Published in final edited form as:

Exp Brain Res. 2012 October ; 222(4): 355–364. doi:10.1007/s00221-012-3219-0.

Magnified visual feedback exacerbates positional variability in older adults due to altered modulation of the primary agonist muscle

Harsimran S. Baweja, MinHyuk Kwon, and Evangelos A. Christou

Department of Applied Physiology and Kinesiology, University of Florida, Gainesville, FL 32611-8205, USA

Evangelos A. Christou: eachristou@hnp.ufl.edu

Abstract

The purpose of this study was to determine whether magnified visual feedback during position-holding contractions exacerbates the age-associated differences in motor output variability due to changes in the neural activation of the agonist muscle in the upper and lower limb. Twelve young (18–35 years) and ten older adults (65–85 years) were instructed to accurately match a target position at 5° of index finger abduction and ankle dorsiflexion while lifting 10 % of their 1 repetition maximum (1RM) load. Position was maintained at three different visual angles (0.1°, 1°, and 4°) that varied across trials. Each trial lasted 25 s and visual feedback of position was removed from 15 to 25 s. Positional error was quantified as the root mean square error (RMSE) of the subject's performance from the target. Positional variability was quantified as the standard deviation of the position data. The neural activation of the first dorsal interosseus and tibialis anterior was measured with surface electromyography (EMG). Older adults were less accurate compared with young adults and the RMSE decreased significantly with an increase in visual gain. As expected, and independent of limb, older adults exhibited significantly greater positional variability compared with young adults that was exacerbated with magnification of visual feedback (1° and 4°). This increase in variability at the highest magnification of visual feedback was predicted by a decrease in power from 12 to 30 Hz of the agonist EMG signal. These findings demonstrate that motor control in older adults is impaired by magnified visual feedback during positional tasks.

Keywords

Aging; Visual feedback; Visual gain; EMG; Motor control

Introduction

Older adults often exhibit greater variability in their motor output than young adults, especially when they perform low-intensity muscular contractions (Christou 2010). This age-associated amplification in motor output variability, which is often correlated with impaired motor control, can be influenced by numerous factors including the amount of visual feedback given to the subject (Kennedy and Christou 2011), the contraction type (Christou and Carlton 2002), and the limb used to perform the task (Kwon et al. 2011).

There is sufficient evidence that magnified visual feedback (zooming into the force trace) impairs the ability of older adults to maintain a constant force (Sosnoff and Newell 2006; Tracy et al. 2007; Vaillancourt et al. 2002). In contrast, magnified visual feedback either does not affect (Christou et al. 2004) or decrease force variability in young adults (Baweja et al. 2010a). Recently, the amplification of force variability with magnified visual feedback in older adults has been linked to changes in the neural activation of the agonist muscle (Kennedy and Christou 2011). Specifically, young adults appear to amplify the power in the activity of the agonist muscle from 13 to 60 Hz with magnification of visual feedback, whereas older adults do not. These findings suggest that older adults are not able to control force equally well to young adults in response to an increase in visual feedback because they cannot effectively modulate the agonist muscle activity.

The age-associated amplification in motor output variability with magnified visual feedback, however, is based on studies that examined constant force contractions. It is important to determine whether visual feedback influences motor output variability in older adults when they attempt to maintain a load at a constant position (position-holding contraction) for the following reasons: (1) there is evidence that position-holding contractions (maintaining a load) compared with constant force contractions (maintaining a force) appear to cause greater differences in motor output variability between young and older adults (Hunter et al. 2002); (2) positional tasks are functionally relevant as many activities of daily living require maintaining a constant position (e.g., maintaining a constant position of the accelerator while driving) (Kwon et al. 2011; Webber and Porter 2010); (3) to our knowledge there is no study to date that has investigated visuomotor processing during position- holding tasks in young and older adults.

Finally, there is evidence to suggest that age-associated differences in motor output variability likely get influenced by the limb used. For example, Tracy et al. (2007) showed that force variability during constant force isometric contractions was greater for the knee extensors than with the elbow flexors. Recently, a study in our laboratory provided support for the findings by Tracy et al. (2007) and demonstrated that age-associated differences in positional variability were exacerbated with ankle dorsiflexion compared with abduction of the index finger (Kwon et al. 2011). There is also evidence that magnification of visual feedback may affect the control of the upper and lower limb differently. Specifically, Prodoehl and Vaillancourt (2010) demonstrated that magnification of visual feedback affected the power spectrum of force more for the elbow than the ankle joint.

It is clear from the above literature that there is a knowledge gap on the interactive effects of visual feedback and limb used on the age-associated differences in motor output variability during position-holding contractions. Therefore, the purpose was to determine whether magnified visual feedback during position-holding contractions exacerbates the age-associated differences in motor output variability due to changes in the neural activation of the agonist muscle in the upper and lower limb. Based on previous findings, described above, we hypothesized that older adults would exhibit greater positional variability with an increase in the amount of visual feedback due to a decreased modulation of the agonist muscle activity from 12 to 60 Hz. Parts of these findings have been reported in abstract form (Baweja et al. 2010b).

