

Brain Activation During Oral Exercises Used for Dysphagia Rehabilitation in Healthy Human Subjects: A Functional Magnetic Resonance Imaging Study

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Received: 12 December 2010 / Accepted: 17 October 2011 / Published online: 11 November 2011
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Abstract Oral exercises, including tongue, lip, and jaw movements, are commonly used in clinical practice as training to improve oral and pharyngeal swallowing in dysphagia patients. These rehabilitation exercises are believed to affect the peripheral and central nervous system at various levels. However, few studies have examined healthy subjects' brain activity while performing oral exercises used in dysphagia rehabilitation. The current study sought to measure brain activation during oral exercises in healthy subjects using functional magnetic resonance imaging (fMRI). Lip-pursing and lip-stretching, tongue protrusion, lateral tongue movement, and oral ball-rolling were selected as tongue and lip exercise tasks. The tasks were performed by eight healthy subjects, and the fMRI data were submitted to conjunction analyses. The results confirmed that head movements during all tasks exhibited translation of <1.0 mm and rotation of $<1.0^\circ$ in

x , y , and z coordinates. We found several clear regions of increased brain activity during all four oral exercises. Commonly activated regions during tongue and lip exercises included the precentral gyrus and cerebellum. Brain activation during ball-rolling was more extensive and stronger compared to the other three oral exercises.

Keywords Brain activity · fMRI · Dysphagia rehabilitation · Oral exercise · Tongue and lip movements · Deglutition · Deglutition disorders

The number of people in Japan requiring nursing care has increased to more than 4.67 million due to the rapid aging of the population [1]. The number of elderly dysphagia patients requiring nursing care has increased accordingly. Dysphagia rehabilitation has been approached from the various perspectives of medical care, nursing, and welfare.

Oral exercise training, such as tongue training, is often used in clinical practice to improve the oral and pharyngeal stages of swallowing. Pharyngeal constrictor muscle weakness, tongue and lip movement disorders associated with swallowing, can be improved by oral exercise training. In addition, oral exercises are thought to have a favorable influence on the peripheral and central nervous systems [2]. However, brain activity during oral exercises has not been systematically examined in healthy elderly subjects.

With the development of functional magnetic resonance imaging (fMRI), brain activity can be visualized using the blood oxygen level-dependent (BOLD) signal [3, 4]. fMRI has several advantages over other methods, i.e., it is a noninvasive technique using nonradioactive isotopes that can achieve high spatial resolution. Functional mapping of the human brain is becoming a standard technique in brain

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science. Brain mapping has been applied in the fields of cerebrophysiology, cognitive science, and psychological neurology, among others [5–28].

Several recent studies have examined brain activity while swallowing saliva or water [12, 20]. However, only a small number of studies have used fMRI to examine brain activity during oral exercises, even in healthy subjects. Kern et al. [29] reported that brain activity during volitional swallowing and swallowing-related motor tasks was similar in terms of regions of activity, volume of activated voxels, and increases in signal intensity. We designed an oral exercise involving ball-rolling inside the mouth as a new exercise for oral disuse-atrophy patients. To test the effectiveness of this novel exercise, we observed brain activity while it was performed. Additionally, we measured brain activity during conventional tongue and lip exercises for comparison with our new technique.

Materials and Methods

Subjects

We tested eight healthy right-handed young adults (four males, four females; mean age = 28.5 years, age range = 27–33 years) without any history of neurological or psychiatric disorders. This study was approved by the Committee of Medical Ethics, Graduate School of Dentistry, Kyushu University (approval No. 2006-2). Informed consent was obtained from each subject after explaining the protocol of the study.

