Characteristics of Postural Muscle Activity in Response to A Motor-Motor Task in Elderly

Yun-Ju Lee 1,*, Jing Nong Liang 2 and Yu-Tang Wen 1

1 Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Hsinchu 30013, Taiwan; pwiadr@gmail.com
2 Department of Physical Therapy, University of Nevada Las Vegas, Las Vegas, NV 89154, USA; jingnong.liang@unlv.edu
* Correspondence: yunjulee@ie.nthu.edu.tw; Tel.: +886-3-5742943

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Featured Application: Prioritization of the postural component in a motor-motor task suggests future individualized exercise programs be developed with different postural control strategies in the elderly.

Abstract: The purpose of the current study was to evaluate postural muscle performance of older adults in response to a combination of two motor tasks perturbations. Fifteen older participants were instructed to perform a pushing task as an upper limb perturbation while standing on a fixed or sliding board as a lower limb perturbation. Postural responses were characterized by onsets and magnitudes of muscle activities as well as onsets of segment movements. The sliding board did not affect the onset timing and sequence of muscle initiations and segment movements. However, significant large muscle activities of tibialis anterior and erector spinae were observed in the sliding condition ($p < 0.05$). The co-contraction values of the trunk and shank segments were significantly larger in the sliding condition through the studied periods ($p < 0.05$). Lastly, heavy pushing weight did not change the timing, magnitude, sequence of all studied parameters. Older adults enhanced postural stability by increasing the segment stiffness then started to handle two perturbations. In conclusion, they were able to deal with a dual motor-motor task after having secured their balance but could not make corresponding adjustments to the level of the perturbation difficulty.

Keywords: postural control strategy; muscle activity; dual-task; older adult; translation perturbation

1. Introduction

Aging-related changes in postural control are associated with balance maintenance regardless of different types of perturbations. In response to perturbations, the central nervous system (CNS) reacts to fast, directional arm movement or reaching by employing feedforward as anticipatory [1–3] and feedback mechanisms as compensatory postural adjustments [4,5] to maintain and restore equilibrium. Older adults accommodate both anticipatory and compensatory postural adjustments related to the perturbations compared to young adults [6–11]. Specifically, for a perturbation from upper limb movement, such as pushing an object, older adults utilize a less efficient strategy such as muscle co-activation [12]. Alternatively, for a translation perturbation from lower limb induced by standing on an unstable or moving surface, older adults employ corresponding postural adjustments with increasing magnitudes of muscle activities and center of pressure displacement [13,14].

Effects of a single perturbation on postural control have been widely studied and well documented. Meanwhile, studies of aging effects on dual-tasking commonly focus on combinations of a cognitive task with a motor task. These studies have shown declined performance in the elderly during the
combination of cognitive and motor tasks [15–17]. When dual-tasking involved walking with a visual cue, older adults showed more difficulties in making corrective step adjustments [18]. However, activities of daily living involve multiple perturbations to balance, such as walking while holding the cellphone, or pushing a shopping cart while walking around in the supermarket. Both activities engage upper and lower limb movements involved in two motor tasks.

Postural control in response to perturbations from upper and lower limb movements simultaneously, such as pushing an object while standing on the sliding board, has been studied in young adults [19]. Our previous findings indicated that when the surface was movable, the onset times of tibialis anterior and rectus femoris were delayed and the magnitudes of muscle activation were decreased. In addition, the ventral muscles (tibialis anterior, rectus femoris, and rectus abdominis) and dorsal muscles (medial gastrocnemius, biceps femoris, and erector spinae) initiated before and after the pushing movement respectively, which suggested that the reciprocal muscle activation pattern was utilized. It also revealed that the CNS of young adults handling these dual-motor tasks as prioritizing upper limb perturbation, pushing movement [19,20] or gripping reactions [21], along with maintaining vertical posture. Subsequently, their postural control responded to lower limb perturbations, such as sliding translation [19–21].

