Immediate Effect of Laryngeal Surface Electrical Stimulation on Swallowing Performance

Keizo Takahashi

Division of Dysphagia Rehabilitation,

Niigata University Graduate School of

Medical and Dental Sciences

(Chief: Prof. Makoto Inoue)

Abstract

Surface electrical stimulation of the laryngeal region is used to improve swallowing in dysphagic patients. However, little is known about how this affects tongue movements or other subsequent functions. We investigated the effect of electrical stimulation on tongue pressure and hyoid movement as well as supra- and infrahyoid muscle activities in 18 healthy young subjects. Electrical stimulation (0.2 ms duration, 80 Hz, 80% of each participant's maximal tolerance) of the laryngeal region corresponding to the infrahyoid muscles was applied. Each subject swallowed 5 mL of barium sulfate liquid 12 times at 10-s intervals before (baseline), during, and after electrical stimulation. Tongue pressure was assessed using a sensor sheet, and the surface electromyography of the supra- and infrahyoid muscles and videofluorography were simultaneously recorded. Tongue pressure during stimulation was significantly less than baseline or after stimulation, with that after stimulation being significantly more than baseline. The suprahyoid electromyographic activity after stimulation was more than baseline while infrahyoid muscle activity did not change. During stimulation, the position of the hyoid at rest was descended, the highest position of hyoid was significantly inferior, and the vertical movement was greater than baseline or after stimulation. After stimulation, the hyoid at rest and at the maximum elevation were positioned more superiorly than baseline. The deviation of the highest positions of the hyoid between baseline and after stimulation corresponded to the differences in tongue pressures at those times. Surface electrical stimulation applied to the laryngeal region during swallowing may facilitate hyoid movement and tongue pressure generation.

Keywords

surface electrical stimulation, tongue pressure, hyoid movement, swallowing, suprahyoid muscles

INTRODUCTION

Older adults often experience several chronic symptomatic diseases as well as general poor health and functioning. They may have underlying medical conditions predisposing them to swallowing difficulties. In particular, older patients recovering from severe conditions such as stroke, pulmonary diseases, dementia, or other mental debilitation, or taking particular medications are at high risk of this as a result of declining function in bolus propulsion and airway protection during swallowing. Pneumonia is a leading cause of hospitalization and death in older adults **(19, 24)** and is now the third leading cause of mortality in Japan. This may be related to the fact that the Japanese population is aging. Teramoto et al. **(32)** have shown that the risk of aspiration pneumonia increases with age and it frequently occurs in older adults with polypathology **(22)**. A decline in feeding ability and/or oral health condition is considered to be a widespread factor leading to malnutrition in older adults **(6, 9, 31)**. As dysphagia is commonly observed in older patients in Japan, dysphagia rehabilitation should be included in clinical interventions whenever necessary.

Swallowing involves complex sensorimotor neural components and sequential movements. Squeezing and propelling the bolus using the tongue, is one of the most critical steps in performing pharyngeal swallowing safely **(3, 20, 21, 29)**. During this movement, the hyolaryngeal complex is elevated, playing an important role in laryngeal closure **(25)** and upper esophageal sphincter (UES) opening **(18)**.

Previous studies have described the normal pattern of tongue pressure generation during voluntary swallowing **(28)** and mastication **(13)**. Recently, a novel sensor sheet for measuring tongue pressure has been developed as a simple and mobile procedure for evaluating tongue function **(14)**. Using this system, tongue pressure in older people **(30)** and stroke patients **(12)** has been measured, and it has been found to be useful for the quantitative evaluation of tongue activity.

Tongue pressure generation is temporally related to hyoid movements during swallowing

(15). The start of tongue pressure is followed by hyoid movement and the end of tongue pressure occurs before the hyoid returns to the resting position from the most superior and anterior position. Furthermore, offset of the posterior-lateral tongue pressure is time locked to the hyoid being in the most superior and anterior position. Such sequential coordination might be critical to the pressure-flow dynamics during normal swallowing **(23, 33)**. Thus, measurement of tongue pressure may be useful in evaluating tongue function during swallowing.

Surface neuromuscular electrical stimulation (NMES) is used as a rehabilitation strategy to increase muscle size, and to improve the range of motion and muscle endurance **(2, 8, 26)**. Ludlow et al. **(26)** and Humbert et al. **(17)** showed that NMES lowered the resting position of the hyoid and larynx in dysphagic patients and healthy subjects, respectively. Heck et al. **(11)** reported no immediate effect but a delayed effect of NMES on swallowing performance. Moreover, the effect of NMES appears to be influenced by stimulus conditions such as stimulus amplitude and frequency **(1, 7)** and varies in different age groups **(1, 4, 5)**. Thus, it may be possible that NMES has the potential to contribute to the modulation of the neuromuscular system of swallowing, including dynamic tongue and hyoid movements, even though previous studies have had conflicting outcomes regarding the effectiveness of NMES.

In considering the functional relationship between hyoid movement and tongue pressure generation, we hypothesized that NMES applied to the laryngeal region affects tongue pressure generation not only during but also after NMES. The aim of this study was to investigate the immediate effect of laryngeal NMES on tongue pressure, hyoid movement, and hyoid muscle activity in healthy young adults.

MATERIALS AND METHODS

Participants. Eighteen healthy adults (15 men and 3 women; age range, 21–39 years; mean ±

standard deviation, 29.1 ± 5.6 years) with no dysfunction of mastication or deglutition, abnormality in the number or position of teeth except for the third molar, history of orthodontic treatment or temporomandibular disorders, or occlusion abnormalities were included in this study. Written informed consent was obtained from each participant after they received an explanation of the aim and methodology of the study. This study was approved by the Ethical Committee of the Faculty of Dentistry of Niigata University.

Electrical stimulation. The electrical stimulator Neuro Pack S1 (Nihon Kohden, Tokyo, Japan) was used for NMES. The stimulating probe was attached to the neck surface in the laryngeal region corresponding to the thyrohyoid muscles using a gum band. The pulse frequency and duration was set to 80 Hz and 0.2 ms.

To determine the maximum tolerated intensity of the stimulus for each participant, the current was increased by 0.2 mA every 1 s. Once the maximum stimulus threshold was determined, according to the participant's feedback, the 80% maximum tolerated intensity was calculated for each participant and used in subsequent procedures.

Tongue pressure. The measurement of tongue pressure has been extensively reported in previous studies **(10, 14, 15, 30)**. In brief, the tactile sensor system Swallow Scan (Nitta, Tokyo, Japan) with a special sensor sheet (0.1 mm thickness) for measuring tongue pressure was attached to the palatal surface **(Fig. 1)**. Three measuring points (Chs. 1–3) were placed along the median line (Ch. 1 at the anterior-median region, Ch. 2 at the mid-median region, and Ch. 3 at the posterior-median region), and two sensors (Chs. 4 and 5) were situated in the posterior-circumferential regions of the hard palate. The signals were conveyed with flexible cables exiting the oral cavity via the oral vestibule to avoid interference with the occlusion. The data were acquired at a sampling rate of 100 Hz.

Videofluorography (VF). The hyoid movement of the participants was observed using the ARCADIS Avantic Gen2 mobile imaging system (Siemens, Munich, Germany). VF images were acquired on the sagittal plane at a speed of 30 frames/s. To provide a distance reference, a metal ball (11 mm diameter) was attached to each participant's chin.

Electromyography (EMG). Pairs of surface electrodes with diameters of 8 mm (NT-211u or NT-212u; Nihon Kohden) were used for EMG recordings of both sides of the supra- and infrahyoid muscle groups. Two electrodes were attached to the skin over the anterior belly of the digastric and thyrohyoid muscles with an inter-electrode distance of 2 cm. Reference electrodes was attached to each earlobe. Signals from the EMG electrodes were amplified (Dual Bio Amp; ADInstruments, Colorado Springs, CO, USA) and stored on a computer through an interface (PowerLab; ADInstruments, Colorado Springs, CO, USA) at a sampling rate of 10 kHz.

