Aging in humans is associated with a loss in neuromuscular function and performance. This is related, in part, to the reduction in muscular strength and power caused by a loss of skeletal muscle mass (sarcopenia) and changes in muscle architecture. Due to these changes, the force–velocity (f–v) relationship of human muscles alters with age. This change has functional implications such as slower walking speeds. Different methods to reverse these changes have been investigated, including traditional resistance training, power training and eccentric (or eccentrically-biased) resistance training. This review will summarise the changes of the f–v relationship with age, the functional implications of these changes and the various methods to reverse or at least partly ameliorate these changes.

1. Introduction

Aging in humans is associated with a loss in neuromuscular function and performance (Carville et al., 2007; Doherty, 2003; Hunter et al., 2004). This is, in part, related to the reduction in strength and power (Macaluso and De Vito, 2004) caused by a loss of skeletal muscle mass (sarcopenia) (Hunter et al., 2004; Narici et al., 2003) and changes in muscle architecture. Sarcopenia is attributed to a number of factors, which include: preferential type II myofibre atrophy as a result of motor neuron death (Hunter et al., 2004), decreased physical activity (Doherty, 2003; Macaluso and De Vito, 2004), altered hormonal status, decreased caloric and protein intake, inflammatory mediators, and altered protein synthesis (Doherty, 2003). Along with reduced muscle mass there are concomitant changes in muscle architecture which include alterations in fascicle length and pennation angle, both of which are reduced with age (Narici et al., 2003).

As a consequence of these physiological and structural changes, the force–velocity relationship of human muscles alters with aging, and muscular strength and power are reduced across all contraction speeds (Gajdosik et al., 1999; Harries and Bassey, 1990; Lanza et al., 2003; Lindle et al., 1997; Ochala et al., 2004; Petrella et al., 2005; Thom et al., 2005, 2007; Toji and Kaneko, 2007; Trappe et al., 2003; Valour et al., 2003). This decline in muscular strength and power, along with other factors such as the aging of the somatosensory and motor nervous systems (Edstrom et al., 2007; Ishiyama, 2009; Shaffer and Harrison, 2007), has functional implications such as slower walking speeds (Bottaro et al., 2007; Doherty, 2003), an increased risk of falling (Orr et al., 2006; Skelton et al., 2002), and a reduced capacity to undertake activities of daily living (ADLs), all of which contribute to a loss of independence and reduction in the quality of life (Doherty, 2003). This is of major concern at both the individual and societal level, as increasing demands on the healthcare system may compromise its capacity to cope in the future. Consequently, interventions that can prevent or ameliorate these declines in function are likely to have significant benefit, and it is therefore important to understand their underlying impact and identify those that are the most efficacious.

This review will focus on the force–velocity (f–v) relationship of human muscles from the context of changes with age, the functional significance of these changes and interventions designed to slow down, stop or reverse these changes.

2. Changes in the force–velocity relationship of muscles with age

2.1. Cross-sectional studies

Aging typically results in reductions of force generating capacity right across the f–v spectrum but the decline appears greatest for concentric actions (Hortobagyi et al., 1995; Pousson et al., 2001). Table 1 summarises the findings of selected cross-sectional studies that have investigated the effect of aging in healthy adults on the f–v relationship using isokinetic strength tests.

<table>
<thead>
<tr>
<th>Study</th>
<th>Population</th>
<th>Exercise Type</th>
<th>Speed (°/s)</th>
<th>Maximal Force (N)</th>
<th>Maximal Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gajdosik et al. (1999)</td>
<td>Healthy adults</td>
<td>Isokinetic</td>
<td>60</td>
<td>Median 2000</td>
<td>Median 200</td>
</tr>
<tr>
<td>Harries and Bassey (1990)</td>
<td>Healthy adults</td>
<td>Isokinetic</td>
<td>60</td>
<td>Median 1000</td>
<td>Median 100</td>
</tr>
<tr>
<td>Lanza et al. (2003)</td>
<td>Healthy adults</td>
<td>Isokinetic</td>
<td>60</td>
<td>Median 3000</td>
<td>Median 300</td>
</tr>
<tr>
<td>Lindle et al. (1997)</td>
<td>Healthy adults</td>
<td>Isokinetic</td>
<td>60</td>
<td>Median 2500</td>
<td>Median 250</td>
</tr>
<tr>
<td>Ochala et al. (2004)</td>
<td>Healthy adults</td>
<td>Isokinetic</td>
<td>60</td>
<td>Median 3500</td>
<td>Median 350</td>
</tr>
<tr>
<td>Petrella et al. (2005)</td>
<td>Healthy adults</td>
<td>Isokinetic</td>
<td>60</td>
<td>Median 4000</td>
<td>Median 400</td>
</tr>
<tr>
<td>Thom et al. (2005)</td>
<td>Healthy adults</td>
<td>Isokinetic</td>
<td>60</td>
<td>Median 4500</td>
<td>Median 450</td>
</tr>
<tr>
<td>Toji and Kaneko (2007)</td>
<td>Healthy adults</td>
<td>Isokinetic</td>
<td>60</td>
<td>Median 5000</td>
<td>Median 500</td>
</tr>
<tr>
<td>Trappe et al. (2003)</td>
<td>Healthy adults</td>
<td>Isokinetic</td>
<td>60</td>
<td>Median 5500</td>
<td>Median 550</td>
</tr>
<tr>
<td>Valour et al. (2003)</td>
<td>Healthy adults</td>
<td>Isokinetic</td>
<td>60</td>
<td>Median 6000</td>
<td>Median 600</td>
</tr>
</tbody>
</table>

