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Visuomotor control of neck surface electromyography in Parkinson's disease

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Abstract

OBJECTIVE—To compare performance of individuals with Parkinson's disease (PD) and age-matched controls on a visuomotor tracking task controlled via surface electromyography (sEMG).

METHODS—Twenty-seven adults with PD and twenty-four older controls produced dry swallows and completed a visuomotor tracking task utilizing both static and dynamic targets. sEMG was recorded at the anterior neck and submental surface during both tasks.

RESULTS—There was no significant difference in visuomotor tracking ability between cohorts. Post hoc analyses indicated that there was no significant difference between participant groups in the strength or duration of swallows as measured by sEMG but that participants with PD showed a trend for decreased swallow durations at the anterior neck (p_{adj}=0.067) whereas controls showed a trend for increased durations at the anterior neck (p_{adj}=0.112), compared to the submental surface. However, there were no significant correlations between swallowing behavior and visuomotor tracking ability.

CONCLUSION—There were no significant differences in visuomotor tracking performance between individuals with PD and controls. Furthermore, there was no relationship between tracking ability and swallowing behavior. We conclude that sEMG-mediated biofeedback may have limited promise as a tool for treating PD-related dysphagia.

Keywords

Swallowing; dysphagia; Parkinson's disease; surface electromyography; biofeedback

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Declaration of interest

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Introduction

Dysphagia, the inability to swallow safely and efficiently, has been linked to higher mortality, lower quality of life (QoL), and increased risk of aspiration pneumonia (Langmore et al., 1998). Dysphagia is common in individuals with Parkinson's disease (PD; Muller et al., 2001), although only about half of individuals with PD who have dysphagia are aware that they have it (Robbins, Logemann, & Kirshner, 1986). Individuals with PD often have difficulty with the voluntary aspects of swallowing, such as impaired bolus formation and manipulation, difficulty with swallow initiation, and use of lingual pumping (small, inefficient, non-propulsive back and forth tongue movements to propel the bolus to the pharynx) (Leopold & Daniels, 2010). The prognosis and care of patients with PD would be improved with more effective treatments for dysphagia.

Neural control of swallowing has traditionally been thought of as reflexive, and most treatments for dysphagia have mainly focused on alternate modes of feeding (Robbins et al., 2008). However, more recent studies suggest that swallowing can be subject to behavioral modification (Robbins et al., 2008), advocating greater potential for new treatments for dysphagia. Although it is not feasible to non-invasively monitor the activity of many of the muscles active during swallowing, anterior laryngeal elevator muscles (accessible via the submental and anterior neck surfaces) contract at the onset and throughout the swallow (Crary, Carnaby Mann, & Groher, 2006) and are easily accessible through surface electromyography (sEMG). sEMG-mediated biofeedback of the anterior neck (Crary, Carnaby Mann, Groher, & Helseth, 2004) and of the submental surface (Huckabee, Butler, Barclay, & Jit, 2005) have been investigated as adjuncts to traditional therapy techniques, and may have promise for assessment and potential rehabilitation of individuals with PD-related dysphagia. However, much more needs to be known about the sEMG of anterior neck and submental musculature in PD during voluntary control tasks, such as those likely to be implemented into rehabilitation platforms.

Examination of non-swallowing voluntary motor control substrates may provide insight into the underlying physiological bases of swallowing difficulties. Visuomotor tracking tasks can provide objective measurements of voluntary motor control capabilities and have been employed in previous studies utilizing orofacial muscles muscles (Ballard & Robin, 2007; Ballard, Robin, Woodworth, & Zimba, 2001; Bronson-Lowe, Loucks, Ofori, & Sosnoff, 2013; Clark, Robin, McCullagh, & Schmidt, 2001; McClean, Beukelman, & Yorkston, 1987; Moon, Zebrowski, Robin, & Folkins, 1993; Ofori, Loucks, & Sosnoff, 2012; Robin, Jacks, Hageman, Clark, & Woodworth, 2008). Consequently, visuomotor tracking could potentially be a beneficial tool in studying PD, which is known to affect general sensorimotor capabilities. During these tasks, individuals are asked to modulate either the movement or force of articulators in order to achieve either static or dynamic (sinusoidal) targets. In healthy individuals, this tracking ability tends to peak in young adulthood and decline with normal aging for both static (Bronson-Lowe et al., 2013) and dynamic (Ballard et al., 2001) targets. Compared to age-matched controls, visuomotor tracking ability is also decreased in several motor-impaired clinical populations (Ballard & Robin, 2007; McClean et al., 1987; Robin et al., 2008). Measurement of static force control of the lip, tongue, and finger in individuals with PD and age-matched controls, found that force production of the