For young adults, the CNS prioritizes motor tasks over postural maintenance because their balance is not in imminent danger during the task performance [22,23]. Contrarily, the CNS prioritizes postural maintenance over motor tasks when one or two tasks involve postural control [24] or threat to balance [25]. However, the organization of postural control is not well understood when older adults perform a dual motor-motor task rather than a cognitive-motor task. Thus, the objective of the present study was to investigate how older adults handle a combination of upper limb activity and a translational perturbation, and how that affect characteristics of muscular strategies used in balance maintenance and restoration. The experimental paradigm involved two body perturbations: the upper extremities performing the pushing of a cart, and the translation perturbation of standing on the sliding board. Hence, we hypothesized that the onset time of muscle activities would be affected by the presence of these perturbations. Additionally, the second hypothesis was that older adults would utilize the strategy of postural muscle co-contraction to maintain vertical posture when exposed to upper and lower limb perturbations.

2. Materials and Methods

2.1. Participants

Fifteen older adults (11 females, 4 males, age = 65.93 ± 3.59 years, height = 1.57 ± 0.06 m, mass = 63.11 ± 6.74 kg) participated in the study. All participants did not suffer any musculoskeletal disorder and neurologic disease that could affect performing the experimental tasks. Furthermore, their Mini-Mental State Examination was 28.13 ± 1.68 points and the Berg’s Balance Score was 55.87 ± 0.35 points. The project was approved by the National Tsing Hua University Institutional Review Board, and all participants provided written informed consent before taking part in the experimental procedures.

2.2. Procedure and Instrumentation

Participants were instructed to stand on a sliding board wearing a safety harness with their feet shoulder-width apart and in parallel, in front of a pushing cart (length 0.74 m, width 0.48 m, and height 0.30 m from the wheels) and push on its horizontal handle. The sliding board (length 0.5 m, width 0.5 m, and height 0.21 m) was made of two layers and had a lock mechanism allowing the top layer to either be free to slide in the anterior-posterior direction or remain stationary. A lightweight (5% body mass) or heavyweight (30% body mass) was placed on the pushing cart. Participants stood with their upper limb in elbow flexion and wrist extension at 90 degrees, and palms were slightly contacting the handle. The height of the pendulum was adjustable to match the subject’s hand position (Figure 1).
The electrical activity of muscles (Electromyography, EMG) was recorded for the left side only due to the symmetric pushing task. EMG was obtained from the tibialis anterior (TA), medial gastrocnemius (MG), rectus femoris (RF), biceps femoris (BF), rectus abdominis (RA), and erector spinae (ES). Six Trigno IM Sensors (Delsys, INC., Natick, MA, USA) were used as EMG electrodes and attached to the muscle bellies after standard skin preparation procedures [26]. EMG signals were band-pass filtered (10–500 Hz) and amplified (gain 2000) by conducting in the Trigno™ Wireless System (Delsys, INC., Natick, MA, USA). These Sensors were also included accelerometers and could represent movements of the trunk (from sensors on RA and ES), thigh (from sensors on RF and BF), and shank (from sensors on TA and MG) segments.