Methods

Participants

Twelve young adults (aged 18–35 years, 5 men and 7 women) and ten older adults (aged 65–85 years, 4 men and 6 women) volunteered to participate in this study. All subjects reported being healthy without any known neurological problems, were right-handed

according to a standardized survey (Oldfield 1971), and had normal or corrected vision. The Institutional Review Board at Texas A&M University approved the procedures, and subjects provided written informed consent before participation in the study.

Experimental arrangement

In this experiment, we tested the left index and left ankle of the subjects. The task was position holding with the two joints. For the index finger task, each subject was seated comfortably in an upright position facing a 27 inch computer screen (Samsung Syncmaster™ 275T+, Samsung Electronics America, NJ, USA) that was located 1.25 m away at eye level. The monitor was used to display the position produced by the abduction of the index finger. All subjects affirmed that they could see the display clearly. The left arm was abducted by 45° and flexed to ~90° at the elbow. The left forearm was pronated and secured in a specialized air pillow (Versa Form™, AB Germa, Sweden). The thumb, middle, ring, and fifth fingers of the left hand were restrained with metal plates and there was approximately a right angle between the index finger and thumb. Only the left index finger was free to move. The left index finger was placed in an adjustable finger orthosis to maintain extension of the middle and distal interphalangeal joints and was abducted 5° from the neutral position. This arrangement allowed abduction–adduction of the index finger about the metacarpophalangeal joint in the horizontal plane, a movement produced almost exclusively by the contraction of the first dorsal interosseous (FDI) muscle (Chao et al. 1989). A light load (10 % 1RM) was attached medially at the level of the proximal interphalangeal joint on the finger orthosis and was suspended using a pulley away from the subject (Fig. 1a). For the left ankle task, subjects were seated comfortably in an upright position with the left hip flexed at 90° and abducted by ~10°. The knee joint was also flexed at ~90°. The left ankle was secured in a customized ankle device that isolated the movement of the ankle to the dorsiflexion and plantar flexion plane (Fig. 1b). A light load (10 % 1RM) was attached to the front of the foot.

Measurement of limb movement

Movement of the index finger was produced by the abduction–adduction of the left index finger over a 10° range of motion (5°–15°) about the second metacarpophalangeal joint. The abduction–adduction movement of the index finger was measured with a low-friction potentiometer (SP22GS-5K, Mouser electronics, Mansfield, TX, USA) that was located directly under the metacarpophalangeal joint. Movement of the foot was produced by the plantar flexion/dorsiflexion of the left ankle over a 10° range of motion (90°–100°) about the left talocrural joint. Similar to the index finger, the dorsiflexion/plantar flexion movement of the ankle was measured with a low-friction potentiometer (SP22G-5K, Mouser electronics, Mansfield, TX, USA) that was located directly lateral to the fibular malleolus. The position signals were sampled at 2 kHz with a Power 1401 data acquisition system (Cambridge Electronic Design, Cambridge, UK) and stored on a computer.

EMG measurement

The FDI muscle is involved significantly when lifting and lowering a light load with the index finger in this experimental setup (Christou and Enoka 2010). The FDI muscle activity was recorded with a pair of Ag–AgCl sintered fixed-wire electrodes (4 mm diameter, model E220N-LS, In Vivo Metric, Healdsburg, CA, USA) and taped on the skin distally to the innervation zone (Homma and Sakai 1991). The reference electrode was placed over the ulnar styloid. The tibialis anterior (TA) muscle is involved significantly when lifting and lowering a light load with the foot in this experimental setup (Griffith et al. 2010). The TA muscle activity was recorded with a pair of Ag–AgCl sintered fixed-wire electrodes (8 mm diameter, model E220N, In Vivo Metric, Healdsburg, CA, USA) and taped on the skin distally to the innervation zone. The reference electrode was placed over the patella. The

recording electrodes were placed in line with the muscle fibers. The center-to-center distance between the two electrodes was 10 mm. The EMG signals were amplified (2000×) and band pass filtered at 3–500 Hz (Grass Model 15LT system, Grass Technologies, West Warwick, RI, USA). The EMG signals were sampled at 1 kHz with a Power 1401 A/D board (Cambridge Electronic Design, UK) and stored on a personal computer.

Experimental procedures

Subjects participated in one experimental session that lasted approximately 2 h. Each subject began the session with familiarization of the experimental procedures. The familiarization period included a demonstration of the index finger and ankle position-holding tasks and an explanation of the visual feedback provided on the monitor. The order of the abduction of the index finger and ankle dorsiflexion was counterbalanced among subjects. After the familiarization, each subject performed the following procedures: (1) 1 repetition maximum (1RM) with the FDI (abduction of the index finger) and TA (dorsiflexion of the ankle) muscles; (2) 5 position-holding trials at three different visual angles (0.1°, 1°, 4°; randomly assigned and blocked at every visual angle); (3) repeat 1RM to assess the level of fatigue; (4) repeat 1 through 3 with the index finger or ankle depending on which joint was used for the first set (counterbalanced); and (5) repeat 1RMs to assess the level of fatigue.

