Normally Aging Older Adults Demonstrate the Bilateral Deficit During Ramp and Hold Contractions

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The bilateral deficit results from the maximum voluntary force of a bilaterally performed task being smaller than the sum of the maximum voluntary force of the unilaterally performed tasks. It is underlain by the limitation of the neural drive during maximum bilateral contractions and has been hypothesized to reflect the inability to fully activate high threshold motor units. Because high threshold motor units atrophy in older adults, a smaller bilateral deficit in older adults compared to young adults would further support the hypothesis. Indeed, K. Häkkinen et al. in 1995 and 1996 reported no bilateral deficit in older adults performing rapid maximum contractions. The present study extends this investigation to slowly developed maximum contractions. The results demonstrated a bilateral deficit (p < .05). This result, combined with the age-related decrease in the number of high threshold motor units, tends to refute the contention that selective restriction of high threshold motor units causes the bilateral deficit during maximum voluntary isometric ramp and hold contractions.

The central nervous system normally seems to limit the neural drive to skeletal muscle during conditions in which bilateral, homologous muscles are simultaneously and voluntarily intended to be maximally activated. This phenomenon, known as the bilateral deficit, is manifested by the maximum voluntary force of a bilaterally performed task being smaller than the sum of the maximum voluntary force of the unilaterally performed tasks. Generally, the size of the deficit is between 10 and 25%. The bilateral deficit in young adults has been demonstrated for small muscles such as those of the hand (1) and for large muscles of the lower extremity (2,3). It has been observed during isometric contractions (3-5), isokinetic concentric contractions (2,6,7), and isokinetic eccentric contractions (8). However, the bilateral deficit is not obligatory. Häkkinen et al. (9,10) reported no bilateral deficit in older adults performing rapid maximum contractions. Howard and Enoka (11) showed that in some subjects the bilateral deficit can be diminished, and even reversed, by training, underscoring the important influence of the central nervous system.

It has been suggested that the neural basis for the bilateral deficit is caused by interhemispheric inhibition (1,12). However, it is not known whether the activation of motor units is selectively restricted or, conversely, if the entire motor unit pool is affected. The latter possibility has not received much attention, but there are conflicting reports as to whether the bilateral deficit results from selective restriction of low or high threshold motor unit activation. Some authors have suggested that the bilateral deficit is caused by a restriction of high threshold motor unit activation (2,3). In contrast, other authors have suggested that the bilateral deficit is caused by a restriction of low threshold motor unit activation (13,14).

Recently, Häkkinen et al. (10) investigated the bilateral deficit for an isometric knee extension task (knee joint angle of 107 degrees flexion) in middle-aged (44–57 years) and older (59–75 years) men and women. Earlier work by Häkkinen et al. (9) examined the bilateral deficit in young (approximately 30 years), middle-aged (approximately 50 years), and older (approximately 70 years) men. In both experiments, subjects generated their maximum effort knee extension force in a "step" fashion, having been instructed to generate force as rapidly as possible. The subjects in these studies did not demonstrate a bilateral deficit. This is notable because the normal aging process is generally associated with an atrophy of and/or a decrease in the number of high threshold motor units (15–17), which are the motor units most difficult to voluntarily activate. Thus, failure of the older subjects to demonstrate a bilateral deficit combined with normal age-related atrophy of high threshold motor units is consistent with an inability to fully activate high threshold motor units during a bilateral condition.

The presently reported data were collected as part of two other studies. One group of subjects were the controls for a one-stage versus two-stage bilateral knee arthroplasty study (18), and the other group of subjects were from an exercise training program (only the pretraining data were used in the present study). The analysis was prompted by the data of Häkkinen et al. (10) and undertaken to extend the literature on the bilateral deficit in older adults to include ramp and hold contractions. The question specifically posed by this analysis was, "Do older adults demonstrate a bilateral deficit during maximum voluntary isometric knee extensions performed in a ramp-and-hold fashion?" Based on the assumptions that the bilateral deficit is caused by a restriction of high threshold motor units and that the normal aging process is generally associated with an atrophy of and/or a decrease in the number of high threshold motor units, it was hypothesized that older adults would not demonstrate a bilateral deficit during maximum voluntary isometric knee extensions performed in a ramp-and-hold fashion.

