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Effect of Age on Human–Computer Interface Control Via Neck Electromyography

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The purpose of this study was to determine the effect of age on visuomotor tracking using submental and anterior neck surface electromyography (sEMG) to assess feasibility of computer control via neck musculature, which allows people with little remaining motor function to interact with computers. Thirty-two healthy adults participated: 16 younger adults aged 18–29 years and 16 older adults aged 69–85 years. Participants modulated sEMG to achieve targets presented at different amplitudes using real-time visual feedback. Root mean squared (RMS) error was used to quantify tracking performance. RMS error was increased for older adults relative to younger adults. Older adults demonstrated more RMS error than younger adults as a function of increasing target amplitude. The differential effects of age found on static tracking performance in anterior neck musculature suggest more difficult translation of human–computer interfaces controlled using anterior neck musculature for static tasks to older populations.

RESEARCH HIGHLIGHTS

- Neck surface electromyography (sEMG) is a promising input modality that allows people to interact with computers after a neurological injury that affects limb movement.
- Older and younger adults used neck sEMG to move an object up and down on a screen. Older adults were less able to control the object's position precisely than younger adults. Older adults also had more problems with reaching positions that required higher muscle activation.
- Interfaces for older adults that use neck sEMG need to take these age effects into account by allowing a higher tolerance for targets and choosing targets that require less muscle activation.

Keywords: accessibility; assistive technologies; age; novel interaction paradigms

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1. INTRODUCTION

Providing a human–computer interface to people who have little or no remaining motor function is a challenge (Birbaumer *et al.*, 1999; Hinterberger *et al.*, 2003; Nijboer *et al.*, 2008; Sellers and Donchin, 2006). Recent studies have shown promise for using residual surface electromyography (sEMG) from the neck and face to interact with software. Several groups have been exploring neck and face sEMG as an input modality that allows selection of targets in 2D space such as moving a computer cursor on a screen in which holding a static target activation is needed to make a selection in the interface (Larson *et al.*, 2013; Perez-Maldonado *et al.*, 2010; Thorp *et al.*, 2014; Williams and Kirsch, 2008). The aim is to provide a communication interface for severely paralyzed individuals, including those with a history of stroke or C1–C3 spinal cord injuries, who may lack primary communication modalities, including speech and manual control (e.g. writing, pointing, typing), but may be able to learn to use residual musculature as a control source. The anterior neck offers a particularly attractive option, with musculature high enough to be spared in most spinal cord injuries, but allowing discreet electrode placement relative to facial locations. In fact, Williams and Kirsch (2008) investigated the ability of users to perform a 2D target selection task using neck sEMG, finding relatively high performance abilities. Anterior neck sEMG has also been explored as an input modality for individuals after removal of the larynx (laryngectomy). Although this result is promising, the end users, individuals with severe paralysis, will have ages across the lifespan. Reduction in anterior neck sEMG visuomotor tracking ability as a function of age would have implications for the design of interfaces that use sEMG as an input modality as well as the amount of user training required.

In fact, the motor system is known to change with age in several ways, which suggests that clinical translation of interfaces relying on visuomotor tracking may need to account for the age of the user. Studies of upper and lower limbs have shown changes to the peripheral nervous system that include a progressive loss of motor neurons (Tomlinson and Irving, 1977), which leads to sarcopenia (age-related loss of muscle mass) and a decline in strength. Furthermore, limb musculature shows an increase in the proportion of Type I muscle fibers with age, which leads to slower contractile properties (D'Antona *et al.*, 2003; Klein *et al.*, 2003). Finally, a greater degree of cortical involvement during the performance of simple motor tasks has been shown with age (Mattay *et al.*, 2002). These physiological changes result in the widely reported reduction in motor coordination and fine control of submaximal forces with age (Cole, 1991; Sarlegna, 2006; Shim et al., 2004; Shinohara *et al.*, 2004; Vaillancourt *et al.*, 2003; Voelcker-Rehage and Alberts, 2005).