Visual feedback manipulation

We manipulated the magnification of visual feedback by varying the visual angle. The use of visual angle to manipulate visual feedback magnification ensures that the amount of feedback provided is the same across subjects (Vaillancourt et al. 2006). Visual angle (degrees) was quantified (Eq. 1) as twice of the inverse tangent of the height of the character (height of the positional fluctuations in meters) divided by the distance from the feedback monitor (meters):

$$\alpha = 2 \tan^{-1}(h/d) \quad (1)$$

where, α is the visual angle, h is half the height of the character (positional fluctuations), and d is the distance of the eye from the computer screen. This can be achieved by manipulating the ordinate scale of the feedback and the seating distance from the feedback monitor. Because the distance to the monitor was kept constant throughout the experiment, we varied visual angle by manipulating the ordinate scale. As done previously (Vaillancourt et al. 2006), we estimated the height of the character to be six times the variability of the position output. The visual angles used for this study were 0.1°, 1°, and 4° (Fig. 1c). Greater visual angles magnify the visual feedback by zooming into the motor output (position trace in this experiment).

1RM task

The 1 repetition maximum (1RM) force was quantified as the heaviest load that was lifted at a normal pace (~2°/s) through the assigned range of motion during one of three trials each, with the index finger and ankle, respectively. The EMGs for FDI and TA were normalized to the peak EMG recorded during the 1RM task. 1RMs were also performed at the end of the session to test whether the experimental task induced muscle fatigue.

Position-holding task—A custom-written program in Matlab® (Math Works™ Inc., Natick, Massachusetts, USA) was used to provide the targeted position and visual angle (0.1°, 1°, and 4°). The target position was provided as a red line in the middle of the screen and the position of the subjects in blue progressing with time from left to right. Abduction of the index finger corresponded to the blue line going up (lifting) and adduction corresponded to the blue line going down (lowering) on the screen. Similarly for the foot, dorsiflexion

corresponded to the blue line going up (lifting) and plantar flexion corresponded to it coming down (lowering). Subjects were asked to match the target position as accurately and smoothly as possible. Each trial lasted 25 s and visual feedback was removed (no-vision) for the last 10 s (15–25 s) of the trial (gray bar, Fig. 2). Within each visual angle (blocked), the rest time between each trial was 30 s and between the visual angles was 60 s. The order for the three visual angle conditions was randomized and limbs were counterbalanced among subjects.

Data analysis—Data were acquired with the Spike2 software (Version 6.02; Cambridge Electronic Design, Cambridge, UK) and analyzed off-line using custom-written programs in Matlab® (Math Works™ Inc., Natick, Massachusetts, USA). The position and surface EMG signals were analyzed in two segments of 4 s each (Fig. 2). For the vision condition, data segment was taken from 100 ms prior to the removal of visual feedback (V in Fig. 2), whereas for the no-vision condition segment was taken 100 ms after the removal of visual feedback (NV in Fig. 2). Prior to data analysis, the position signal was filtered with a 4th-order (bidirectional) Butterworth filter using a 50 Hz low-pass cut-off. Positional error was quantified as the root mean square error (RMSE) of the subject's performance from the target. The positional variability was quantified from the detrended position output of the 4 s because any drift from the targeted position (especially during the absence of visual feedback condition) could influence the positional variability. This was achieved by removing the linear trend from the position data. The dependent variables for the position data were the root mean square error (RMSE) and standard deviation (SD). Neural activation was quantified as the root mean square of the FDI and TA interference EMG signals.

Furthermore, continuous wavelet transforms (Eq. 2) were performed on the position and interference EMG signals of the FDI and TA muscles. The wavelet transform of a signal determines both the amplitude versus frequency characteristics of the signal and how this amplitude varies with time. The wavelet transform provides other advantages over the Fourier transform that have been discussed elsewhere (Zazula et al. 2004). Wavelet transforms were calculated using a base Matlab function developed by Torrence and Compo (1998) (available at <http://paos.colorado.edu/research/wavelets>).

$$W(s, \tau)^X \int X(t) \Psi_{s,\tau}^*(t) dt \quad (2)$$

where s represents the dilation parameter (scale shifting), τ represents the location parameter (time shifting), and the basic function $\Psi_{s,\tau}(t)$ is obtained by dilating and translating the mother wavelet $\Psi_0(t)$ (Addison 2002).

From the wavelet transform, we defined the absolute wavelet spectra (WPS) as

$$\text{WPS}(s, \tau)^X = |W^X(s, \tau)|^2 \quad (3)$$

Similarly, we quantified the normalized scale-averaged wavelet power spectrum (NWPS) as WPS normalized by the sum of WPS over all scales for each instant to time (Eq. 4):

$$\text{NWPS}(s, \tau)^X = \frac{|W^X(s, \tau)|^2 / s}{\sum_s \left(\frac{|W^X(s, \tau)|^2}{s} \right)} \times 100(\%) \quad (4)$$

The dependent variable for the spectral analysis of the position signal was the normalized (%) wavelet power in the 0–3, 3–7, 7–12, 12–30, and 30–50 Hz frequency bands and of the FDI and TA EMG signals was the normalized (%) wavelet power in the 5–12, 12–30, 30–60, and 60–100 Hz frequency bands averaged across trials.