2.3. Data Processing

All data were processed offline using MATLAB software (MathWorks, Natick, MA, USA). The signals from the first and second accelerometers were used to determine the timing that the pendulum (T0) and the sliding board (bT0) started moving away. The onsets of the accelerometer signals were detected using the Teager-Kaiser onset time detection method [27,28]. The sensors on these segments also used the Teager-Kaiser method to identify the onset timing of segment movements.
All EMG data were high-pass filtered at 20 Hz, full-wave rectified, and low-pass filtered using linear envelope at 2 Hz (2nd order Butterworth) \[26,29\]. Subsequently, the Teager-Kaiser method was used to identify the onset of muscle activity for individual muscle (EMG\textsubscript{onset}). The integrals of EMG activity of all studied muscles (\(\int \text{EMG}\)) were calculated during the six epochs: (1) from \(-750\) ms to \(-550\) ms, (2) from \(-550\) ms to \(-350\) ms, (3) from \(-350\) ms to \(-150\) ms, (4) from \(-150\) ms to \(+50\) ms, (5) from \(+50\) ms to \(+250\) ms, and (6) from \(+250\) ms to \(+450\) ms in relation to T0. The 1–4 epochs were used to calculate components of feedforward postural adjustments and the 5–6 epochs for feedback postural adjustments \[30,31\]. Moreover, \(\int \text{EMG}\) of the baseline activity were obtained during a 200 ms time window at the beginning of the trial. Subtraction of \(\int \text{EMG}_{\text{baseline}}\) was used to eliminate the effects of each muscle baseline activity. Values larger than zero \((\int \text{EMG} - \int \text{EMG}_{\text{baseline}} > 0)\) were referred as activation of muscles and values smaller than zero \((\int \text{EMG} - \int \text{EMG}_{\text{baseline}} < 0)\) as inhibition of muscles. Thus, \(\int \text{EMG}\) Epochs 1–6 were normalized by \(\int \text{EMG}_{\text{max}}\) \[26\], which was the maximum value throughout all experimental trials for each muscle in each epoch and shown the example of \(\int \text{EMG}\) Epoch 1 as:

\[
\int \text{EMG}_{\text{Epoch 1}} = \int_{T0-550}^{T0-750} \text{EMG} - \int \text{EMG}_{\text{baseline}} / \int \text{EMG}_{\text{max}} \tag{2}
\]

Subsequently, the sums and differences between normalized \(\int \text{EMG}\) values (Equation (2)) of RA and ES muscles for the trunk segment, RF and BF muscles for the thigh segment, and TA and MG muscles for the shank segment were calculated in Epochs 1–6, separately.

\[
C = \int \text{EMG}_{\text{ventral}} + \int \text{EMG}_{\text{dorsal}} \tag{3}
\]

\[
R = \int \text{EMG}_{\text{ventral}} - \int \text{EMG}_{\text{dorsal}} \tag{4}
\]

C indexes were calculated as the sum of \(\int \text{EMG}\) of the antagonist-agonist muscle pairs to represent co-contraction and R indexes as the difference between \(\int \text{EMG}\) in the muscle pairs to represent reciprocal activation \[32\]. Using the shank segment as an example, the C and R values in the Epoch 1 were calculated as:

\[
C_{\text{shank Epoch 1}} = \int \text{TA}_{\text{Epoch 1}} + \int \text{MG}_{\text{Epoch 1}} \tag{5}
\]

\[
R_{\text{shank Epoch 1}} = \int \text{TA}_{\text{Epoch 1}} - \int \text{MG}_{\text{Epoch 1}} \tag{6}
\]

The same C and R values were calculated for the thigh and trunk segments in the Epochs 2–6. All variables were calculated for each trial then averaged over five trials and presented with means and standard errors.

2.4. Statistics

Two-way repeated measures ANOVA were performed with two factors: board (2 levels: fixed and sliding) and weight (2 levels: 5% and 30% body mass) on EMG\textsubscript{onset}, the onset timing of three segments movements, EMG integrals of \(\int \text{EMG}_{\text{Epochs 1–6}}\) for individual muscles. Post hoc comparisons were performed using Tukey’s Honestly Significant Difference test where statistically significant interactions were observed. For the analysis of C and R values, identification of either co-contraction (C) or reciprocal (R) activation pattern was done in the Epochs 1–6 for each segment. The EMG integrals of muscle coupling for the trunk, thigh, and shank segments were compared using C and R values.
by paired-sample t-tests. When ventral and dorsal muscles were activated (larger than the baseline), calculations from both positive values of coupling muscles revealed higher C value than R-value and vice versa. If R values were significantly larger than C values, this would indicate reciprocal activation [33]. Subsequently, if muscle coupling of the trunk, thigh, and shank segments had C value larger than R-value, two-way repeated measures ANOVA were performed with two factors: board (2 levels: fixed and sliding) and weight (2 levels: 5% and 30% body mass), to evaluate the C rather than R, and vice versa. Statistical significance was set at \( p < 0.05 \).