articulator muscles in individuals with PD was slower, more variable, and less easily maintained than in healthy controls (Gentil, Perrin, Tournier, & Pollak, 1999). However, a separate study reported that articulator control was primarily affected by age and not by PD (McAuliffe, Ward, Murdoch, & Farrell, 2005).

The purpose of this study was to determine whether there were differences in visuomotor tracking ability using anterior neck and submental sEMG in individuals with PD. We hypothesized that the individuals with PD would have poorer visuomotor tracking ability compared with age-matched controls and that this difference would be apparent in both the anterior neck and submental sEMG control.

Methods

Participants

Participants were a group of 24 older adults aged 55–89 (12 females) without, and a group of 27 older adults aged 53–85 (8 females) with PD (see Table 1 for demographics). No participants reported a history of neurological, swallowing, speech, language, or hearing disorders other than PD, with the exception of minor age-related hearing loss. Participants with PD were all recorded while on their typical medication schedule. Informed consent was obtained from all participants in accordance with the Boston University Institutional Review Board.

sEMG data acquisition

One single differential sEMG electrode was placed on the anterior neck surface, positioned approximately 2.5 cm lateral to the neck midline and with the superior aspect of the sensor approximately 1 cm from the submental surface. This electrode was expected to detect activity from the thyrohyoid, sternohyoid, and possibly omohyoid muscles. A second electrode placed on the submental surface was intended to measure the combined activations of the digastric, mylohyoid, and geniohyoid muscles. Both electrodes may have also recorded activity from the platysma muscle, which extends from the jaw to the fascia of the pectoralis muscles near the clavicle and contributes to recordings from the neck surface.

The skin surface was prepared with alcohol and exfoliation (Stepp, 2012). A ground electrode was placed on the superior aspect of the participant’s left shoulder. The sEMG signals were pre-amplified (1000×) and band-pass filtered from 20 Hz to 450 Hz, using a Delsys™ Bagnoli system (Boston, MA) and sampled at 8000 Hz.

Experimental protocol

At the start of the experiment, all participants completed the Dysphagia Handicap Index (DHI), a validated swallowing function and QoL scale (Silbergleit, Schultz, Jacobson, Beardsley, & Johnson, 2012b). The relationship between DHI and the number of years post-diagnosis in participants with PD is summarized in Figure 1. Participants were asked to produce three effortful dry swallows on command. Raw sEMG signals recorded during these swallows were visually inspected by experimenters to ensure signal quality. The participants’ maximum voluntary swallow value (MVSV) for the sEMG at the anterior neck

and submental surface was defined as the maximum root-mean-square (RMS) value that the participant was able to achieve during the task and was used to calibrate signals during the later tracking portion of the experiment.

Participants were provided visual feedback of their sEMG activity by a custom interface programmed in MATLAB that required them to reach various visuomotor targets. Participants were provided with real-time feedback of their sEMG via the position of a cartoon avatar. The vertical position of this avatar was controlled via muscle activation. Increases in sEMG allowed the avatar to move up vertically, while decreases in the signal allowed the avatar to drop. Participants were instructed to move this avatar up and down to "swallow" targets at varying heights on the screen corresponding to values between 0 and 100% of their MVSV. Self-normalization to each participant's MVSV allowed each individual to perform the tracking tasks using his or her own available range of muscle activation, controlling for inter-subject variability in signal strength and small differences in electrode placement. Participants completed eight trials: four using the anterior neck electrode signal and four using the submental surface electrode signal for control. The order of which signal was used first was counter-balanced to avoid learning effects.

Participants were asked to attain six static targets and three dynamic targets during each trial. Static targets were presented at 33%, 67%, or 100% of the participant's MVSV (depicted in Figure 2), which the participant was required to maintain in order to achieve that target for 1.5 or 0.5s. Dynamic targets consisted of three 12 s sinusoidal functions (0.14-0.3 Hz).

