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Research Article

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RESEARCH ARTICLE

Mental Practice of Lingual Resistance and Cortical Plasticity in Older Adults: An Exploratory fNIRS Study

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Purpose: Mental practice using motor imagery (MP) improves motor strength and coordination in the upper and lower extremities in clinical patient populations. Its effectiveness as a rehabilitation tool for patients with lingual weakness is not yet well understood, nor are the underlying mechanisms within the context of swallow or lingual MP. Using previously published data on a lingual and MP exercise program, the objective of this study was to explore how MP of lingual exercise affects cortical activation in healthy older adults over time and how neural changes correlate with functional oral pressure outcomes.

Method: A prospective randomized controlled study was previously completed; older healthy participants were randomized to one of four treatment groups receiving lingual MP, lingual physical practice, a combination of both, and a sham control. This paper reports descriptive data on cortical activation during both the physical and mental forms of lingual resistance in a subgroup of 13 participants using functional near-infrared spectroscopy at baseline and after 6 weeks of the assigned exercise regimen.

Results: Aggregated data indicates that participants who completed 6 weeks of lingual exercise, either in physical or in MP form, had decreased oxygenated hemoglobin when completing a maximal lingual pressure task.

Conclusions: Some participants in a lingual resistance MP program demonstrated trends similar to those seen after strength training. Combining MP with physical training may lead to greater changes in oxygenation compared to a physical or mental training program alone, although given the small number of participants, it is important not to overinterpret the results. MP is a promising, innovative approach that may enhance traditional exercise-based swallowing rehabilitation.

Keywords: *dysphagia, mental practice, motor imagery, neuroimaging, functional near-infrared spectroscopy, fNIRS, swallowing*

INTRODUCTION

Given that dysphagia (swallowing difficulty) affects one in 25 people in the U.S., novel, efficacious treatment methods are in high demand (Bhattacharyya, 2014). Mental practice with motor imagery (simplified to MP throughout the manuscript) is a cognitive process in which a person imagines that they are performing a movement repeatedly without overt execution of that movement. The goal is to improve motor performance (e.g., speed and accuracy of movements, force production, activities of daily living), such as for sports training or rehabilitation (Dickstein & Deutsch, 2007; Guillot et al., 2010). Cognitive frameworks for mental practice can include auditory, visual, tactile, gustatory, and kinesthetic, used in isolation or in various combinations (Dickstein & Deutsch, 2007). A recent review indicates that MP has moderate-certainty evidence when used in combination with other treatment methods for improving upper extremity activity and impairment (Barclay et al., 2020).

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Several studies have demonstrated that MP in conjunction with physical training improves upper and lower extremity motor outcomes in patients with Parkinson's disease (Caligiore et al., 2017; Heremans et al., 2011; Tamir et al., 2007), as well as following stroke (García Carrasco et al., 2016; Malouin et al., 2013) and acquired immobilization (Newsom et al., 2003). While much of the MP literature focuses on skilled movements, there is also evidence for the use of MP in conjunction with strength training of the upper and lower extremities (Fontani et al., 2007; Ranganathan et al., 2004; Reiser et al., 2011; Slimani & Cheour, 2016; Slimani et al., 2016; Zijdewind et al., 2003). One of the leading theories on the mechanism for MP improving physical outcomes is that imagery of physical movement activates the central nervous system areas responsible for that movement, strengthening neural connections and priming the motor program for the specific movement (Mulder, 2007; Slimani et al., 2016).

This central theory of engagement likely comes from research describing the underlying neural mechanisms of strength training in the extremities of healthy participants. Although extremity strength training leads to an immediate increase in regional cerebral blood flow as greater resistance is exerted (Dettmers et al., 1996), repeated movements and later stages of physical training are associated with a decrease in cortical activity and excitability (Morgen et al., 2004; Nyberg, et al., 2006; Sale et al., 2017). This may be attributable to a more efficient network; as motor units fire more synchronously after training, less neural activity is required to generate a specific level of muscular force, resulting in maximum efficiency between the muscles and the central nervous system (CNS; Carroll et al., 2001). These results are seen in lingual strength training as well. Five days of lingual protrusion training resulted in larger tongue motor cortex map areas, suggesting neuroplastic changes (Komoda et al., 2015). Furthermore, strength loss involves central neurological factors. Unilateral lower limb suspension leads to loss of strength in that limb with neural factors accounting for 48% of the variability in strength loss and muscular factors accounting for 39% (Clark et al., 2006).

Although oral and oropharyngeal strength training is widely used in swallowing rehabilitation (de Felicio et al., 2010, McCullough et al., 2012; Robbins et al., 2007; Shaker et al., 2002; Troche et al., 2010), MP is an untapped resource in dysphagia management. If proven efficacious, MP has potential to augment the management of dysphagia as it can be implemented in any clinical setting and without specialized equipment, has no additional cost, and does not cause physical fatigue. These advantages are particularly relevant for patients with limited ability to participate in traditional swallowing exercise. Given that 39% of patients discharge to home after an acute event (Werner et al., 2019), therapies that can be completed as a part of a home exercise program, such as MP, are in demand.

Research on MP as a part of dysphagia management is limited, but studies are beginning to emerge. In a recent uncontrolled, feasibility case series, MP alone improved tongue strength in healthy older adults (Szynkiewicz et al., 2019). Additionally, MP combined with physical practice of a simple lingual resistance task increased lingual isometric pressure and swallowing pressure, the latter of which potentially demonstrates behavioral transference (Szynkiewicz et al., 2021). Although these studies are promising, more research is required to establish the validity of MP in the context of dysphagia rehabilitation and guide best practices. In a recent survey of speech-language pathologists' practice patterns regarding MP in dysphagia management, 75% of the respondents were interested in learning more about MP, but only 25% were already incorporating it into clinical practice with a lack of evidence base being cited as one of the limitations (Szynkiewicz et al., 2020).

