Characterizing upper limb muscle volume and strength in older adults: A comparison with young adults

Meghan E. Vidić, Melissa Daly, Michael E. Miller, Cralen C. Davis, Anthony P. Marsh, Katherine R. Saul

1. Introduction

Sarcopenia is an age-associated loss of muscle mass (Jones et al., 2008; Macaluso and De Vito, 2004; Narici and Maffulli, 2010; Rosenberg, 1989). Muscle fiber atrophy is accompanied by reduced muscle force, decreased neural activation, and diminished contractile protein quality (Clark and Manini, 2010; Macaluso and De Vito, 2004; Merletti et al., 2002; Narici and Maffulli, 2010). Some suggest that sarcopenia and muscle force reductions begin as early as the second decade of life (Macaluso and De Vito, 2004; Narici and Maffulli, 2010), with more pronounced changes later in life (Metter et al., 1997).

To better elucidate the functional declines experienced by older adults there is a need to describe the relationship between upper limb muscle volume (MV) and strength by joint (Clark and Manini, 2010). One reason for this is that muscular atrophy may differ by functional group. While overall muscle mass declines with age, the lower limb loses proportionately more mass than the upper limb (Ferreira et al., 2009; Hughes et al., 2001; Janssen et al., 2000; Janssen and Ross, 2005; Landers et al., 2001; Macaluso and De Vito, 2004; Narici and Maffulli, 2010; Reimers et al., 1998). It is hypothesized that older adults’ sedentary behavior is partly responsible for lower limb muscle mass reductions, while upper limb muscle mass is conserved, since arms are used for activities of daily living (Landers et al., 2001; Narici and Maffulli, 2010). Within the upper limb, differential muscle atrophy by functional group has been reported at the elbow (Klein et al., 2001). Understanding how atrophy varies among major upper limb functional groups in older adults may provide information important to future work designed to mitigate age-related functional declines from experimental and computational modeling perspectives.

Muscle strength reductions may exceed muscle mass reductions with age, indicating a muscle quality decrement (Clark and...
Manini, 2010; Goodpaster et al., 2001; Newman et al., 2003; Park et al., 2007). Strength losses 2–5 times greater than muscle size decreases have been reported in the lower limb (Delmonico et al., 2009). Maximal isometric joint moment-generating capacity (IJM) provides a strength assessment of muscles crossing a joint. In young adults, IJM variability is largely explained by MV variations (Akagi et al., 2009b; Fukunaga et al., 2001; Holzbaur et al., 2007a; Jones et al., 2008). Relative IJM of functional muscle groups crossing the shoulder, elbow, and wrist joints have been reported for young adults (Holzbaur et al., 2007a), while reports from older adults have focused on single joints (Akagi et al., 2009b; Bazzucchi et al., 2004; Frontera et al., 2000; Hughes et al., 2001; John et al., 2009; Klein et al., 2001; Landers et al., 2001; Metter et al., 1997; Park et al., 2007; Yassierli et al., 2007). No studies have thoroughly investigated the relationship between IJM and MV for functional groups in the shoulder, elbow, and wrist of older adults.

By measuring upper limb MV and IJM in the same older adult cohort we can evaluate the distribution of and relationship between MV and strength of major upper limb functional groups. The study aims were to (1) measure MV and IJM at the shoulder, elbow, and wrist; (2) characterize the relationship between MV and IJM; and (3) compare these data on older adults to young adult data reported previously.

2. Methods

We recruited eighteen healthy older adults (Table 1). This study was approved by our institutional review board and all participants provided written informed consent in accordance with the institutional guidelines. MV and IJM were evaluated for each subject’s dominant arm. Previously established methods (Holzbaur et al., 2007a,b) were used to assess MV and IJM to facilitate comparison between young and old cohorts. IJM testing postures were chosen because they assess functional group MV fraction (Eq. (1)). Mean MV was calculated across participants (Table 4):

$$f_{ijm} = \frac{\bar{V}_{ijm}}{V_{total}} \times 100$$

Muscles were grouped based on their moment arm in the postures used for MV assessments. In a posture of 60° coronal plane abduction, Kuechle et al. (1997) report posterior deltoid with an adductor moment arm, while Ackland et al. (2008) report an adductor moment arm close to zero. Posterior deltoid was grouped with shoulder abductors, according to the whole muscle’s average moment arm (Ackland et al., 2008; Hughes et al., 1998; Kuechle et al., 1997).

