aged w/m vs young w/m (\(P < 0.05\)).
Table 2. Maximal leg extension power, force, and selected kinematic variables obtained during a standardized SSC maneuver (CMJ) in young (18–34 years), middle-aged (35–55 years), and old (65–81 years) women and men, respectively [group means and standard deviation (SD)]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Young n = 107</th>
<th>Middle aged n = 54</th>
<th>Old n = 154</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Women n = 79</td>
<td>Men n = 28</td>
<td>Women n = 28</td>
</tr>
<tr>
<td>Ppeak-Con (W/kg)</td>
<td>35.7 (4.9)†</td>
<td>47.6 (6.0)***†§</td>
<td>22.0 (4.2)</td>
</tr>
<tr>
<td>Fpeak-Con (N/kg)</td>
<td>18.0 (1.4)†</td>
<td>23.2 (2.7)**†§</td>
<td>19.5 (3.2)</td>
</tr>
<tr>
<td>FPpeak-Con (N/kg)</td>
<td>2.0 (0.2)††</td>
<td>4.4 (1.1)***††§</td>
<td>3.3 (0.8)</td>
</tr>
<tr>
<td>T-Con (ms)</td>
<td>289.9 (37.6)</td>
<td>280.4 (30.6)</td>
<td>278.4 (71.0)</td>
</tr>
<tr>
<td>dS-Con (cm)</td>
<td>37.4 (4.8)†</td>
<td>42.3 (6.2)***†</td>
<td>25.6 (6.1)</td>
</tr>
<tr>
<td>RFD at 0–100 ms</td>
<td>93.8 (29.8)†</td>
<td>84.0 (37.8)†</td>
<td>78.8 (21.3)</td>
</tr>
</tbody>
</table>

P-values show difference between women (w) and men (m): * < 0.05, ** < 0.01, *** < 0.001; statistically significant differences between age groups.
†Young w/m vs old w/m (P < 0.05).
‡Old w/m vs middle-aged w/m (P < 0.05).
§Middle-aged w/m vs young w/m (P < 0.05).
Ppeak-Con, peak power in concentric phase; VPpeak-Con, velocity at peak power; FPpeak-Con, force at peak power; dS-Con, downward displacement of body center of mass (BCM); dS-Ecc, downward displacement of BCM; T-Con, duration concentric phase; Fpeak-Ecc, peak force eccentric phase; Fpeak-Con, peak force concentric phase; Work-Con, work produced on BCM concentric phase; RFD, rate of force development 0–100 ms; SSC, stretch-shortening cycle; CMJ, countermovement jump.

Results

Physical characteristics and maximal jump height of women and men in all three age groups are presented in Table 1. Descriptive data for power and force production (expressed per kg body mass) and selected kinematic parameters recorded during SSC CMJ testing in women and men are shown for separate age groups in Table 2. Within all age groups, men showed higher values compared with women for a majority of parameters (Fig. 1).

Maximal SSC muscle power production ($P_{\text{peak}}$) declined at an annual rate of 0.29 and 0.44 W/kg for women and men (Fig. 2a), respectively, and this decline differed between genders ($P < 0.001$) (Table 3). Regression analysis revealed that 68% and 74% ($r^2$) of the observed decline in $P_{\text{peak}}$ in women and men, respectively, was explained by increasing age per se.

Age was the strongest factor and explained the variation in $FP_{\text{peak}}$ by 22% and 46% ($r^2$) in women and men, respectively.

As the other governing component of $P_{\text{peak}}$, velocity at peak power ($VP_{\text{peak}}$) showed an annual decline rate of 0.01 and 0.02 m/s in women and men, respectively, which was significantly greater in men than in women ($P = 0.002$) (Fig. 2c). About 74% and 68% ($r^2$) of the observed decline in $VP_{\text{peak}}$ in women and men, respectively, was explained by age (Table 3).