Statistical analysis—A mixed four-way ANOVA (2 age groups $\times$ 3 visual angles $\times$ 2 visual feedback conditions $\times$ 2 limbs) with repeated measures on visual angles, visual feedback conditions, and limbs compared positional error, positional variability, and agonist EMG amplitude for the two age groups. Furthermore, to investigate the amplification in the SD of position with visual feedback at different visual angles (0° (no-vision), 0.1°, 1°, and 4°) in older adults, a mixed three-way ANOVA (2 age groups $\times$ 4 visual feedback gains $\times$ 2 limbs) with repeated measures on visual angles and limbs compared positional error, positional variability, and agonist EMG amplitude for the two age groups was performed. A four-way ANOVA (2 age groups $\times$ 4 visual angles $\times$ 2 limbs $\times$ 5 frequency bands) with repeated measures on visual angles and limbs compared the normalized wavelet power in the position spectrum for the two age groups. A similar model (2 age groups $\times$ 4 visual angles $\times$ 2 limbs $\times$ 2 frequency bands) with repeated measures on visual angles and limbs compared the normalized wavelet power in the EMG spectrum for the two age groups. In addition, multiple linear regression analysis (stepwise) was used to examine the contribution of the power at each frequency band from the EMG power spectra to the SD of position at 4°. Any subjects that exhibited values outside ± 3 SD were excluded as outliers. The relative importance of the predictors was estimated with the part correlations (part r), which provide the correlation between a predictor and the criterion, partialling out the effects of all other predictors in the regression equation from the predictor but not the criterion (Green and Salkind 2002).

Analyses were performed with the PASW Statistics 18.0 statistical package (SPSS Inc., Chicago, IL, USA). Significant interactions from the ANOVA were followed by appropriate post hoc analyses. For example, age-associated differences were followed with independent t tests, whereas differences across visual feedback conditions, visual angles, limbs, and frequency bands were examined with paired t tests. Multiple t test comparisons were corrected using the Bonferroni corrections. The alpha level for all statistical tests was 0.05 unless corrected. Data are reported as mean $\pm$ standard deviation (SD) in the text and mean $\pm$ standard error of the mean (SEM) in the figures.

Results

Strength and fatigue

We quantified strength before and after the submaximal task for the following reasons: (1) to determine whether young and older adults exhibited similar strength with the index finger and foot movements; (2) to examine whether muscle fatigue was similar for young and older adults following the experimental protocol. To accomplish these, we compared the 1RM before and immediately after the experimental session. On average, young and older adults lifted similar 1RM loads (5.33 ± 3.85 kg vs. 4.20 ± 2.92 kg; $P = 0.07$). Furthermore, there were no significant age interactions. The 1RM did not significantly change following our experimental protocol for either age group ($P = 0.69$). Specifically, 1RM for the index finger abduction before and after the experimental session was 2.06 ± 0.61 kg versus 1.87 ± 0.87 kg for young adults and 1.88 ± 0.58 kg versus 1.86 ± 0.56 kg for older adults. The 1RM for ankle dorsi-flexion before and after the experimental session was 8.64 ± 2.44 kg versus 8.68 ± 2.53 kg for young adults and 6.50 ± 2.44 kg versus 6.43 ± 2.39 kg for older adults. These findings demonstrate that any differences in positional accuracy and variability between the two age groups were not related to fatigue or differences in strength.

Removal of visual feedback

To understand whether removal of visual feedback interacted with the age of the subjects, magnification, and limb used, we used a four-way repeated measures ANOVA (Age $\times$ visual feedback condition $\times$ visual magnification $\times$ limb). Position-holding performance was quantified with the positional error and variability. Only the interactions with visual feedback condition were of interest.

Positional error—Subjects were more accurate in the presence of visual feedback ($F_{2, 40} = 22.57$, $P < 0.001$; Fig. 3a). The limb $\times$ visual feedback condition interaction was also significant ($F_{1, 20} = 9.45$, $P = 0.006$). Post hoc analysis indicated that subjects were more accurate with their fingers compared with the ankle especially in the presence of visual feedback. All other visual feedback condition interactions were not significant.

Positional variability—Subjects were more variable in the presence of visual feedback ($P = 0.001$). In addition, the positional variability during the visual feedback and no-visual feedback conditions was influenced by the magnification of visual feedback before its removal (visual feedback $\times$ visual magnification interaction; $P = 0.029$; Fig. 3b). Specifically, removal of visual feedback significantly reduced positional variability only at 1° and 4° of visual angle. Positional variability was similar with and without visual feedback when the visual angle was 0.1° . All other visual feedback condition interactions were not significant.