Task Paradigm

The following four exercises were selected as tasks from the range of oral exercises used for dysphagia rehabilitation:

1. Lip-pursing and lip-stretching exercise: repeatedly pulling a corner of the mouth and projecting the lip.
2. Tongue protrusion exercise: repeatedly projecting and pulling on the tongue.
3. Lateral tongue exercise: repeatedly pushing the tongue edge against the right and left buccal mucosa alternately.
4. Oral ball-rolling exercise: repeatedly rolling a spherical object to the right and left sides of the mouth, as if tasting a piece of candy. The object consisted of a ϕ 1.8-cm ball made of polyvinyl chloride plastic (Fig. 1), with 40-cm nylon strings attached to the ball surface to prevent accidental ingestion.

All four tasks were performed at the subjects' own pace. Each task session was presented in a block design. Subjects

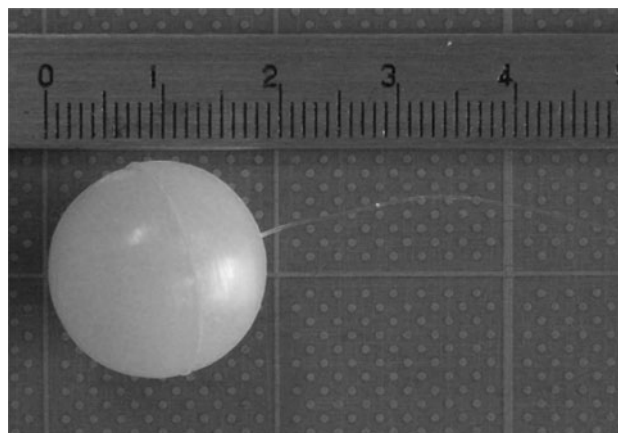


Fig. 1 Plastic ball used in oral ball-rolling exercise

performed six alternating rest blocks of 32 s with five task blocks of the same duration. Each scanning paradigm began with a rest block. Each task session lasted for a total of 352 s (Fig. 2). Subjects were allowed to swallow saliva in the first 4 s of each block, which was designated as the swallowing period. All tasks were practiced in order to acquire appropriate data within a couple of days before the scanning procedure.

Subjects lay supine on the scanner bed. Their heads were fixed with cushions and medical tape to minimize head movement. Subjects wore eye masks to help them keep their eyes closed, and earplugs to listen to an auditory signal and block out the loud noise of the scanner.

Image Acquisition

fMRI data were acquired with a 1.5-T MR scanner (Symphony; Siemens AG, Erlangen, Germany) using a gradient-echo echo-planar imaging (EPI) sequence. An EPI pulse sequence was used with the following parameters: repetition time (TR) = 4,000 ms, echo time (TE) = 50 ms, field of view = 230 mm, matrix size = 64 × 64 pixels, voxel size = 3.6 mm × 3.6 mm × 3.0 mm, and slice thickness = 3.0 mm. The anatomical data (T1 weighted) from each subject was scanned after functional data (T2 weighted) scanning.

Data Analysis

Individual data were analyzed using Statistical Parametric Mapping software (SPM5, Wellcome Department of Cognitive Neurology, London, UK) implemented in Matlab (Mathworks, Natick, MA, USA). The first eight volumes were discarded because of the instability of magnetization. Remaining data were realigned to remove the effects of head motion. After coregistration, the data were

Fig. 2 The block design. *R* rest 32 s, *T* task 32 s, *S* allowed swallowing region 4 s