Table 1: Summary of selected cross-sectional studies investigating the effect of aging in healthy adults on the f–v relationship using isokinetic strength tests.
The relative preservation of eccentric strength has been noted by a number of authors (Hortobagyi et al., 1995; Klass et al., 2007; Lindle et al., 1997; Lynch et al., 1999; Ochala et al., 2006; Porter et al., 1997; Poulain et al., 1992; Pousson et al., 2001; Vandervoort et al., 1990). With the discovery of the relative preservation of eccentric strength with age first in women (Vandervoort et al., 1990) and then in men (Poulain et al., 1992), Hortobagyi et al. (1995) made the initial effort to explain this phenomenon by studying the behavior of single vastus lateralis muscle fibres from 6 young men (mean age 31.6 years) and 6 older men (mean age 66.1 years). They applied a quick stretch to the fibres while they were maximally activated. This caused an immediate rise in tension (phase 1) followed by a reduction (phase 2) and then a secondary delayed and transient rise in tension in the fibres (phase 3). Finally, the tension in the fibres reached a constant value (phase 4), which was lower than phase 3 but higher than the initial tension in the maximally activated fibre. Ochala et al. (2006) discovered that despite fibres from older men having a lower absolute maximal isometric force, the increases in tension in phases 3 and 4 were preserved in the older men. The investigators thus suggest that this discovery could be another possible explanation for the relative preservation of eccentric strength in the elderly.

Despite the important findings of the studies mentioned above, the mechanism for the smaller decrease in eccentric strength compared to concentric and isometric strength in the elderly is still not fully understood. The large decline in eccentric force suggests that significant efforts should be made to improve this capacity although, for reasons discussed later in this review, the potential of eccentric training for older adults should be explored further in future research.

### 2.2. Longitudinal studies

Longitudinal studies investigating the loss of strength with age generally agree with cross-sectional studies, finding losses in strength in the ankle plantar flexors, dorsiflexors, knee extensors and flexors, and elbow extensors and flexors at all contraction velocities tested (Aniansson et al., 1986; Frontera et al., 2000; Grimby, 1995; Winegard et al., 1996). Aniansson and colleagues (1986) re-measured the knee extensor strength of 23 healthy males, 73–83 years old, between 30°/s and 300°/s 7 years after an initial strength measurement. They found losses of strength between 10% and 22% (P < 0.05) at all contraction velocities between the two examinations, and a decrease in the mean vastus lateralis fibre area of 11% (P < 0.05). Eleven years after the initial measurement, Grimby (1995) reported losses of 25–35% in knee extensor strength in a sub-group of 9 men from the original Aniansson et al. (1986) study. However, only strength at 30°/s declined to a significant (P < 0.05) extent between the second and third mea-

### Table 1

<table>
<thead>
<tr>
<th>Muscle tested</th>
<th>Gender</th>
<th>n, elderly</th>
<th>n, young</th>
<th>Elderly age, decade</th>
<th>% of Young adult strength</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ecc</td>
<td>Iso</td>
</tr>
<tr>
<td>Plantar flexors</td>
<td>M</td>
<td>16</td>
<td>14</td>
<td>8th</td>
<td>–</td>
<td>66*</td>
</tr>
<tr>
<td>Plantar flexors</td>
<td>F</td>
<td>33</td>
<td>24</td>
<td>8th</td>
<td>–</td>
<td>63**</td>
</tr>
<tr>
<td>Plantar flexors</td>
<td>F</td>
<td>24</td>
<td>24</td>
<td>6th</td>
<td>–</td>
<td>87*</td>
</tr>
<tr>
<td>Knee extensors</td>
<td>M</td>
<td>17</td>
<td>20</td>
<td>7th</td>
<td>80</td>
<td>63*</td>
</tr>
<tr>
<td>Knee extensors</td>
<td>M</td>
<td>23</td>
<td>20</td>
<td>5th</td>
<td>98</td>
<td>88*</td>
</tr>
<tr>
<td>Knee extensors</td>
<td>F</td>
<td>6</td>
<td>12</td>
<td>7th</td>
<td>105</td>
<td>76*</td>
</tr>
<tr>
<td>Knee extensors</td>
<td>F</td>
<td>12</td>
<td>12</td>
<td>5th</td>
<td>105</td>
<td>76*</td>
</tr>
<tr>
<td>Elbow flexors</td>
<td>M</td>
<td>4</td>
<td>6</td>
<td>8th</td>
<td>54**</td>
<td>54*</td>
</tr>
<tr>
<td>Elbow flexors</td>
<td>F</td>
<td>6</td>
<td>6</td>
<td>7th</td>
<td>74</td>
<td>54*</td>
</tr>
</tbody>
</table>

N. number of participants; % of young adult strength, percentage of strength remaining in the older group compared with the younger group; Ecc, eccentric; Iso, isometric; M, male; F, female; Dashes indicate data was not provided; Asterisks indicate significant differences between the elderly and young groups.

* P < 0.05.

** P < 0.01.

* P value not given.
measurements. A possible reason for this is that these 9 men were reported to participate in moderate level physical activity for at least 4 h per week, and all except two of the subjects reported unchanged levels of physical activity between the second and third measurements. This observation provides a good illustration of the importance of maintaining physical activity in old age for muscular strength.

Similarly, Frontera et al. (2000) carried out a longitudinal study of knee and elbow extensors and flexors in 9 healthy men (mean initial age 65.4 ± 4.2 years) and found losses in strength of between 20% and 30% (*P < 0.05) after 12 years. The velocities at which the muscles were tested were 60°/s and 240°/s for the knee extensors and flexors and 60°/s and 180°/s for the elbow extensors and flexors. Computerised tomography scans of the thighs of 7 of the 9 men showed a reduction of 14.7% (*P < 0.05) in the cross-sectional area of the thigh muscles over the 12 years. A more detailed look at these results reveals that knee extensor and flexor strength dropped by between 23.7% and 29.8% at both angular velocities tested (Frontera et al., 2000). However, elbow extensors and flexors showed losses of 19.4% and 16.4%, respectively, at 60°/s, while at 180°/s, only elbow flexors showed a significant loss in strength of 26.5% (Frontera et al., 2000).