Women and men demonstrated similar decline rates for the kinetic and kinematic variables obtained in the eccentric CMJ phase (ds-Ecc, Fpeak-Ecc) (Table 3). A similar pattern was observed for a number of parameters obtained in the concentric phase (ds-Con, T-Con, Fpeak-Con, Work-Con) (Table 3). Middle-aged and old women showed a higher $RFD$ per kg body mass compared with age-matched men (Table 2). Aging had a negative effect on $RFD$ in both women (annual decline rate: $-0.79$ Nm/s) and men ($-0.88$ Nm/s), and $-20\%$ of the observed decline in $RFD$ was explained by aging in both women and men (Table 3).

Relative decline rates

Relative age-related decrements in maximal SSC leg extension power, force, and selected kinematic variables did not differ between women and men, except for $FP_{\text{peak}}$ (Table 4). In this analysis, regression coefficients (relative decline slopes) were calculated after all force, power, and kinematic values were normalized relative to the respective mean values in 20-year-old women and men, respectively, with the latter being determined from the absolute regression equations.
Discussion

This study was the first to assess maximal SSC leg extension power across the full-adult life span. As the main and novel finding, men showed ~50% greater age-related decline rate in SSC muscle power (W/kg/year) compared with women when examined across the full-adult age span (18–81 years). While maximal SSC leg extension power ($P_{\text{peak}}$) expressed per kg body mass was greater in men than in women throughout the age span, this gender difference was found to progressively diminish in middle-aged (35–55 years) and old (65–81 years) adults, resulting in a convergence between genders in maximal SSC power at old age.

Fig. 1. Maximal SSC leg extension power production (a), vertical propulsive work produced during the concentric phase (b), and rate of force development (RFD) (c) separated for gender and age groups. * $P < 0.05$: difference between genders. Error bars: SD.

Kinetic SSC performance

Maximal SSC muscle power ($P_{\text{peak}}$) appeared to be severely affected by aging irrespectively of gender, resulting in an ~50% reduction for individuals in the ninth decade compared with young subjects (20 years of age). A comparable magnitude of decline in muscle mass has previously been observed when old and young subjects were compared using cross-sectional study designs (Larsson et al., 1979; Vandervoort, 2002). Notably, the
Table 3. Age-related decline rate (regression slopes) for maximal leg extension power, vertical takeoff force, and selected kinematic variables obtained during a standardized SSC maneuver (CMJ) in young (18–34 years), middle-aged (35–55 years), and old (65–81 years) women and men. Values are given as slope decline per year (slope/year), 95% confidence interval (95% CI), and r-squared (r²). *P-value shows differences in annual decline rates (slope values) between women and men. Asterisk (*) shows if slope is significantly different from zero.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Women n = 188</th>
<th>Men n = 127</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope/year</td>
<td>95% CI</td>
<td>r²</td>
</tr>
<tr>
<td>Ppeak (W/kg)</td>
<td>−0.29</td>
<td>−0.32 to −0.26</td>
<td>0.68*</td>
</tr>
<tr>
<td>FPpeak (N/kg)</td>
<td>−0.04</td>
<td>−0.05 to −0.03</td>
<td>0.22*</td>
</tr>
<tr>
<td>VPeak (m/s)</td>
<td>0.01</td>
<td>0.01 to 0.74</td>
<td>0.26</td>
</tr>
<tr>
<td>dS-Ecc (cm)</td>
<td>−0.27</td>
<td>−0.31 to −0.24</td>
<td>0.58*</td>
</tr>
<tr>
<td>dS-Con (cm)</td>
<td>−0.25</td>
<td>−0.28 to −0.21</td>
<td>0.51*</td>
</tr>
<tr>
<td>T-Con (ms)</td>
<td>−0.25</td>
<td>−0.61 to 0.10</td>
<td>0.01</td>
</tr>
<tr>
<td>FPeak-Ecc (N/kg)</td>
<td>0.09</td>
<td>−0.10 to −0.07</td>
<td>0.34*</td>
</tr>
<tr>
<td>FPeak-Con (N/kg)</td>
<td>0.05</td>
<td>−0.07 to −0.04</td>
<td>0.19*</td>
</tr>
<tr>
<td>Work-Con (J/kg)</td>
<td>0.05</td>
<td>−0.05 to −0.04</td>
<td>0.66*</td>
</tr>
<tr>
<td>RFD (N/s kg)</td>
<td>−0.79</td>
<td>−1.03 to −0.56</td>
<td>0.19*</td>
</tr>
</tbody>
</table>

P: Differences in slope between women and men; P < 0.05.
*Slope is significantly different from zero.