IJM was assessed at the wrist (flexion/extension), elbow (flexion/extension), and shoulder (abduction/adduction) using a KIN-COM dynamometer (Isokinetic International, Harrison, TN). Postures were consistent with Holzbaur et al. (2007a) (Table 5). For each functional group, three 5-s trials were collected. Order of joints tested was randomized across participants. Participants rested for 60 s between trials, with ~2 min of rest between testing at each joint to reconfigure the dynamometer. Participants were verbally encouraged to provide maximal effort.

A custom Matlab (The MathWorks, Natick, MA) program was used to assess the maximum IJM sustained for 0.5 s. The maximal moment across all trials was considered the subject’s maximum IJM (Table 4).

Our first objective was to measure MV and IJM at the shoulder, elbow, and wrist for older adults. For our second objective, linear regression was used to report an adductor moment arm close to zero. Posterior deltoid was grouped with shoulder abductors, according to the whole muscle’s average moment arm (Ackland et al., 2008; Hughes et al., 1998; Kuechle et al., 1997).

**Table 2** 3-Dimensional spoiled gradient imaging parameters.

<table>
<thead>
<tr>
<th>Body coil</th>
<th>Long bone coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echo time (TE) (ms)</td>
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<tr>
<td>Relaxation time (TR) (ms)</td>
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<tr>
<td>Flip angle (FA) (deg.)</td>
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<tr>
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<td>Field of view (FOV) (cm)</td>
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<td>Slice thickness (mm)</td>
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<tr>
<td>Total scan time (min)</td>
<td>~16</td>
</tr>
</tbody>
</table>

**Table 1** Characteristics of older adult sample (mean ± SD). All subjects were right hand dominant except M09.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Height (cm)</th>
<th>Percentile (height)</th>
<th>Body mass (kg)</th>
<th>Percentile (body mass)</th>
<th>Total arm length (cm)</th>
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<tbody>
<tr>
<td>F01</td>
<td>75</td>
<td>154.9</td>
<td>10.0</td>
<td>56.7</td>
<td>30.0</td>
<td>51.0</td>
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<tr>
<td>F02</td>
<td>72</td>
<td>160.0</td>
<td>35.0</td>
<td>54.4</td>
<td>20.0</td>
<td>53.0</td>
</tr>
<tr>
<td>F03</td>
<td>77</td>
<td>167.6</td>
<td>75.0</td>
<td>78.0</td>
<td>85.0</td>
<td>56.0</td>
</tr>
<tr>
<td>F04</td>
<td>83</td>
<td>167.6</td>
<td>75.0</td>
<td>71.7</td>
<td>85.0</td>
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</tr>
<tr>
<td>F05</td>
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<td>5.0</td>
<td>54.5</td>
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<tr>
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<td>86.2</td>
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</tr>
<tr>
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<td>50.0</td>
<td>72.6</td>
<td>90.0</td>
<td>53.0</td>
</tr>
<tr>
<td>F08</td>
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<td>83.9</td>
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<tr>
<td>M01</td>
<td>72</td>
<td>171.5</td>
<td>25.0</td>
<td>78.0</td>
<td>50.0</td>
<td>54.0</td>
</tr>
<tr>
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<td>76</td>
<td>180.3</td>
<td>75.0</td>
<td>81.6</td>
<td>65.0</td>
<td>61.0</td>
</tr>
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<td>81.6</td>
<td>65.0</td>
<td>60.5</td>
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<td>65.0</td>
<td>90.7</td>
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<tr>
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<td>1.0</td>
<td>63.0</td>
<td>5.0</td>
<td>51.5</td>
</tr>
<tr>
<td>M06</td>
<td>73</td>
<td>185.4</td>
<td>90.0</td>
<td>81.6</td>
<td>65.0</td>
<td>62.5</td>
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<tr>
<td>M07</td>
<td>74</td>
<td>172.7</td>
<td>35.0</td>
<td>90.7</td>
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<td>180.3</td>
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<td>59.0</td>
</tr>
<tr>
<td>M10</td>
<td>74</td>
<td>172.7</td>
<td>35.0</td>
<td>78.0</td>
<td>50.0</td>
<td>54.0</td>
</tr>
</tbody>
</table>