Data collection. Participants were asked to sit on a chair with their head vertical to the Frankfort plane. The sensor sheet for tongue pressure measurement and EMG electrodes were attached. A catheter was fixed to the anterior teeth to supply liquid to the oral cavity.

During the recording session, 5 mL of barium sulfate (Britop Sol, Kaigen Pharma Co., Ltd., Osaka, Japan) solution (40 % w/v) was injected through the catheter and the participant was instructed to immediately swallow it. The injection was repeated every 10 s for 2 min, giving a total of 12 swallows. The 2-min recording was performed three times with no time interval between trials so that a total of 36 swallows was recorded. During the middle 2-min period, NMES was applied. The participant was asked not to open their mouth throughout the recording period.

As mentioned, each participant swallowed 36 times in the whole session. As repetitive swallows might lead to the fatigue of swallowing-related organs, the effect of repetitive swallows on performance was assessed using the same procedure (36 swallows with 10-s time intervals) but without NMES in 10 participants. At this time, VF images were not recorded.

Data analysis. The maximum amplitude, duration, and area of tongue pressure for each channel were obtained. The averages of those values before (baseline), during, and after NMES were calculated.

VF images were analyzed frame-by-frame with the anterio-inferior point of the hyoid bone, C2 and C4 marked and traced on each frame **(Fig. 2)**. Before analysis, head movement was corrected using C2 and C4. The lower anterior corners of the second and fourth cervical vertebrae were marked, and a line drawn through these two points served as the y-axis. The x-axis was drawn at a 90° angle to the y-axis through the point on the fourth cervical vertebra. The resting, most superior, and most anterior (Sp-An) positions of the hyoid during swallowing were identified. Furthermore, the distance of deflection, entire pathway, and vertical and horizontal movement of the hyoid were calculated for each swallow **(Fig. 3)**. The deflection distance was defined as that between the resting and Sp-An positions. The averages of those values before (baseline), during, and after NMES were calculated.

EMG bursts were full-wave rectified and smoothed (time constant, 20 ms). In each burst, the times of onset, peak, and offset were obtained. Subsequently, the time sequence was calculated using the onset of hyoid elevation as a reference. To determine the onset and offset times, we used the mean value (± SD) of a 5-sec EMG segment recorded at rest as a control. When data values exceeded the control by more than 2 SDs, the EMG burst was considered to be active. The peaks and durations of the EMG bursts were compared between before (baseline) and after NMES.

For comparison, repeated one-way analysis of variance and Tukey's post-hoc test were performed. Student's *t*-test was used to examine the differences in EMG values before (baseline) and after NMES. Statistical analysis was performed using SPSS 20.0J (IBM Japan, Tokyo, Japan) and statistical significance was set at $P < 0.05$.

RESULTS

The average intensity of NMES (80% maximum tolerated intensity) was 9.1 ± 1.8 mA and the range was 7.2–11.4 mA. All participants completed all tasks.

Tongue pressure. During swallowing, mono- or bi-phasic tongue pressure was observed **(Fig. 4*A*)**. The waveforms of tongue pressure varied between swallows even under the same conditions in the same participant **(Fig. 4*B*)**. On most channels, the maximum amplitude of the tongue pressure was significantly less during NMES compared with before (baseline) and after NMES. The exceptions were Chs. 2 and 4, in which there were no differences between before (baseline) and during NMES. Tongue pressure was significantly more after NMES than before NMES (baseline) on all channels **(Fig. 5*A*)**. Furthermore, in most channels, with the exception of Chs. 4 and 5, the duration of tongue pressure was significantly shorter during NMES compared with before (baseline) and after NMES **(Fig. 5*B*)**. The duration was significantly longer after NMES than before NMES (baseline) in Chs. 1, 4, and 5. In the session without NMES, the maximum amplitude and duration of tongue pressure were no different in the first, second, and third 2-min periods **(Fig. 6)**.

Hyoid movement. During swallowing, the hyoid first moved rapidly superiorly and posteriorly and then moved anteriorly. Once it reached the Sp-An position, it moved posteriorly and downwards as it returned to its resting position **(Figs. 3 and 7)**.

The resting position of the hyoid was significantly inferior and anterior during NMES compared with before (baseline) and after NMES, and was significantly inferior and anterior before NMES (baseline) than after NMES **(Fig. 8*A*)**. The Sp-An position of the hyoid during swallowing was significantly inferior during NMES compared with before (baseline) and after NMES and was significantly inferior before NMES (baseline) than after NMES. Anterio-posteriorly, the Sp-An position was not different among before (baseline), during, or after NMES.

The deflection distance, entire pathway distance, and vertical distance of hyoid movement during NMES were significantly longer during NMES than before (baseline) or after NMES **(Fig. 8*B*)**. The horizontal distance of hyoid movement was significantly shorter during NMES than before (baseline) and after NMES. The entire pathway distance and vertical distance was significantly shorter before NMES (baseline) than after NMES.

Muscle activity. The peak amplitude of the EMG burst of the suprahyoid muscles was significantly higher after NMES than before NMES (baseline) **(Figs. 9 and 10*A*)** while that of the infrahyoid muscles was not different before (baseline) and after NMES. The duration of the EMG burst of all the muscles was not changed throughout the recordings **(Fig 10*B*)**. As expected, in the recording without NMES, the peak amplitude and duration of the EMG bursts were not different between the first and third 2-min periods **(Fig. 11)**.

Relationship between changes in tongue pressure and hyoid movement. Finally, we investigated the relationship between changes in the Sp-An position and increase of tongue pressure before (baseline) and after NMES. The deviation of the Sp-An position of the hyoid was significantly related to the increase in tongue pressure on Chs. 2 (P = 0.030, r = 0.512) and 3 (P = 0.049, r = 0.470).

DISCUSSION

NMES has recently been introduced as a novel therapeutic strategy for dysphagic patients. Despite the popularity of NMES application to patients, there is limited evidence supporting its efficacy **(16)**. In this study, we recorded tongue pressure, hyoid movement, and muscle activity to clarify the immediate effect of NMES on swallowing performance. Tongue pressure decreased during NMES but increased after NMES. This does not appear to be because of habituation or fatigue as all of the parameters measured were not affected by consecutive swallows without NMES.

Stimulus amplitude is one of the important parameters that may affect sensory and motor functions **(7)**. We used a level of 80% of each participant's maximum tolerance intensity. Different amplitudes appear to have distinct impacts on different levels of the neural circuit. For example, Ludlow et al. **(26)** reported that low sensory threshold stimulation only reduced aspiration and pooling in chronic pharyngeal dysphagia. However, Humbert et al. **(17)** used a stimulus of 100% of tolerance intensity in healthy adults. They found that, during NMES, significant laryngeal and hyoid descent occurred at rest, and significant reductions in both the larynx and hyoid bone peak elevation occurred during swallowing. In the current study, high-threshold, but not painful, NMES might induce muscle contraction directly or by peripheral motor axon depolarization **(27)**.

In our study, the resting position of the hyoid was significantly descended during NMES. The distance of descent was likely to be different between the at-rest and the Sp-An position. That is, the effect of NMES was smaller on the Sp-An position than on the resting position, although we did not directly compare them. In this respect, we suspect that effortful force generation during swallowing might contribute to a reduction in the descent of the Sp-An position.