Agonist muscle activity—The amplitude of FDI and TA EMG was quantified as the root mean square amplitude of the interference signals. The agonist muscle activity was greater in the presence of visual feedback (visual feedback main effect: $F_{1, 20} = 8.046$, $P = 0.01$). Additionally, the limb $\times$ visual feedback interaction was significant ($F_{1, 20} = 11.89$, $P = 0.003$), indicating that the average activation was significantly greater for the FDI compared with the TA and these differences in activation were exacerbated in the presence of visual feedback. All other visual feedback condition interactions were not significant.

Interaction of age and visual gain

To understand the interaction between the age of the subjects and visual magnification during contractions with the FDI and TA muscle, we used a three-way repeated measures ANOVA (Age $\times$ visual gain $\times$ limb). In this model, we only used data from the visual feedback conditions and one no-visual feedback condition. We used the values from no-vision at 0.1° (0°) because there were no differences in positional variability between vision and no-vision conditions at that visual angle. Therefore, visual magnification in this model had 4 factors (0° , 0.1° , 1° , and 4°). Position-holding performance was quantified with the positional error and variability. In addition, we examined muscle activity (amplitude and frequency structure) using similar statistical models.

Positional error—The positional error was significantly (age group main effect: $F_{1, 20} = 19.326$, $P < 0.001$) greater for older adults compared with young adults. In addition, we found that both age groups exhibited more accuracy with higher visual magnification (visual angle main effect: $F_{3, 60} = 37.68$, $P < 0.001$; Fig. 4). Accuracy was impaired for all subjects at 0° and 0.1° visual angles. All other main effects and interactions were not significant.

Positional variability—Older adults exhibited significantly greater positional variability compared with young adults (age group main effect: $F_{1, 20} = 11.58$, $P = 0.003$). Positional variability increased with higher visual angles (visual angle main effect: $F_{3, 60} = 13.922$, $P < 0.001$). The age-associated differences in positional variability were greater at higher visual angles (age $\times$ visual angle interaction; $F_{3, 60} = 9.18$, $P < 0.001$; Fig. 5). Specifically, the

positional variability increased with visual angle in older adults, whereas it remained unchanged in younger adults. Therefore, the greater age differences in positional variability were at 1° and 4° of visual angles. The age $\times$ limb interaction was also significant ($F_{1, 20} = 5.58$, $P = 0.028$) indicating that the age-associated differences in positional variability were exacerbated during ankle dorsiflexion compared with index finger abduction. All other age-associated interactions were not significant.

Amplitude and modulation of agonist muscle activity—To determine whether young and older adults activated the primary agonist muscle, similarly, we compared the amplitude and modulation of EMG at different visual angles. The amplitude was quantified with the RMS of the EMG signal from the FDI and TA muscles, whereas the modulation was quantified with the normalized wavelet power from 12 to 60 Hz of the same muscles.

EMG amplitude: The age-associated main effect and interactions for the amplitude of the EMGs were not significant.

EMG modulation: Older adults exhibited significantly lower power in the agonist EMG from 12 to 60 Hz compared with younger adults (age group main effect: $F_{1, 20} = 5.278$, $P = 0.033$; Fig. 6). On average, normalized wavelet power was significantly greater for young than older adults for both frequency bands ($10.45 \pm 2.8\%$ vs. $7.8 \pm 2.6\%$). The power in the 30–60 Hz band was higher at 1° and 4° compared with no-vision and 0.1° of visual angle (visual angle $\times$ frequency band interaction; $F_{3, 60} = 5.58$, $P < 0.001$). The age-associated interactions were not significant.

Associations between positional variability and normalized wavelet power of the EMG—The greatest difference in positional variability between young and older adults occurred at the highest visual angle. Therefore, we performed a multiple regression analysis to determine whether the positional variability at the highest visual angle could be explained by the normalized wavelet power from 12–30 to 30–60 Hz in the EMG. The magnified positional variability in older adults was associated with lesser power from 12 to 30 Hz in the EMG signal ($R^2 = 0.186$, part $r = -0.431$, $P = 0.04$).

Discussion

We performed this experiment to determine whether magnified visual feedback during position-holding contractions exacerbates the age-associated differences in motor output variability and the neural activation of the primary agonist muscles. The novel findings of the study indicate that magnified visual feedback exacerbated the age-associated differences in positional variability regardless of the end effector used to perform the task. In addition, we demonstrate that the impaired position control of older adults at the highest magnification of visual feedback (4°) was associated with an altered modulation of the agonist muscle activity (lesser power from 12 to 30 Hz). Our findings, therefore, support and extend the current literature on the interaction of aging and visual feedback on the motor output variability during constant force tasks (Kennedy and Christou 2011; Sosnoff and Newell 2006; Tracy et al. 2007; Vaillancourt et al. 2003) to constant position tasks.

Magnified visual feedback impairs position control in older adults

Based on previous studies on force control, we expected that older adults would exhibit impaired positional control with magnified visual feedback. As expected, we found that age-associated differences in positional variability were exacerbated with magnification of visual feedback, which supports and extends the previous findings with constant force tasks (Kennedy and Christou 2011; Sosnoff and Newell 2006; Tracy 2007a; Vaillancourt et al. 2003).