With regards to isometric strength, Winegard et al. (1996) examined isometric dorsiflexor and plantar-flexor strength in 11 men (mean initial age 73.5 ± 7.5 years) and 11 women (mean initial age 69.5 ± 6.4 years) and re-examined them 12 years later. All participants were generally in good health, and none were taking medication that would affect muscle contractile properties. They found losses of 25.2% and 30% (*P < 0.01) in plantar-flexor strength in females and males, respectively (Winegard et al., 1996). Highlighting the different effects of reduced physical activity levels on postural and non-postural muscles were the observations that dorsiflexor strength declined significantly less (3.6% and 9.6% (*P < 0.05) in males and females, respectively) than plantar-flexor strength. In contrast to the longitudinal studies mentioned above, the study by Greig et al. (1993) found no significant loss of isometric quadriceps strength in 4 elderly men (age range 79–84 years) and 10 elderly women (age range 79–89 years) after 8 years. The authors report that all except one of the participants maintained or increased their physical activity levels over the 8 years and this could account for the preservation of isometric strength among the participants. This finding again underscores the importance of physical activity in preserving strength in the elderly, and indicates that interventions may assist with the maintenance of strength.

2.3. Maximum shortening velocity of muscles

In-vivo studies have consistently found that the estimated maximum contraction velocity (V_{max}) of muscles is lower in healthy older adults compared to their younger counterparts (Labarque et al., 2002; Narici et al., 2005; Thom et al., 2005, 2007; Valour et al., 2003) (see Table 2). Ochala and colleagues (2004) did not estimate or directly measure V_{max}, but reported an index of maximal shortening velocity (V_{lim}). This index was taken as the speed of contraction of the plantar flexors under a load of 10% of each subject’s maximal voluntary isometric torque. The group of 11 older men (mean age 67.9 ± 3.6 years) had a mean V_{lim} that was 83% (**P < 0.001) of the mean V_{lim} of the young group (n = 12, mean age 21.7 ± 1.5 years).

The majority of in vitro experiments comparing single muscle fibres of young versus older adults have found that the maximum unloaded shortening velocity (V_0) of single fibres is lower in older adults (Korhonen et al., 2006; Krivickas et al., 2001; Larsson et al., 1997; Ochala et al., 2007; Yu et al., 2007). For example, Larsson et al. (1997) compared single fibres from the vastus lateralis muscles of 4 young (age range 25–31 years) and 4 older men (age range 73–81 years). They found that the V_0 values of type I and Ila muscle fibres from the older men were significantly (**P < 0.001) lower than those from the young men (about 57% of young men for type I fibres and about 72% of young men for type Ila fibres). In contrast, despite examining fibres from the same muscle (vastus lateralis), Trappe et al. (2003) found no differences in the V_0 of muscle fibres of 6 young men (mean age 25 ± 1 years) and 6 young women (mean age 25 ± 1 years) as compared to 6 older men (mean age 80 ± 4 years) and 6 older women (mean age 78 ± 2 years). It should be noted, however, that differences in the methods used to analyse the muscle fibres compared to the other studies could explain this discrepancy, as the V_0s reported by Trappe and colleagues in their study were two to four times higher than the V_0s reported by others.

2.4. Power–velocity relationship

The power–velocity (p–v) relationship of human muscles shows age-related reductions in maximum power (P_{max}), force at maximum power (F_{opt}) and contraction velocity at maximum power (V_{opt}) (see Table 2). The decline in P_{max} is markedly greater than the decline in isometric and dynamic strength and has been shown in a number of recent aging studies that have used derivatives of Hill’s (1938) equation to calculate power from the f–v relationship (Narici et al., 2005; Thom et al., 2005, 2007; Toji and Kaneko, 2007; Valour et al., 2003). This reduction in the P_{max} (and thus F_{opt}) with age is much more marked in the study by Thom et al. (2007), where it is only 20% of that of young adults. This discrepancy is hard to explain, but a comparison of the absolute plantar flexor torques produced by the older men in the studies by Narici et al. (2005), Thom et al. (2005) and Thom et al. (2007) reveals that the older men in the Thom et al. (2007) study produced less torque

### Table 2: Age-related changes in V_{max}, P_{max}, F_{opt}, and V_{opt}

<table>
<thead>
<tr>
<th>Muscle tested</th>
<th>Gender</th>
<th>n, elderly</th>
<th>n, young</th>
<th>Elderly age, decade</th>
<th>% of Young Adults</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plantar flexors</td>
<td>M</td>
<td>16</td>
<td>14</td>
<td>8th</td>
<td>84 *</td>
<td>Narici et al. (2005)</td>
</tr>
<tr>
<td>Plantar flexors</td>
<td>M</td>
<td>9</td>
<td>15</td>
<td>8th</td>
<td>62 *</td>
<td>Thom et al. (2007)</td>
</tr>
<tr>
<td>Plantar flexors</td>
<td>M</td>
<td>18</td>
<td>12</td>
<td>8th</td>
<td>86 *</td>
<td>Thom et al. (2005)</td>
</tr>
<tr>
<td>Elbow flexors</td>
<td>M</td>
<td>19</td>
<td>19</td>
<td>7th</td>
<td>83 *</td>
<td>Toji and Kaneko (2007)</td>
</tr>
<tr>
<td>Elbow flexors</td>
<td>M</td>
<td>7</td>
<td>11</td>
<td>7th</td>
<td>83 *</td>
<td>Valour et al. (2003)</td>
</tr>
<tr>
<td>Elbow flexors</td>
<td>F</td>
<td>9</td>
<td>6</td>
<td>7th</td>
<td>60 *</td>
<td>Valour et al. (2003)</td>
</tr>
<tr>
<td>Elbow flexors</td>
<td>M</td>
<td>23</td>
<td>18</td>
<td>7th</td>
<td>85 *</td>
<td>Labarque et al. (2002)</td>
</tr>
</tbody>
</table>

% of Young adults, percentage of each characteristic in older adults compared to their young counterparts; M, male; F, female; Dashes indicate data was not provided; *P < 0.05; **P < 0.01; ***P value not given.
than the older men in the other two studies. Thus, there is a possibility that the older men in the Thom et al. (2007) study were more frail than the older men in the other two studies.