METHODS

Subjects.—Two experiments were conducted in which 35 older adults (mean age ± SD: 72.1 ± 5.7 yrs; Table 1) volun-
teered to participate and provided informed consent. All subjects were right leg dominant, as indicated by their preference for kicking a ball. An important difference between the protocols was the knee flexion angle at which the isometric knee extension task was performed. All subjects were healthy and living independently, but not involved in recreational activities associated with bilateral contractions (i.e., rowing, weight lifting). Exclusion criteria included musculoskeletal, neurological, and cardiovascular pathologies that would have interfered with the ability to perform the tasks.

**Instrumentation.**—A Kin-Com isokinetic dynamometer (Chattanooga Corporation, Chattanooga, TN), customized for bilateral force measurements, was used in this study. The knee extension forces produced by the left and right legs during a bilateral contraction were measured individually using strain gauge load cells (Figure 1; model MC3-3-500, AMTI, Newton, MA). The signals from the strain gauge load cells were used as input to an A/D circuit (Data Translation, 2801A, Marlboro, MA). The signals were digitized at 100 Hz and stored for processing.

**Protocol.**—Subjects were seated upright in the Kin-Com and stabilized with Velcro straps across their waist and each thigh (Figure 2). The axes of rotation of the Kin-Com were aligned with the putative flexion-extension axis of both knee joints. The pad of each load cell was placed over the distal shank, proximal to the ankle joint. For Group I, the isometric contractions were performed with the knee joint at 45 degrees of flexion (full extension = 0 degrees). For Group II, isometric contractions were performed with the leg vertical to the floor (knee flexion angle approximately 90 degrees).

Subjects performed maximum voluntary isometric contractions (MVC) of the knee extensor muscles under three different conditions (right leg only, left leg only, and both legs). Three trials for each condition were collected. The collection order was randomized, and subjects were given a practice trial prior to each condition. Subjects were instructed to generate an MVC over a period of 3 seconds. Upon achieving MVC, the subject indicated that to the experimenter (either by verbal “okay” or by a nod of the head), and data were collected for one second. One minute of rest was allowed between each trial.

**Data Analysis.**—The digitized force data were smoothed using a recursive Butterworth filter (cutoff frequency = 10 Hz) and converted to moments. The peak knee extension moment and the average knee extension moment were extracted for the one-second data collection period. The

<p>| Table 1. Descriptive Statistics (mean ± SD) of Subject Physical Characteristics by Group/Sex |
|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Subjects</th>
<th>Age (yrs)</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group I</strong> *</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>4</td>
<td>70.0 ± 4.8</td>
<td>1.72 ± 0.08</td>
</tr>
<tr>
<td>Women</td>
<td>5</td>
<td>66.6 ± 7.0</td>
<td>1.63 ± 0.07</td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>68.1 ± 6.0</td>
<td>1.67 ± 0.08</td>
</tr>
<tr>
<td><strong>Group II†</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>8</td>
<td>74.3 ± 3.3</td>
<td>1.71 ± 0.06</td>
</tr>
<tr>
<td>Women</td>
<td>18</td>
<td>73.2 ± 5.5</td>
<td>1.57 ± 0.08</td>
</tr>
<tr>
<td>Total</td>
<td>26</td>
<td>73.5 ± 4.9</td>
<td>1.62 ± 0.10</td>
</tr>
<tr>
<td><strong>Combined groups</strong></td>
<td>35</td>
<td>72.1 ± 5.7</td>
<td>1.63 ± 0.10</td>
</tr>
</tbody>
</table>

*Knee angle 45 degrees.
†Knee angle 90 degrees.
The interaction terms were not significant.

The bilateral index was determined for each leg and was calculated as defined by Howard and Enoka (11):

\[ 100 \times \left( \frac{\text{bilateral value of } x}{\text{unilateral value of } x} \right) - 100 \]

in which \( x \) represented the knee extension moment for either the left or the right leg. A negative value indicated a bilateral deficit, such that a smaller moment was generated during the bilateral condition than during the unilateral condition. A positive value indicated a bilateral facilitation, such that a larger moment was generated during the bilateral condition than during the unilateral condition.

Statistical Analysis.—A 2 \( \times \) 2 \( \times \) 2 (Group by Leg [i.e., left vs right] by Condition [i.e., unilateral vs bilateral]) analysis of variance (ANOVA) was used to determine inter-condition and inter-leg differences for the knee extension moments generated. The leg and condition factors were repeated measures. A 2 \( \times \) 2 (Group by Leg) ANOVA was used to determine intergroup and interleg differences for the calculated bilateral indices. Paired samples \( t \)-tests were used to compare the knee extension moments of the unilateral conditions to the bilateral condition. One-sample \( t \)-tests were used to indicate if the bilateral indices were different from zero. A probability level of .05 was used as the maximum acceptable value indicating significant differences.