Cohort average 75.1 ± 4.3 168.8 ± 9.4 50.6 ± 26.7 75.7 ± 12.2 62.4 ± 30.7 55.6 ± 4.0
Male average 75.6 ± 3.0 176.0 ± 7.2 54.6 ± 28.8 81.0 ± 7.8 60.0 ± 23.1 57.7 ± 3.9
Female average 74.4 ± 5.6 161.9 ± 4.7 45.6 ± 24.7 69.2 ± 13.9 65.4 ± 39.8 53.1 ± 2.3

* Letter in the subject code designates sex (F=female; M=male).
* Percentiles are determined using the work of Gordon et al. (1989).
assess the association between IJM and functional group MV among older adults. For the third objective, these data on older adults were compared to previously reported measurements from young adults (Holzbaur et al., 2007a,b). Mixed effects models for repeated measures were used to evaluate age group differences for IJM, MV, and percent MV, adjusting for sex and body mass. Within these models, age group variation was explored by assessing differences between functional groups. Due to our small sample size, males and females were evaluated together with covariate adjustments for sex. Holm sequential Bonferroni (Holm, 1979) was used to control type I error at the 0.05 level for comparisons of young and older adults for each outcome. Functional group ordering for IJM, MV, and percent MV by age group was compared using tests ($p < 0.0125$ level) of proportions under binomial distribution assumptions. We used SAS software (Cary, NC) for all analyses.

### 3. Results

We measured upper limb functional group MV (Table 3) and IJM at the shoulder, elbow, and wrist (Table 4) in older adults. Although older adults spanned a 2.5-fold range of total MV, small coefficients of variation (range 0.043–0.118) of functional group percent MV indicate low muscle distribution variability relative to means across individuals. There was a positive relationship between functional group MV and IJM at all joints for older adults ($p \leq 0.027$) (Fig. 2). On average, MV changed accounted for 40.6% of the variation in IJM.

We evaluated differences between age groups for MV, IJM, and the relationship between MV and IJM. On average, total upper limb MV in older adults was 16.5% lower than young adult total MV, despite similar body mass (older adults 5–99th percentile, young adults 5–90th percentile) (Table 1) (Holzbaur et al., 2007b). Older adult MV was reduced significantly compared to young adults for shoulder abductors (mean difference 155.7 cm$^3$; $p=0.0002$), elbow flexors (mean difference 77.7 cm$^3$; $p=0.0001$), and elbow extensors (mean difference 75.5 cm$^3$; $p=0.0007$) (Fig. 3). We observed a significant increase in MV as a percentage of total upper limb MV for wrist extensors (mean difference $-1.8$%; $p < 0.0001$) (Fig. 4). For both age groups, ordering of functional groups by volume remained consistent; shoulder abductors and wrist extensors comprised the largest and the smallest upper limb volumes, respectively.

IJM was significantly reduced in older adults compared to young adults for shoulder adduction (mean difference 25.3 N m; $p=0.01$), shoulder abduction (mean difference 28.9 N m; $p < 0.0001$), and wrist flexion (mean difference 8.1 N m; $p < 0.0001$) (Fig. 5). Mixed effects analyses showed that differences in IJM between shoulder abduction and wrist flexion ($p=0.0003$), shoulder adduction and elbow extension ($p=0.0181$), and shoulder adduction and wrist extension ($p=0.0146$) were significantly lower in older adults, indicating the shoulder is relatively weaker compared to distal joints in older adults.