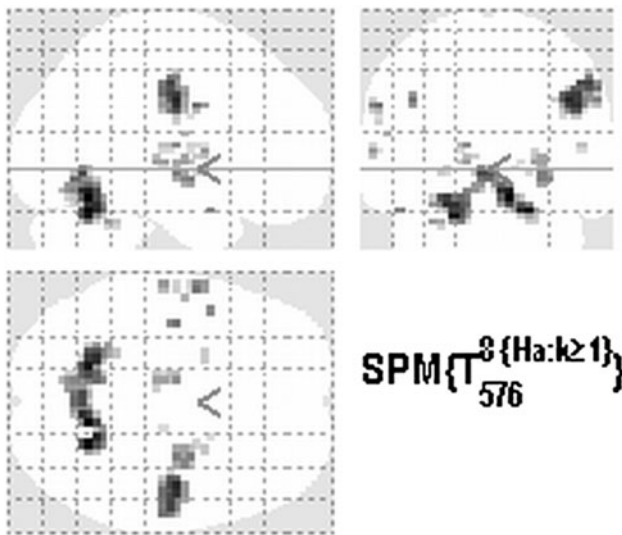
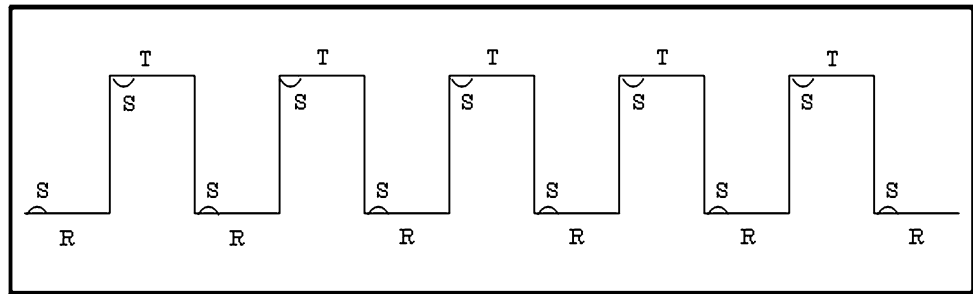


Fig. 3 Regions of activation during lip-pursing and stretching revealed by conjunction analysis ($n = 8$). Activated regions are superimposed on a MNI template. A voxel height threshold was set at by FWE < 0.01 . Signal intensity is represented by an arbitrary color scale

normalized to the Montreal Neurological Institute (MNI) template. The data were then spatially smoothed with an 8-mm full-width at half-maximum (FWHM) kernel. All individual data were incorporated into group analysis using conjunction analyses [30–32]. Increases in the BOLD signal were evaluated by comparing the rest and task conditions in both analyses.

The conjunction analysis was performed using one-sample t -tests. Statistical significance was established at

family-wise error (FWE) < 0.01 . The anatomical locations of brain activity increases were transformed into MNI coordinates and identified using free Wake Forest University (WFU) PickAtlas software. The activated region was characterized in terms of peak height over 15 clusters.

Results

A total of 80 functional MR images were obtained, and residual head movement after realignment of all subjects exhibited translation < 1.0 mm and rotation $< 1.0^\circ$ in x , y , and z coordinates in all four tasks. Therefore, the data were considered validated and reliable, reflecting brain activation related to the motor tasks being performed. Regions of increased brain activation during the four tasks were observed in all subjects. However, the regions of brain activation and maximal t -values differed among tasks. The results of the four tasks are discussed below.

Figure 3 shows the brain areas exhibiting increases in activation during the lip-pursing and lip-stretching exercise. The results revealed activation increases in both hemispheres of the cerebellum, the precentral gyrus, post-central gyrus, and the lentiform nucleus of the right hemisphere. Regarding focal brain activation, the increase in the BOLD signal was greater in the right than in the left hemisphere (see Table 1 for MNI coordinates).

Figure 4 shows areas of increased brain activation during the tongue protrusion exercise. The results revealed activation increases in the bilateral precentral gyrus and the right hemisphere of the cerebellum. Increases in the BOLD

Table 1 Localization (MNI coordinates) for significantly activated voxels located within a cluster larger than 15 voxels, maximal t -value, cluster size, and regions of activation during lip-pursing and stretching

R/L	Region of activation	Cluster size	Maximal t -value	MNI coordinates of max-voxel		
				x	y	z
R	Cerebellum	143	2.55	11	-58	-15
R	Cerebellum		2.51	22	-58	-21
L	Cerebellum		2.40	-18	-58	-24
R	Precentral gyrus	82	2.28	43	-11	36
R	Precentral gyrus		2.06	54	-14	45
R	Precentral gyrus		1.61	58	-14	36
R	Lentiform nucleus	17	1.65	29	-11	-3