Table 4. Relative (%) age-related decline rate (regression slopes) for maximal leg extension power, force, and selected kinematic variables obtained in healthy women and men (age 18–81 years) during a standardized SSC maneuver (CMJ). Values show slope decline rate expressed in percent per year (slope mean), 95% confidence interval (95% CI), and r-squared (r²). *P-value shows differences in relative annual decline rates (slope values) between women and men.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Women n = 188</th>
<th>Men n = 127</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope mean</td>
<td>95% CI</td>
<td>r²</td>
</tr>
<tr>
<td>Ppeak (W/kg)</td>
<td>−0.77</td>
<td>−0.85 to −0.70</td>
<td>0.68</td>
</tr>
<tr>
<td>FPpeak (N/kg)</td>
<td>−0.21</td>
<td>−0.26 to −0.15</td>
<td>0.22</td>
</tr>
<tr>
<td>VPeak (Fz/kg)</td>
<td>−0.65</td>
<td>−0.70 to −0.59</td>
<td>0.74</td>
</tr>
<tr>
<td>dS-Ecc (cm)</td>
<td>−0.91</td>
<td>−1.02 to −0.79</td>
<td>0.58</td>
</tr>
<tr>
<td>dS-Con (cm)</td>
<td>−0.62</td>
<td>−0.71 to −0.53</td>
<td>0.50</td>
</tr>
<tr>
<td>T-Con (ms)</td>
<td>0.06</td>
<td>0.17 to 0.06</td>
<td>0.00</td>
</tr>
<tr>
<td>FPeak-Ecc (N/kg)</td>
<td>0.39</td>
<td>−0.46 to −0.31</td>
<td>0.34</td>
</tr>
<tr>
<td>FPeak-Con (N/kg)</td>
<td>0.17</td>
<td>−0.26 to −0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>Work-Con (J/kg)</td>
<td>0.85</td>
<td>−0.93 to −0.77</td>
<td>0.69</td>
</tr>
<tr>
<td>RFD (N/s kg)</td>
<td>−0.79</td>
<td>−1.03 to −0.54</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Differences in slope between women and men (P < 0.05).

As the main and novel finding of the present study, male individuals demonstrated an ~50% faster decline rate in Ppeak with progressive aging compared with women. Although Ppeak declined at a greater absolute decline rate (W/kg/year) in men compared with women, relative rates of decline did not differ between men and women from 20 to 81 years (~8% per decade). In contrast, lean body mass has been reported to decline at a steeper relative rate (~% per annum) in women than in men (Melzer et al., 2003). The disparate trends in absolute vs relative rates of decline observed in the present study suggest that age-related changes in qualitative muscle–tendon properties and/or neuromuscular function may be less severe in women compared with men. Speculatively, such qualitative changes could comprise a greater loss in fast-twitch type II fiber area and/or more marked decreases in tendon stiffness in male adults due to reduced endogenous testosterone and IGF-1 production observed at increasing age (Grounds, 2002; Aagaard et al., 2010).