RESULTS

The analysis performed on the maximum knee extension moments and the analysis performed on the computed bilateral indices confirmed the presence of a bilateral deficit in older adults. The bilateral indices were not different between the peak and averaged values, so only the averaged values will be reported. The ANOVA revealed a significant decrease in maximum knee extension moment when the contractions were performed bilaterally (\( p < .001 \)). This was true for both the right and left legs (Table 2). The differences between the two groups of subjects, which effectively tested the effect of knee joint angle, were not significant. The interaction terms were not significant.

The ANOVA performed on the bilateral indices revealed that the differences between the right and left legs were not significant (\( p = .282 \)). Further, the differences between the two groups of subjects were not significant (\( p = .222 \)). The Group by Leg interaction term was not significant. One-sample \( t \)-test revealed that the bilateral index was significantly greater than zero for each of the four comparisons (\( p < .05 \)). Of the 70 calculated bilateral indices, only 12 showed a positive value (bilateral facilitation) with an additional four having an index approximately equal to zero (Figure 3). Three subjects showed a bilateral facilitation in both legs.

DISCUSSION

Based upon the work by Håkkinen et al. (10), using maximum voluntary knee extension contractions performed in a step fashion, we performed an analysis of data from two other studies that allowed evaluation of the bilateral deficit in older adults performing the task in a ramp-and-hold fashion. It has been suggested that the bilateral deficit reflects increased difficulty of activating large motor units during bilateral contractions activation (2,3). The work by Håkkinen et al. (10), in which the bilateral deficit was not detected in older adults, supported this hypothesis. Because normal aging is expected to be associated with atrophy of high threshold motor units (15,16), the potential contribution of these motor units during bilaterally performed maximum effort contractions is also expected to be reduced. A neurally mediated restriction of these motor units during bilateral maximum contractions would effectively reduce the size of the bilateral deficit. Based on older adults’ data that were collected as part of two other studies, the question specifically addressed in the present study was, “Do older adults demonstrate a bilateral deficit during maximum voluntary isometric knee extension performed in a ramp-and-hold fashion?” The results of the analysis confirmed the presence of a bilateral deficit under these conditions.

Table 2. The Bilateral Indices and the Right and Left Leg Unilateral and Bilateral Knee Extension MVC Averages (mean ± SD) for Each Group (3 trials per subject)

<table>
<thead>
<tr>
<th></th>
<th>Group I</th>
<th></th>
<th>Group II</th>
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<tbody>
<tr>
<td></td>
<td>Bilateral</td>
<td>Unilateral</td>
<td>Bilateral</td>
</tr>
<tr>
<td></td>
<td>Index (%)</td>
<td>Condition (Nm)</td>
<td>Index (%)</td>
</tr>
<tr>
<td>Left leg</td>
<td>-12.9 ± 5.3*</td>
<td>82.3 ± 18.4</td>
<td>71.6 ± 15.8**</td>
</tr>
<tr>
<td>Right leg</td>
<td>-11.1 ± 6.8*</td>
<td>94.7 ± 24.8</td>
<td>83.0 ± 17.9**</td>
</tr>
</tbody>
</table>

Note: Group I knee angle 45 degrees; Group II knee angle 90 degrees.
*Statistically different from zero (\( p < .05 \)).
**Statistically less than corresponding unilateral condition (\( p < .05 \)).
By showing that the bilateral deficit did occur in older men and women, the results of the present study are consistent with what we believe to be the dominant number of published studies on this topic involving younger adults. The size of the bilateral deficit in our older adults (ranging from 6.5 ± 13.7% to 12.9 ± 5.3%) was comparable to the 9.5 ± 6.8% (11) and 17.0 ± 7.4% (3) measured in young adults under similar conditions. Because the magnitudes of the unilateral and bilateral forces were greater for the younger adults, it seems that the degree of the bilateral deficit is independent of strength.

The present findings are contradictory to those of the heretofore only published studies on the bilateral deficit in older adults (9,10). This naturally raises questions about those factors that may have caused such differences. Based on simple descriptions of the subjects, it does not seem that this would be the source of differences. The subjects in each study seem reasonably matched for age, height, and weight. Further, the subjects in each study seemed similar regarding their independent living lifestyles and, on average, participation in recreational activities. One can not discount the importance of the differences afforded by the different countries in which the studies were performed but similarly, there is no precedent to expect differences in the bilateral deficit based upon this factor. Interestingly, the younger subjects in Häkkinen et al. (9) also failed to produce a bilateral deficit. This is contradictory to numerous studies involving younger adults (2,4,5), and specifically Koh et al. (3), in which young subjects performed step contractions.