Although less studied, these changes with aging are also evidenced in the axial (head and trunk) motor systems of the head and neck. Both tongue and laryngeal muscles show atrophy (Bassler, 1987; Malmgren *et al.*, 1999), and several oral and anterior neck muscles show changes in motor unit activity (Bardan *et al.*, 2000; Takeda *et al.*, 2000) with age. Additionally, older adults show greater activity of cortical structures during swallowing relative to younger adults (Humbert *et al.*, 2009). These physiological changes mirror kinematic and dynamic changes in this musculature as well as functional changes in speech and swallowing. The muscles of the tongue, in particular, have been repeatedly found to show a reduction of both strength and movement with aging (Crow and Ship, 1996; Robbins *et al.*, 1995). During swallowing, older adults show delayed initiation of laryngeal and pharyngeal events, smaller movements and longer food transport time (Robbins *et al.*, 1992). The primary acoustic features of the speech in aging adults are slower rates of production and decreased accuracy (Torre and Barlow, 2009). However, somewhat less is known about motor coordination and fine control of submaximal forces during motor tasks other than speech or swallowing such as those required to operate human–computer interfaces.

Studies on non-speech/swallowing motor control of head and neck musculature have been previously performed using visuomotor tracking in both healthy children and adults using orofacial systems. These studies measured kinematics or dynamics of the jaw and lips and the laryngeal system through tracking of fundamental frequency (Ballard *et al.*, 2001; Barlow and Netsell, 1986; Bronson-Lowe *et al.*, 2013; Clark *et al.*, 2001; Moon *et al.*, 1993; Ofori *et al.*, 2012). Only one study has examined fine force control in orofacial musculature as a function of age, finding a greater level of variability in force production of lower lip as a function of aging (Bronson-Lowe *et al.*, 2013).

The purpose of this study was to determine whether there are age-related changes in individuals' abilities to use submaximal fine motor control of anterior neck musculature to control a human–computer interface. We examined visuomotor tracking of static targets using anterior neck sEMG as a function of different target levels and durations in a group of younger and older healthy adults, hypothesizing reduced performance in older relative to younger adults.

2. METHODS

2.1. Participants

Participants were a group of 16 younger adults aged 18–29 years (8 females, mean age 21.5 years; 8 males, mean age 21.1 years) and a group of 16 older adults aged 69–85 years (8 females, mean age 75.1 years; 8 males, mean age 74.9 years). Informed consent was obtained from all participants in compliance with the Boston University Institutional Review Board. No participants reported history of any neurological, swallowing, speech, hearing or language disorders except that several individuals in the group of older adults reported minor age-related hearing loss. All participants (younger and older) reported that they were able to see the screen and targets easily. Participants who typically wore contact lenses or glasses used them during the tracking tasks.

2.2. sEMG data acquisition

Two single differential sEMG electrode pairs (Delsys DE2.1) were placed on the neck surface, at sites referred to as the *anterior neck* and *submental surface* (the underside of the chin; see Fig. 1). These two sites were selected based on their high cervical (anterior neck) and mix of high cervical and cranial (submental surface) nerve innervation. The anterior neck electrode pair was centered ∼1.5 cm lateral (left) to the neck midline, with the superior aspect of the sensor ∼1 cm posterior from the submental surface. This position was intended to measure activations of the thyrohyoid, sternohyoid and possibly omohyoid muscles. The submental surface electrode pair