All of the work on neural organization in MP has focused on mental motor training (i.e., imagery of skilled movements such as sequential finger tapping) rather than mental strength training (i.e., imagery of strengthening exercises such as a bicep curl). A large meta-analysis concluded that motor imagery and motor execution of the leg, arm, and face utilize 30-40% of similar neural networks, including the bilateral cortical sensorimotor and premotor clusters, putamen, cerebellum, bilateral pre-supplementary motor area (SMA) and the SMA proper (Hardwick et al., 2018). Recent work by Persichetti and colleagues supports the premise that MP is represented by the superficial cortical layers (II/III) but not in the deeper layers (Vb) in contrast to movement execution which is represented in both (Persichetti et al., 2020). This evidence indicates that while imagined movement and executed movement do not use the exact same neural network, these networks appear to overlap.

The neural effects of long-term lingual MP use have not been extensively explored. Many prior studies on the neural underpinnings of MP primarily involve the upper and lower extremities, which are controlled by spinal nerves in contrast to the oropharyngeal structures, which are mediated by cranial nerves. Motor imagery of swallowing may cause an immediate decrease in cortical blood oxygenation in the inferior frontal gyrus, which has been attributed to inhibition of movement during imagery (Kober & Woods, 2014). However, it is not known how participation in a MP program over the course of several weeks affects cortical activation for lingual movement. As suggested by Robbins and colleagues (2008), there is evidence that neural plasticity plays a role in both the pathophysiological and recovery processes following cerebral injury. Therefore, the integration of clinical and neuroimaging science may help inform the design and dosing of dysphagia rehabilitation techniques to maximize both central and functional outcomes. Therefore, the objective of this study was to observe directional differences between cortical responses to physical and imagined lingual resistance as well as differences between signals recorded before and after 6 weeks of training. Specific questions included: 1) How does a lingual resistance exercise protocol, in physical, MP, and combined physical/MP form, affect cortical hemodynamic responses in healthy older adults? 2) What is the association between cortical response changes and changes in maximum isometric tongue pressure after lingual resistance training in physical, MP, and combined physical/MP form? Exploratory studies on MP in healthy participants validate and inform the design of future studies on MP in various patient models.

MATERIALS AND METHODS

Design

This exploratory study represents data from a smaller cohort of a previously published prospective randomized controlled study (Szynkiewicz et al., 2021) who participated in additional exploratory measures to compare hemodynamic responses (HDR) before and after a six-week lingual exercise regimen in groups with and without an MP component. Lingual exercise was chosen in this preliminary study given its relative simplicity for both physical practice and the conceptualization of the mental practice to novice users.

Participants

This study was approved by the Institutional Review Board prior to participant recruitment. All participants voluntarily signed approved consent forms. Thirteen healthy older adults (seven female) with a mean age of 65.7 years (range: 60-75) and without swallowing or neurological disorders were recruited from the university and community (Appendix). Other inclusion criteria included grossly normal oral structures and function with the ability to raise the body of the tongue to the hard palate, a score of <3 on the Eating Assessment Tool (EAT-10) (Belafsky et al., 2008) to screen out swallowing difficulty, mean score of >2.5 on the Kinesthetic and Visual Imagery Questionnaire (KVIQ-10, short version) (Malouin et al., 2007) to verify at least moderate imagery ability, and a score of >24 on the Mini Mental State Examination (MMSE) (Rovner & Folstein, 1987) to screen out probable cognitive impairment. Figure 1 illustrates the recruitment flowchart.

MP and Physical Practice Training

Participants were randomly assigned using a random number generator-created list to one of four exercise groups as previously described (Szynkiewicz et al., 2021) and outlined in Table 1. The exercises as described here represent one set. All participants were instructed to complete 3 exercise sets per day as assigned, 3 days per week for 6 consecutive weeks.

During an initial training session, participants in groups with physical-training components were instructed and allowed to practice the exercise until they demonstrated 100% accuracy on all physical exercises. Simple written instructions were given so participants could complete the exercises in their home environment, and exercises were reviewed in person every 2 weeks with re-education as needed. Participants with an MP component were observed during training to confirm that no overt physical muscle activation in the head/neck area occurred during the MP exercise (Szynkiewicz et al., 2021). A sensor in the mouth was not used during training so as to replicate the sensation and movement (or lack of movement) the participant would experience when completing their exercises at home.

Pre/post measures of maximum isometric lingual pressure were taken using an Iowa Oral Performance Instrument (IOPI, Version 2.3) with the bulb placed along the anterior dorsum of the tongue with the proximal end of the bulb just behind the maxillary central incisors as indicated by the manufacturer (IOPI Medical 2019). These values have been previously reported in a larger cohort (Szynkiewicz et al., 2021) and are reported again in this limited cohort for comparison to cortical activation changes.

Functional Near-Infrared Spectroscopy

Functional near infrared spectroscopy (fNIRS) is a non-invasive optical imaging technique that uses low levels of near-infrared light to measure blood flow changes in the brain associated with cortical activity, such as a movement task. Light emitter and light