3. Results

Figure 2 illustrates the sequence of events in the conditions of standing on the sliding and fixed board while performing the pushing task. Both ventral and dorsal muscles were initiated before the T0 (0 ms) in both conditions. Two-way repeated measures ANOVA revealed that the onset of all postural muscles, except MG, was not affected by the factors of board and weight. All muscles were activated prior to the timing of pushing the cart away (T0). Thus, the RA onset was \(-577.20 \pm 34.26 \text{ ms}\), the ES onset was \(-637.35 \pm 56.21 \text{ ms}\), the RF onset was \(-698.71 \pm 51.32 \text{ ms}\), the BF onset was \(-684.96 \pm 36.71 \text{ ms}\), the TA onset was \(-789.99 \pm 56.22 \text{ ms}\), and the MG onset was \(-709.85 \pm 35.93 \text{ ms}\), averaged across four conditions.

![Figure 2](image_url)

**Figure 2.** Onset times of muscle activation (black) for RA, ES, RF, BF, TA, and MG in the fixed condition (square) and in the sliding condition (circle). Onset times of the trunk, thigh, and shank segments movements (white) in the fixed condition (square) and in the sliding condition (circle). In addition, the dash vertical lines represent its mean ± standard error from \(-300.82 \text{ ms}\) to \(-203.22 \text{ ms}\) of the onset of the sliding board.

The onset timings of the trunk, thigh, and shank segment movements are shown in Figure 2. Three segments made movements before the T0 in both sliding and fixed conditions. Two-way repeated measures ANOVA revealed that the movement of segments was not affected by the factors of board and weight. In the sliding condition, the onset timing of the trunk segment movement was \(-282.85 \pm 65.98 \text{ ms}\), similar to the timing of the board movement, followed by the thigh \((-159.31 \pm 77.21 \text{ ms})\) and shank \((-157.36 \pm 74.35 \text{ ms})\) segments.

Two-way repeated measures ANOVA revealed that the factor of the board only affected ES and TA in Epochs 1–6 (Table 1) and was higher in the sliding conditions than in the fixed conditions (Figure 3). In addition, \( \int EMG \) was gradually decreased from the Epoch 1 to Epoch 6, particularly after the cart movement (Epoch 5 and Epoch 6). The C values were significantly larger than the R values and indicated co-contraction of muscles for the three segments in four conditions through Epoch 1 to Epoch 6 (Table 2). Subsequently, the C values of the trunk segment and the shank segment were significantly affected by the factor of board in Epochs 2–6 and in Epochs 1–5, respectively. In Epoch 1, the C value of the shank segment was significantly higher in the sliding condition \((0.56 \pm 0.05)\) than in the fixed condition \((0.40 \pm 0.06)\). In Epochs 2–5, the C values of the trunk segment were
significantly higher in the sliding conditions (0.36 ± 0.04, 0.38 ± 0.06, 0.36 ± 0.05, 0.35 ± 0.05) than in the fixed conditions (0.27 ± 0.04, 0.25 ± 0.04, 0.24 ± 0.04, 0.24 ± 0.04). As well shown in Figure 4, the C values of the shank segment was significantly higher in the sliding conditions (0.54 ± 0.04, 0.54 ± 0.05, 0.50 ± 0.05, 0.46 ± 0.05) than in the fixed conditions (0.36 ± 0.06, 0.32 ± 0.05, 0.30 ± 0.05, 0.28 ± 0.04) in Epochs 2–5. In Epoch 6, the C value of the trunk segment was significantly higher in the sliding condition (0.33 ± 0.05) than in the fixed condition (0.21 ± 0.04). Finally, \( \mathcal{EMG} \) of all muscles were not significantly affected by the factor of weight in Epochs 1–6 (Table 1).