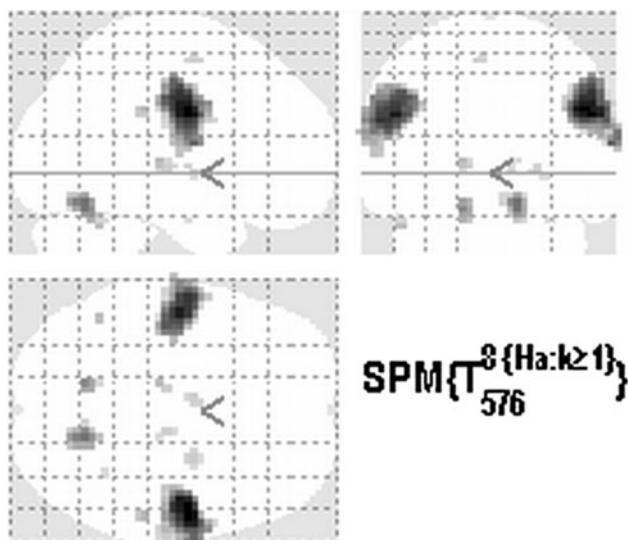


Fig. 4 Regions of activation during tongue protrusion exercise revealed by conjunction analysis ($n = 8$). Activated regions are superimposed on a MNI template. A voxel height threshold was set at by FWE < 0.01 . Signal intensity is represented by an arbitrary color scale

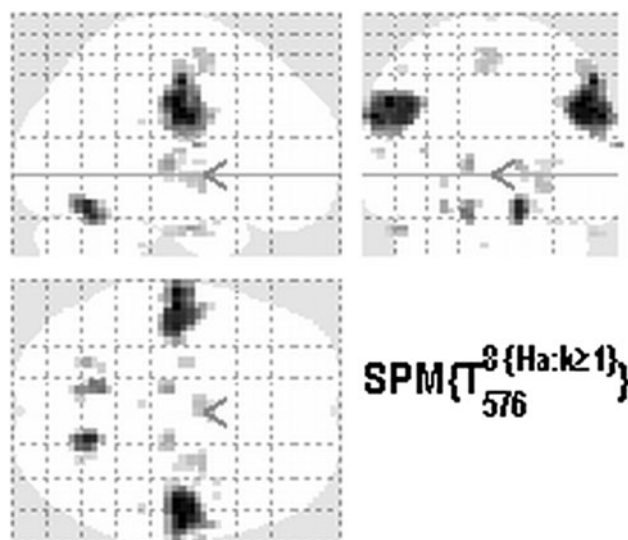


Fig. 5 Regions of activation during lateral tongue exercise revealed by conjunction analysis ($n = 8$). Activated regions are superimposed on a MNI template. A voxel height threshold was set at by FWE < 0.01 . Signal intensity is represented by an arbitrary color scale

signal were observed in both hemispheres (see Table 2 for MNI coordinates).

Figure 5 shows the brain areas that exhibited increased activation during the lateral tongue exercise. Regions exhibiting significant activation were in the precentral gyrus and cerebellum of both hemispheres, the lentiform nucleus of the right hemisphere, and the medial frontal gyrus of the left hemisphere. Increased brain activation during the lateral tongue exercise task was found to be bilateral (see Table 3 for MNI coordinates).

Figure 6 shows the brain areas that exhibited increased activity during the oral ball-rolling exercise. The results revealed bilateral activation increases in the cerebellum, precentral gyrus, thalamus, and medial frontal gyrus, as well as activation in the left postcentral gyrus and left lentiform nucleus (see Table 4 for MNI coordinates).