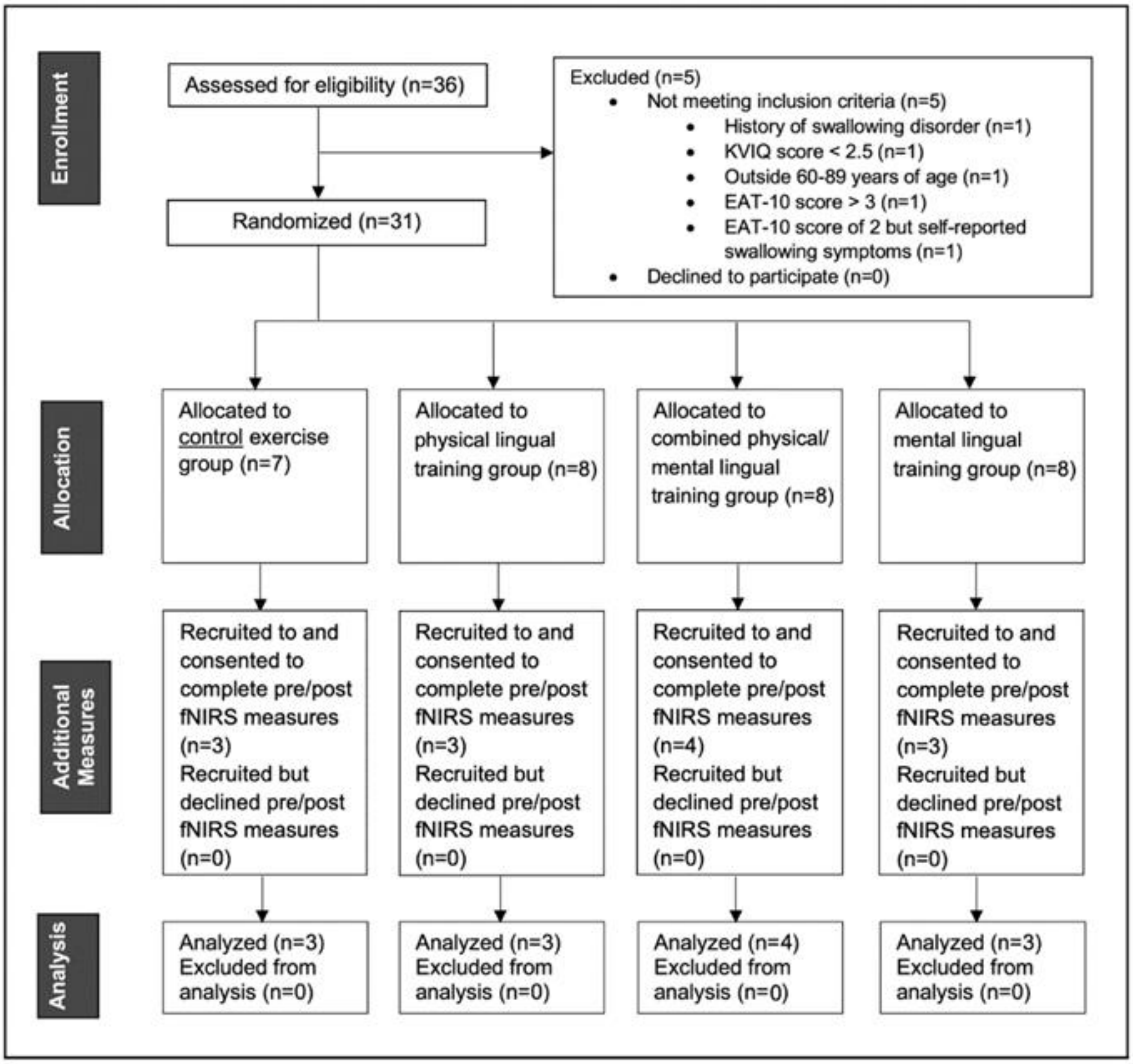


Figure 1. Consolidated Standards of Reporting Trials (CONSORT) flow chart

detector probes are placed on the scalp to continuously monitor regional tissue oxygenation. FNIRS has excellent temporal resolution (~1 ms), can control for head or body motion, and allows for measurements to be taken with the participant in an upright, natural position.

FNIRS recordings were completed at baseline prior to assigned exercise training and after the 6-week exercise regimen for each participant. Regions of interest (ROIs) were recorded bilaterally and included the lateral precentral motor (M1), lateral postcentral somatosensory (S1), and premotor cortex (PMC). ROIs corresponded with Montreal Neurological Institute (MNI) coordinates previously shown to be active during swallowing and lingual movement (Table 2) (Lowell et al., 2008; Martin et al., 2004). Each participant's head was normalized into MNI brain space using a 3-D digitizer (Brainsight, v2.0, Rogue Research Inc.) and a standard gender-matched MRI. Eyeglasses with optical position sensors (Polaris, Model 8800072, NDI) co-registered the MRI image to the participant's head using specific head/face anatomical locations as references. Ten emitter and detector pairs were spaced 3 cm apart from each other, 1.5 cm on either side of the MNI coordinates of interest (Figure 2, Table 2). A continuous wave fNIRS system (model CW6, Techen Inc.) recorded changes in concentrations of oxygenated and deoxygenated hemoglobin, which constituted the hemodynamic response (HDR). Each channel was gained individually prior to each recording session, and the sampling rate was 25 Hz.

Table 1. Participant group descriptions. Exercises described represent one set which was completed 3 times per day, 3 days per week, for 6 weeks.

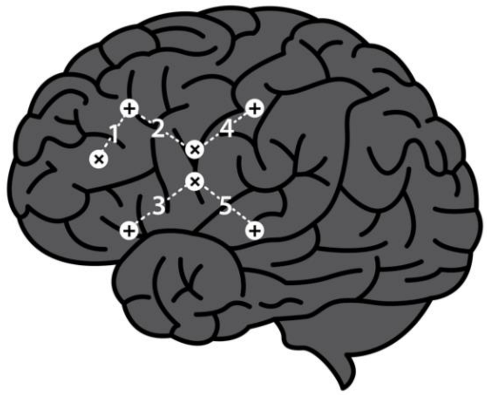
Control group	Jaw exercises 1. Opening against manual, self-applied maximal resistance[1] x 10 2. Closing against manual, self-applied maximal resistance[1] x 10 3. Lateralization against manual, self-applied maximal resistance[1] x 10 4. Protrusion against manual, self-applied maximal resistance[1] x 10 Mental component 1. 10 minutes of visualization relaxation exercises
Physical training group	Lingual exercises[2] 1. Protrusion against manual, self-applied maximal resistance[3] x 10 2. Elevation against manual, self-applied maximal resistance[3] x 10 3. Left lateralization against manual, self-applied maximal resistance[3] x 10 4. Right lateralization against manual, self-applied maximal resistance[3] x 10
Mental/Physical training group	Lingual exercises[2] 1. Protrusion against manual, self-applied maximal resistance[3] x 10 2. Elevation against manual, self-applied maximal resistance[3] x 10 3. Left lateralization against manual, self-applied maximal resistance[3] x 10 4. Right lateralization against manual, self-applied maximal resistance[3] x 10 Mental practice[4] of 1. Maximal effort lingual protrusion x 10 2. Maximal effort lingual elevation x 10 3. Maximal effort lingual left lateralization x 10 4. Maximal effort lingual right lateralization x 10
Mental training group	Mental practice of 1. Maximal effort lingual protrusion x 10 2. Maximal effort lingual elevation x 10 3. Maximal effort lingual left lateralization x 10 4. Maximal effort lingual right lateralization x 10