Our results demonstrate that older adults exhibited significantly greater positional variability during trials with visual feedback and with greater magnification of the visual feedback (1 and 4°). Furthermore, we found that the increase in positional variability with magnification of visual feedback in older adults was associated with a decrease in power from 12 to 30 Hz power of the agonist EMG signal. This result compliments recent findings by Kennedy and Christou (2011), who demonstrated that during constant isometric contractions the decrease in force control with magnified visual feedback in older adults is associated with their inability to modulate the agonist EMG from 12 to 60 Hz. The amplified positional variability with greater amount of visual information may also be due to the following factors: (1) The processing of positional feedback in older adults is impaired due to a slower transmission of visual information (Raz et al. 1997; van der Lubbe and Verleger 2002) and consequently a slower and more variable motor correction (Sosnoff et al. 2004). (2) There is evidence that different areas of the brain get activated for low- (bilateral V3 and V5, contralateral primary motor cortex, and ventral premotor cortex) and high-visual feedback magnification (bilateral dorsal and ventral premotor cortex and ipsilateral inferior parietal lobule) conditions (Coombes et al. 2010). It is possible therefore that older adults have specific impairments in activating areas of the brain associated with high magnification of visual feedback. (3) Greater amount of visual feedback exerts more attentional demands on the nervous system and is more stressful (Nafati et al. 2005). There is evidence that when older adults get stressed with noxious electrical stimuli, they exhibit greater impairments in force variability than young adults (Christou et al. 2004). Overall, our findings suggest that age-associated increases in motor output variability with magnified visual feedback of the motor task may be due to altered processing of visual information at higher centers, reduced attentional capacity, or stress. It is possible that one or more of these factors alter the modulation of the agonist muscle activity.

Removal of visual feedback reduces positional variability

Previous studies that have compared force variability with the removal of visual feedback during constant isometric tasks have demonstrated that the removal of visual feedback can reduce force variability (Tracy 2007b), can increase force variability (Slifkin et al. 2000), or has no effect on force variability (Christou et al. 2004; Vaillancourt et al. 2002). A potential methodological issue in the above studies is that the magnification of visual feedback was not controlled well prior to the removal of visual feedback (Baweja et al. 2010a; Baweja et al. 2009; Christou et al. 2004; Tracy et al. 2007; Vaillancourt et al. 2002). In the present study, we manipulated the magnification of visual feedback prior to its removal, in order to understand its effect on positional variability.

We found that the positional variability during the novisual feedback conditions was influenced by the magnification of visual feedback before its removal. Although positional variability was similar at the lowest visual angle between the two visual feedback conditions, removal of visual feedback significantly reduced positional variability at 1° and 4° of visual angle (Fig. 3b). These results are contradictory to our recent findings during force tasks (Kennedy and Christou 2011), where removal of visual feedback decreased force variability independent of the gain of the visual feedback prior to its removal. A potential explanation of the differential findings between the force and position tasks at the lowest visual feedback magnification is the differential mechanisms that mediate motor control for the two tasks (Hunter et al. 2002). For example, spinal reflexes are enhanced during the position task due to greater excitability of the muscle spindles (Baudry et al. 2010). It is possible, therefore, that subjects were able to better maintain a steadier output of the limbs at the lowest magnification of visual feedback during a position task because of enhanced proprioception. Further research is needed to identify the exact mechanisms that will explain these behavioral differences between constant force and position-holding tasks.

Disproportionate decline in function of lower limb with aging

Previous findings during constant force contractions have demonstrated greater variability with the lower limb compared with the upper limb (Prodoehl and Vaillancourt 2010; Tracy et al. 2007). Recently, we extended this finding by demonstrating that age-associated differences in positional variability are amplified during ankle dorsiflexion compared with index finger abduction (Kwon et al. 2011). Similarly, in this task, we found that the age-associated differences in positional variability were exacerbated during ankle dorsiflexion. This difference in motor output variability between the two ipsilateral limbs in older adults suggests that there is a disproportionate decline in the function of the upper and lower limb with aging (Kwon et al. 2011).

In conclusion, our novel findings demonstrate that the age-associated increase in positional variability is exacerbated with magnified visual feedback of the motor task, due to altered neural activation of the agonist muscle. This paper, therefore, demonstrates that magnification of visual feedback impairs motor control in older adults during positional tasks, which supports and extends previous findings that incorporated force tasks.

Acknowledgments

We would like to thank Jonathan Leake for computer programming, Deanna M. Kennedy and Shauna Q. Glover for subject recruitment. This study was supported by NIH R01 AG031769 to Evangelos A. Christou.