Data analysis

Performance on tracking tasks was quantified using the RMS error (in % MVSV) between the participant's activations and the targets during both static and dynamic tracking tasks.

Based on our visuomotor tracking results, post hoc analyses were performed on the sEMG data collected during swallowing tasks. These data were used to calculate two features of swallowing: *average-max-from-baseline* and *percent duration*. Baseline RMS for each channel was manually-selected during a period when the participant was instructed to relax during the task. Average-max-from-baseline for each channel was calculated as the mean of each maximum RMS value (33 ms window length) within a designated period of 'swallow activity' (defined as 0.5 s before and 3 s after each swallow command), normalized by the baseline value for that channel. Percent duration was defined as the percent of time within a larger window (1 s before the swallow command to 4 s after) that the sEMG activity was at least 10% above the baseline.

Statistical Analysis

A two-factor mixed model analysis of variance (ANOVA) was performed on each of the visuomotor tracking measures, static RMS error and dynamic RMS error, as well as each of the swallowing outcome measures, average-max-from-baseline and percent duration. Factors were group (PD vs. control) and electrode position (anterior neck vs. submental surface). An alpha of 0.05 or less was determined to be statistically significant, using

Bonferroni corrections in *post hoc* testing. Pearson-product moment correlation coefficients were used to estimate correlations between each measure (static RMS error, dynamic RMS error, average-max-from-baseline, and percent duration), DHI, and years post-diagnosis.

Results

Results from the four measures—static RMS error, dynamic RMS error, average-max-from-baseline, and percent duration—are detailed in Figure 3.

ANOVAs were applied for both the static and dynamic RMS error (detailed in Table 2). The ANOVA on static RMS error found no significant main effect for group, electrode position, or the interaction between group and electrode position. The ANOVA on the dynamic task RMS error showed a significant main effect for the interaction between group and electrode position (with a medium associated effect size of $\eta_p^2 = 0.08$), but not for either factor on its own. *Post-hoc* unpaired t-tests comparing control vs. PD performance on the anterior neck electrode and comparing control vs. PD performance on the submental electrode were both non-significant. Further, paired t-tests comparing PD performance on the anterior neck electrode vs. the submental electrode and comparing the controls' performance on the anterior neck electrode vs. the submental electrode were also non-significant. Within participants with PD only, correlations between static RMS error and DHI ($r = 0.07$) and static RMS error and years post diagnosis ($r = 0.06$) were both non-significant, as were the correlations between dynamic RMS error and DHI ($r = 0.04$) and dynamic RMS error and years post diagnosis ($r = -0.09$).

Based on these negative findings, we sought to determine whether the swallowing outcome measures of average-max-from-baseline and percent duration differed as a function of cohort. The results of the ANOVA on average-max-from-baseline during swallowing indicated statistically significant ($p < 0.05$) effects of differences in electrode position, with a large associated effect size of $\eta_p^2 = 0.41$, but there was no main effect of group or of the interaction between electrode position and group (Table 3). A single *post hoc* paired t-test found that the average-max-from-baseline activations at the anterior neck (PD MEAN = 7.91, SD = 6.55; Control MEAN = 9.67, SD = 5.87) were significantly lower than the activations at the submental surface (PD MEAN = 14.82, SD = 7.09; Control MEAN = 14.50, SD = 8.72), with $p < 0.001$, T = 5.74, and DF = 49. The ANOVA on percent duration of swallowing (Table 3) did not show a significant effect of group or electrode position, but there was a significant interaction between group and electrode. Four *post hoc* tests were applied to determine the nature of the interaction. Unpaired t-tests comparing control vs. PD sEMG from the anterior neck electrode and control vs. PD sEMG from the submental electrode were non-significant. Interestingly, a paired t-test comparing anterior neck vs. submental within the PD group found that the duration of swallow activity at the submental electrode was significantly longer than at the anterior neck (Submental MEAN = 69%, SD = 16 vs. Anterior Neck MEAN = 60%, SD = 18), whereas the paired t-test comparing electrode sites within the control group found instead that the duration of swallow activity at the submental surface was significantly *shorter* than at the anterior neck (Submental MEAN = 63%, SD = 11 vs. Anterior Neck MEAN = 66%, SD = 8). However, after the Bonferroni correction for the four comparisons was applied, neither of these comparisons reached