Binomial distribution analysis showed consistent ordering of MV between age groups, with shoulder $>$ elbow $>$ wrist ($p < 0.001$, all comparisons), although relative functional group IJM was altered. Young adults were significantly stronger in shoulder adduction compared to elbow extension ($p < 0.001$), whereas older adults were significantly stronger in elbow flexion compared to shoulder abduction ($p=0.004$). Both age groups

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Muscle volumes by functional group for older adults (mean ± SD).</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shoulder adductor functional group</strong></td>
<td><strong>Male average volume (cm$^3$)</strong></td>
</tr>
<tr>
<td>Coracobrachialis</td>
<td>13.1 ± 3.7</td>
</tr>
<tr>
<td>Latissimus dorsi</td>
<td>268.1 ± 91.9</td>
</tr>
<tr>
<td>Pectoralis Major</td>
<td>203.6 ± 86.2</td>
</tr>
<tr>
<td>Teres major</td>
<td>34.4 ± 10.7</td>
</tr>
<tr>
<td>Teres minor</td>
<td>25.3 ± 8.1</td>
</tr>
</tbody>
</table>

**Shoulder abductor functional group**

- Deltoid | 313.7 ± 77.3 | 370.1 ± 39.8 | 243.2 ± 47.2 |
- Infraspinatus | 101.7 ± 28.4 | 118.6 ± 26.7 | 80.7 ± 11.5 |
- Subscapularis | 102.5 ± 31.5 | 122.2 ± 26.4 | 77.8 ± 16.1 |
- Supraspinatus | 39.9 ± 15.0 | 48.1 ± 15.0 | 29.5 ± 6.3 |

**Elbow flexor functional group**

- Biceps brachii | 142.8 ± 50.6 | 178.7 ± 37.5 | 97.9 ± 16.5 |
- Brachialis | 96.7 ± 25.1 | 111.0 ± 20.0 | 78.9 ± 19.0 |
- Brachioradialis | 41.7 ± 16.5 | 54.2 ± 9.2 | 26.1 ± 6.8 |
- Pronator teres | 31.9 ± 15.0 | 41.2 ± 13.7 | 20.4 ± 5.2 |

**Elbow extensor functional group**

- Anconeus | 6.4 ± 2.4 | 7.8 ± 2.3 | 4.7 ± 1.1 |
- Supinator | 16.8 ± 6.1 | 19.0 ± 6.7 | 14.0 ± 4.1 |
- Triceps brachii | 303.9 ± 87.4 | 309.1 ± 53.6 | 222.4 ± 34.6 |

**Wrist flexor functional group**

- Flexor carpi radialis | 41.2 ± 9.8 | 46.9 ± 8.6 | 34.1 ± 5.8 |
- Flexor carpi ulnaris | 39.1 ± 12.5 | 48.4 ± 8.5 | 27.8 ± 4.2 |
- Wrist flexors$^a$ | 160.3 ± 59.2 | 198.8 ± 52.6 | 112.1 ± 14.2 |

**Wrist extensor functional group**

- Extensor carpi radialis$^b$ | 50.1 ± 15.5 | 59.7 ± 13.9 | 38.1 ± 6.2 |
- Wrist extensors$^c$ | 93.8 ± 27.6 | 112.7 ± 19.7 | 70.2 ± 14.3 |
- Pronator quadratus | 6.4 ± 2.9 | 8.2 ± 2.8 | 4.3 ± 1.1 |
- Total | 2133.8 ± 615.1 | 2588.9 ± 387.9 | 1565.0 ± 244.7 |

$^a$ Wrist flexor volume includes palmaris longus, flexor digitorum superficialis, flexor digitorum profundus, flexor pollicis longus, and abductor pollicis longus.

$^b$ Extensor carpi radialis volume includes extensor carpi radialis longus and extensor carpi radialis brevis.

$^c$ Wrist flexor volume includes extensor carpi ulnaris, extensor digitorum communis, extensor digiti minimi, extensor indicis proprius, extensor pollicis longus, and extensor pollicis brevis.