**Table 1.** Grand mean (mean of the combination of conditions) of normalized EMG integrals (%\( \mathcal{EMG}_{max} \)) for each epoch.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Epoch 1</th>
<th>Epoch 2</th>
<th>Epoch 3</th>
<th>Epoch 4</th>
<th>Epoch 5</th>
<th>Epoch 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES</td>
<td>20.18 ± 3.31</td>
<td>18.77 ± 3.27</td>
<td>16.97 ± 3.16</td>
<td>16.39 ± 3.22</td>
<td>16.23 ± 3.29</td>
<td>14.05 ± 3.21</td>
</tr>
<tr>
<td>RF</td>
<td>24.45 ± 4.42</td>
<td>22.02 ± 4.06</td>
<td>19.82 ± 4.12</td>
<td>18.75 ± 4.10</td>
<td>18.44 ± 4.31</td>
<td>15.99 ± 4.30</td>
</tr>
<tr>
<td>TA</td>
<td>21.33 ± 3.52</td>
<td>21.02 ± 3.34</td>
<td>21.15 ± 3.11</td>
<td>19.82 ± 2.88</td>
<td>17.25 ± 2.56</td>
<td>15.22 ± 2.53</td>
</tr>
<tr>
<td>MG</td>
<td>26.55 ± 4.60</td>
<td>24.19 ± 4.34</td>
<td>21.60 ± 3.96</td>
<td>20.43 ± 3.68</td>
<td>19.00 ± 3.56</td>
<td>17.15 ± 3.52</td>
</tr>
</tbody>
</table>

* significant effect of the board, † significant effect of interaction between the factor of board and weight.

**Figure 3.** EMG integrals of ES and TA calculated for the sliding conditions (black) and fixed conditions (white) are shown for each epoch. * represents statistical significance \((p < 0.05)\) of the factor of sliding board and ** for \(p < 0.001\).

**Table 2.** The results of paired-samples \(t\)-test for the trunk, thigh, and shank segments in Epoch 1 to Epoch 6.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Epoch 1</th>
<th>Epoch 2</th>
<th>Epoch 3</th>
<th>Epoch 4</th>
<th>Epoch 5</th>
<th>Epoch 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk</td>
<td>−9.95 &lt;0.001</td>
<td>−9.16 &lt;0.001</td>
<td>−7.80 &lt;0.001</td>
<td>−7.64 &lt;0.001</td>
<td>−7.58 &lt;0.001</td>
<td>−7.04 &lt;0.001</td>
</tr>
<tr>
<td>Thigh</td>
<td>−8.66 &lt;0.001</td>
<td>−8.74 &lt;0.001</td>
<td>−7.80 &lt;0.001</td>
<td>−7.78 &lt;0.001</td>
<td>−7.46 &lt;0.001</td>
<td>−6.71 &lt;0.001</td>
</tr>
<tr>
<td>Shank</td>
<td>−9.76 &lt;0.001</td>
<td>−9.15 &lt;0.001</td>
<td>−8.22 &lt;0.001</td>
<td>−8.12 &lt;0.001</td>
<td>−8.19 &lt;0.001</td>
<td>−7.94 &lt;0.001</td>
</tr>
</tbody>
</table>
which was observed in young adults. Although older adults initiated the same distal-to-proximal weight of the cart is pushed. All these temporal events occurred prior to cart movement. The onset of muscle activation depended on the direction of translation perturbation [20]. The function of this adjustment is to ensure that the body moves as an inverted pendulum to coordinate the reciprocal movement of the upper and lower limbs [34]. The earlier onset of either ventral or dorsal muscle activation was associated with co-contraction strategy [35,36], which was also revealed by the C–R analysis in the current study.

The sequence of muscle activation onset was TA → MG → RF → ES → RA (Figure 2). The sequence of muscle activation observed in the elderly was very different from that observed in young adults (TA → RF → RA → ES → MG) performing the same dual-task. When young adults were exposed to upper and lower limb perturbations, they initiated ventral muscles of all three segments, then the dorsal muscles [19]. This sequential activation of distal-to-proximal muscles is usually observed during translation perturbation from the lower limbs [34]. The earlier onset of either ventral or dorsal muscle activation depends on the direction of translation perturbation [20]. The function of this adjustment is to ensure that the body moves as an inverted pendulum to coordinate the reciprocal strategy [19,34], which was observed in young adults. Although older adults initiated the same distal-to-proximal sequence as young adults, the onsets of ventral and dorsal muscles of the three segments were very close and all occurred before the cart movement (Figure 2). Similar onset of ventral and dorsal muscle activation was associated with co-contraction strategy [35,36], which was also revealed by the C–R analysis in the current study.