significance, leaving just a trend for decreased durations during swallowing for individuals with PD at the anterior neck vs. submental (p_{adj} = 0.067) and increased durations for age-matched controls at the anterior neck vs. submental (p_{adj} = 0.112). Within participants with PD, correlations between average-max-from-baseline and DHI (r = 0.02) and average-max-from-baseline and years post diagnosis (r = 0.04) were both non-significant, as were the correlations between percent duration and DHI (r = 0.08) and percent duration and years post diagnosis (r = −0.05).

The only significant correlations among the four measures (static RMS error, dynamic RMS error, average-max-from-baseline, and percent duration) were between average-max-from-baseline and percent duration (r = 0.24, p = 0.017) and between static and dynamic RMS error (r = 0.56, $p < 0.001$). Correlations between average-max-from baseline and tracking performance (r = 0.03 and r = −0.16 for static and dynamic RMS error, respectively) were non-significant, as were correlations between percent duration and tracking performance (r = 0.04 and r = −0.06 for static and dynamic RMS error, respectively).

Discussion

In this study, we evaluated performance on a visuomotor tracking task in which participants were asked to modulate their muscle activation using visual feedback. We hypothesized that individuals with PD would have reduced tracking ability compared to controls; surprisingly, we found no significant difference in tracking performance between the two participant groups. We then conducted a post-hoc analysis of the sEMG activity generated from the dry swallows in calibration, to investigate whether there were differences in swallowing between the individuals with PD and age-matched controls, and whether poorer tracking ability was linked to more deviant swallowing behavior. We hypothesized that our outcome measures for analyzing swallows (average-max-from-baseline, percent duration) and for the tracking task (static RMS error, dynamic RMS error) would correlate with one another and with DHI. However, we found that there was no significant correlation between measures of swallowing behavior and measures of tracking performance.

Performance on visuomotor tracking task

We found no difference in static RMS error for electrode placement or for participant group. An ANOVA on the dynamic RMS error found a significant main effect for the interaction between electrode location and participant group, but all post-hoc tests were non-significant. The interaction is likely driven by the large standard deviation in the PD group at the anterior neck electrode, indicating that the PD group had a much wider variation in performance than the control group, although the average performance of both groups was similar. Thus, some individuals with PD may have reduced dynamic tracking ability, and some may not. However, this variability was not explained by DHI, PD progression, or sEMG features during swallows.

There is some other evidence that visuomotor tracking may not adequately address the sensory and motor deficits found in individuals with PD. For instance, Martens et al. have reported that when individuals with PD rely on proprioception to step over an obstacle, they consistently overestimate the height of that obstacle. However, when they have visual

feedback of their foot in relation to the obstacle, their movements mirror those of controls (Martens & Almeida, 2012), suggesting that individuals with PD can use visual information to correct their actions. If so, then the visual feedback provided during the tracking task could have enabled the participants with PD to compensate for any underlying sensorimotor deficits, resulting in an overall performance that was similar to the control group. Since the visual information provided during a visuomotor task would enable individuals with PD to perform similarly to controls, visuomotor tracking may not be a useful assessment tool for individuals with PD. Based on these negative results, we sought to more fully characterize the sEMG during swallowing in our sample.

Analysis of sEMG signals during swallowing

Neither average-max-from-baseline nor percent duration showed significant differences between groups. However, there were trends noted for the percent duration at the anterior neck electrode to be longer than the percent duration at the submental space electrode in the control group, and *shorter* than at the submental electrode in the PD group. One possible explanation for increased durations at the submental electrode in the participants with PD could be due to the submental electrode detecting activity generated by lingual pumping, which is often observed in individuals with PD (Leopold & Daniels, 2010). Conversely, a trend for decreased duration of activation of anterior neck musculature in PD could possibly be a result of weakened hyolaryngeal elevation. In controls, we observed a trend for increased durations at the anterior neck electrode compared to the submental electrode. Previous studies examining differences in swallowing behavior in healthy populations at different ages found that healthy older adults use more hyoid movements, and require more time to move the hyoid anteriorly when swallowing (Dejaeger & Pelemans, 1996; Sonies, Parent, Morrish, & Baum, 1988). The increased duration of activations at the anterior neck electrode that we observed could be due to slower and more frequent hyoid movements generally seen in older adults.