Tongue muscles such as the hyoglossus muscle directly connect with the hyolaryngeal complex. Tongue pressure is generated not only by contraction of the lingual muscles but is also affected by changing the position of the surrounding organs (e.g., hyoid or thyroid). We previously reported the temporal relationship between hyoid movement and tongue pressure generation during swallowing **(15)**. In the present study, tongue pressure decreased during NMES, accompanied by descent of the hyoid, and it increased after NMES with recovery of the hyoid position. In addition, after NMES, tongue pressure during swallowing was greater than that before NMES. Taken together, it can be assumed that, after NMES, the compensatory motor action remained. Using NMES to descend the hyoid may be a therapeutic strategy working as a resistive exercise of the suprahyoid muscles for elevation of the hyoid and possibly thyroid.

In this study, inter-individual variation in the change of tongue pressure and hyoid movement was observed. However, those participants whose tongue pressure changed more showed greater descent of the hyoid bone. The positive correlation between the increase in tongue pressure and deviation of the hyoid might suggest that tongue pressure measurement may be used to assess hyoid action.

In the present study, we could not identify which muscles were activated during NMES and contributed to the changes in hyoid position, and hence swallowing performance, after NMES. Furthermore, we only investigated the immediate effects of NMES on tongue pressure and hyoid movement in healthy adults. We recorded hyoid movement before, during, and after 2-min NMES because we had a limited time for X-ray exposure. Further studies should be performed to evaluate the long-term effects of NMES on each muscle and to investigate which stimulus condition is more effective in modifying swallowing performance. In conclusion, our results indicate that surface electrical stimulation applied to laryngeal regions may have a positive effect on swallowing by facilitating hyoid elevation and tongue pressure generation.

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to all participants for their understanding and cooperation in this study. I also sincerely appreciate Professor Makoto Inoue, Division of Dysphagia Rehabilitation, Niigata University Graduate School of Medical and Dental Sciences, who gave me valuable advice in the course of the study and kindly reviewed the manuscript, Prof. Takahiro Ono, Prof. Masako Kurachi, Dr. Kazuhiro Hori, and all staff of Division of Dysphagia Rehabilitation. This study was partly supported by Grants-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan (#24390431 to M. Inoue) and by the Strategic Young Researcher Overseas Visits Program for Accelerating Brain Circulation (S2504) from the Japan Society for the Promotion of Science (to M. Inoue).

DISCLOSURES

The authors declare that they have no conflicts of interest.

References

1. **Barikroo A, Berretin-Felix G, Carnaby G, Crary M**. Effect of transcutaneous electrical stimulation amplitude on timing of swallow pressure peaks between healthy young and older adults. *Gerodontology*, in press.

2. **Carnaby-Mann GD, Crary MA**. Examining the evidence on neuromuscular electrical stimulation for swallowing: a meta-analysis. *Arch Otolaryngol Head Neck Surg* 133: 564–571, 2007.

3. **Chiba Y, Motoyoshi M, Namura S**. Tongue pressure on loop of transpalatal arch during deglutition. *American Journal of Orthodontics and Dentofacial Orthopedics* 123: 29–34, 2003.

4. **Connelly DM, Rice CL, Roos MR, Vandervoort AA**. Motor unit firing rates and contractile properties in tibialis anterior of young and old men. *J Appl Physiol (1985)* 87: 843–852, 1999.

5. **Cupido CM, Hicks AL, Martin J**. Neuromuscular fatigue during repetitive stimulation in elderly and young adults. *Eur J Appl Physiol Occup Physiol* 65: 567–572, 1992.

6. **Dormenval V, Budtz-Jorgensen E, Mojon P, Bruyere A, Rapin CH**. Associations between malnutrition, poor general health and oral dryness in hospitalized elderly patients. *Age Ageing* 27: 123–128, 1998.

7. **Doucet BM, Lam A, Griffin L**. Neuromuscular electrical stimulation for skeletal muscle function. *Yale J Biol Med* 85: 201–215, 2012.

8. **Freed ML, Freed L, Chatburn RL, Christian M**. Electrical stimulation for swallowing disorders caused by stroke. *Respir Care* 46: 466–474, 2001.

9. **Furuta M, Komiya-Nonaka M, Akifusa S, Shimazaki Y, Adachi M, Kinoshita T, Kikutani T, Yamashita Y**. Interrelationship of oral health status, swallowing function, nutritional status, and cognitive ability with activities of daily living in Japanese elderly people receiving home care services due to physical disabilities. *Community Dent Oral Epidemiol* 41: 173–181, 2013.

10. **Hayashi H, Hori K, Taniguchi H, Nakamura Y, Tsujimura T, Ono T, Inoue M**.

Biomechanics of human tongue movement during bolus compression and swallowing. *J Oral Sci* 55: 191–198, 2013.

11. **Heck FM, Doeltgen SH, Huckabee ML**. Effects of submental neuromuscular electrical stimulation on pharyngeal pressure generation. *Arch Phys Med Rehabil* 93: 2000–2007, 2012.

12. **Hirota N, Konaka K, Ono T, Tamine K, Kondo J, Hori K, Yoshimuta Y, Maeda Y, Sakoda S, Naritomi H**. Reduced Tongue Pressure Against the Hard Palate on the Paralyzed Side During Swallowing Predicts Dysphagia in Patients With Acute Stroke. *Stroke* 41: 2982–2984, 2010.

13. **Hori K, Ono T, Nokubi T**. Coordination of tongue pressure and jaw movement in mastication. *J Dent Res* 85: 187–191, 2006.

14. **Hori K, Ono T, Tamine K, Kondo J, Hamanaka S, Maeda Y, Dong J, Hatsuda M**. Newly developed sensor sheet for measuring tongue pressure during swallowing. *J Prosthodont Res* 53: 28–32, 2009.

15. **Hori K, Taniguchi H, Hayashi H, Magara J, Minagi Y, Li Q, Ono T, Inoue M**. Role of tongue pressure production in oropharyngeal swallow biomechanics. *Physiol Rep* 1: e00167, 2013.

16. **Humbert IA, Michou E, MacRae PR, Crujido L**. Electrical stimulation and swallowing: how much do we know? *Semin Speech Lang* 33: 203–216, 2012.

17. **Humbert IA, Poletto CJ, Saxon KG, Kearney PR, Crujido L, Wright-Harp W, Payne J, Jeffries N, Sonies BC, Ludlow CL**. The effect of surface electrical stimulation on hyolaryngeal movement in normal individuals at rest and during swallowing. *J Appl Physiol* 101: 1657–1663, 2006.

18. **Jacob P, Kahrilas PJ, Logemann JA, Shah V, Ha T**. Upper esophageal sphincter opening and modulation during swallowing. *Gastroenterology* 97: 1469–1478, 1989.

19. **Kaplan V, Angus DC, Griffin MF, Clermont G, Scott Watson R, Linde-Zwirble WT**. Hospitalized community-acquired pneumonia in the elderly: age- and sex-related patterns of care and outcome in the United States. *Am J Respir Crit Care Med* 165: 766–772, 2002.

20. **Kennedy D, Kieser J, Bolter C, Swain M, Singh B, Waddell JN**. Tongue pressure patterns during water swallowing. *Dysphagia* 25: 11–19, 2010.

21. **Kieser J, Singh B, Swain M, Ichim I, Waddell JN, Kennedy D, Foster K, Livingstone V**. Measuring Intraoral Pressure: Adaptation of a Dental Appliance Allows Measurement During Function. *Dysphagia* 23: 237–243, 2008.

22. **Langmore SE, Skarupski KA, Park PS, Fries BE**. Predictors of aspiration pneumonia in nursing home residents. *Dysphagia* 17: 298–307, 2002.

23. **Li Q, Minagi Y, Hori K, Kondoh J, Fujiwara S, Tamine K, Inoue M, Maeda Y, Chen Y, Ono T**. Coordination in oro-pharyngeal biomechanics during human swallowing. *Physiol Behav* 147: 300–305, 2015.