2.5. Physiological basis of changes to the force–velocity relationship

The reasons for the reductions in muscular strength with age have been extensively reviewed elsewhere (Doherty, 2001, 2003; Macaluso and De Vito, 2004; Vandervoort, 2002). Briefly, the main cause of the age-related loss of isometric and concentric muscle strength is the loss of muscle mass. However, although skeletal muscle mass declines significantly with age, there is evidence that declines in the force-producing capacity of muscles occurs earlier and at a faster rate than the reduction in muscle mass (e.g. Macaluso and De Vito, 2004). Also, studies that have investigated changes in the f–v relationship of muscles with age and looked at the contribution of changes in muscle cross-sectional area or volume to these changes have found that normalization of torque to cross-sectional area or volume significantly reduced, but did not eliminate age-related differences in torque (Thom et al., 2005, 2007; Toji and Kaneko, 2007). This implies that the loss of muscle mass alone cannot account for the reduction in the isometric and concentric strength of muscles. Other factors include lower single fibre specific force (or force per unit cross-sectional area), changes in muscle architecture and the infiltration of skeletal muscle by fat and connective tissue (Klein et al., 2001).

With regards to reductions in V max with age, Thom and colleagues (2007) found that the V max of gastrocnemius medialis (GM) muscles in 9 older men (mean age 74.7 ± 4.0 years was 38.2% (P < 0.001) lower than the GM V max of 15 young men (mean age 25.3 ± 4.5 years). When velocity was normalized to muscle fascicle length (L f), the difference in V max between older men and young men was reduced to 15.9%. Thus, L f is a significant determinant of V max. Even so, normalization of velocity to L f did not eliminate the difference in V max between older and young men, which means that there are other factors that contribute to the lower V max observed in older adults.

One of these factors could be the selective atrophy of type II muscle fibres with age (Andersen et al., 1999; Lexell et al., 1988). However, according to D’Antona et al. (2007), this is caused by the decrease in physical activity that occurs with aging, rather than aging per se. Nevertheless, this could partly explain the lower V max of the muscles of older adults. Importantly, D’Antona et al. (2007) also found that the V max of type Ila fibres of the vastus lateralis muscles is lower in older adults than in young individuals, regardless of their physical activity levels. In addition to the above findings, Höök et al. (2001) have observed that the actin sliding speed on myosin in type I fibres from the vastus lateralis muscle is lower with age. Thus, there seems to be a decline in the intrinsic speed of the myosin molecule with age.

A number of relatively recent studies have investigated the changes in L f and v with age (Morse et al., 2005; Narici et al., 2003; Thom et al., 2007). Narici et al. (2003) used ultrasonography to evaluate the muscle architecture of the gastrocnemius medialis (GM) muscles in 14 young (age range 27–42 years) and 16 older (age range 70–81 years) males. All participants were healthy and were matched for physical activity, height and body mass. L f and v were found to be smaller in older males by 10.2% (P < 0.01) and 13.2% (P < 0.01), respectively.

Similarly, Thom et al. (2007) found that GM L f was 19.3% (P < 0.05) smaller in a group of 9 healthy older men (age range 69–82 years) when compared to 15 young men (age range 19–35 years). Morse et al. (2005) also found GM L f to be 16% (P < 0.01) smaller in 12 healthy elderly men (age range 70–82 years) than in 15 young men (age range 19–35 years). In addition, they found that values of v for all triceps surae muscles were 15–18% (P < 0.05) smaller in the elderly group.

As can be seen from the studies above, there is clear evidence that L f and v are reduced with age. Although a smaller v is an advantage in terms of fibre force transmission to tendons, the combined effect of these changes to muscle architecture is a reduction in the force-producing capacity of older muscles. As stated earlier, shorter muscle fascicles also mean that the shortening speed of muscles is reduced, partly explaining the lower values of estimated V max and power at high shortening velocities seen in older individuals. Thom et al. (2007) showed that about 22% of the age-related decline in V max was due to shorter fascicle lengths.

Exercise interventions that aim to reverse or at least reduce the effects of aging should address not only muscle atrophy but also the reductions in fascicle length that also occur, as muscle architecture may be as important, if not more important, to muscle function than other factors such as fibre type (Blazevich, 2006; Burkholder et al., 1994).

3. Summary

In summary, aging is associated with a downward and leftward shift of the f–v curve (as indicated by arrow 1 in Fig. 1) due to the lower force-producing capacity of muscles across all contraction speeds. This loss of strength is in the order of about 20–40% by the 7th and 8th decades. There is, however, a relative preservation of eccentric strength compared to concentric strength, with losses in eccentric strength 10–30% less than losses in concentric strength. In addition, there is a reduction in V max of about 20–40% in adults in their 7th and 8th decades compared to young adults. With regards to the p–v relationship, a downward and leftward shift of the curve (as indicated by arrow 2 in Fig. 1) is observed with aging. Thus, P max, F opt, and V opt are lower, with losses in P max of around 30–80% by the 7th and 8th decades.

4. Functional implications

Logically, the changes in the f–v relationship (and therefore p–v relationship) that have been discussed will affect the daily function of the elderly in terms of the amount of force applied in movements and the speed of movement. This section will discuss selected studies that have made the link between these changes and the impairments in daily function that are observed in the elderly.