The precentral gyrus (considered to function as a motor area) and the cerebellum (thought to control motor and sensory function) were observed in all tasks. In addition, we found no significant differences between hemispheres

in any task. However, of the four tasks, the greatest number of areas of bilateral activation and the highest t -value were observed during the ball-rolling task. Moreover, the cluster sizes during the oral ball-rolling exercise were larger than those in the other three tasks.

Discussion

Since only eight subjects were examined in this study, we applied conjunction analyses. Friston et al. [30] recommend that conjunction analyses provide a conservative approach for dealing with small numbers of subjects.

A number of studies have reported that head movements can cause problematic artifacts in fMRI recording. However, only a few previous studies examined the effects of head movements on brain activity during functional motor movements in the oral and maxillofacial regions [33]. It is a widely accepted guideline that head movements should not exceed translation of 1 mm and a rotation of 1° [10],

Table 2 Localization (MNI coordinates) for all significantly activated voxels located within a cluster larger than 15 voxels, maximal t -value, cluster size and regions of activation during tongue protrusion exercise

R/L	Region of activation	Cluster size	Maximal t -value	MNI coordinates of max-voxel		
				x	y	z
R	Precentral gyrus	239	4.59	54	-7	30
R	Precentral gyrus		2.85	65	-4	15
L	Precentral gyrus	230	4.11	-50	-11	30
L	Precentral gyrus		3.69	-58	-7	27
R	Cerebellum	34	2.71	14	-61	-15

Table 3 Localizations (MNI coordinates) for all significantly activated voxels located within a cluster larger than 15 voxels, maximal t -value, cluster size and regions of activation during lateral tongue exercise

R/L	Region of activation	Cluster size	Maximal t -value	MNI coordinates of max-voxel		
				x	y	z
R	Precentral gyrus	239	4.12	47	-14	36
R	Precentral gyrus		4.01	54	-11	33
R	Precentral gyrus		3.81	54	-11	48
L	Precentral gyrus	187	4.10	-54	-14	36
L	Precentral gyrus		3.94	-61	-14	30
L	Precentral gyrus		3.70	-43	-14	36
R	Cerebellum	39	3.60	14	-61	-18
L	Cerebellum	23	2.54	-11	-54	-21
L	Cerebellum		2.16	-11	-65	-18
R	Lentiform nucleus	20	1.51	25	-0	-3
R	Lentiform nucleus		1.12	29	-14	6
L	Medial frontal gyrus	17	1.47	-4	-0	54
L	Medial frontal gyrus		1.45	-4	-4	63

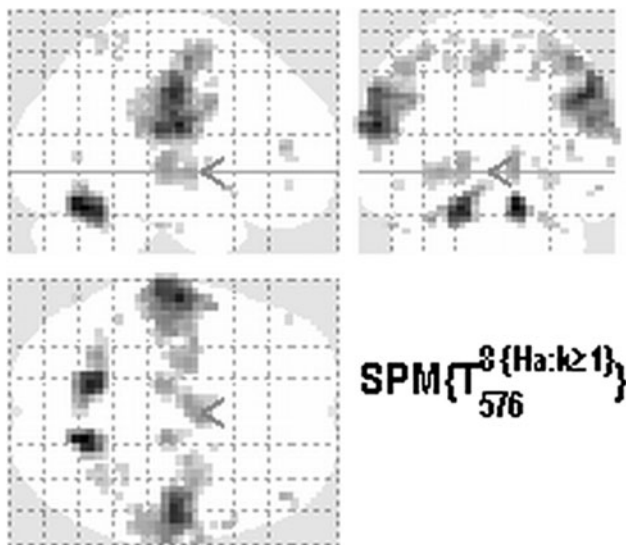


Fig. 6 Regions of activation during oral ball-rolling exercise revealed by conjunction analysis ($n = 8$). Activated regions are superimposed on a MNI template. A voxel height threshold was set at by FWE < 0.01 . Signal intensity is represented by an arbitrary color scale

and approximately 1–0.5 mm or less during scanning. In cases where head movement is greater than 1 mm, motion artifacts increase and can inhibit sharp contrast interfaces [33]. In the present study, residual head movements after realignment were confirmed to exhibit translation < 1.0 mm and rotation $< 1.0^\circ$ in x , y , and z coordinates across all sessions. Therefore, we considered that the data in this study were valid and reliable.