24. **Loeb M, McGeer A, McArthur M, Walter S, Simor AE**. Risk factors for pneumonia and other lower respiratory tract infections in elderly residents of long-term care facilities. *Arch Intern Med* 159: 2058–2064, 1999.

25. **Logemann JA, Kahrilas PJ, Cheng J, Pauloski BR, Gibbons PJ, Rademaker AW, Lin S**. Closure mechanisms of laryngeal vestibule during swallow. *Am J Physiol* 262: G338–344, 1992.

26. **Ludlow CL, Humbert I, Saxon K, Poletto C, Sonies B, Crujido L**. Effects of surface electrical stimulation both at rest and during swallowing in chronic pharyngeal Dysphagia. *Dysphagia* 22: 1–10, 2007.

27. **Mesin L, Merlo E, Merletti R, Orizio C**. Investigation of motor unit recruitment during stimulated contractions of tibialis anterior muscle. *J Electromyogr Kinesiol* 20: 580-–589, 2010.

28. **Ono T, Hori K, Nokubi T**. Pattern of tongue pressure on hard palate during swallowing. *Dysphagia* 19: 259–264, 2004.

29. **Shaker R, Cook IJ, Dodds WJ, Hogan WJ**. Pressure-flow dynamics of the oral phase of swallowing. *Dysphagia* 3: 79–84, 1988.

30. **Tamine K, Ono T, Hori K, Kondoh J, Hamanaka S, Maeda Y**. Age-related changes in tongue pressure during swallowing. *J Dent Res* 89: 1097–1101, 2010.

31. **Tamura F, Kikutani T, Tohara T, Yoshida M, Yaegaki K**. Tongue thickness relates to nutritional status in the elderly. *Dysphagia* 27: 556–561, 2012.

32. **Teramoto S, Fukuchi Y, Sasaki H, Sato K, Sekizawa K, Matsuse T**. High incidence of aspiration pneumonia in community- and hospital-acquired pneumonia in hospitalized patients: a multicenter, prospective study in Japan. *J Am Geriatr Soc* 56: 577–579, 2008.

33. **Yano J, Aoyagi Y, Ono T, Hori K, Yamaguchi W, Fujiwara S, Kumakura I, Minagi S, Tsubahara A**. Sequential coordination between lingual and pharyngeal pressures produced during dry swallowing. *Biomed Res Int* 2014: 691352, 2014.

FIGURE LEGENDS

Fig. 1. Swallowing scan system and location of the sensing points. *A*: swallowing scan system and sensor sheet. *B*: intra-oral view of the attached sensor sheet and location of the sensing points.

Fig. 2. Traced points on the videofluorographic image. Anterio-inferior point of the hyoid bone, C2, and C4 were marked on each frame. X- and y-axes were set by referring to C2 and C4.

Fig. 3. Example trace of hyoid movement during swallowing. See text for details.

Fig. 4. Example waveforms of tongue pressure. *A*: single swallow. *B*: whole sequence of 36 swallows before (baseline), during, and after stimulation.

Fig. 5. Changes in tongue pressure before (baseline), during, and after electrical stimulation. *A*: maximum amplitude of tongue pressure. *B*: duration of tongue pressure. *$P < 0.05$.

Fig. 6. Changes in tongue pressure during first, second, and third 2-min periods without electrical stimulation. *A*: maximum amplitude of tongue pressure. *B*: duration of tongue pressure.

Fig. 7. Example of hyoid movement in an entire sequence of recording including before (baseline), during, and after electrical stimulation.

Fig. 8. Changes in hyoid movement before (baseline), during, and after electrical stimulation. *A*: hyoid at resting (Rest) and most superior and anterior (Sp-An) positions during swallowing. *B*: deflection distance between Rest and Sp-An positions of hyoid during swallow, and horizontal and vertical distance of hyoid movement. *$P < 0.05$.

Fig. 9. Example of electromyography in left (Lt) and right (Rt) supra- and infrahyoid muscles during an entire sequence of recording including before (baseline), during, and after stimulation). EMGs are not detectable owing to stimulus artifacts.

Fig.10. Changes in electromyographic (EMG) activity before (baseline) and after electrical stimulation. *A*: peak amplitude. *B*: duration of EMG burst. *$P < 0.05$. Lt; left, Rt; right.

Fig. 11. Changes in EMG activity during first, second and third 2-min periods without electrical

stimulation. *A*: peak amplitude. *B*: duration of EMG burst. Lt; left, Rt; right.