[1]Resistance applied with hand; [2]Exercise routine replicated from Lazarus et al. (2003); [3]Resistance applied with a standard wooden tongue depressor; [4]Mental practice completed separately from physical practice

Table 2. MNI Coordinates of Regions of Interest* for Hemodynamic fNIRS Recordings (x, y, z)

	Left	Right
Precentral Cortex (M1)	-50, -6, 37 -53, 2, 21	50, -6, 37 53, 2, 21
Postcentral Cortex (S1)	-57, -2, 40 -59, -19, 24	52, -21, 40 57, -19, 24
Premotor Cortex (PMC)	-45, 6.5, 40	42, 6.5, 42

*ROIs determined by coordinates previously shown to be active during lingual movement by Lowell et al. (2008) and Martin et al. (2004).



X: Emitters; +: Detectors
Pairing 1= Premotor cortex; Pairings 2 & 3= Precentral gyrus (M1);
Pairings 4 & 5= Postcentral gyrus (S1)

Figure 2. Topographical illustration of fNIRS array, which was recorded bilaterally

Tasks During fNIRS Recording

Tasks during the fNIRS recording were presented in an event-related design and included pushing the anterior tongue against the IOPI bulb with maximal force for 2-3 seconds (s) (lingual maximum isometric pressure [MIP]) and motor imagery of pushing the anterior tongue against the IOPI bulb with maximal force for 2-3 s (MP-MIP). Participants were trained to each task prior to the recording. Tasks were completed in two separate blocks of lingual MIP and MP-MIP with 20 trials in each block. This reduced the risk for mental fatigue during motor imagery (Gentili et al., 2010). The order of the blocks was randomized. Interstimulus intervals alternated between 20 s and 30 s. Participants were seated upright in front of a large screen which provided written instructions, including "Push your tongue up hard," and "Imagine pushing your tongue up hard." Kinesthetic imagery was encouraged (e.g., "Think about how it feels."). Between stimuli, the screen read "Rest" and participants were instructed to try not to move during the rest periods.

Lingual MIP task completion was verified from the oral pressure patterns. Lingual to hard palate pressure was recorded using an Iowa Oral Performance Instrument (IOPI, Version 2.3) with the same bulb placement as previously indicated. During the fNIRS tasks, the IOPI sampling rate was 4 kHz and the instrument was calibrated from volts to kilopascals (kPa) at every session. MP-MIP trials were confirmed by asking the participants to push a hand-held button when they began to mentally imagine the tongue push and to stop pushing the button when they were done. To minimize procedural differences between tasks, the participants were also asked to push the hand-held button during MIP. Digital signals were recorded using PowerLab 16/35 and LabChart 8 software (AD Instruments, Inc.) and were also transposed into fNIRS recording using auxiliary channels to time synchronize the physiological and hemodynamic signals.

Signal Processing

Oral pressure signals from the IOPI were used to mark the onset of lingual MIP trials. Oral pressure signals were low pass filtered at 50 Hz and then normalized to percent effort with the largest oral pressure wave across the entire session equaling 100%. The mean signal during rest was averaged across at least 10 segments and normalized as 0%.

The onset time for MIP trials was defined as the moment when oral pressure signal reached 10% of maximum at the beginning of a cued push. MP-MIP onset was defined as the moment when the pulse generator signal left zero indicating the participant pushed the button at the beginning of motor imagery. MP-MIP trials that demonstrated oral pressure >10% of maximum when the participant indicated they were performing mental practice were discarded as the participant had actively moved the tongue, contrary to instructions. This eliminated 43 out of 520 mental push trials from the analysis (8%). The average number of trials eliminated per participant per session was 1.7 ± 2.8 (range: 0-11).

FNIRS data preprocessing was completed in HOMER3 (Huppert et al., 2009) using Matlab 2017 (The MathWorks Inc., Natick, MA). Raw wavelengths were converted to optical density values. Physiological signals (Mayer's waves, respiratory, cardiac) were removed with a bandpass filter at 0.01-0.5 Hz. Motion correction was completed using a correlation-based signal improvement filter (Cui et al., 2010) and adaptive short separation filtering. Optical density was converted to hemoglobin concentrations with the application of the modified Beer-Lambert law. The event-related averages of oxygenated hemoglobin (OxyHb) from -5 s to 20 s from task onset were exported from HOMER3 into Excel. In order to control for baseline level hemodynamic activity, OxyHb signals were normalized to baseline activity by subtracting out the average of the baseline signal for each channel. Baseline was defined at -5 s to 0 s prior to task onset. The median value from each channel from 5-20 s post task onset was computed (Herold et al., 2018), similar to the analysis methods of other fNIRS studies (Kober et al., 2014). Any channel with a median value standard deviations above or below the hemispheric mean was removed from the analysis as having excessive noise, eliminating 3 of the 520 channel signals recorded for the study (0.0058%). Given the limited spatial resolution of fNIRS and that the specific location of each channel was not confirmed with MRI, a reliable comparison between motor and sensory areas could not be completed. Therefore, all of the remaining channels were averaged for each participant and each task so that each participant had one median OxyHb value for each task per visit. The change in aggregated median value from baseline to after the 6-week exercise regimen was computed for each participant and each task (OxyHb change).

Analysis

Given the small number of participants in each group, statistical group comparisons were not completed. Descriptive statistics including means and standard deviations were computed in SPSS (V.27, IBM).