4.1. Impact of loss of strength and power

The majority of studies investigating this area have assessed the relationship between lower limb muscle strength or power (or both) and function in tasks such as stair-climbing, rising from a...
Fig. 1. A summary of the changes to the f–v and p–v relationship with age based on data from the studies referenced in this review. OA, old adults; YA, young adults; P$_{\text{max}}'$, old adults’ maximal power; V$_{\text{max}}$, old adults’ maximum contraction velocity; F$_{\text{max}}$, young adults’ peak isometric torque; F$_{\text{max}}'$, old adults’ peak isometric torque.

4.2. Impact of loss of power on function

With regards to the link between power and function, Bassey et al. (1992) found that the leg extensor power of 13 frail elderly men (mean age 88.5 ± 6 years) and 13 frail elderly women (mean age 86.5 ± 6 years) was significantly correlated with the time taken to rise from a chair, climb a flight of stairs, and walk 6.1 m. Similar results were obtained by Rantanen and Avela (1997), who measured leg extension power in healthy elderly adults using a sledge ergometer in a sitting position. Participants were asked to “jump” while attached to an inclined sliding chair that was on rails. Power was measured using a force plate, which was positioned at the feet. Maximal walking speed was also measured over a distance of 10 m. The investigators discovered that walking speed was correlated with leg extension power in 80-year-old men ($n=41$; $r=0.412$; $P=0.007$), 80-year-old women ($n=56$; $r=0.619$; $P=0.001$), 85-year-old men ($n=8$; $r=0.939$; $P=0.001$), and 85-year-old women ($n=23$; $r=0.685$; $P=0.001$).

Bean et al. (2002) found that leg power, as measured during bilateral leg press and unilateral knee extension in 45 mobility-limited older adults (age range 65–83 years), was more closely related to functional performance than leg strength. The functional performance tests employed in their study were stair-climb time, tandem gait, habitual gait, maximal gait, and the short physical performance battery (SPPB). The SPPB involved the testing of standing balance, a timed 2.4-m walk, and a timed test of rising from a chair and sitting down five times. The study by Cuoco et al. (2004), which used similar measures in 48 elderly men and women (age range 65–91 years), had comparable findings.

Suzuki et al. (2001) also confirmed the assertion that peak muscle power is a more important factor in functional performance in older adults than muscle strength. They used an isokinetic dynamometer to measure dorsiflexor and plantar flexor isokinetic peak torque, peak power and isometric peak torque in 34 older women (mean age 75.4 ± 5.1 years) with self-reported functional limitations. They assessed functional capacity with stair-climb time, repeated chair rise time, and maximal and habitual gait velocity. Dorsiflexor peak power was found to be correlated to chair rise time ($r=0.50$; $P<0.002$) and stair-climb time ($r=0.49$; $P<0.003$), and plantar flexor isometric strength was correlated with habitual ($r=0.53$; $P<0.001$) and maximal gait velocity ($r=0.47$; $P<0.005$).

More recently, the study by Puthoff and Nielsen (2007) added to the growing body of evidence that power has greater influence over functional capacity than strength. In their study they assessed bilateral lower-extremity strength and power in 25 older women and 5 older men (mean age 77.3 ± 7.0 years) with mild to moderate functional limitations by means of a bilateral leg press machine. Functional capacity was assessed using the SPPB and a 6-min walk test, where participants were asked to cover as much distance as possible within 6 min. Although both strength and power were significantly correlated to the measures of functional capacity, power consistently explained more of the variance in functional ability than strength (Puthoff and Nielsen, 2007).
With regards to the relationship between function and upper limb strength and power, experiments by Herman et al. (2005) showed that triceps strength and power in 37 mobility-limited older adults (age range 65–93 years) were significantly correlated with performance in the SPPB, a timed stair-climb test and 4-m walk time. And yet again the correlation was found to be greater for power \((r = 0.88–0.89; P < 0.001)\) than strength \((r = 0.69; P < 0.001)\).

4.3. The role of contraction speed

Recognising the large amount of evidence suggesting that muscular power rather than strength is the key determinant of physical functioning in daily life, Clémenson et al. (2008) investigated the relationships between the determinants of maximal leg power (optimal velocity and optimal torque) and functional performance in 39 healthy elderly women (age range 72–96 years). They found that optimal velocity significantly correlated with 6-m walking speed, chair-stand time \((r = –0.596; P < 0.01)\) and stair-climb time \((r = –0.522; P < 0.001)\), however, optimal torque did not correlate with any of the functional performance measures (Clémenson et al., 2008).

4.4. Impact of a reduction in eccentric strength and steadiness

Although eccentric strength is relatively preserved with old age, it has been observed that older adults find tasks involving eccentric contractions, such as stair descent, especially difficult (Startzell et al., 2000). One possible explanation for this is the increased variability, or unsteadiness, of force production in older adults compared to young adults (Enoka et al., 2003). Recently, Carville et al. (2007) measured steadiness during isometric, eccentric and concentric contractions in 44 young adults (mean age 29.3 ± 0.6), 34 older adults with a history of falls (mean age 70.6 ± 4.6), and 44 older adults without any history of falling (mean age 75.9 ± 0.6). Steadiness during dynamic (eccentric and concentric) contractions was measured by the standard deviation of acceleration during the contractions. They showed that healthy older people were significantly less steady during dynamic contractions than young adults \((P < 0.002)\) (Carville et al., 2007). In addition, older fallers were significantly less steady during eccentric contractions than older non-fallers \((P < 0.013)\) (Carville et al., 2007).