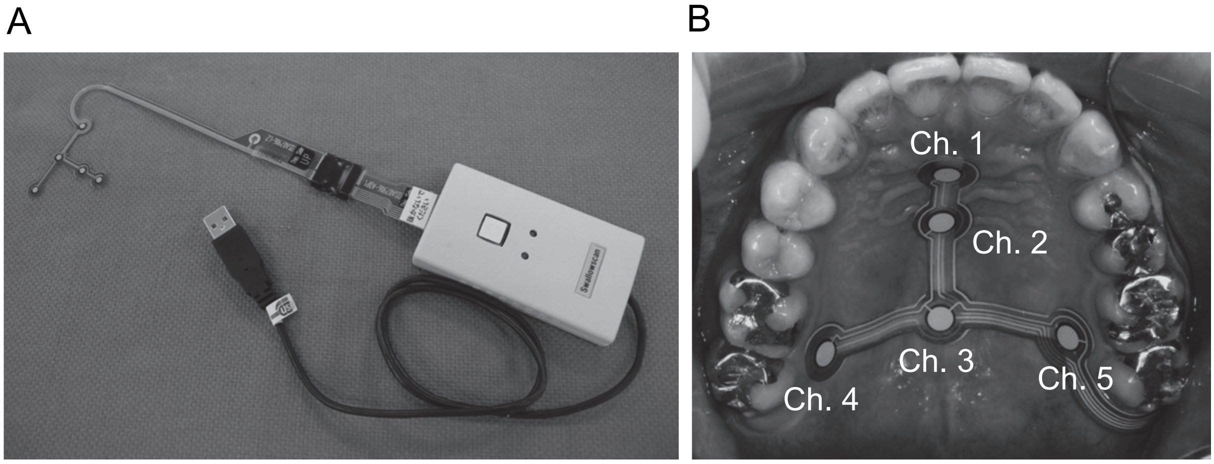


Fig. 1

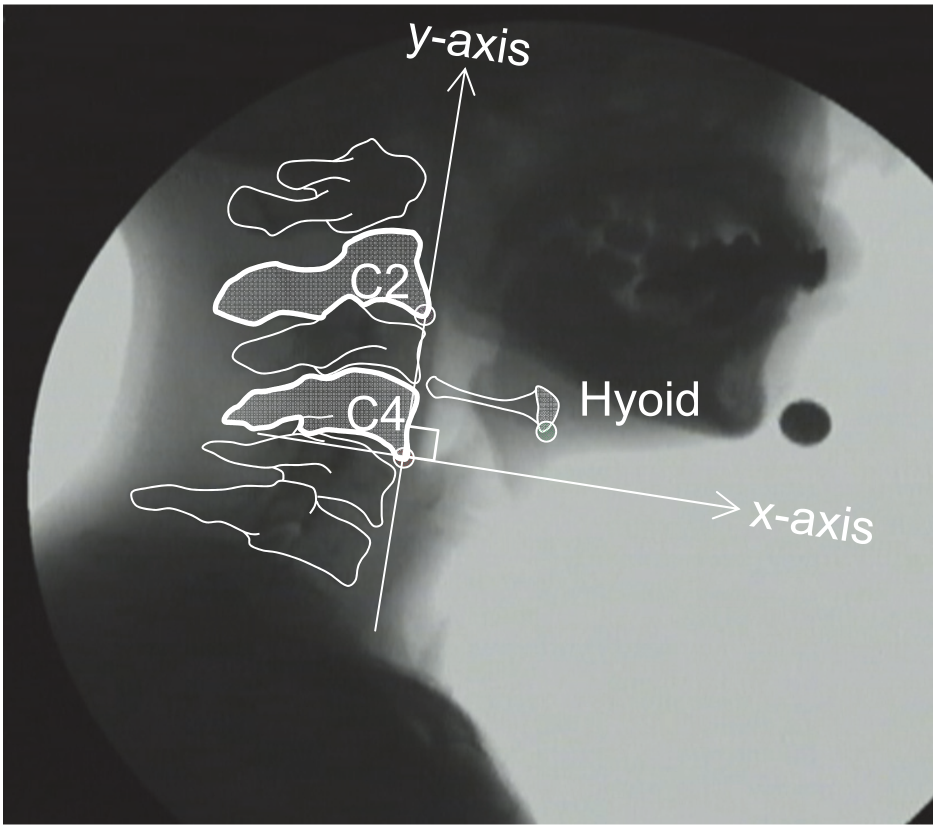


Fig. 2

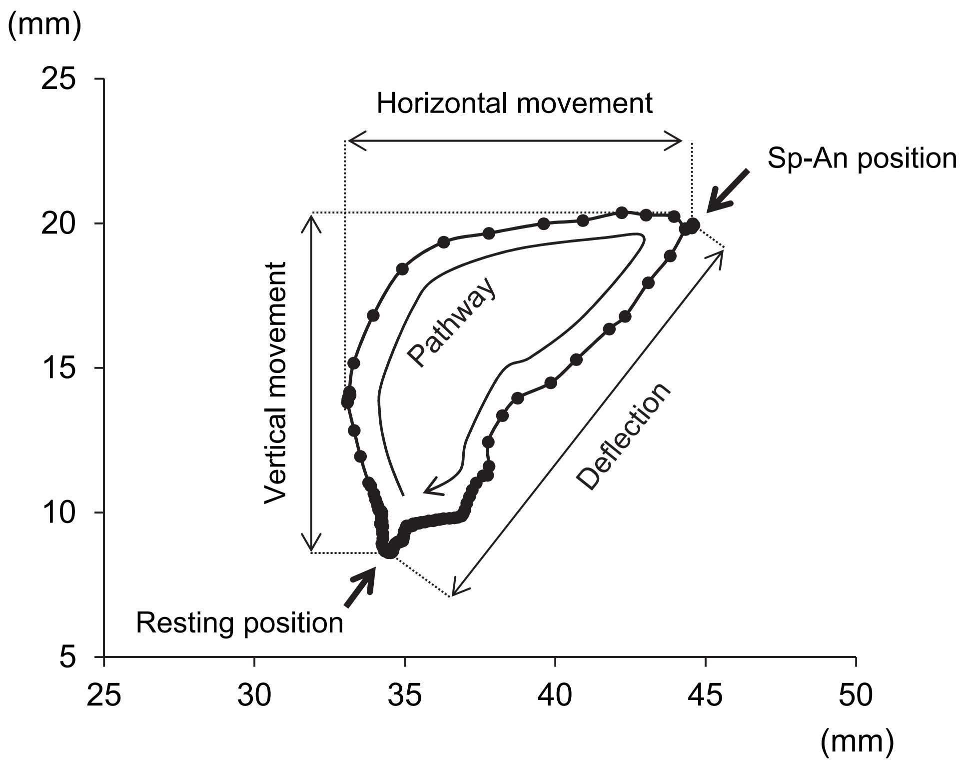

(mm)
25
20
15
10
5
25
30
35
40
45
50
(mm)
Horizontal movement
Sp-An position
Vertical movement
Pathway
Deflection
Resting position