Other studies analyzing the characteristics of PD vs. control swallows via sEMG have found significant differences in swallowing behavior compared to controls (Coriolano et al., 2012; Tawadros, Cordato, Cathers, & Burne, 2012). Tawadros et al. characterized the sEMG activity at the submental and anterior neck during swallowing water boluses of varying volumes in participants with PD and healthy, age-matched controls, reporting that PD swallows had increased duration (Tawadros et al., 2012). Coriolano et al. also analyzed sEMG of PD swallows, with both water and yogurt boluses of varying volumes, and found that PD swallows were significantly longer than those of controls (Coriolano et al., 2012). Neither study found a significant difference in maximum amplitude between PD participants and controls, which is supported by our finding that there is no significant difference in average-max-from-baseline values between PD participants and controls. However, unlike these previous studies, our results showed no difference in swallow duration between the two participant groups, potentially due to differences in bolus volume. Both other studies looking at sEMG of PD swallows found that the duration of swallow activity increased with bolus volume. The participants in this study were instructed to dry swallow, so the bolus volume may have been affected by the availability of saliva, which could vary widely among our participants. Dry mouth is a common symptom of PD, often occurring even

before the onset of motor symptoms (Cersosimo et al., 2013), and individuals with PD have been shown to have decreased saliva production (Proulx, de Courval, Wiseman, & Panisset, 2005). It is possible that the boluses our participants were able to produce were too small to show a robust effect for duration via sEMG.

Correlations between measures

Contrary to our hypothesis, there were no significant correlations between visuomotor tracking ability and our measures of swallowing activity (average-max-from-baseline and percent duration), which suggests that these tasks are not strongly related. Furthermore, there were no significant relationships between DHI or PD progression (measured as years post-diagnosis) and any of the measures. This negative result could be due to a true lack of relationship between sEMG measures of swallowing and swallowing function, or it could potentially indicate that neither are reliable indicators of swallowing function in individuals with PD. There are few studies evaluating the validity of DHI with respect to individuals with PD. However, research with this population suggests that participants' perception of their swallowing does not correlate with their actual swallowing ability, and may be susceptible to placebo effects or other similar confounds (Silbergleit et al., 2012a). Additionally, a large portion of individuals with PD-related dysphagia do not report having a swallowing problem (Robbins et al., 1986), providing further evidence that individuals with PD have altered perception of their swallowing ability. Similarly, years post-diagnosis may not be a good estimate of disease severity in PD. PD has a wide range of clinical presentations, suggesting the existence of different subgroups of the disease (Gasparoli et al., 2002; Halliday, Hely, Reid, & Morris, 2008; Selikhova et al., 2009). The rate of disease progression can be influenced by factors such as age at disease onset, lateralization of symptoms, and the predominance of tremor or bradykinesia (Gasparoli et al., 2002). These issues limit the ability to determine whether swallowing function or disease progression are related to sEMG activity in PD.

Study limitations and future directions

All of our participants were self-selected to be relatively healthy and willing to participate in a long, physically demanding study, and thus may not have had PD-related deficits severe enough to significantly impact their performance in the study. For this reason, our results may not generalize to all individuals with PD. Additionally, all of our participants with PD were on medication, which may have affected their swallowing behavior and tracking ability. The influence of levodopa on swallowing behavior is unclear (Fuh et al., 1997; Hunter, Crameri, Austin, Woodward, & Hughes, 1997; Lim, Leow, Huckabee, Frampton, & Anderson, 2008; Tawadros et al., 2012), but it is possible that the effects of medication could have masked differences in swallowing between participant groups. Further studies should investigate the relationship between swallowing behavior and medication state in individuals with PD.

Conclusions

In this study we investigated the ability of individuals with PD to perform a visuomotor tracking task using neck sEMG. We found that there was no clear difference in tracking

ability between the two participant groups; furthermore, we found no evidence that performance on the tracking task was related to atypical swallowing. Post hoc analysis of the characteristics of sEMG during dry swallows in the sample did not indicate a relationship between swallowing behavior and visuomotor tracking performance. This suggests that visuomotor tracking of neck EMG may not be suitable for assessment or treatment of PD-related dysphagia.