References

- Addison, PS. The illustrated wavelet transform handbook. New York: Taylor & Francis Group; 2002.
- Baudry S, Maerz AH, Enoka RM. Presynaptic modulation of Ia afferents in young and old adults when performing force and position control. *J Neurophysiol.* 2010; 103:623–631. [PubMed: 19939955]
- Baweja HS, Patel BK, Martinkewiz JD, Vu J, Christou EA. Removal of visual feedback alters muscle activity and reduces force variability during constant isometric contractions. *Exp Brain Res.* 2009; 197:35–47. [PubMed: 19544059]
- Baweja HS, Kennedy DM, Vu JL, Vaillancourt DE, Christou EA. Greater amount of visual feedback decreases force variability by reducing force oscillations from 0–1 and 3–7 Hz. *Eur J Appl Physiol.* 2010a; 108:935–943. [PubMed: 19953262]
- Baweja, HS.; Kwon, MH.; Glover, SQ.; Christou, EA. Greater amount of visual feedback decreases error but not variability during movements and positional tasks with the finger and foot. San Diego: Society for Neuroscience; 2010b.
- Chao, EYS.; An, KN.; Cooney, WP.; Linschied, RL. A basic research study. Teaneack: World Scientific Publishing; 1989. Biomechanics of the hand.
- Christou EA. Aging and variability of voluntary contractions. *Exerc Sport Sci Rev.* 2010; 39:77–84. [PubMed: 21206281]
- Christou EA, Carlton LG. Age and contraction type influence motor output variability in rapid discrete tasks. *J Appl Physiol.* 2002; 93:489–498. [PubMed: 12133855]
- Christou EA, Enoka RM. Aging and movement errors when lifting and lowering light loads. *Age (Dordr).* 2010; 33:393–407. [PubMed: 20945163]
- Christou EA, Jakobi JM, Critchlow A, Fleshner M, Enoka RM. The 1- to 2-Hz oscillations in muscle force are exacerbated by stress, especially in older adults. *J Appl Physiol.* 2004; 97:225–235. [PubMed: 15220319]
- Coombes SA, Corcos DM, Sprute L, Vaillancourt DE. Selective regions of the visuomotor system are related to gain-induced changes in force error. *J Neurophysiol.* 2010; 103:2114–2123. [PubMed: 20181732]
- Green, SB.; Salkind, NJ. Using SPSS for the windows and macintosh: analyzing and understanding data. Upper Saddle River, NJ: Prentice Hall; 2002.

- Griffith EE, Yoon T, Hunter SK. Age and load compliance alter time to task failure for a submaximal fatiguing contraction with the lower leg. *J Appl Physiol*. 2010; 108:1510–1519. [PubMed: 20299610]
- Homma T, Sakai T. Ramification pattern of intermetacarpal branches of the deep branch (ramus profundus) of the ulnar nerve in the human hand. *Acta Anat (Basel)*. 1991; 141:139–144. [PubMed: 1746222]
- Hunter SK, Ryan DL, Ortega JD, Enoka RM. Task differences with the same load torque alter the endurance time of submaximal fatiguing contractions in humans. *J Neurophysiol*. 2002; 88:3087–3096. [PubMed: 12466432]
- Kennedy DM, Christou EA. Greater amount of visual information exacerbates force control in older adults during constant isometric contractions. *Exp Brain Res*. 2011; 213:351–361. [PubMed: 21800256]
- Kwon MH, Baweja HS, Christou EA. Age-associated differences in positional variability are greater with the lower limb. *J Mot Behav*. 2011; 43:357–360. [PubMed: 21809912]
- Nafati G, Schmied A, Rossi-Durand C. Changes in the inhibitory control exerted by the antagonist Ia afferents on human wrist extensor motor units during an attention-demanding motor task. *J Neurophysiol*. 2005; 93:2350–2353. [PubMed: 15563550]
- Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*. 1971; 9:97–113. [PubMed: 5146491]
- Prodoehl J, Vaillancourt DE. Effects of visual gain on force control at the elbow and ankle. *Exp Brain Res*. 2010; 200:67–79. [PubMed: 19680640]
- Raz N, Gunning FM, Head D, Dupuis JH, McQuain J, Briggs SD, Loken WJ, Thornton AE, Acker JD. Selective aging of the human cerebral cortex observed in vivo: differential vulnerability of the prefrontal gray matter. *Cereb Cortex*. 1997; 7:268–282. [PubMed: 9143446]
- Slifkin AB, Vaillancourt DE, Newell KM. Intermittency in the control of continuous force production. *J Neurophysiol*. 2000; 84:1708–1718. [PubMed: 11024063]
- Sosnoff JJ, Newell KM. Information processing limitations with aging in the visual scaling of isometric force. *Exp Brain Res*. 2006; 170:423–432. [PubMed: 16328264]
- Sosnoff JJ, Vaillancourt DE, Newell KM. Aging and rhythmical force output: loss of adaptive control of multiple neural oscillators. *J Neurophysiol*. 2004; 91:172–181. [PubMed: 14507987]
- Torrence C, Compo GP. A practical guide to wavelet analysis. *Bull Amer Meteor Soc*. 1998; 79:61–78.
- Tracy BL. Force control is impaired in the ankle plantarflexors of elderly adults. *Eur J Appl Physiol*. 2007a; 101:629–636. [PubMed: 17701201]
- Tracy BL. Visuomotor contribution to force variability in the plantarflexor and dorsiflexor muscles. *Hum Mov Sci*. 2007b; 26:796–807. [PubMed: 17765988]
- Tracy BL, Dinunno DV, Jorgensen B, Welsh SJ. Aging, visuomotor correction, and force fluctuations in large muscles. *Med Sci Sports Exerc*. 2007; 39:469–479. [PubMed: 17473773]
- Vaillancourt DE, Slifkin AB, Newell KM. Inter-digit individuation and force variability in the precision grip of young, elderly, and Parkinson's disease participants. *Mot Control*. 2002; 6:113–128.
- Vaillancourt DE, Larsson L, Newell KM. Effects of aging on force variability, single motor unit discharge patterns, and the structure of 10–20, and 40 Hz EMG activity. *Neurobiol Aging*. 2003; 24:25–35. [PubMed: 12493548]
- Vaillancourt DE, Haibach PS, Newell KM. Visual angle is the critical variable mediating gain-related effects in manual control. *Exp Brain Res*. 2006; 173:742–750. [PubMed: 16604313]
- van der Lubbe RH, Verleger R. Aging and the Simon task. *Psychophysiology*. 2002; 39:100–110. [PubMed: 12206290]
- Webber SC, Porter MM. Effects of ankle power training on movement time in mobility-impaired older women. *Med Sci Sports Exerc*. 2010; 42:1233–1240. [PubMed: 20019625]
- Zazula, D.; Karlsson, S.; Doncarli, C. *Electromyography: physiology, engineering, and noninvasive applications*. Merletti, R., editor. Hoboken: Wiley; 2004. p. 259–304.