Fig. 3

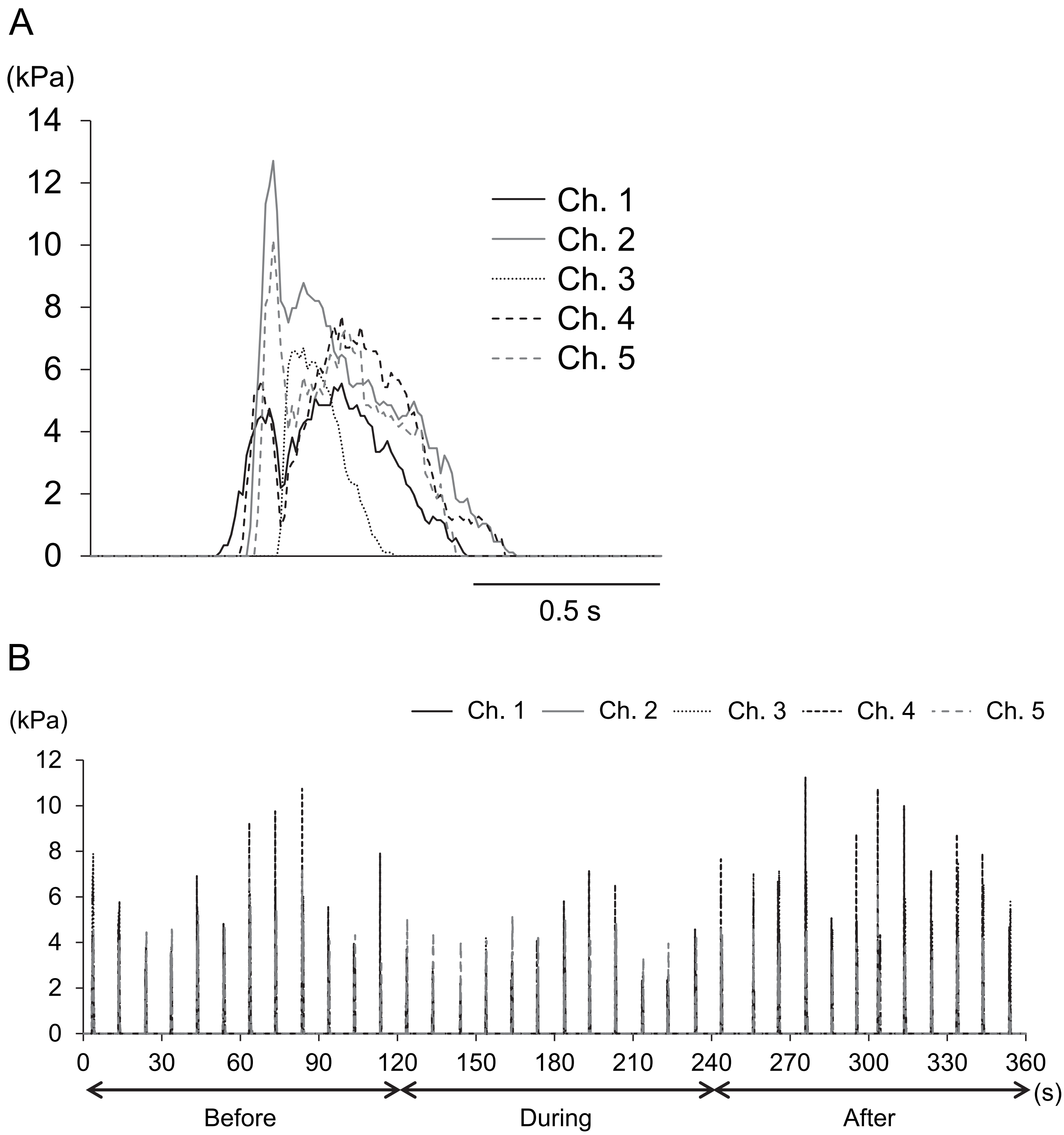
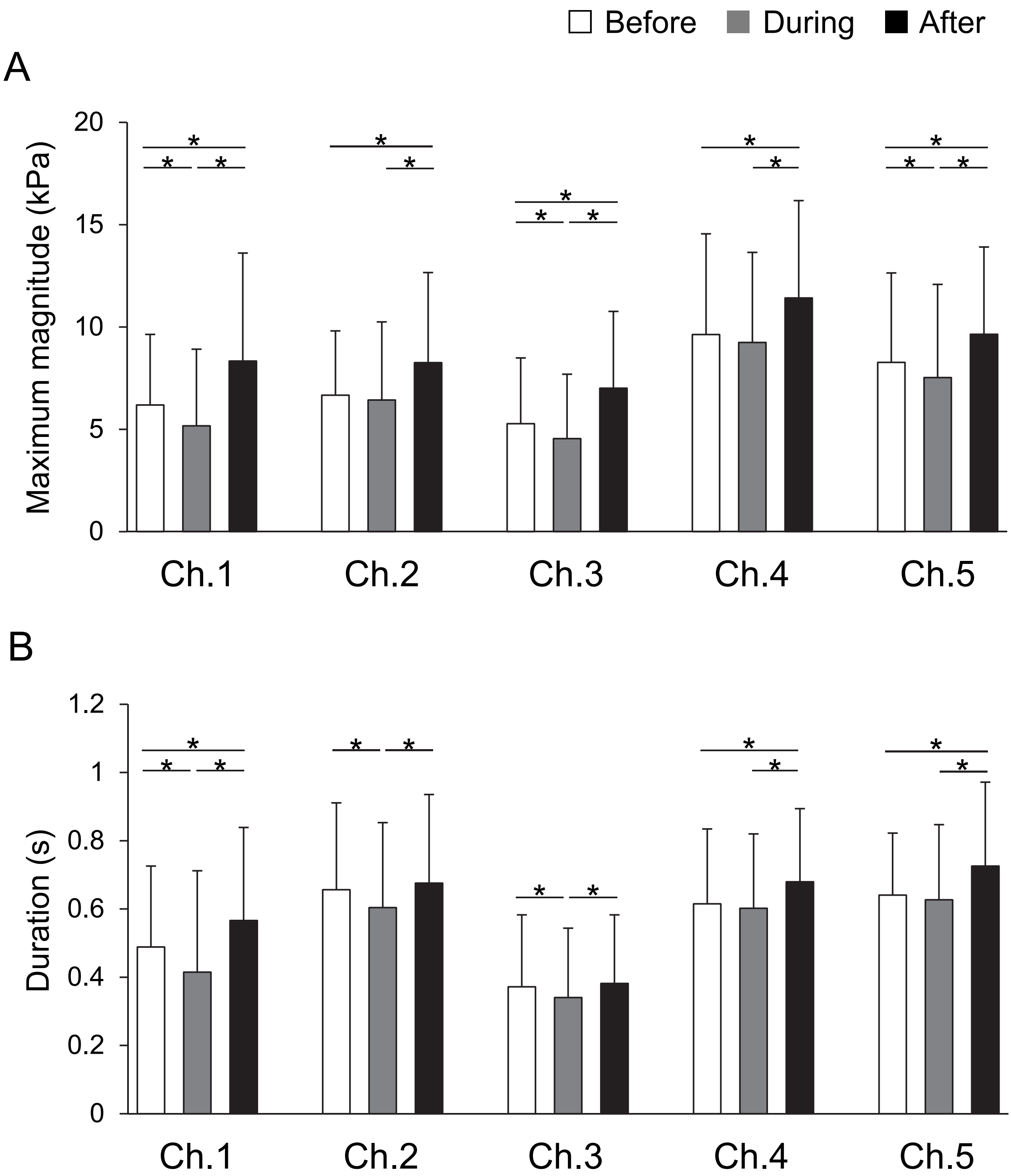
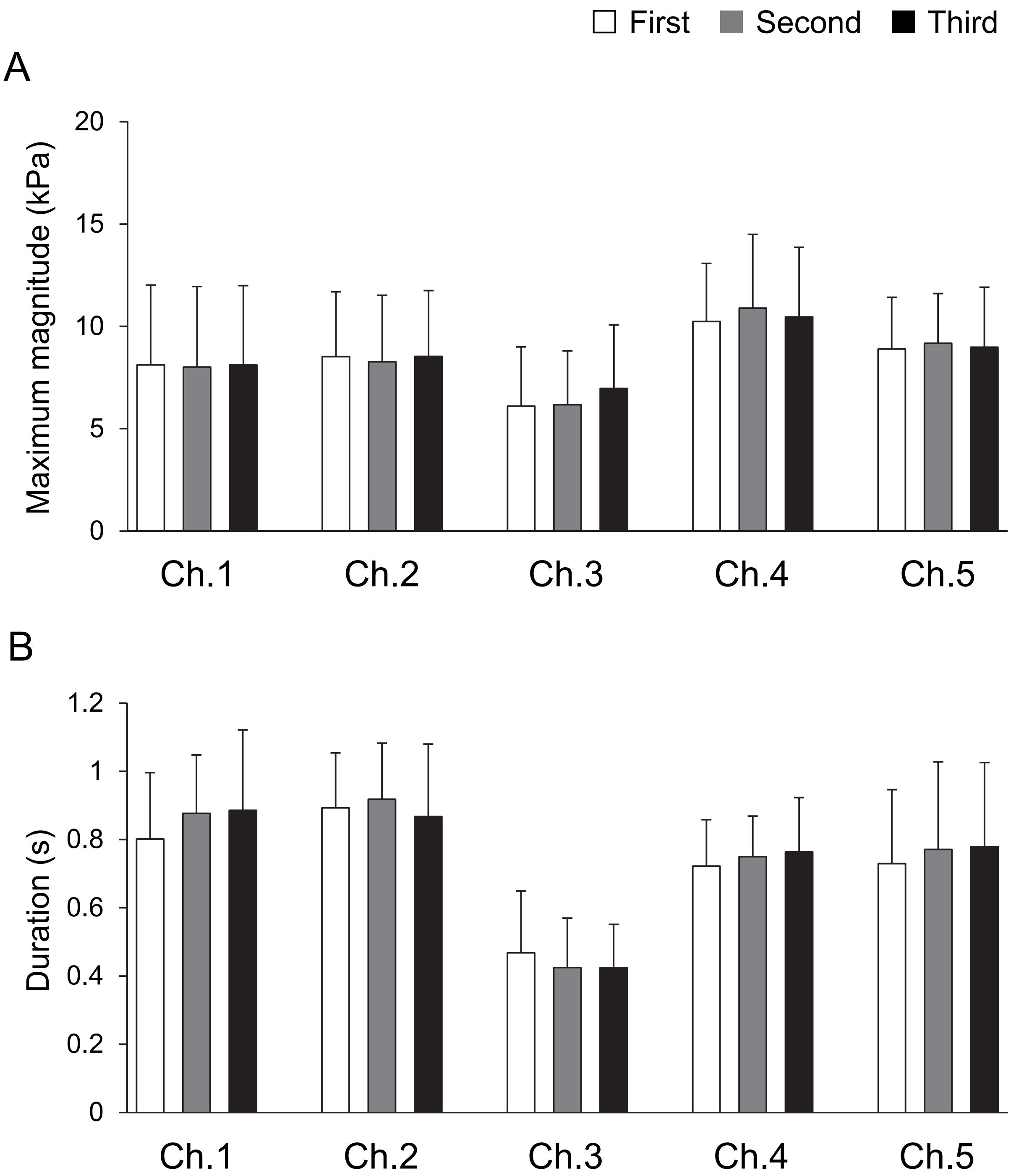