Not unexpectedly, the differences between how the bilateral deficit was computed in the current study as well as Häkkinen et al. (9,10) are not a factor. We were able to recompute the bilateral deficit in our older adults using the equation of Häkkinen et al. (10) [(bilateral force / sum of unilateral forces) X 100]. The mean and standard deviation (n = 35) were found to be 91.5 ± 10.6. A t test revealed that this value was significantly different from 100.

An interesting possibility that may have contributed to the differences in the two studies was provided by Vint and Hinrichs (19). Their data suggest that the size of the bilateral deficit for maximum voluntary knee extension force is significantly affected by the time separating the onset of force generated in one leg from that of the other leg. Specifically, when bilateral knee extension force was generated asynchronously (on an average of 267 msec), the bilateral deficit was absent. But a synchronously generated bilateral knee extension force (within 18 msec) produced a bilateral deficit. Therefore, although this was not investigated, one can not discount the possibility that the findings of Häkkinen et al. (10) were influenced to some extent by asynchronous timing of bilateral force onset. This may also account for the absence of the bilateral deficit in not only older, but also young and middle-aged, men and women (9,10,20), yet not all studies involving step contractions have failed to produce a bilateral deficit in younger adults (3). It would seem that during a ramp-and-hold contraction, asynchronous onset would not have likely been an issue. A more comprehensive study of the bilateral deficit in older adults is necessary and should include both step and ramp-and-hold conditions. Such a design could more effectively address the questions raised by the differences between the present results and those of Häkkinen et al. (10).

Combining the presence of a similar bilateral deficit in older adults compared to young adults with the expected age-related atrophy of high threshold motor units, tends to refute the contention that the inability to fully activate high threshold motor units underlies the bilateral deficit. Recent studies in our laboratory (21) also dispute this contention. With similar assumptions, such as Vandervoort et al. (2), this study investigated the effects of fatigue on bilateral deficit and if these effects were speed dependent. Our findings showed that the size of bilateral deficit was not affected by fatigue induced isokinetically at 150 degrees per second, yet increased when fatigue was induced at 30 degrees per second. If a restriction of high threshold motor units is the cause of the bilateral deficit, the size of the deficit following fatigue should have diminished.

Most studies have focused on selective motor unit recruitment as the cause for the bilateral deficit, but could it be possible that the bilateral deficit, in young and older adults, is a result of the nervous system restricting the maximum discharge frequency of active motor units? That is, the bilateral deficit represents the influence of altered rate coding rather than recruitment. There is a precedence supporting this as a possible mechanism. Specifically, there is accumulating evidence that the central nervous system uses a different control strategy for concentric and eccentric contractions. In particular, the discharge frequency of motor units is lower during eccentric contractions than during concentric contractions (22–24). If the central nervous system employs different motor unit discharge frequencies for concentric and eccentric contractions, it would not be unreasonable to suggest that different motor unit discharge frequencies occur for bilateral and unilateral contractions.

Electromyographic activity (EMG) was not collected in the present study, but those investigations recording EMG have showed conflicting results. Some have shown a decline in the EMG that parallels the decline in force during a bilateral contraction (2), whereas others have shown no decline in EMG (5). It has been suggested that the changes in the force between a bilateral and a unilateral condition may not be large enough to detect changes in EMG (11). More refined measures of EMG may be needed in order to detect the small changes in either motor unit recruitment or discharge frequency.

Returning to the findings of the present study, the purpose of calculating the bilateral index was to compare the total force generated by both legs during the bilateral condition to the sum of unilaterally generated forces. The unique design of our testing apparatus allowed for simultaneous, independent force measurements from the left and the right leg during the bilateral condition. Thus, the bilateral index could be calculated for each leg separately. There were a total of 70 individual conditions (35 subjects X 2 legs each). Of these 70 conditions, 4 displayed no difference, and 12 demonstrated a bilateral facilitation. Although Figure 3 does not differentiate between subject groups, these 16 conditions were from Group II. Three subjects showed a bilateral facilitation in both legs, four subjects showed a facilitation in their right leg only, and two subjects showed a facilitation in their left leg.
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Georgia, 1996. remains open for discussion.

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