Lip-pursing and Lip-stretching

Previous studies have reported focal brain activation in the left hemisphere during lip movements. Hesselmann et al.

[10] reported that brain activity during a lip-pursing exercise was lateralized to the left hemisphere in a group analysis, while the primary motor cortex was activated bilaterally in individual analyses of six right-handed subjects. Fukunaga et al. [8] reported that sensorimotor areas were activated bilaterally, but that the left side was more strongly activated than the right side, when eight right-handed participants performed the same exercise.

In the current study, some regions of activation were found only in the right hemisphere. While the cerebellum, precentral gyrus, and postcentral gyrus showed bilateral activation, the lentiform nucleus showed activation only on the right, and a group analysis revealed that the right hemisphere was more strongly activated than the left. According to the results of the individual analyses, the right hemisphere was dominantly activated in four subjects, while the left was dominant in one subject, and both hemispheres were equally activated in three subjects. Individual analysis revealed that brain activity among subjects was highly variable. It is possible that examining a greater number of subjects would reveal activation in both hemispheres.

A previous study [10] reported that the lateralization of brain activity in group analysis could not be observed in individual analysis using the number of significant voxels and t -values. The current results suggest that the data in the individual analysis was as important as the group analysis data when brain activity was observed using fMRI.

Tongue Exercise

Previous studies of brain activity during tongue exercise have reported regions of bilateral and unilateral activation. Corfield et al. [5] reported that the sensorimotor area,

Table 4 Localizations (MNI coordinates) for all significantly activated voxels located within a cluster larger than 15 voxels, maximal *t*-value, cluster size and regions of activation during oral ball-rolling exercise

R/L	Region of activation	Cluster size	Maximal <i>t</i> -value	MNI coordinates of max-voxel		
				<i>x</i>	<i>y</i>	<i>z</i>
R	Cerebellum	60	4.87	14	-61	-18
L	Precentral gyrus	426	4.37	-58	-11	24
L	Precentral gyrus		3.70	-61	-22	21
L	Precentral gyrus		3.51	-58	-18	42
L	Cerebellum	106	4.31	-14	-58	-18
L	Cerebellum		2.22	-29	-54	-24
R	Precentral gyrus	429	4.06	50	-14	39
R	Precentral gyrus		3.11	54	-7	27
R	Precentral gyrus		2.81	43	-7	57
R	Thalamus	28	2.21	14	-18	0
R	Medial frontal gyrus	59	2.18	4	-0	60
L	Medial frontal gyrus		2.16	-4	-7	54
L	Thalamus	35	2.10	-14	-22	3
L	Lentiform nucleus	42	2.10	-25	-7	0
L	Lentiform nucleus		1.77	-29	-14	-3

cerebellum, supplementary motor area, operculum, insula, putamen, and thalamus were all activated bilaterally during tongue protrusion exercises with eight right-handed subjects. Shinagawa et al. [23] reported that regions similar to those reported by Corfield et al. exhibited increased bilateral activation during protrusion and horizontal tongue exercises. On the other hand, Vincent et al. [27] reported that the motor area and premotor area were activated only in the right hemisphere during vertical and horizontal tongue exercise with six right-handed subjects.

In the current study, the precentral gyrus was found to be activated bilaterally during tongue protrusion and lateral tongue exercises. These results indicate that the activated regions during the tongue exercises were bilateral, in accord with the previous studies by Corfield et al. [5] and Shinagawa et al. [23]. In addition, we found that brain activation changes were more spatially extended, and *t*-values were greater during tongue exercises compared to lip movements. This finding confirms the results of a previous report [10].