The lower maximal SSC leg muscle power (Ppeak) observed in women compared with men was mainly due to a reduced velocity component (VPeak) rather than a reduced force component (FPpeak) (except in young women). Similar findings have previously been reported when old women and men were compared using identical testing procedures (Caserotti et al., 2001). The present data further support Valour et al. (2003) and Caserotti et al. (2001) in their conclusion that maximum muscle power output in women seems to rely more heavily on maximal contraction velocity rather than on maximal force generating capacity (Caserotti et al., 2001; Valour et al., 2003). A decrease in maximum contraction speed of aging muscle has been observed in...
vivo, which may partly be due to a selective loss of fast-contracting type II fibers (Bottinelli & Reggiani, 2000). In the present study, the age-related decline in $P_{peak}$ observed in women seemed to mainly rely on a slowing of its velocity determinant ($VP_{peak}$) in accordance with previous observations in old adults when examined in a more narrow age span (Caserotti et al., 2001; Valour et al., 2003). The velocity-dependent decline in $P_{peak}$ in aging women combined with a low body weight and decline in endogenous estrogen secretion (Jakobsen et al., 2012) may be an important factor associated with the higher incidence of falls observed in women (Suzuki et al., 1992), hence exposing women to a greater risk of loss in functional capacity.

In the present study, the force component of maximum SSC power ($FP_{peak}$) declined at a higher absolute rate in men compared with women, with men demonstrating a slightly stronger age-related variance than women ($r^2 = 46\%$ vs $22\%$). The greater rate of reduction in $FP_{peak}$ in aging men than in women may be related to altered in vivo whole muscle properties, that is, possibly reflecting a more marked loss in muscle mass (Guralnik & Ferrucci, 2003; Melzer et al., 2003), and greater negative changes in muscle architecture and/or neuromuscular activation, respectively (Aagaard et al., 2010; Narici & Maffulli, 2010). Aging per se may be associated with a decline in the maximal unloaded shortening speed of single isolated myofibers in vitro (Reid et al., 2012) that may be accompanied by a reduction in single fiber specific force (force/CSA) (D’Antona et al., 2003; Korhonen et al., 2006), and both factors are likely to contribute to the observed decline in peak power with increasing age. In support of these observations, maximum contraction velocity obtained for intact muscles in vivo appears to be reduced in old adults compared with their young counterparts (Valour et al., 2003; Narici et al., 2005; Thom et al., 2007).

Mechanical work is defined as the product between propulsive force production and the distance that an object is moved. Thus, in the present study the elevated work ($J/kg$) produced during the concentric CMJ phase in old to middle-aged men compared with age-matched women appeared to be mainly caused by a greater magnitude of vertical BCM displacement because propulsive force ($F_{peak-Con}$) did not differ between elderly men and women.

The higher vertical force production during the eccentric (i.e., downward) CMJ phase observed in men compared with women across all age groups inevitably must result from higher levels of eccentric force exertion by the knee and/or hip extensors, respectively. In turn, this likely enables male individuals to achieve a greater degree of knee/hip flexion and extended joint range(s) of motion during the eccentric and concentric phases of the SSC maneuver (indirectly reflected by the observation of greater $dS_{Ecc}$ and $dS_{Con}$) that likely contributes to the elevated magnitude of work production in male vs female individuals (discussed above).

The capacity for rapid force exertion (RFD) has important functional significance for older individuals because RFD correlates positively with objective measures of postural control (Izquierdo et al., 1999) and predicts the ability to sustain postural balance during unexpected tripping, that is, when reversing a fall (Pijnappels et al., 2005). Furthermore, RFD is a vital component in movement situations characterized by short contraction times and limited range of motion, while itself depending strongly on muscle CSA and efferent neuromuscular drive (Aagaard et al., 2002). In the present study, RFD was determined in the first 100 ms time interval of the eccentric deceleration phase (Thorlund et al., 2008; Jakobsen et al., 2012). Notably, a large drop in RFD was observed in the oldest group, which may reflect an age-related loss in type II fiber area (Aagaard et al., 2010; Narici & Maffulli, 2010) and/or maximal motorunit (MU) firing frequency (Kamen & Knight, 2004; Klass et al., 2008). Surprisingly, women in all three age groups demonstrated greater RFD per kg body mass during the SSC maneuver than men. This could not be explained by differences in maximum eccentric force production because $F_{peak-Ecc}$ did not differ between women and men at any age. Therefore, it is more likely that the higher RFD exerted by women was the result of a jumping strategy that involved short BCM displacement in the eccentric phase, which implies the presence of a more rapid (shorter) deceleration phase. Hence, RFD obtained during SSC CMJ is unlikely to reflect the maximum capacity for rapid muscle force generation per se as typically evaluated using isolated isometric muscle testing (Aagaard et al., 2002; Thorlund et al., 2008). Rather, RFD recorded during CMJ seems to represent a parameter that is finely and individually tuned by the CNS to ensure a specific range of vertical motion for the BCM during the SSC maneuver.