RESULTS

Adherence to the prescribed exercise regimens was documented by participants' logs and ranged from 72-100%. Adherence by group is detailed in Table 3. The control group had the highest adherence (100%), while the physical training group averaged the lowest (90.7%).

Examination of the average duration for each task indicate that a similar amount of time was spent on the execution of both tasks (lingual MIP = 2.34 ± 1.5 s; MI-MIP = 2.34 ± 1.8 s), which is important for the comparison of signals across tasks. Figure 3 demonstrates the time course of the oxygenated hemodynamic signal during both tasks (MIP/MP-MIP) and time points (baseline/post exercise program) aggregated across all participants. Table 4 provides group averages and standard deviations.

Figure 4 illustrates changes in cortical activation by task and group. During lingual MIP, all three treatment groups demonstrated a decrease in cortical activation over time, which was not demonstrated by the control group. The group completing physical/mental training demonstrated the greatest negative change in oxygenation post-treatment. During lingual MP-MIP, only the two groups who were assigned mental training as part of their exercise protocol demonstrated a decrease in cortical activation. The control and the physical training group demonstrated an increase in cortical activation.

Figure 5 demonstrates the association between changes in oxygenated hemoglobin during each task to changes in maximum lingual isometric pressure (lingual MIP in kPa) at the end of treatment. Nine out of 13 participants made positive changes in their MIP, indicating gained lingual strength. Of those participants, the majority demonstrated negative changes in their oxygenated hemoglobin during MIP and MP-MIP (6/9 and 7/9, respectively). Individual changes are also provided in the Appendix.

Table 3. Group Adherence (mean, standard deviation) expressed in percentage of exercise completed relative to assigned

Control	100 (0.00)
Active Training	90.7 (16.2)
Mental/Active Training	96.7 (3.1)
Mental Training	96.2 (7.9)
	Mean = 96.2 (7.9)

DISCUSSION

This exploratory descriptive study contributes to the limited data regarding changes in cortical activation following a lingual resistance mental training program. Examination of the hemodynamic signal across groups (Figure 3) shows that while MP of lingual resistance (MP-MIP) resulted in some positive signal at baseline, the overall effect is small, and the signal is predominantly negative compared to the magnitude of the cortical response to physical MIP. These results are similar to those seen by Kober et al. (2014), who compared sequential swallowing to the motor imagery of swallowing in a block design. Their results indicated an increase in oxygenated hemoglobin following swallowing execution and a decrease following the MP of swallowing, the latter of which was attributed to motor inhibition. Reduced oxygenation has also been observed during visuomotor response inhibition and was enhanced with improved inhibitory performance (Gentili et al., 2013). New work completed with non-blood-oxygen-level-dependent (BOLD) fMRI found that imagined finger tapping suppresses the cortical response to subsequent finger tapping in the superficial layers while it enhances the response in the deeper cortical layers (Persichetti et al., 2020). Therefore, it is possible that the negative response seen during motor imagery (MP-MIP) in this study, particularly at 10-20 seconds, is related to suppressive or inhibitory mechanisms.

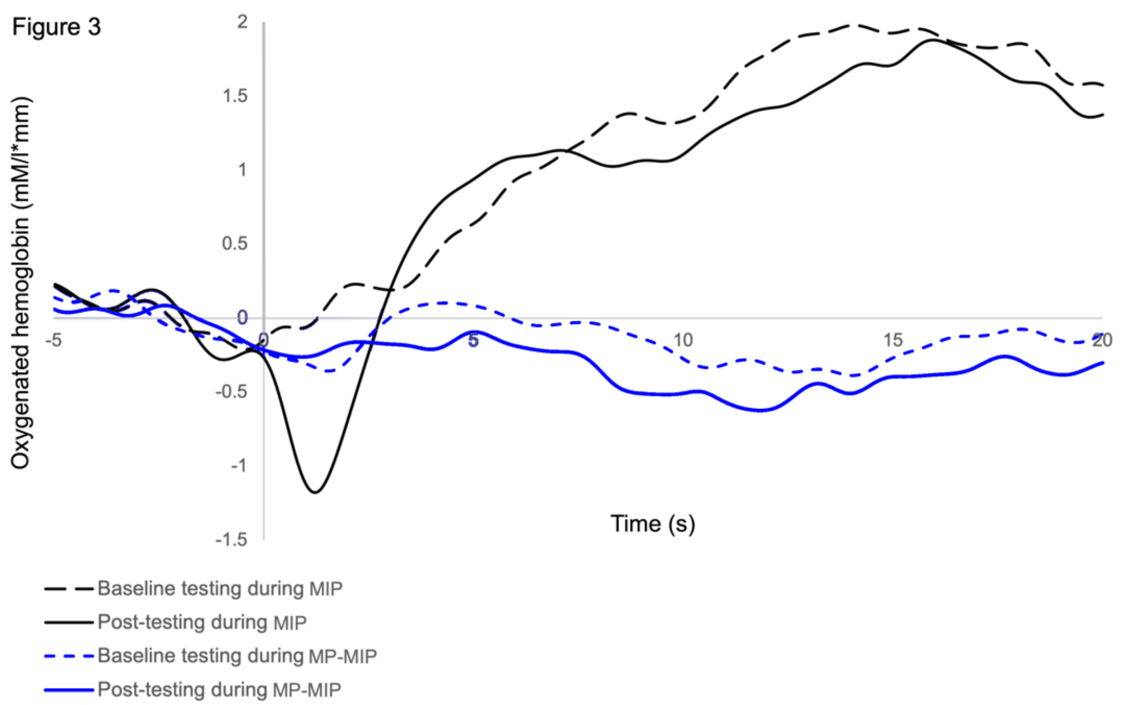


Figure 3. Time course of aggregated oxygenated hemodynamic response for lingual maximal isometric pressure and mental practice of maximal isometric pressure at baseline and post-training averaged across all participants.