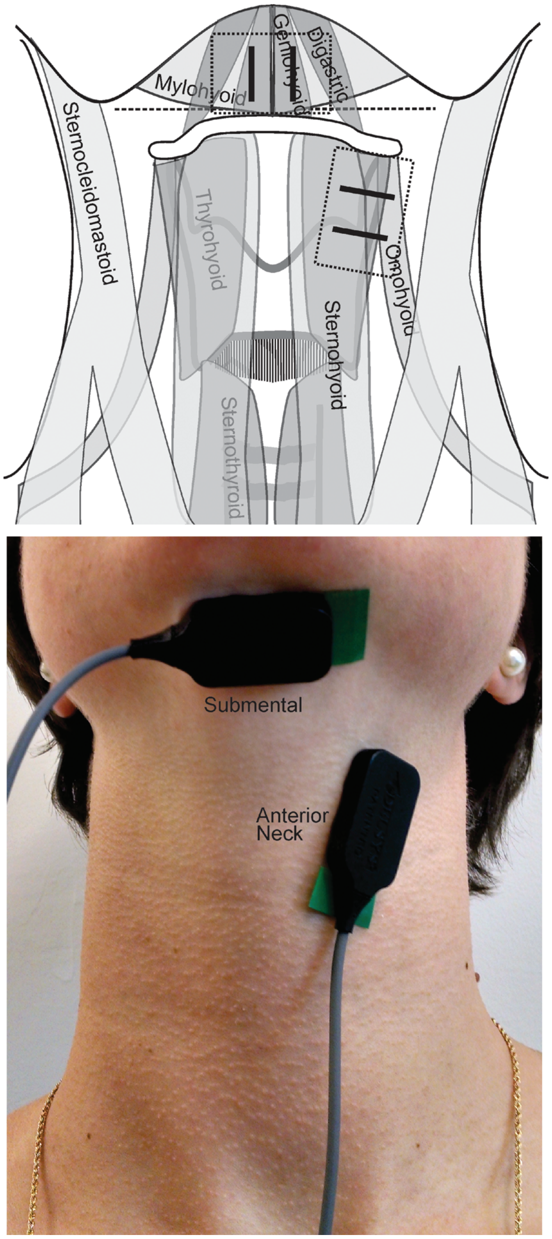

Figure 1. Upper: Schematic of sEMG electrode pair recording locations: submental and anterior neck. Solid lines indicate the two differential recording bars of each electrode pair. Dotted rectangles indicate the location of sensor casings. Lower: Photo of electrode pair recording locations.

measured the combined activations of the digastric, mylohyoid and geniohyoid muscles (muscles of the tongue base). Although the goal of the experiment was to record activations of the muscles mentioned, both electrode pair positions may have also picked up activation of the platysma muscle, a thin sheet of muscle that lies from the jaw to the fascia of the pectoralis muscles near the clavicle. The skin surface was prepared with alcohol and skin peeling (exfoliation) to reduce

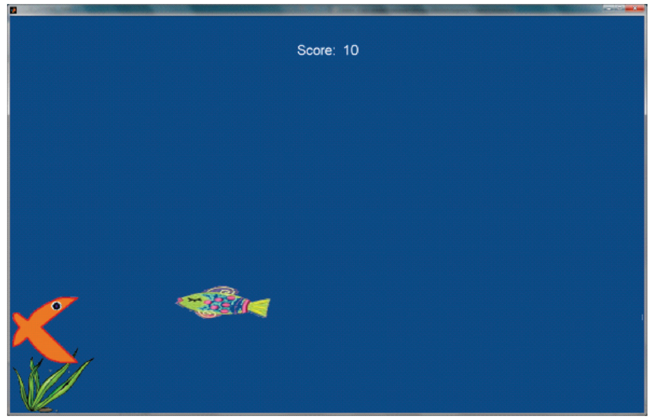

Figure 2. Screenshot of FishGame 2.0. Participants were asked to use sEMG to control the height of the large fish on the left of the screen to achieve targets as indicated by the smaller fish.

the skin-electrode impedance (e.g. Stepp, 2012). All participants reported to the experiment clean-shaven, since even moderate hair at the electrode sites could cause deterioration of the sEMG signal. A ground electrode was placed on the acromion process. The analog sEMG signals were pre-amplified (1000×) and bandpass filtered using an active Delsys Bagnoli system (Delsys, Boston, MA, USA) with low and high cutoffs of 20 and 450 Hz, respectively. These cutoff frequencies allow the majority of sEMG energy to pass through while removing potential sources of higher energy (e.g. electronic) or lower energy (i.e. movement artifact) noise from the signal (De Luca *et al.*, 2010). sEMG signals were digitalized and oversampled at 8 kHz using a National Instruments data acquisition system and custom software written in MATLAB (Mathworks, Natick, MA, USA).