Oral Ball-rolling Exercise

The oral ball-rolling exercise, involving similar movements to those associated with tasting a piece of candy, was originally developed as an exercise for dysphagia rehabilitation. This exercise involves coordinated movement of the lips, tongue, and buccal mucosa. Of the four exercises, we found that regions of significant activation were the most spatially extended and *t*-values were highest during the ball-rolling exercise.

Activation was observed in the precentral gyrus and postcentral gyrus during both the lip protrusion and ball-

rolling exercises. A previous study reported that motor preparation involves the precentral gyrus, while oral sensory processing activates the precentral gyrus and postcentral gyrus [34]. In the present study, the brain activity we observed in the postcentral gyrus may have been related to the sensory stimulation experienced during lip stretching and when the ball touched the buccal mucosa.

Activation in the medial frontal gyrus was observed during the lateral tongue exercise and the ball-rolling exercise. It has been previously reported that spatial attention, memory, and motor preparation all engage the medial frontal gyrus [35].

Activation was observed in the cerebellum during all tasks, and the thalamus was activated during the ball-rolling exercise. Significant signal increases in the cerebellum and thalamus were reported during tongue movements in a previous study [5]. In addition, these regions have been associated with the voluntary control of movement. The cerebellum and its pathways are thought to be associated with motor learning [36]. The *t*-values in the cerebellum were higher during the ball-rolling exercise than in the other three tasks. This finding suggests that the level of activation in the cerebellum may be related to the complexity of the exercise being performed. External sensory stimulation is relayed to the sensorimotor cortex via the thalamus. In the current study, it is likely that sensory stimulation related to the ball-rolling exercise affected activity in the thalamus.

A region of activation in the lentiform nucleus (putamen) was observed in three of the four tasks: the lip protrusion exercise, the lateral tongue exercise, and the ball-rolling exercise. It has been proposed that the putamen and cortical projection sites constitute a possible substrate for

motor learning [37]. The main function of the putamen is thought to be the regulation of movement and mediation of various types of learning. The *t*-values in the putamen during the ball-rolling exercise in the current study were higher than in the other three tasks. This was likely to have occurred for reasons similar to those discussed in relation to the cerebellum.

The current fMRI results suggest that tongue movement training was more effective without food. The tongue also plays an important role in chewing movements such as bolus formation, bolus retention, and bolus feeding. As such, we propose that tongue movement training should be widely adopted in dysphagia rehabilitation.

Furthermore, the current results revealed that brain activity during a ball-rolling exercise was stronger and more extensive than that elicited by the other three exercises. We propose that this increased activation was due to the complexity of the movement involved in the task, requiring the coordinated movement of various motor and sensory organs. Overall, these findings indicated that the ball-rolling exercise may be useful in dysphagia rehabilitation.

The currently proposed training method provides an appropriate step for patients to proceed from a simple exercise to a more complex movement, without proceeding as far as using food. As such, this exercise is well suited to dysphagia rehabilitation in clinical practice. Training using food is a suitable next step in the rehabilitation process. Following this sequence, patients can practice making boluses of food and experience the sensory stimulation using nonfood items before using food. Thus, the proposed exercise allows patients to practice oral movements such as mastication, and can provide suitable intermediate training steps to proceed to more difficult movements.

We propose that effective dysphagia rehabilitation programs should be established on the basis of scientific evidence rather than relying solely on personal experience. The current findings in healthy subjects indicate that the differences in neural processing between simple and complex exercises might be useful in devising rehabilitation programs for patients with dysphagia.

Conclusion

We measured brain activity during oral exercises in healthy subjects using fMRI. Common activation during tongue and lip exercises was found in the precentral gyrus and cerebellum. Importantly, brain activation during a novel oral ball-rolling exercise was stronger and more extensive than that elicited by the other oral exercises tested. These results indicate that the ball-rolling exercise may be useful in dysphagia rehabilitation.

Acknowledgments This work was supported by KAKENHI (No.17592029) from the Japan Society for the Promotion of Science.

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