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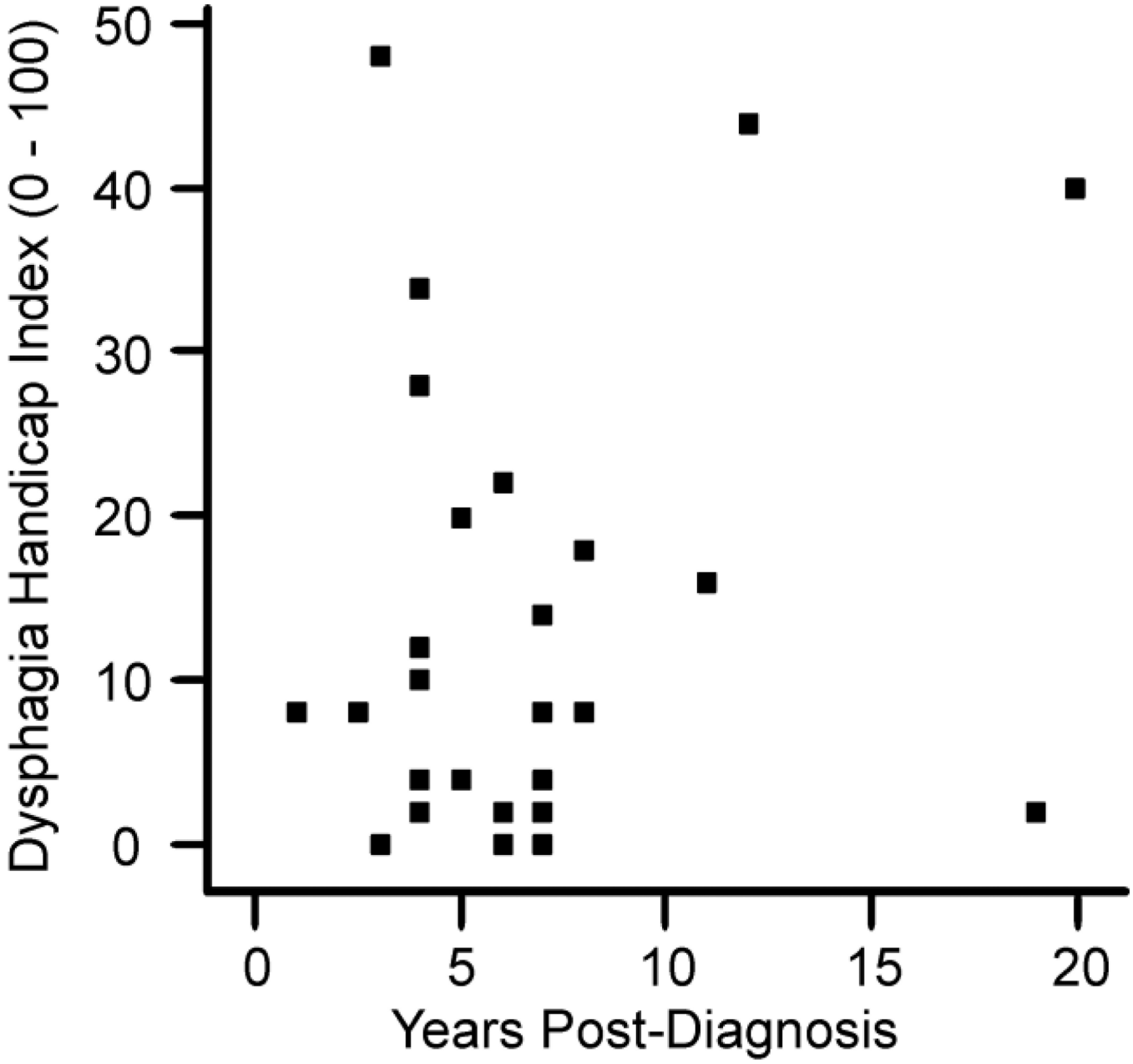

Figure 1.
Years post-diagnosis as a function of Dysphagia Handicap Index for each participant with Parkinson's disease.