2.3. Experimental procedure

Participants produced a series of three effortful dry swallows on command at the start of the experiment. The raw sEMG signals were visually inspected to ensure high signal quality (high signal-to-noise, lack of motion artifact and electrical line noise). The participant's maximum voluntary swallow value (MVSV) for the sEMG of the two electrode pair locations was estimated and used to calibrate signals during tracking tasks. The MVSV was used for normalization so that tasks were produced in activation ranges relevant to functional motor tasks; swallows were chosen to provide stereotyped and thus more reliable normalization value than one based on maximum voluntary contraction measures, which can be difficult to reliably measure in head and neck musculature (Stepp, 2012).

Participants sat in front of computer screen on which visual feedback was presented using a custom application programmed in MATLAB, *FishGame 2.0* (see Fig. 2). FishGame 2.0 is an updated version of FishGame 1.0, an earlier application that was developed as a potential rehabilitation platform (Stepp *et al.*, 2011), in which targets are presented to the user in randomized order. Participants were asked to control the vertical position of a large orange fish on the screen using their sEMG activity. Participants were asked to achieve targets at varying locations on the screen located at 33, 66 and 100% of their MVSV; these targets were indicated by smaller fish. These tracking tasks were presented to participants over eight total trials: four using the anterior neck electrode pair signal for control and four using the submental surface electrode pair for control. The order of which signal was used first was counterbalanced. Participants were always aware of which of the two electrode pairs was being used in the trial.

Visual feedback of the large fish's location was based on a smoothed version of the root mean squared (RMS) sEMG. The increases in sEMG allowed the fish to move up vertically, whereas decreased activation allowed the fish to drop. Participants were encouraged to control their sEMG in any way they were able, but not through swallowing or speech production. The self-normalization to each participant's MVSV allowed each individual to perform the tracking tasks using their own available range of sEMG and accounted for intersubject variability in electrode placement and electrode impedance as well as any actual differences in strength. The RMS values of sEMG collected were computed in online in 33 ms windows (266 samples) with no overlap. The motion of the fish was controlled by the exponential weighted average of the RMS sEMG with $\alpha = 0.05$, which was chosen empirically *a priori* for relatively smooth but timely control (cf. Equation (1)). In this scheme, the current position of the avatar for a 33-ms time frame was equal to the sum of (i) 5% of the current window's normalized RMS and (ii) 95% of the previous time frame's fish position.

$$\begin{aligned}\text{Current fish position} &= \alpha \times \text{Current normalized RMS}\\ &\quad + (1-\alpha) \times \text{previous fish position.}\end{aligned} \tag{1}$$

During each trial of human–computer interface interaction, participants were presented with six static targets. Participants were instructed to produce and maintain static sEMG activation at the target levels of 33, 67 and 100% of their MVSV for periods of 0.5 and 1.5 s (the target durations). These targets were presented to the user as six single fish targets that appeared at the right of the screen and traveled slowly to the left toward the participant's avatar. Fish length corresponded to the target durations (participants had to hold their sEMG activation at the target level longer for the fish with longer lengths). Participants were instructed to reach the target level and minimize deviations from that level during the target duration as much as possible. In between tasks, participants were asked to relax and were awarded points periodically for being 'home' (denoted as seaweed in Fig. 2), located at 0–10% MVSV, in order to avoid fatigue over the experiment. The raw sEMG signals collected during tracking were visually inspected offline to confirm signal quality (e.g. lack of movement artifacts and electrical line noise).