Table 4. Oxygenated hemoglobin (mean, standard deviation) by group, task, and time

	Control, N=3		Physical training, N=3		Mental/physical training, N=4		Mental training, N=3	
Task	Baseline	Post	Baseline	Post	Baseline	Post	Baseline	Post
Physical lingual resistance	0.73 (1.1)	0.78 (1.3)	0.44 (0.4)	0.16 (0.4)	1.8 (1.4)	0.49 (0.5)	1.4 (2.6)	1.2 (1.2)
Mental lingual resistance	-0.28 (0.6)	-0.12 (0.33)	-0.6 (1.6)	-0.19 (0.8)	-0.39 (0.5)	-0.72 (0.8)	0.45 (0.9)	-0.15 (0.5)

Note. Unit is oxygenated hemoglobin in mM/l*mm

The main goal of this study was to determine how participation in a lingual exercise program in both physical and MP forms affects cortical plasticity for those tasks. These preliminary findings suggest that for healthy participants, participation in a lingual exercise program may decrease cortical activation for lingual resistance. This aligns with previous findings on exercise and neural plasticity with decreased activation in the primary sensorimotor cortex and premotor cortex during the physical task across all groups who received training (Ruffino et al., 2017). A combination of physical and mental training may increase the neural changes compared to participants who completed just a single type of exercise (either physical or mental alone, Figure 4A). Interestingly, our findings indicate that MP may decrease the oxygenation levels similarly to physical training, even without physical exercise (Figure 4A). Therefore, it is

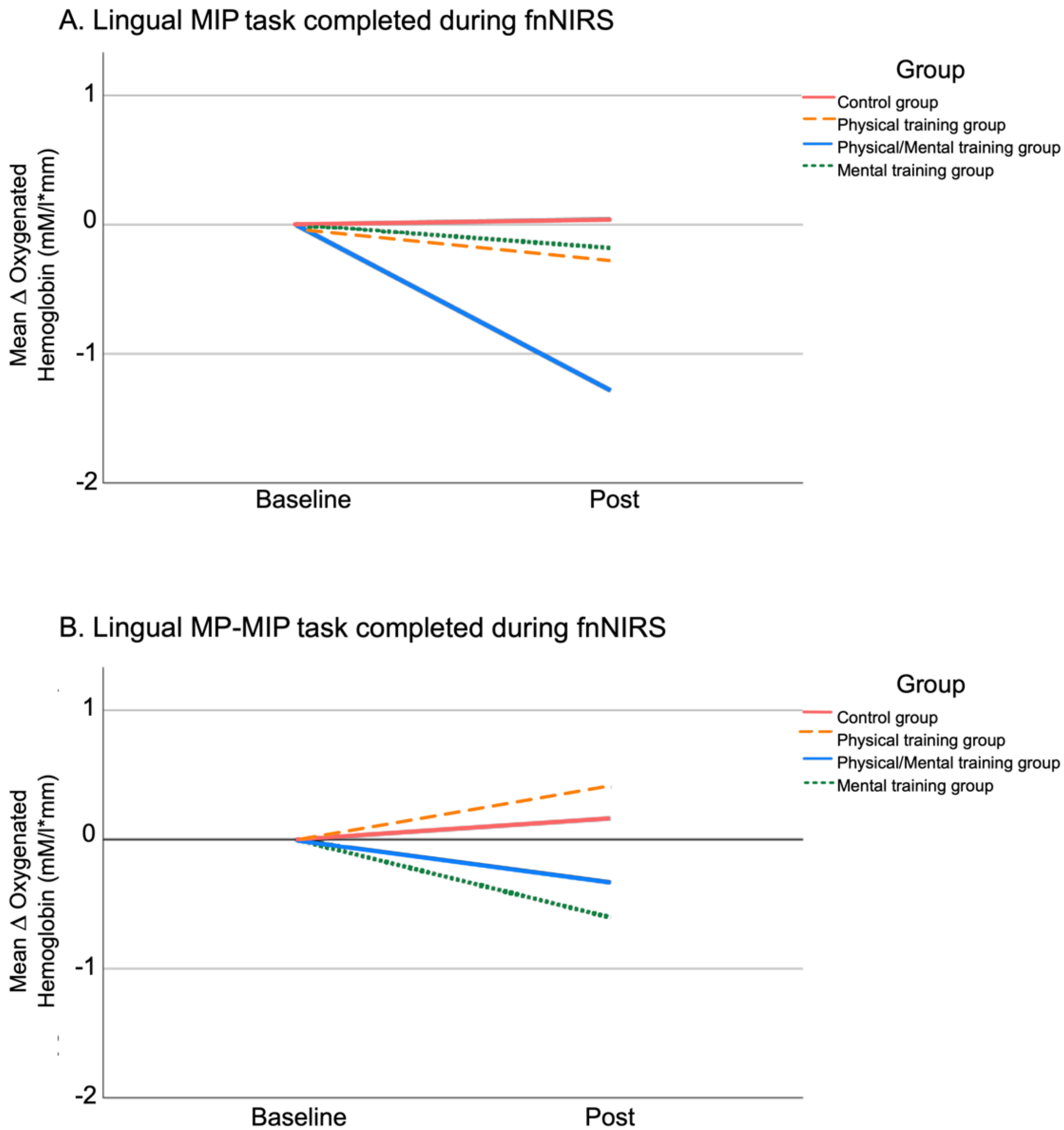


Figure 4. Average change in oxygenated hemoglobin from baseline to post-training per group during (A) lingual maximal isometric pressure task (MIP) recorded during fNIRS, and (B) mental practice of lingual maximum isometric pressure task (MP-MIP) recorded during fNIRS.

possible that mental practice training may result in cortical neuroplastic changes analogous to those seen after physical training, albeit likely to a lesser effect. This phenomenon was not observed for the physical practice group during MP recordings; however, this group did not have oxygenation decreases during the motor imagery of lingual resistance task (Figure 4B). The changes during MP were specific only to the groups who were trained to this task.