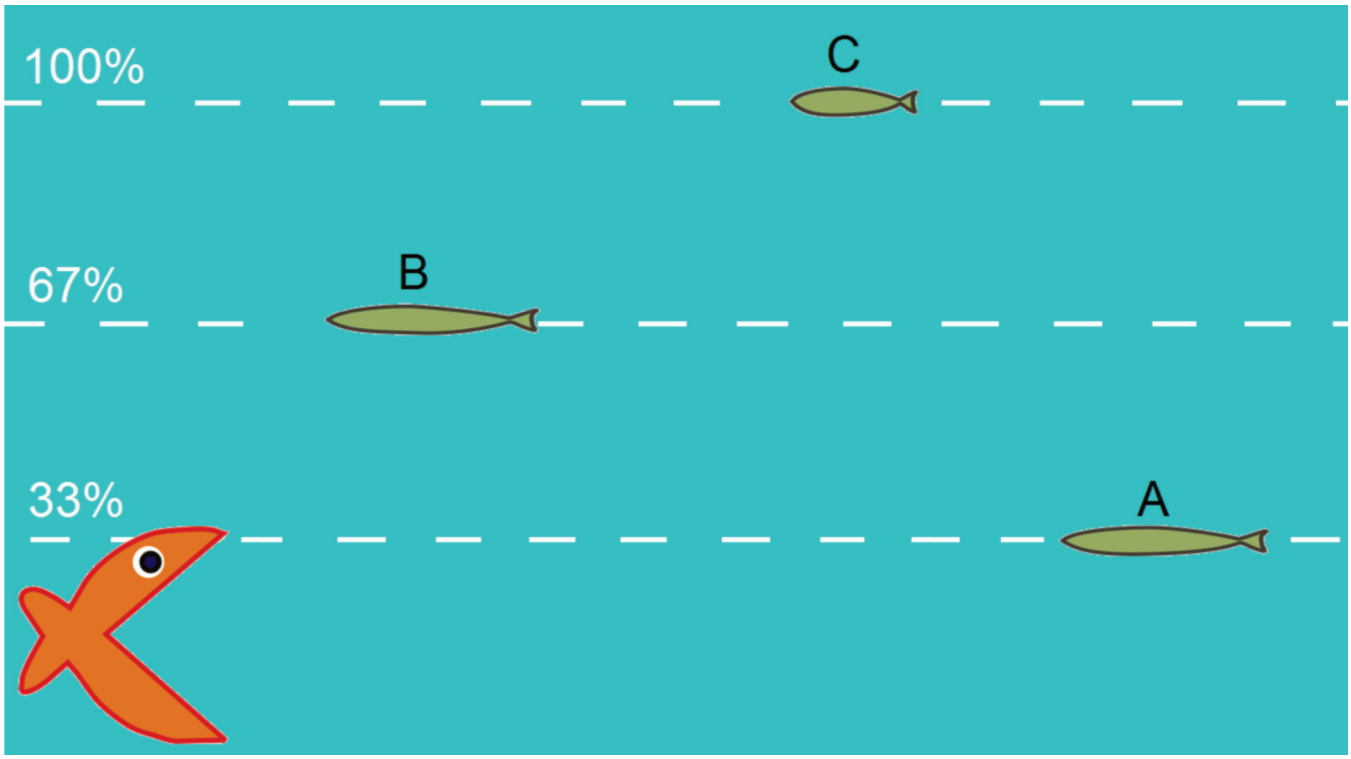

Figure 2.

Diagram of static target activations presented to participants during the visuomotor tracking task. Participants activated muscles at either the anterior neck or submental space to move their avatar (the orange fish at the bottom left) up and down. Static targets consisted of single fish moving towards the avatar at a constant vertical height, which corresponded to 33% (target A), 67% (target B) or 100% (target C) of the participant's maximum voluntary swallow value.