2.4. Data analysis

Human–computer interface control performance was quantified using the RMS error (in % MVSV) between the targets and achieved activations, which was computed offline using custom software in MATLAB (Mathworks, Natick, MA). Statistical analysis was completed using Minitab Statistical Software (Minitab, Inc., State College, PA, USA). A five-factor mixed model analysis of variance (ANOVA) was performed on the RMS error to determine the effects of age group (younger vs. older; between-subjects factor), target duration (0.5 s vs. 1.5 s; within-subjects factor), target level (33, 66, 100% MVSV; within-subjects factor), electrode pair position (anterior neck vs. submental surface; within-subjects factor) and trial (1–8), as well as all interactions between age group and the other factors. An α level of 0.05 or less was considered significant. Factor effect sizes were quantified using the squared partial curvilinear correlation, η_P^2 and *post hoc* effect sizes using Cohen's d (Witte and Witte, 2010). The study was powered to detect the between-subject factor with a medium effect size, within-subject factors with small effect sizes and interactions between factors with small effect sizes, all at significance levels of 0.05 with a power of 0.8. Pearson-product moment correlation coefficients were used to estimate correlations between variables.

3. RESULTS

The results of the ANOVA on RMS error are shown in Table 1. The ANOVA indicated statistically significant ($P < 0.05$) effects of all factors and interactions. However, only age group, target level and their interaction showed larger than 'small' effect sizes. The mean RMS errors at each target level are depicted in Fig. 3 for each age group (older vs. younger adults). The significant main effect of age group indicated that the older adults demonstrated more RMS error than the younger adults with a medium to large effect size ($\eta_P^2 = 0.15$). The significant effect of target level indicated that there was a difference in RMS error at different target levels with a large effect size ($\eta_P^2 = 0.24$). The significant interaction between these two factors (target level × age group, $\eta_P^2 = 0.05$) suggests that there were differential effects of target height on RMS error between the two age groups with a small-medium effect size. *Post hoc* t-tests were applied between RMS errors of the older and younger adults as a function of target level. After applying a Bonferroni correction, only the target levels of 66 and 100% MVSV showed a significant ($P_{adj} < 0.05$) difference between older and younger adults, with higher RMS errors in the older adults. The associated Cohen's d effect sizes between the older

Table 1. Results of five-factor mixed models ANOVA on RMS error.

Effect	DF	F	p	η^2_P
Age group (older vs. younger; between subjects)*	1	16.9	<0.001	0.15
Target duration (0.5 s vs. 1.5 s)	1	19.8	<0.001	0.01
Target level (33, 66, 100% MVSV)*	2	228.5	<0.001	0.24
Electrode position (submental vs. anterior neck)	1	4.7	0.031	0.03
Trial (1–8)	7	5.0	<0.001	0.02
Age group × target duration	1	9.5	0.002	0.01
Age group × target level*	2	40.4	<0.001	0.05
Age group × electrode position	1	5.9	0.015	<0.01
Age group × trial	7	2.4	<0.001	0.01

All factors were statistically significant. Factors with moderate or high effect sizes are denoted by asterisk.

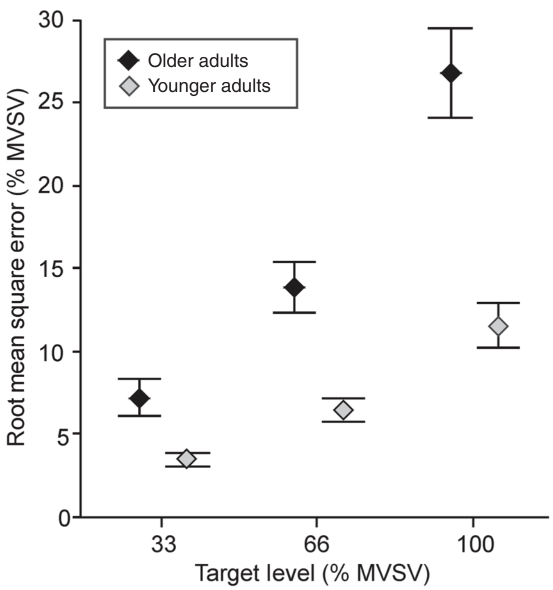

Figure 3. RMS error during human–computer interface control as a function of target level and age group. Black symbols indicate error of older adults and grey symbols indicate error by younger adults. MVSV, maximum voluntary swallow value. Error bars represent 95% confidence intervals.

and younger adults were both large: 1.18 at 66% MVSV and increased to 1.58 at 100% MVSV.