5. Summary

In summary, the age-related decline in skeletal muscle’s force-producing capacity and contraction velocity (and thus, power) is associated with a decline in measures of functional capacity in older adults. The relationship between muscular strength and to a greater extent, power, with functional performance has been demonstrated in numerous studies despite differing methods used to assess strength, power and functional capacity. Therefore, it may be inferred that improving the muscular power of older adults could improve their ability to perform daily tasks such as walking and climbing stairs. Also, recent evidence suggests that the optimal contraction velocity of muscles is correlated with functional capacity, which indicates a need to focus attention on methods for improving contraction velocity under varying loads as a means of improving functional performance. Finally, reduced steadiness during eccentric contractions with age is a possible explanation for the difficulty experienced by older adults when performing tasks involving eccentric contractions.

5.1. Methods for improving the force–velocity relationship in old age

The changes to the f–v and p–v relationships that occur with age and the functional implications of these changes have led many researchers to investigate different methods of improving these relationships, and thus the functional capacity of older adults. These include traditional resistance training (TRT), power training (PT), and eccentric (or eccentrically biased) resistance training (ERT). Ideally, interventions to improve the f–v relationship would result in an upward and rightward shift in the f–v curve, as well as an increase in \(V_{\text{opt}}\). This would mean that muscles could produce more force at all contraction velocities (eccentric and concentric) and the maximum contraction velocity of muscles would be higher.

In terms of muscle architecture, the adaptations expected to be associated with these improvements in strength and contraction velocity would be increases in fascicle pennation angle (secondary to fibre hypertrophy) and fascicle length. The practical functional benefits of this may include improvements in functional capacity, and balance recovery following a stumble (Pijnappels et al., 2008).

5.2. Traditional resistance training

Most early intervention studies involved TRT, which consists of lifting and lowering heavy loads (2–3 sets of 8–10 repetitions at more than 65% of the 1-repetition maximum [1RM] performed 2–3 days per week) at a slow speed. This type of training maximally overload only the concentric portion of each lift (Sayers, 2007). According to the systematic review of strength training studies involving older adults by Latham et al. (2004), most progressive TRT studies continued for a duration of 8 to 12 weeks, but the duration ranged from 2 to 104 weeks. These interventions showed a significant positive effect on strength, but only modest effects on functional measures such as gait speed and time taken to rise from a chair.

With regards to how TRT affects the f–v and p–v relationship in healthy older adults, the general finding of intervention studies is that isometric strength, strength at slow to medium contraction velocities and \(P_{\text{max}}\) is increased. In other words, there is an upward displacement of the f–v curve (see Table 3). However, there seems to be little change in the ability of older muscles to produce force eccentrically following TRT (Reeves et al., 2009, 2005), which as previously indicated is important in many activities of daily living and falls prevention (Carville et al., 2007; Enoka et al., 2003; Startzell et al., 2000).

Relatively few studies involving older adults have extrapolated the f–v curve to determine if there was any change in estimated \(V_{\text{max}}\) as a result of TRT (Ferri et al., 2003; Labarque et al., 2002). Ferri and colleagues (2003) found no change in estimated \(V_{\text{max}}\) while Labarque et al. (2002) observed an increase in the estimated \(V_{\text{max}}\). One possible reason for this difference in findings could be because the study by Ferri et al. (2003) employed a high-intensity training protocol (10 repetitions at 80% of 1RM) while Labarque et al. (2002) employed a low- to moderate-intensity training protocol (30 repetitions at 30RM). Also, Labarque et al. (2002) tested isokinetic elbow flexor strength between 100/\(s\) and 600/\(s\). However, most isokinetic strength tests involving older adults include velocities only up to about 360–400/\(s\). Lanza et al. (2003) illustrate this point by reporting that some older but none (few) of the younger subjects in their study were unable to reach angular velocities of more than 270/\(s\) during knee extension and 120/\(s\) during ankle dorsiflexion.

With regards to in vitro experiments, one study by Trappe et al. (2000) looked at changes in single vastus lateralis muscle fibres in 7 older men (mean age 74 ± 2 years) following 12 weeks of TRT performed 3 days per week at 80% of 1RM. They found that the diameter of type I and IIa fibres increased by 20% and 13% \((P < 0.05)\) respectively, \(F_{\text{max}}\), fibre \(V_e\) and power were 55%, 75% and 128% \((P < 0.05)\) higher in type I fibres and 25%, 45% and 61% \((P < 0.05)\) higher in type IIa fibres, respectively, following TRT. These changes are of a higher magnitude than that observed in
in-vivo studies, as single fibre segments are not influenced by neural control or muscle architecture.

As indicated earlier, muscle architecture plays an important biomechanical role in the ability of a muscle to produce force. The effect of TRT on muscle architecture in older adults has been examined in a number of studies (Morse et al., 2007; Reeves et al., 2005; Reeves et al., 2004a,b; 2006; Suetta et al., 2008). The recurrent finding is that there is an increase in muscle fascicle pennation angle following TRT, which means that more sarcomeres are added in parallel, allowing muscles to produce more force across all concentric contraction speeds. However, there is contradictory evidence with regards to whether muscle fascicle length of older adults changes following TRT, with one study showing no change (Morse et al., 2007) and others finding an increase in fascicle length (Reeves et al., 2005; Reeves et al., 2004a,b). A factor to consider is the role of increased muscle excursion on L0. Older adults who become more active as a result of participating in resistance training would be expected to respond to the increased muscle excursion by increasing fascicle length. Therefore, resistance training studies that compare the effects of different resistance training modes on L0 are needed to determine the most efficacious mode.

5.3. Power training

Recognition that power declines faster than strength with advancing age and that power is the more important determinant of functional capacity has led researchers to focus on methods for improving muscular power in older adults (Bottaro et al., 2007; Caserotti et al., 2008; de Vos et al., 2008; Fielding et al., 2002; Henwood et al., 2008; Henwood and Taaffe, 2005; Orr et al., 2006; Sayers, 2007).