Fig. 1. Muscle volumes by functional group in the upper limb, including shoulder abductors (cyan), shoulder adductors (orange), elbow flexors (green), elbow extensors (purple), wrist flexors (red), wrist extensors (yellow), pronator quadratus (blue), and bones (white). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
were significantly stronger at the elbow compared to the wrist ($p<0.001$, flexion and extension). Young adults had a 6.7-fold mean difference between the strongest (shoulder adduction) and the weakest (wrist extension) functional groups, while older adults had a 5-fold mean difference between the strongest (elbow flexion) and the weakest (wrist extension) functional groups.

We observed significant linear relationships between functional group MV and IJM in older adults ($p<0.027$) (Fig. 2), consistent with previous observations in young adults. However, corresponding functional group MV explained less variation in IJM for older adults (mean $r^2=40.6\%$) than for young adults (mean $r^2=81.0\%$). No statistically significant difference between slopes was observed, but there was a trend toward markedly lower shoulder volume and strength in old compared to young adults.

4. Discussion

We measured upper limb functional group MV and obtained maximum IJM at the shoulder, elbow, and wrist in 18 older adults. In older adults, total MV, functional group MV, and IJM were reduced compared to young adults, despite similar body mass between groups. We observed markedly reduced MV at the shoulder in older adults compared to young adults. Older adults were not the strongest at the shoulder like young adults, suggesting that relative differences between strength at different joints are not consistent with age. Although age-related MV and IJM reductions occur, the linear relationship between functional group MV and IJM was maintained in older adults. While older adults presented with overall decreases in functional group MV and IJM compared to young adults, the shoulder had the most marked deficits.

Shoulder abductor MV and IJM were significantly reduced in older compared to young adults. Other age-related neuromuscular changes, in addition to a decline in MV, that have been implicated in IJM deficits, include infiltration of intramuscular fat, increased connective tissue, reduced contractile tissue, reduced neural drive, changes at the neuromuscular junction, increased antagonist muscle coactivation, decreased muscle fiber specific tension, and preferential atrophy of type II muscle fibers (Dey et al., 2009; Frontera et al., 2000; Janssen and Ross, 2005; Jones et al., 2008; Klein et al., 2001; Landers et al., 2001; Lynch, 2004; Lynch et al., 1999; Merletti et al., 2002; Narici et al., 1991, 2003; Narici and Maffulli, 2010; Valdez et al., 2010). The difference in upper limb MV observed in older adults may also be due to disuse, either alone or in combination with a pre-existing injury, like an asymptomatic rotator cuff tear. Between 20% and 50% of older adults have a torn rotator cuff, so it is possible that some participants had asymptomatic tears, causing atrophy and decreased strength of affected muscles (Lin et al., 2008; Yamamoto et al., 2010). This was not explicitly investigated because our images were not T2-weighted. On the other hand, wrist extensors represented proportionally more total upper limb volume in older compared to younger adults. One possible explanation for the observed differences is that daily living tasks may use wrist and elbow joints more than the shoulder, causing both MV and IJM deficits at the shoulder (Landers et al., 2001).

We investigated shoulder, elbow, and wrist joints concurrently in older adults to assess relative differences in IJM of major upper extremity functional groups. Our data expand upon findings of Klein et al. (2001), who observed differing MV and strength changes among elbow functional groups. Our finding of reduced IJM in older adults is consistent with previous studies investigating single joints (Akagi et al., 2009b; Bazzucchi et al., 2004; Frontera et al., 2000; Hughes et al., 2001; John et al., 2009; Klein et al., 2001; Landers et al., 2001; Metter et al., 1997; Park et al., 2007; Yassierli et al., 2007). Our assessment of multiple joints concurrently allowed us to describe relationships in MV and IJM between upper limb joints. Differences between functional groups were the largest at the shoulder; young adults were the strongest at the shoulder, whereas older adults had markedly reduced shoulder strength.