Spatial and temporal SSC performance
As yet a novel finding, the magnitude of vertical displacement of the BCM during the SSC maneuver decreased with increasing age at a similar rate of decline in women and men. Interestingly, a greater relative decline rate was observed for the magnitude of downward BCM displacement ($dS_{Ecc}$) compared with that of upward BCM displacement ($dS_{Con}$), indicating that the eccentric phase of the SSC movement may be more affected by aging than the concentric phase. As discussed above, this observation may reflect a reduced range of flexor range of motion (ROM) in the hip, knee, and/or ankle joints during the eccentric CMJ phase, in possible consequence of a reduced eccentric strength capacity of the knee and hip extensors with aging (Roig et al., 2010).

Although it would seem reasonable to expect a prolonged CMJ takeoff phase at increasing age, the duration
of the takeoff phase (T-Con) remained unaffected by aging. Specifically, all three age groups spent approximately the same amount of time in the concentric phase; however, older subjects moved their BCM a shorter distance than younger subjects, in turn reflecting that old subjects moved their BCM at a slower speed than younger subjects. There was a tendency for older women to be better able than men to transfer the force generated in the eccentric contraction phase into the concentric phase of the SSC movement, because with increasing age men showed a greater decline rate than women in maximal vertical force exertion (per kg body mass) during the concentric (i.e., upward) movement phase (Fpeak-Con) but not during the eccentric (downward) CMJ phase (Fpeak-Ecc). A greater potentiation effect of eccentric pre-stretch has previously been observed in young women compared with men (22–23 years) at low pre-stretch loads, whereas men conversely demonstrated greater potentiation effects at high pre-stretch loads (Aura & Komi, 1986). It is possible that this gender switch of low vs high eccentric pre-stretch loads is partially diminished by aging, as suggested by the greater relative decline in maximal concentric SSC force production (Fpeak-Con) observed in the male adults examined in the present study.

As a potential methodological limitation, the present study used a cross-sectional design, which may be confounded by interindividual age-related differences in physical activity levels and other living habits. On the other hand, similar problems will arise in conducting long-term longitudinal studies only at the intra-individual level by study participants, showing a gradual decline in physical activity levels with ageing.

In conclusion, the present study shows for the first time that maximal SSC leg extension power is greater in men than in women throughout the full-adult life span, but declines at a greater rate in men, leading to a progressive convergence in maximal SSC power production between women and men at old age.

**Perspectives**

Adults aged 60 years and older are the fastest growing demographic group worldwide, which poses a challenge for public health and represents a rapidly growing global socioeconomic challenge. From this societal perspective as well as from the perspective of individual quality of life, it is of vital importance that elderly adults are able to sustain vital locomotive ADL functions to thereby remain autonomous and uphold an independent lifestyle for as long as possible in order to maximize health and quality of life. Therefore, the ability to detect early deteriorations in muscle function and functional capacity, such as impairments in SSC muscle power by means of CMJ testing, may have strong relevance in both preclinical and clinical settings. The markedly elevated decline rate in Ppeak observed in male adults may play a role for the accelerated mortality observed in men compared with women when approaching old age. Consequently, future studies should be conducted to examine if CMJ-based SSC testing will be particularly sensitive for identifying male individuals at risk of early onset of frailty and loss of independence.

**Key words:** force plate, stretch-shortening cycle, RFD, countermovement jumping, mechanical muscle function, ageing, gender.

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**References**


Caserotti P, Aagaard P, Larsen JB, Puggaard L. Explosive heavy-resistance training in old and very old adults:


Edwén et al.