A
(kPa)
14
12
10
8
6
4
2
0
Ch. 1
Ch. 2
Ch. 3
Ch. 4
Ch. 5
0.5 s
B
(kPa)
Ch. 1
Ch. 2
Ch. 3
Ch. 4
Ch. 5
12
10
8
6
4
2
0
0
30
60
90
120
150
180
210
240
270
300
330
360
(s)
Before
During
After

Fig. 4



Before
During
After
A
Maximum magnitude (kPa)
20
15
10
5
0
Ch.1
Ch.2
Ch.3
Ch.4
Ch.5
B
Duration (s)
1.2
1
0.8
0.6
0.4
0.2
0
Ch.1
Ch.2
Ch.3
Ch.4
Ch.5

Fig. 5



First
Second
Third
A
Maximum magnitude (kPa)
20
15
10
5
0
Ch.1
Ch.2
Ch.3
Ch.4
Ch.5
B
Duration (s)
1.2
1
0.8
0.6
0.4
0.2
0
Ch.1
Ch.2
Ch.3
Ch.4
Ch.5

Fig. 6

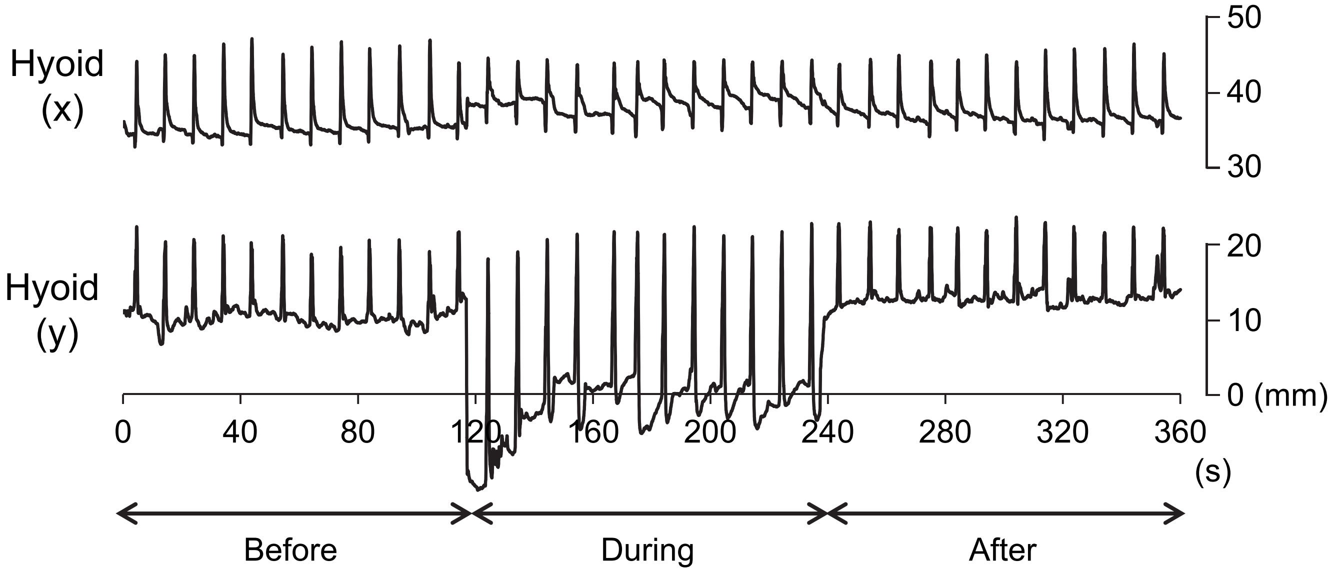

Hyoid (x)
Hyoid (y)
50
40
30
20
10
0 (mm)
0
40
80
120
160
200
240
280
320
360
(s)
Before
During
After