A glimpse at a potential trend in association between functional change with increased lingual pressure and cortical activation changes is evident from Figure 5. Correlation statistics are not appropriate given the small sample size in this exploratory study. However, the scatterplots in Figure 5 suggest a trend for the majority of non-control participants having a positive change in lingual pressure with an associated decrease in cortical activation at the end of 6 weeks. Participants

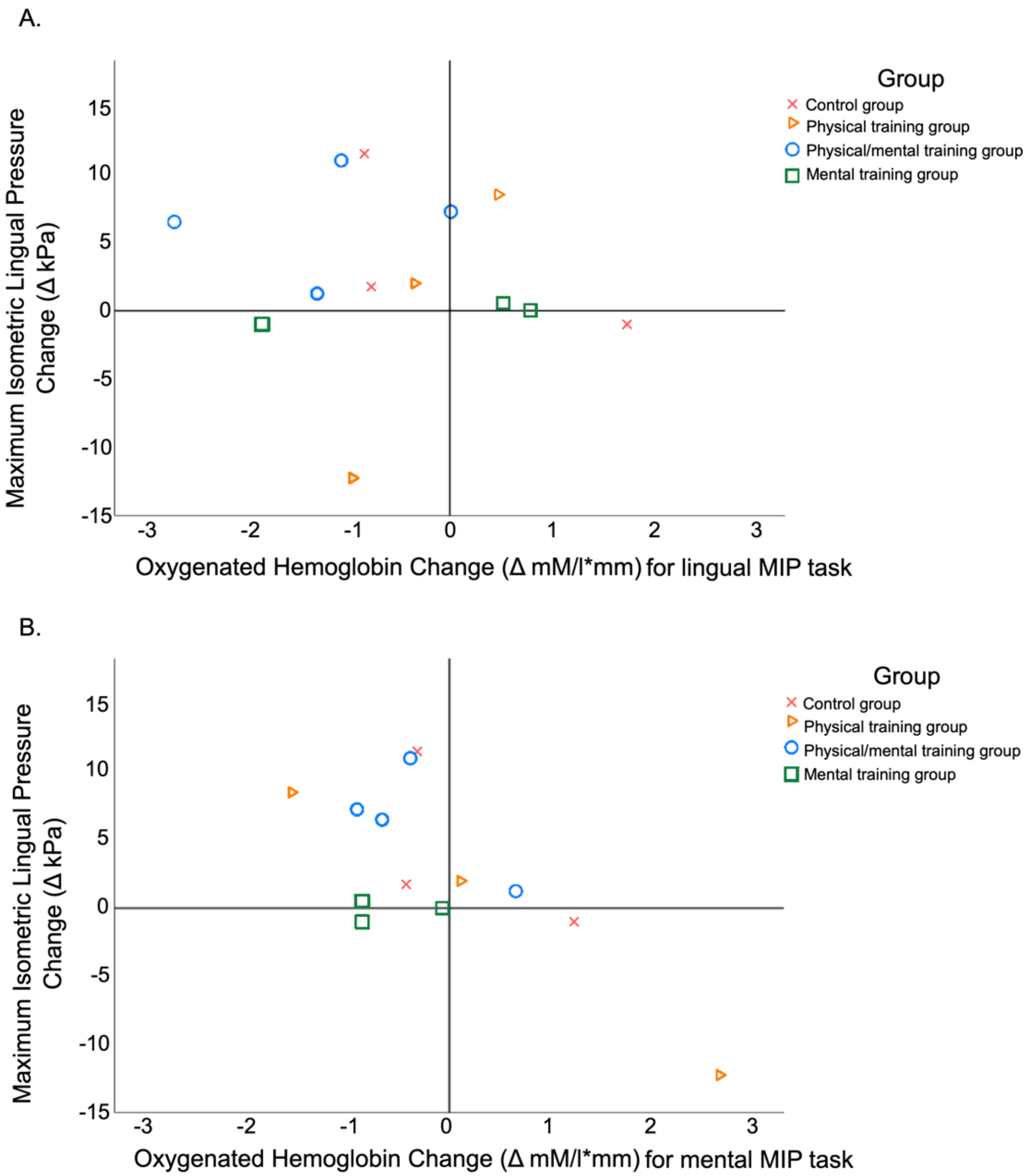


Figure 5. Scatterplots of individual associations between lingual pressure changes and oxygenated hemoglobin changes post-training during (A) lingual maximum isometric pressure (MIP) task recorded during fNIRS and (B) mental practice of lingual maximum isometric pressure (MP-MIP) task recorded during fNIRS. In each figure, the x-axis represents changes in cortical activation changes as measured by OxyHb differences between weeks 0 to 6. The y-axis represents change in lingual strength from weeks 0 to 6, as measured by maximal isometric pressure. Lingual pressures and fNIRS recordings were not taken simultaneously.

in the physical/mental training group particularly show this associative trend. This emerging direction warrants further investigation and, in combination with the data showing groups that included mental training with the greatest apparent decrease in oxygenated hemoglobin at 6 weeks, suggests the promise for continued research that includes a mental component of exercise.

The decrease in cortical activation shown across the treatment groups reflects similar patterns previously demonstrated for strength training. In chronic stroke patients, an inverse correlation has been established between CNS activation magnitude and the degree of recovery (Lotze & Cohen, 2006). The neural substrates responsible for complex motor sequences tend to become smaller with physical training in normal volunteers (Morgen et al., 2004) and with rehabilitation in patients post-stroke (Ward, 2004). MP has been shown to have similar neural plastic effects to strength training in past research as well (Cicinelli et al., 2006). In patients post-stroke who have abnormal asymmetry between the affected and non-affected hand cortex, MP prompted increased cortical hand-representation volume that partly normalized the asymmetry (Cicinelli et al., 2006).