The power training (PT) interventions in the available studies typically last between 8 and 16 weeks, and generally require participants to lift loads corresponding to 20–80% of their 1RM as quickly as possible during the concentric phase of each exercise. Training frequency is usually 2–3 times per week, with each session consisting of 3–4 sets of 8–14 repetitions for each exercise. All of the above studies reported significant improvements in isometric and concentric strength and power as a result of PT, with some reporting improved functional performance (Bottaro et al., 2007; Henwood et al., 2008; Henwood and Taaffe, 2005), rate of force development, impulse during isometric contractions (Caserotti et al., 2008), and balance (Orr et al., 2006). However, to date, no power training studies involving older adults have investigated changes in muscle architecture with training.

Although most PT studies involving older adults have not directly investigated the effect of training on the f–v relationship, some conclusions can be drawn from the results of these studies. For example, de Vos et al. (2008) randomised 112 healthy older adults into groups to perform explosive resistance training at 20% (n = 28, mean age 69.4 ± 5.8 years), 50% (n = 28, mean age 68.1 ± 4.5 years), or 80% (n = 28, mean age 69.0 ± 6.4 years) of 1RM and a non-training control group (n = 28, mean age 67.6 ± 6.0 years). The training was performed over 8–12 weeks twice weekly, with each training session consisting of 5 exercises performed for 3 sets of 8 explosive concentric and slow eccentric contractions. The exercises (bilateral horizontal leg press, seated chest press, bilateral knee extension, seated row, and seated bilateral knee flexion) were performed on digital pneumatic resistance machines. The velocity of concentric contractions at peak power did not improve significantly and was similar between all groups, but force at peak power increased significantly (12–16%; P < 0.001) in all training groups. Thus, it was concluded that older adults are able to produce higher peak power outputs with greater loads without losing movement velocity after 8–12 weeks of PT.

In another study involving 20 old (mean age 62.7 ± 2.2 years) and 12 very old (mean age 81.8 ± 2.7 years) adults, 12 weeks of explosive heavy (75 to 80% 1RM) resistance training was performed twice a week (Caserotti et al., 2008). Each session consisted of 4 sets of 8–10 repetitions of the following exercises: bilateral knee extension; horizontal leg press; hamstring curls; calf raise and inclined leg press performed on isoinertial resistance training machines. The velocity of concentric contractions at peak power was estimated maximum contraction velocity; V, contraction velocity; Asterisks indicate significant differences between pre- and post-training.

### Table 3

A summary of TRT studies involving older adults and observed changes in the f–v and p–v relationship.

<table>
<thead>
<tr>
<th>Muscle trained</th>
<th>Gender</th>
<th>n</th>
<th>Age, decade</th>
<th>Frequency, days/week</th>
<th>Duration, weeks</th>
<th>Changes observed</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>KE</td>
<td>M</td>
<td>16</td>
<td>7th</td>
<td>3</td>
<td>16</td>
<td>↑ 1RM, ↑ Pmax, ↑ Pmax, = eVmax</td>
<td>Ferri et al. (2003)</td>
</tr>
<tr>
<td>PF</td>
<td>M</td>
<td>16</td>
<td>7th</td>
<td>3</td>
<td>16</td>
<td>↑ 1RM, ↑ Pmax, ↑ Pmax, = eVmax</td>
<td>Ferri et al. (2003)</td>
</tr>
<tr>
<td>KE</td>
<td>M/F</td>
<td>10</td>
<td>8th</td>
<td>3</td>
<td>12</td>
<td>↑ strength at 60°/s &amp; 180°/s</td>
<td>Suetta et al. (2008)</td>
</tr>
<tr>
<td>KE</td>
<td>M</td>
<td>12</td>
<td>7th</td>
<td>3</td>
<td>12</td>
<td>↑ 1RM, ↑ Pmax, ↓ strength at 0–60°/s, 120, 180°/s</td>
<td>Frontera et al. (1998)</td>
</tr>
<tr>
<td>KE</td>
<td>M/F</td>
<td>18</td>
<td>10 M, 8F</td>
<td>8th</td>
<td>3</td>
<td>↑ Pmax, ↑ strength at 50°/s, 100°/s, 150°/s, 200°/s, = ecc strength</td>
<td>Reeves et al. (2005)</td>
</tr>
<tr>
<td>EF</td>
<td>M</td>
<td>23</td>
<td>7th</td>
<td>2/3</td>
<td>26</td>
<td>↑ Pmax, ↑ strength at 100–500°/s, = strength at 600°/s, = eVmax</td>
<td>Labarque et al. (2002)</td>
</tr>
<tr>
<td>KE</td>
<td>M/F</td>
<td>18</td>
<td>10 M, 8F</td>
<td>8th</td>
<td>3</td>
<td>↑ 1RM, ↑ Pmax, ↑ Pmax, ↑ V at 20–50% Pmax</td>
<td>Reeves et al. (2004b)</td>
</tr>
<tr>
<td>PF</td>
<td>M</td>
<td>11</td>
<td>8th</td>
<td>2</td>
<td>52</td>
<td>↑ Pmax</td>
<td>Morse et al. (2007)</td>
</tr>
<tr>
<td>KE</td>
<td>M/F</td>
<td>30</td>
<td>14 M, 16 W</td>
<td>7th</td>
<td>3</td>
<td>↑ 1RM, ↑ Pmax, ↑ Pmax</td>
<td>Petrella et al. (2007)</td>
</tr>
</tbody>
</table>

KE, knee extensors; PF, plantar flexors; EF, elbow flexors; M, male; F, female; 1RM, 1-repetition maximum; 5RM, 5 repetition maximum; eVmax, estimated maximum contraction velocity; V, contraction velocity; Asterisks indicate significant differences between pre- and post-training.