We observed a significant relationship between MV and IJM in older adults, but an important observation was that less variation in IJM was accounted for by MV for older compared to young adults. This may be due to age-related decreases in neural stimulation and muscle tissue composition changes (Jones et al., 2008), or caused by reduced contractile protein and fat-free mass in aged muscle (Dey et al., 2009; Janssen and Ross, 2005; Narici and Maffulli, 2010; Narici et al., 2003). These changes may affect the ability of older adults to maximally activate all muscle volume that could contribute to IJM generation. The relationship between muscle strength and cross-sectional area (CSA) has been presented previously for young and older adults (Akagi et al., 2009a; Ikai and Fukunaga, 1968; Jones et al., 2008). We measured MV, which is the product of physiological CSA and optimal fiber length (e.g. Fukunaga et al., 2001). Volume is consistent with calculations utilizing physiological CSA measurements (Holzbaur et al., 2007b) and does not depend on optimal fiber length or pennation angle estimates, which are difficult to measure in vivo and can

Table 4

<table>
<thead>
<tr>
<th>Functional group</th>
<th>Cohort average volume fraction (%)</th>
<th>Male average volume fraction (%)</th>
<th>Female average volume fraction (%)</th>
<th>Cohort average isometric joint moment (N m)</th>
<th>Male average isometric joint moment (N m)</th>
<th>Female average isometric joint moment (N m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder abductors</td>
<td>25.2 ± 2.8</td>
<td>26.0 ± 2.9</td>
<td>24.2 ± 2.6</td>
<td>42.6 ± 24.7</td>
<td>54.4 ± 26.0</td>
<td>27.9 ± 13.1</td>
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<tr>
<td>Shoulder abductors</td>
<td>26.5 ± 2.4</td>
<td>25.6 ± 2.4</td>
<td>27.6 ± 2.2</td>
<td>25.8 ± 10.7</td>
<td>31.7 ± 7.6</td>
<td>18.3 ± 9.5</td>
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<td>Elbow flexors</td>
<td>14.6 ± 0.9</td>
<td>14.9 ± 1.0</td>
<td>14.2 ± 0.7</td>
<td>44.7 ± 23.4</td>
<td>53.5 ± 25.9</td>
<td>33.7 ± 14.8</td>
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<tr>
<td>Elbow extensors</td>
<td>15.4 ± 0.7</td>
<td>15.3 ± 0.8</td>
<td>15.4 ± 0.5</td>
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<tr>
<td>Wrist flexors</td>
<td>11.3 ± 1.3</td>
<td>11.3 ± 1.3</td>
<td>11.3 ± 1.4</td>
<td>10.0 ± 5.6</td>
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<tr>
<td>Wrist extensors</td>
<td>6.8 ± 0.8</td>
<td>6.6 ± 0.5</td>
<td>7.0 ± 1.1</td>
<td>8.9 ± 4.3</td>
<td>11.3 ± 4.0</td>
<td>5.9 ± 2.4</td>
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Table 5

<table>
<thead>
<tr>
<th>Wrist (flexion/extension)</th>
<th>Elbow (flexion/extension)</th>
<th>Shoulder (adduction/adduction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrist in neutral posture, forearm pronated, elbow flexed at 90°, shoulder in neutral abduction</td>
<td>Elbow flexed at 90°, forearm supinated with wrist braced, shoulder in neutral abduction</td>
<td>Shoulder abducted at 60°, elbow braced in extension, forearm in neutral rotation</td>
</tr>
</tbody>
</table>
decrease with age. Our results expand on previous work reporting the relationship between MV and force-generating ability to include older adults (Akagi et al., 2009b; Fukunaga et al., 2001; Holzbaur et al., 2007a; Jones et al., 2008). Our findings are consistent with previous studies reporting decreased peak IJM with each decade past 50 years (Jones et al., 2008; Lynch et al., 1999; Macaluso and De Vito, 2004).