There has been limited application of mental practice in dysphagia rehabilitation. Previous work in mental practice indicates that the hemodynamic response during imagined swallowing can be modulated with neurofeedback (Kober et al., 2015). Training in mental practice with neurofeedback over the course of several sessions also affected the cortical activation patterns seen during post-testing, which the authors interpreted as a plasticity process (Kober et al., 2015). A follow-up study further elucidated that neurofeedback during mental practice of swallowing allows for the up-regulation of deoxygenated hemoglobin and the downregulation of oxygenated hemoglobin but not a reverse pattern, which enhances the natural course of the hemodynamic response during motor imagery as seen in their work (Kober et al., 2018) and in the data presented here. While this concept holds promise, it is not yet known if the combination of mental practice with neurofeedback augments dysphagia rehabilitation.

MP of a simple task involving an oral structure translated into behavioral (Szynkiewicz et al., 2019; Szynkiewicz et al., 2021) and potentially neural plastic changes, especially when combined with physical practice. This adds to previous data suggesting that adding MP to a therapy program may have applicability for other oropharyngeal structures and functions, possibly impacting the oral and pharyngeal phases of swallowing and other oropharyngeal disorders. While this line of research is just beginning, it has relevance for patients who are at a high risk of aspiration and who fatigue easily. Given the promising research from the limb literature (Caligiore et al., 2017; Garcia Carrasco et al., 2016; Page et al., 2011), lingual and swallow MP have the potential to expand management of dysphagia and other oral therapies by enhancing physical training outcomes for patients with limited ability to participate in traditional swallowing exercises. Potential patient populations that may benefit from this technique include patients with stroke, Parkinson’s disease, myasthenia gravis, amyotrophic lateral sclerosis, and orofacial myofunctional disorders. There is some evidence that children and adolescents, including those who have physical impairments or mild cognitive impairments, can implement and may benefit from MP (Behrendt et al., 2021). Given the abstract nature of MP, it is likely that cognitive abilities will play a role, like it does for many rehabilitative methods, in determining which patients are appropriate for this technique moving forward. MP may also provide additional motivation for patients to complete their physical home-exercise program. Generally, patient adherence to dysphagia treatment recommendations is low (21.9-51.9%) (Krekeler et al., 2018). Common reasons for not participating in a home exercise program include fear of injury, fatigue, and pain (Miller et al., 2017). If an efficacious MP plus rehabilitation program can be made simple and easy, it may help improve adherence to therapy as additional negative physical consequences would be unlikely, thus promoting both motor gains and neural plasticity.

Limitations

This study has a small sample size (n=13), prohibiting statistical group comparisons, thus limiting its interpretation. Relatedly, there is large variability in the data and multiple baselines were not obtained, which also limits its interpretability. Individual differences are reflected in Figure 5 and the Appendix and illustrate variability even within groups.

Despite asking participants to log their adherence to exercise practice, it is impossible to unequivocally confirm their practice or to know its quality, which is a limitation of this design. However, diaries such as those used in this study have been found to have a moderate-to-high concordance with nonself-reported measures (Garber et al., 2004).

As with all studies using fNIRS as a tool to measure cortical activation, subcortical structures could not be monitored and the area of the regions of interests was limited by the size of the optode array. While there may be some participant movement during the fNIRS tasks that could lead to motion artifact within the signal, several procedures mitigated this problem. First, two motion correction filters were applied to the data during processing, including short separation channels. Second, data were taken from the signal 5-20 s after task onset. Tasks lasted an average of just over 2 s, so any motion artifact would not be included in the utilized signal. Finally, all signals were reviewed visually and channels excluded if they exceeded a preset standard deviation limit.

An IOPI bulb was used during the fNIRS recording to verify absence or presence of lingual movement. During exercise training, we visually confirmed that the participants did not move their tongue during the MP practice (Szynkiewicz et al., 2021), but this was not confirmed with electromyography or an oral pressure reading. Further, other than explicit training and instruction, there was no confirmation for the lack of tongue movement during MP home practice, which may be a limitation. Also, it is acknowledged that strength is not the only factor that can change following physical exercise. As the participants progressed through their exercise programs, they likely gained not only strength but improved in other areas as well, such as task coordination, endurance, and general cognitive familiarity with the task, all of which may have influenced the neural responses.

CONCLUSION

This study provides preliminary, exploratory evidence that participation in a lingual resistance program for 6 consecutive weeks may result in neural plastic changes similar to those seen after other strength training programs. While MP alone also resulted in cortical activation changes, a combination of physical practice with mental practice seemed to increase these changes beyond those seen with physical exercise alone. The possibility of an association between functional lingual pressure changes and decreased cortical activation deserves further exploration. MP is a promising, innovative approach that may enhance physical swallowing practice, particularly for those patients with limited physical ability, fatigue, or pain. Further research is needed regarding functional outcomes in a patient model. Future directions include utilizing various patient models to continue investigating the neural correlates of functional physiological improvements, as well as to validate the addition of mental practice to dysphagia rehabilitation programs.

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APPENDIX

Participant Demographics and Individual Changes in OxyHb and Maximum Isometric Lingual Pressure Organized by Group

Participant ID	Group	Age	Sex	OxyHB Δ during Physical Lingual Resistance Task (mM/L*mm)	OxyHB Δ during Mental Lingual Resistance Task (mM/L*mm)	Maximum Isometric Lingual Pressure Δ (kPa)
1	Control	65	M	-0.85	-0.32	11.5
7	Control	71	F	-0.78	-0.43	1.75
11	Control	64	F	1.76	1.24	-1.0
3	Physical Training	66	M	-0.35	0.11	2.0
9	Physical Training	68	M	-0.97	2.69	-12.25
10	Physical Training	75	F	0.48	-1.57	8.5
2	Physical/Mental Training	66	F	-1.32	0.66	1.25
6	Physical/Mental Training	62	F	-2.74	-0.67	6.5
8	Physical/Mental Training	61	F	0.01	-0.92	7.25
13	Physical/Mental Training	67	M	-1.08	-0.39	11.0
4	Mental Training	64	F	0.80	-0.07	0.0
5	Mental Training	60	M	-1.87	-0.87	-1.0
12	Mental Training	65	F	0.53	-0.87	0.5