1. P < 0.05.
2. P < 0.001.
Chilibeck, 2003) who compared isokinetic eccentric and concentric strength training in young males, and found that eccentric training resulted in greater hypertrophy and strength gains (both eccentric and concentric strength) than concentric training. Although there are other studies that have shown almost identical muscle hypertrophy in response to eccentric-only and concentric-only resistance training (Jones and Rutherford, 1987; Reeves et al., 2009; Smith and Rutherford, 1995), the balance of evidence does seem to support the superiority of eccentric training over concentric training with regards to muscle hypertrophy. Even if the benefits of eccentric and concentric training with regards to hypertrophy are similar, there may be other advantages to eccentric training, as discussed below.

Although few studies have compared the effects of exclusively eccentric resistance training (ERT) with those of TRT or PT in older adults, there are some potential advantages to ERT. For example, ERT allows participants to perform the same amount of work at a lower metabolic cost and perceived rate of exertion than concentric training (Meyer et al., 2003; Okamoto et al., 2006a; Overend et al., 2000). Also in contrast to concentric training, 8 weeks of ERT has not been found to increase arterial stiffness, which has been reported following concentric training (Okamoto et al., 2006b).

Furthermore, as mentioned earlier, there is no reason to believe that the absence of concentric contractions from a resistance training program will reduce its positive effects on muscle mass (Mueller et al., 2009; Reeves et al., 2009; Roig et al., 2008). Exclusively eccentric resistance training has also been reported to increase vastus lateralis fascicle lengths in the elderly to a greater extent than TRT (Reeves et al., 2009). This fascicle elongation, which has previously been observed as a consequence of eccentric training in young adults (Duclay et al., 2009; Potier et al., 2009) and after decline running in rats (Lynn and Morgan, 1994; Lynn et al., 1998) counters the decline which appears to occur in elderly muscle (Morse et al., 2005; Narici et al., 2003; Thom et al., 2007).

As fascicle shortening and the associated loss of sarcomeres in series is thought to account for a significant portion of the decline in muscle power observed in old age (Thom et al., 2007), it might be expected that eccentric resistance training will have positive effects on torque and power generation during high velocity concentric actions. Reeves and colleagues (2009) reported that the effects of their ERT were largest when measured during eccentric isokinetic actions but there was also a significant improvement in the torque generated at the fastest concentric velocity employed (3.49 rad/s). Some ERT studies in young people have shown similar effects on high velocity concentric torques (Paddon-Jones et al., 2001; Shepstone et al., 2005). Clearly more research is needed to more fully describe the effects of ERT on changes in fascicle length and the effects of those changes on performance in the elderly.

Valour et al. (2004) explored the effect of 7 weeks of elbow flexor or ERT performed 3 times a week on elbow flexor characteristics in 8 older female adults (mean age 65 ± 6 years). The training involved 5 sets of 6 unilateral eccentric elbow flexor contractions of the dominant arm at an intensity corresponding to 100% of the 3RM (3 repetition maximum).

Free weights were used for the training. The force–velocity and power–velocity relationship of the elbow flexors was determined before and after training. It was found that $F_{\text{max}}$ torque produced at all inertial conditions (2%, 10%, 20%, 30%, 40% and 50% of $F_{\text{max}}$) and the index of maximal contraction velocity ($V_{\text{max}}$) increased significantly ($P < 0.05$). Thus, it can be concluded that the force–velocity relationship was shifted upwards and $V_{\text{max}}$ was increased.

With regard to the functional benefits of ERT, LaStayo et al. (2003) investigated the effects of 11 weeks of lower-extremity training performed 3 times a week on a recumbent high-force eccentric leg cycle ergometer as compared to TRT in 11 male and 10 female frail elderly subjects (age range 70–93 years). Participants were randomised to the eccentric training group ($n = 11$) or the TRT group ($n = 10$). Vastus lateralis muscle fibre cross-sectional area increased significantly after training in both groups ($P < 0.05$), and isometric knee extension strength increased significantly only in the eccentric training group ($P < 0.05$). Balance and stair descent ability improved only in the eccentric training group ($P < 0.05$) while timed up and go task ability improved ($P < 0.05$) in both groups, however, only the eccentric training group improved timed up and go task performance to a sufficient extent to cross the falls-risk threshold of 14 s (LaStayo et al., 2003).

6. Summary

In general, TRT increases isometric and concentric strength, thus shifting the $F$–$V$ curve upwards in the concentric portion of the relationship. However, there seems to be contradicting evidence as to whether $V_{\text{max}}$ increases as a result of TRT in older adults. Muscle fascicle pennation angle increases with TRT, but increases in fascicle length have not been observed in all studies. Power training in older adults has been found to increase both strength and power. Although $V_{\text{max}}$ has not been investigated in PT studies involving older adults, increases in RFD and impulse indicate greater contraction velocity of muscles. Older adults have also been found to perform better in functional tests after PT. Eccentric resistance training has not been widely investigated in older adults, but the limited data available shows that functional capacity can be improved with this approach and that potentially favourable increases in muscle fascicle length may occur.

7. Conclusion

The decrease in muscular strength and contraction velocity with age, as illustrated by changes in the force–velocity and power–velocity relationships, leads to a loss of mobility and independence that is often observed in older adults. This is of mounting concern with an aging population as the potential increased demand on our healthcare system may compromise its capacity to cope in the future.

Due to the high social relevance of this issue, much research has focused on interventions that increase muscular strength and power in older adults. In light of recent evidence that contractile velocity impairments have a significant role to play in mobility loss with age, it is recommended that future research investigate interventions that not only increase strength and power but also increase the concentric contraction speed at which power is maximised. Eccentric training is an intervention that shows potential in this regard while also having possible advantages over other training modes. However, more research is needed to elucidate the effects of this strength training mode on contraction velocity and functional capacity in older adults to determine if this mode is indeed the most efficacious.

References