Although the effects were small, there was a significant effect of trial and the interaction of trial and age group. While younger adults showed relatively higher error during trial 1 compared with all subsequent trials, older adults showed relatively high error throughout all trials. Similarly, small but significant effects of electrode pair location and age group indicated slightly higher errors during submental neck control relative to anterior neck control, primarily driven by the older adults. Finally, small but significant effects of target duration and the interaction between age group and target duration showed slightly increased errors for targets of longer duration, especially in the older adults.

Although not presented here, the 'percent correct' of targets achieved based on arbitrary ± bounds around targets was also investigated; results of this measure strongly mimicked the outcome measure of RMS error and thus were not included.

4. DISCUSSION

This study examined the ability of younger and older adults to control the movement of a visually presented target using submental and anterior neck sEMG. Our results showed that older adults controlled the interface with significantly increased RMS errors relative to younger adults. Within each group, RMS error was found to increase as target level increased. Most interestingly, there was a significant interaction between age group and target level: older adults showed significantly increased RMS errors compared with younger adults as the target level increased. This is the first study to directly evaluate the effects of aging on motor performance during static tracking tasks in axial musculature.

4.1. Effects of age on tracking

The effects of aging on the ability to perform submaximal static force tracking in the limbs have been studied extensively, with many groups finding increased error as a function of age (Galganski *et al.*, 1993; Laidlaw *et al.*, 2000; Vaillancourt *et al.*, 2003; Vaillancourt and Newell, 2003). However, Ofori *et al.* (2012) studied the ability of healthy young individuals to produce static isometric force via index finger flexion (a 'manual' effector) and lower lip elevation (an 'oral' effector) using visual feedback, and have suggested that there are differences between the sensorimotor tracking capabilities of these two effector systems. Specifically, they found that the oral effector was more variable (e.g. higher coefficient of variation) than the manual effector control and suggested that oral and manual visuomotor force control involve different control mechanisms (Ofori *et al.*, 2012). Bronson-Lowe *et al.* (2013) specifically studied the effects of age on static tracking of more axial musculature vs. distal, measuring static fine force control of the lower lip and finger in 13 younger adults (8 women, mean age 21 years) and 13 older adults (6 women, mean age 66 years). These individuals were asked to produce a steady force for 25 s (the middle 19 s were used for analysis) with either the index finger or lower lip at 10 and 20% of their maximum voluntary force using visual feedback. Static force control using both effector systems was associated with a greater level of variability in the older group, for both lip and finger. Similarly, our study of static control using anterior neck and submental musculature showed a decrease in control ability (larger RMS error) in older adults relative to younger adults. These results suggest a similar mechanism for decreases in fine static force control with age and decreases in muscle activation control, which has been less studied.

In addition to the known motor changes in aging, the specific ability to utilize visual feedback could have played a role in our results. Previous work has shown that the amount of visual feedback presented to the user has an effect on older adults' performance operating human–computer interfaces but does not affect the performance of younger adults. Kennedy and Christou (2011) compared the ability of younger and older adults to control their force production and agonist muscle contraction across varying visual feedback conditions. Subjects in this study had to use their index fingers to produce a force that matched that of a target force at three different visual angles. Their results determined that the older adults performed with more variability than the younger adults with higher levels of visual feedback; there was no difference at the lowest visual angle, but older adults showed more variability in their ability to contract at higher visual angles. Additionally, older adults did not change the normalized power of their EMG signal, whereas younger adults were able to. These results suggest that older individuals have less capability to control their force production with more visual feedback, and thus it is possible that the feedback interface used in the present study had a negative effect on their force production abilities. Ofori *et al.* (2010) also studied the effects of visual display type on age-related differences in force variability, finding older adults to be less capable of visuomotor processing and eye movements control compared with younger adults. It is possible that the increased error by the older adults in our study is in part due to decreased visuomotor processing and eye tracking abilities in addition to motor issues.