This work provides a foundation for understanding clinically-relevant, age-related upper limb changes, and for ultimately making rehabilitation or injury treatment recommendations for older adults. Efforts to mitigate age-related strength losses to retain an unimpaired strength profile are necessary for older adults to maintain independence. We anticipate that upper limb coordination will be affected by musculoskeletal system changes, such as antagonist co-contraction or a decreased ability to activate the entire muscle volume. Subsequently, some functional tasks may not be possible to perform. This work also provides a foundation for future studies characterizing coordination changes in older adults with reduced MV and altered IJM. Further analyses of upper extremity movements in healthy or impaired older adults.

Fig. 2. Separate regression lines are fit to data from older and younger adults. Maximum isometric joint moment versus functional group muscle volume for (a) shoulder adduction, \( p < 0.001 \); (b) shoulder abduction, \( p = 0.026 \); (c) elbow flexion, \( p = 0.003 \); (d) elbow extension, \( p = 0.006 \); (e) wrist flexion, \( p = 0.025 \); (f) wrist extension, \( p = 0.002 \). Older adults are shown with circles (males—white circles; females—black circles) and young adults (Holzbaur et al., 2007a,b) are shown with triangles (males—white triangles; females—black triangles). Correlation coefficients represent the different age groups and \( p \)-values presented above represent the significance of the older adult linear regression. In older and young adult groups, there was a significant linear relationship between maximal isometric joint moment and functional group muscle volume for each joint. However, the older adult cohort demonstrated more variation in this relationship than the young adult group.
adults would benefit from development of musculoskeletal models better reflecting the force-generating characteristics of older individuals described here.

This study has several limitations. Males and females were evaluated in the same analyses, due to our small sample size. While absolute volumes and strengths differed by sex, similar relationships were seen across groups. However, sex-based differences warrant further study. Our small sample also limits generalizability of our data.

Intramuscular fat content was not measured. An additional fat quantification scan was not included to reduce scan time and participant burden. While our method may have overestimated the amount of contractile tissue, reduced upper limb MV and altered relationships between MV and IJM at the shoulder were detected. Accounting for intramuscular fat in future work may improve our ability to explain age-related differences in MV and IJM.

Muscle force generation is posture dependent (Zajac, 1989), but we tested IJM in a single posture for each joint. Postures were selected for comparison with previously reported young adult measurements (Holzbaur et al., 2007a,b). Therefore, our functional group classifications and results are limited to these specific postures. While different muscle compartments (e.g., anterior, middle, posterior deltoid) may play different mechanical roles (Ackland et al., 2008; Kuechle et al., 1997), compartments are not easily distinguished using MR. Therefore, we grouped compartments according to the whole muscle's primary function (Kuechle et al., 1997) and electromyographic activity (Wickham et al., 2010) in the postures used to assess IJM.

Muscle moment arm, like MV, is an important determinant of strength and is posture dependent. Moment arms were not measured in this study. MR images were not obtained in IJM testing postures due to scanner size constraints. However, previous studies have shown that MV is a major determinant of strength variation (Akagi et al., 2009b; Fukunaga et al., 2001), and we postulate that age-related MV changes are more remarkable than moment arm changes. Variation of moment arm with age may be an area for future study.

Three degrees of freedom at the shoulder are used in activities of daily living (Kuechle et al., 2000). We observed relative weakness in shoulder abduction/adduction in older adults, but did not measure flexion or axial rotation due to concerns regarding participant burden and fatigue. Weakness in flexion or axial rotation could also have important functional implications and may be associated with the decreased MV reported here. Our group is currently investigating shoulder MV and IJM in 3 degrees of freedom in healthy and impaired older adults.
We investigated upper limb MV and IJM at the shoulder, elbow, and wrist joints in older adults and compared these data to measurements previously collected on younger adults. Our findings of reduced MV and IJM with notable differences at the shoulder show that older adults are not simply weaker than younger adults, since declines are not uniform across functional groups. While volume was a significant predictor of IJM in older adults, variation in IJM accounted for by MV was half that of young adults. These data provide a foundation for exploring functional deficits in older adults from an experimental perspective and as a resource for developing simulation-based analyses reflecting older adult strength and muscle characteristics, which we have shown cannot be simply scaled from young adult characteristics.

Conflict of interest statement

None.

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References