Fig. 1.

a Experimental setup for testing the abduction–adduction of the index finger. The subject's hand was flat on the platform and the forearm arm was placed in a form-fitting vacuum pillow. The forearm and hand were prone and position of hand and fingers was held stationary with metal plates. The index finger was placed in an orthosis to prevent flexion at the interphalangeal joints. The loads were attached medially at the level of the proximal interphalangeal joint on the finger orthosis and suspended using a pulley away from the subject. **b** Experimental setup for testing the ankle dorsiflexion/plantar flexion. The subject's foot was placed in an adjustable foot plate and secured at the level of the metatarsals with a padded metal plate. The loads were attached directly in front of the foot. **c** Experimental conditions and the visual feedback angles for the experiment were 0.1° (*left column*), 1° (*center column*), and 4° (*right column*). Subjects were asked to match a position with the abduction–adduction of their index finger and the dorsiflexion/plantar flexion of their ankle at an amplitude of 5° range of motion. Each subject was instructed to match a constant position with abduction of the index finger or ankle dorsiflexion for 25 s. Visual feedback of the target and exerted position was given to the subjects from 0 to 15 s (visual feedback condition), whereas visual feedback of the target and exerted position was removed (*gray bars*) from 15 to 25 s (no-visual feedback condition) at all three gains

Fig. 2.

Representative example of the constant position task with the index finger. A representative trial from 1 young (*left panel*) and 1 older subject when matching a constant 5° position with a 10 % 1RM load. The position and EMG analysis was based on selected segments from each trial. The *top row* represents the force trace for the trials represented and the *bottom row* is the corresponding FDI EMG activity. The analysis was performed from 4.1 to 0.1 s prior to the removal of visual feedback (visual feedback condition; V) and 0.1 to 4.1 s after the removal of the visual feedback (no-visual feedback condition; NV)

Fig. 3.

a Positional error during different visual feedback conditions and **b** variability during different visual gain conditions. **a** The positional error by young (*filled circles*) and older (*open circles*) adults with vision and no-vision. Positional error at the 0.1° was significantly (#) higher during the no-vision condition. Older adults exhibited significantly greater (*) positional error when compared with young adults across all visual angles regardless of the effector used. **b** Subjects exhibited significantly greater (*) positional variability during the visual feedback condition (*open diamonds*) when compared with the no-vision condition (*filled diamonds*) with 1 and 4° regardless of the effector used. Furthermore, subjects exhibited significantly (#) lower positional variability at 0.1° when compared with variability at 1° and 4° visual angles during the vision condition

Fig. 4.

The interaction of aging and visual gain on positional error. The positional error produced by young (*filled circles*) and older (*open circles*) adults at four different visual angles (0°, 0.1°, 1°, and 4°). The positional error at 0° and 0.1° was significantly (#) higher than 1° and 4°. Older adults exhibited significantly greater (*) positional error when compared with young adults across all visual angles regardless of the effector used

Fig. 5.

The interaction of aging and visual gain on positional variability. The positional variability exhibited by young (*filled circles*) and older (*open circles*) adults at four different visual angles (0°, 0.1°, 1°, and 4°). The positional error at 0° and 0.1° was significantly (#) lower than 1° and 4°. Older adults exhibited significantly greater (*) positional error when compared with young adults across all visual angles regardless of the effector used

Fig. 6.

The effect of aging on EMG modulation from 12 to 60 Hz. Older adults (*open bar*) exhibited significantly lower (#) power from 12 to 60 Hz in the agonist EMG power spectrum when compared with young adults (*filled bar*) across all visual angles regardless of the effector used