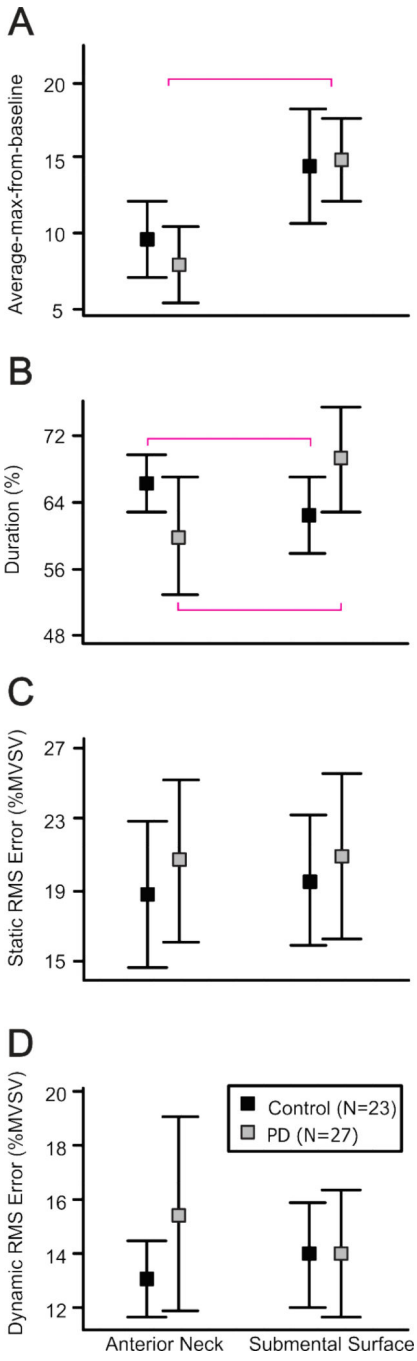

Figure 3.

Results from the four outcome measures. Error bars indicate 95% confidence intervals and magenta brackets denote significant differences. Black nodes represent the control group and gray nodes represent the PD group. A: Average-max-from-baseline. B: Percent duration. C: Static RMS Error. D: Dynamic RMS error.

Table 1

Participant characteristics including age, dysphagia handicap index (DHI) and years post-diagnosis (participants with PD only).

Cohort	Sex	N	Age in Years (Mean ± SD)	DHI (Mean ± SD)	Years post-diagnosis (Mean ± SD)
CTRL	M	12	62.8 ± 3.2	0.3 ± 1.2	-
	F	12	77.8 ± 11.4	1.4 ± 1.8	-
PD	M	19	66.8 ± 7.4	14.6 ± 15.1	6.8 ± 4.0
	F	8	72.2 ± 6.9	11.2 ± 11.6	6.1 ± 5.3

N = number of participants; SD = standard deviation; PD = participants with Parkinson's disease; CTRL = healthy controls.

Table 2

Results of the two factor mixed models ANOVAs on the two outcome measures of performance on the visuomotor tracking task:static RMS error and dynamic RMS error.

Measure	Source	DF	η_p^2	F	*p*
Static RMS error	Group (PD vs. controls)	1	0.13	0.31	0.58
	Electrode Position (anterior neck vs. submental)	1	0.01	0.75	0.39
	Group × Electrode Position	1	0.00	0.2	0.66
Dynamic RMS error	Group (Parkinson's vs. controls)	1	0.09	0.52	0.47
	Electrode Position (anterior neck vs. submental)	1	0.01	0.19	0.67
	Group × Electrode Position	1	0.08	4.17	0.047

Table 3

Results of the two factor mixed models ANOVAs on the two outcome measures of sEMG signals during dry swallowing: Average-max-from-baseline of the sEMG signal during swallowing (mean of each maximum RMS value within a window 0.5s before and 3 s after each swallow command, normalized by the baseline value for that channel), and percent duration (defined as the percent of time within a window 1 s before a swallow command to 4 s after that the sEMG activity at least 10% above baseline).

Measure	Source	DF	η_p^2	F	*p*
Average-max-from-baseline	Group (PD vs. controls)	1	0.01	0.2	0.68
	Electrode Position (anterior neck vs. submental)	1	0.41	31.8	<0.001
	Group × Electrode Position	1	0.02	1.0	0.32
Percent duration	Group (PD vs. controls)	1	<0.01	<0.01	0.966
	Electrode Position (anterior neck vs. submental)	1	0.05	1.74	0.194
	Group × Electrode Position	1	0.17	9.59	0.003