4.2. Differential difficulty with fine motor control at higher target levels

Seminal work from Enoka *et al.* (2003) in distal musculature has shown that the coefficients of variation of force during contractions are similar between old and young adults at higher forces, and less similar at *low* forces. It is unclear whether this difference is due to inherent differences between axial and distal musculature or to differences in outcome measures. However, an increase in the variability of the activation of individual motor units and a decrease in the rate of activation in distal musculature at higher force levels are also typical of older adults (Roos *et al.*, 1997), which is consistent with our finding that older adults performed with higher RMS error at higher target amplitudes. Regardless, in neck musculature, we have shown that age is associated with more pronounced differential effects on human–computer interface control at higher target levels. It is likely that these differences in task performance were in part due to the changes in motor unit function and size as well as reduction in muscle mass, number of fibers and muscle fiber size in older adults. Oral muscles have shown both atrophy (Bassler, 1987; Malmgren *et al.*, 1999) and changes in motor unit activity (Bardan *et al.*, 2000; Takeda *et al.*, 2000) with age. This implies that targets at relatively high activation levels (in % MVSV) should be avoided in interfaces designed for older adults.

4.3. Study limitations, translational implications and future directions

Limitations of this study should be considered when interpreting the current results. Older adults may present with differences in overall vision or in experience with technology, which could have reduced their ability to perform the visuomotor tracking tasks. Participants were not screened for visual acuity. Although we do not think it is likely, visuomotor tracking in the older adults could have been reduced due to problems with vision. In addition, although none of our participants had previous experience with anterior neck sEMG for device control, it is likely that the young subjects had substantially more experience with human–machine interfaces in general, such as computers, smartphones and videogames. We did not establish the extent to which younger and older adults in this study had experience with technology. Experience with technology may have mediated the effect of age on sEMG performance, but given that this input modality is not used in everyday life, any effect would be expected to be small. There may also have been differences in the quality of the skin properties between older and younger adults; previous work has shown that there are small but significant increases in skin impedance in older adults relative to younger adults (Nicander *et al.*, 1997). However, given that offline inspection indicated that high quality signals were recorded from all participants, this is unlikely to have played a significant role in the findings of this study. Finally, differences in performance as a function of age and task type are only representative of 1D control. Future work in 2D control is necessary in order to have direct application to some of the sEMG human–computer interfaces currently being developed (Larson *et al.*, 2013; Perez-Maldonado *et al.*, 2010; Williams and Kirsch, 2008), including more complex gesture-based applications (Zhang *et al.*, 2014).

Our findings have direct implications on the use of anterior neck sEMG-controlled human–computer interfaces in older adults. The main effect of group suggests that older adults may have decreased capabilities for interfaces utilizing sEMG that require 'hold' capability to select a target. The significant interaction between age group and target amplitude suggests that this problem can be addressed by (i) choosing lower target amplitudes or (ii) increasing the acceptable error allowed around target activations for 'correct' target selection for higher target amplitudes. On a positive note, only very small effects on performance were seen as a function age group and target duration, suggesting that older adults may be just as able as younger adults to maintain motor activity over 0.5–1.5 s in order to make selections. Finally, the visuomotor tracking performance reported here represents relatively 'untrained' abilities, with skills demonstrated over just ~1 h of interaction. Future work is needed to determine the effects of training on anterior neck visuomotor tracking to determine whether such training can allow older adults to achieve similar performance to younger individuals.

5. CONCLUSION

This study showed that older adults perform worse than younger adults on a task that involved visuomotor tracking of static targets using submental and anterior neck sEMG. This difference was strongest when higher amplitudes of sEMG were necessary to achieve the targets. The results have implications for using anterior neck sEMG as an input modality in technology for older adults.

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