Only ES and TA were significantly affected by the factor of board and larger magnitudes of muscle activities in the sliding conditions (Figure 3). All other muscles maintained similar magnitudes of muscle activities in all conditions. Hence, co-contraction patterns were observed in all three segments, and the corresponding C values were higher in the sliding conditions than in the fixed conditions on the trunk and shank segments (Figure 4). Older adults have shown to be utilizing less efficient postural control with the co-contraction strategy when performing the pushing task [12]. Together with the early onset time, co-contraction patterns indicated that older adults not only prepared for the pushing task...
but also enhanced the segment stiffness in preparation for potential translation perturbation [12,37,38]. Furthermore, the co-contraction strategy has been associated with increasing the available time to overcome the forthcoming perturbations [38,39] and for further motor responses [40]. Therefore, it might explain that older adults utilized co-contraction strategy much earlier than anticipatory postural adjustment attended to earn more time for postural stabilization. Additionally, the CNS increased significant muscle activation for the lower limb perturbation in the sliding condition.

In the current study, the trunk and board movements were observed with the comparable period in the sliding condition (Figure 2), which was different from young adults who coordinate shank segment for the moving surface while pushing [19]. Instead of the ankle strategy seen in young adults, older adults executed the trunk segment to counteract the board movement, followed by both shank and thigh segments. Young adults are capable of controlling the motor task and postural component when dealing with the dual-task perturbations. On the contrary, older adults initiated all postural muscles only to secure their posture first. The differences between young and older adults have also been reported in effects of visual movement during self-motion perception on postural control, in which young adults were able to adjust muscle activities, but older adults incorporated spatial conflicts, which further compromised their mobility performances [41–43]. Afterward, older adults could handle the upper (pushing) and significant extensive muscle activities for the lower limb (translational) perturbations. In addition, older adults did not adjust studied parameters for the different pushing weights, which was unlike the young adults [19,44]. It suggested that dealing with dual motor-motor tasking might still cost too much attention and could not allocate resources for additional postural adjustments [45]. Older adults exercised similar muscle activities regardless of the effects of pushing weight under the threat of dual motor-motor tasking. Perturbation-based balance training with single perturbation or dual cognitive-motor tasking has been conducted to reduce falls in elderly [46]. However, training effects may not be generalizable to handle functional activities with more than one motor task, which are commonly encountered in daily life. Specialized balance re-training paradigms involving dual motor-motor tasking could be an alternative approach, pending further investigation.

5. Conclusions

In older adults, when handling upper and lower limb perturbations, the chronological sequence of muscle onset time from distal-to-proximal segments is comparable to young adults, but older adults initiated ventral and dorsal muscles much earlier and almost simultaneously. Together with increased magnitudes of TA and ES muscle activity, older adults utilized co-contraction strategy on the trunk and shank segments when pushing while standing on the sliding board. In addition, older adults did not adjust corresponding muscle activities to different pushing weight. These results reveal that older adults increase the segment stiffness for the postural component to gain stabilization and prepare for the motor component. While it is capable of controlling the dual motor-motor task, it could not further adjust the magnitudes of muscle activities for the level of the primary motor task. For older adults, the co-contraction of postural muscles with similar magnitudes indicates that their balance was in imminent danger during the dual motor-motor task. The findings provide new insights for future studies focused on improving postural strategy while handling upper and lower extremity perturbations in the elderly. Furthermore, studying the combined effects of changes in the level of either motor task may contribute to establishing new rehabilitation approaches for improving motor control and resource allocation.

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