Fig. 7

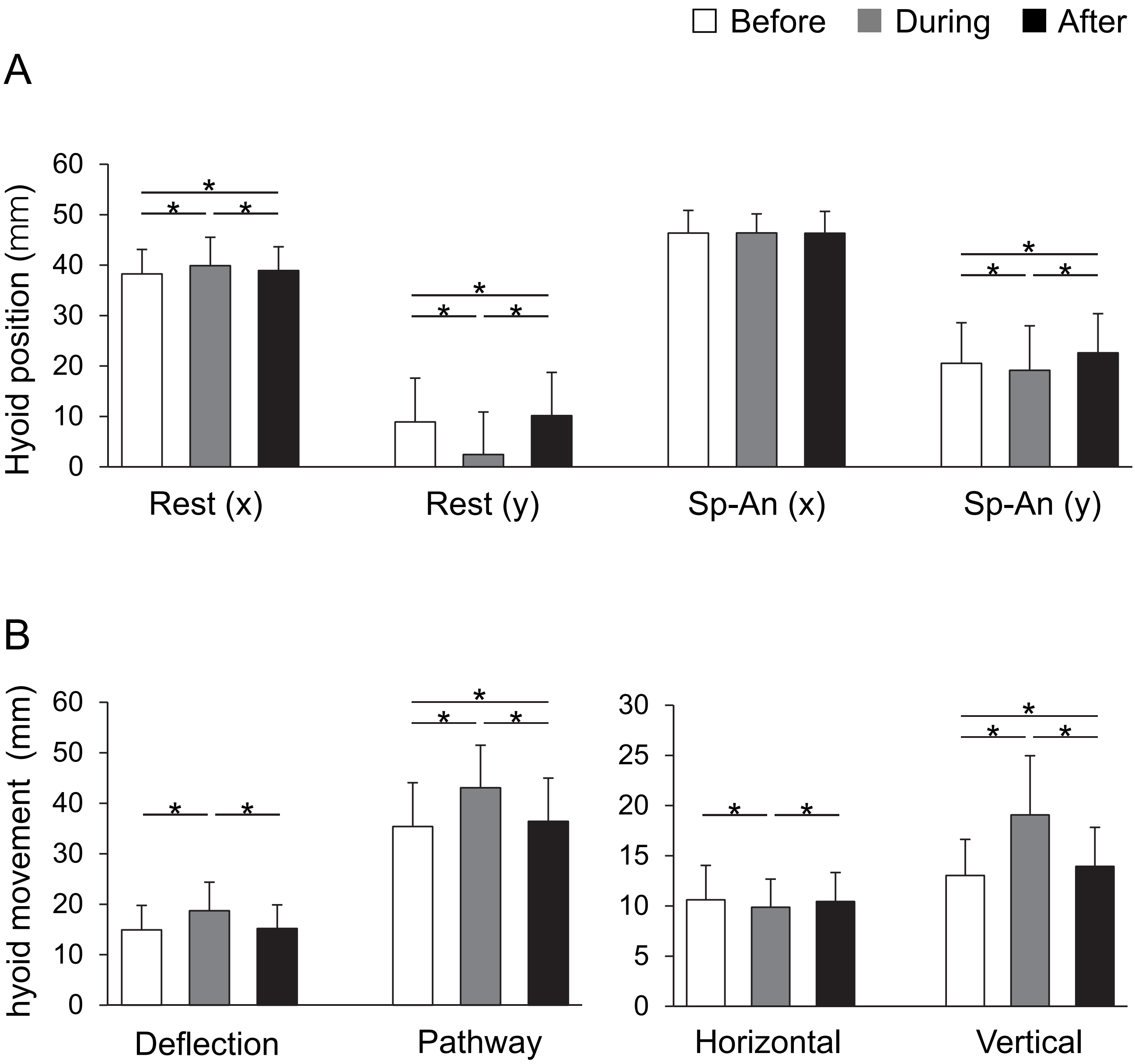
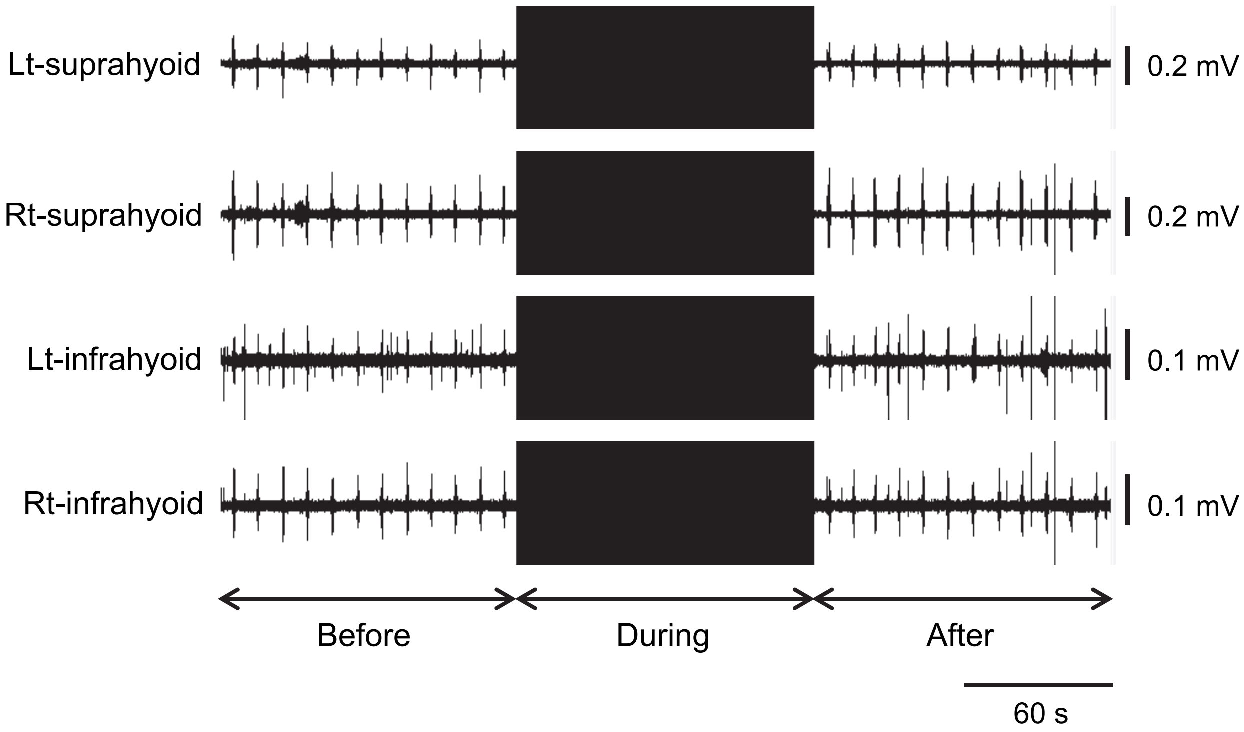
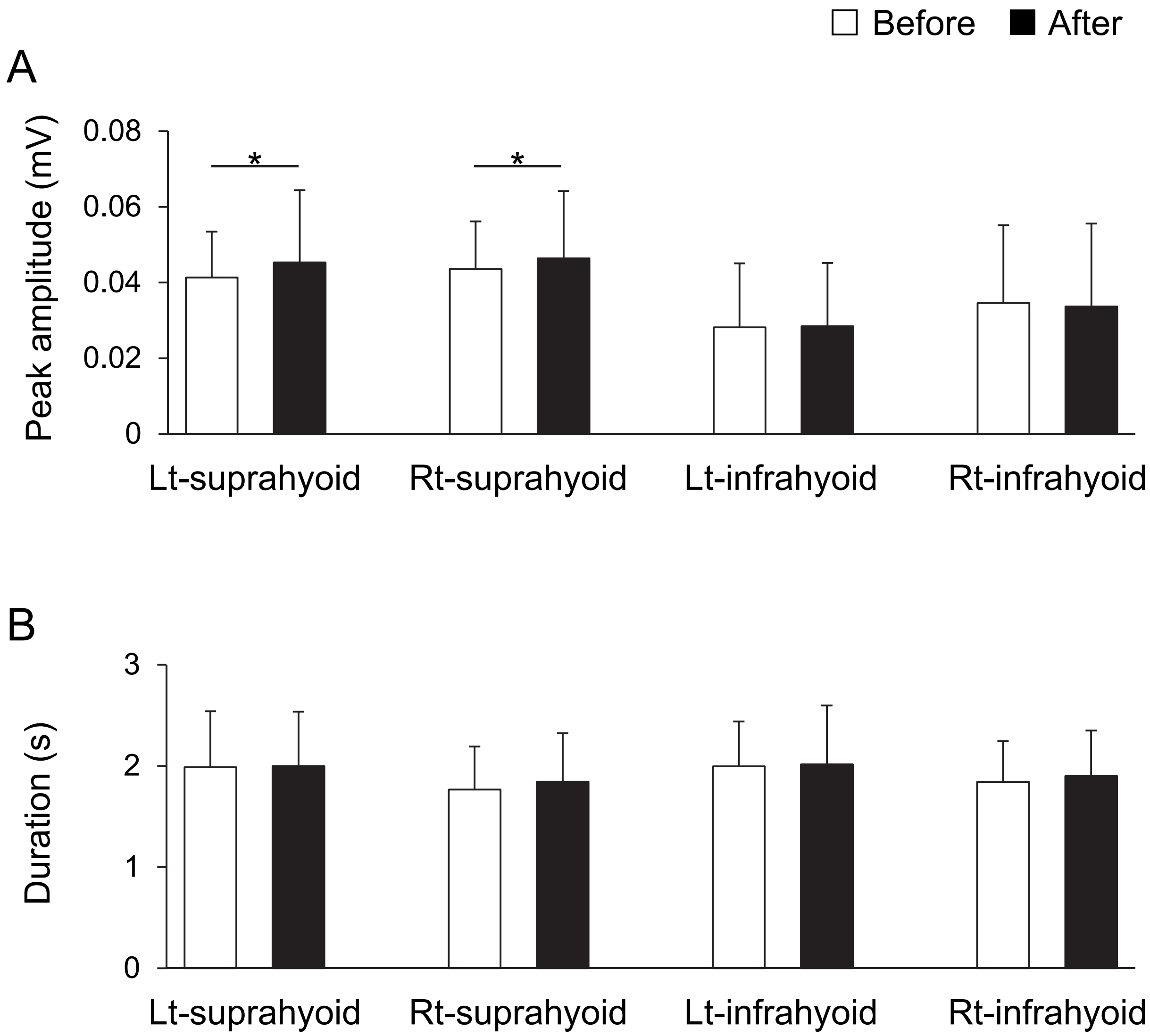

Before
During
After
A
Hyoid position (mm)
60
50
40
30
20
10
0
Rest (x)
Rest (y)
Sp-An (x)
Sp-An (y)
B
hyoid movement (mm)
60
50
40
30
20
10
0
Deflection
Pathway
30
25
20
15
10
5
0
Horizontal
Vertical

Fig. 8



Lt-suprahyoid
Rt-suprahyoid
Lt-infrahyoid
Rt-infrahyoid
0.2 mV
0.2 mV
0.1 mV
0.1 mV
Before
During
After
60 s

Fig. 9



Before
After
A
0.08
0.06
0.04
0.02
0
Peak amplitude (mV)
*
*
Lt-suprahyoid
Rt-suprahyoid
Lt-infrahyoid
Rt-infrahyoid
B
3
2
1
0
Duration (s)
Lt-suprahyoid
Rt-suprahyoid
Lt-infrahyoid
Rt-infrahyoid

Fig. 10

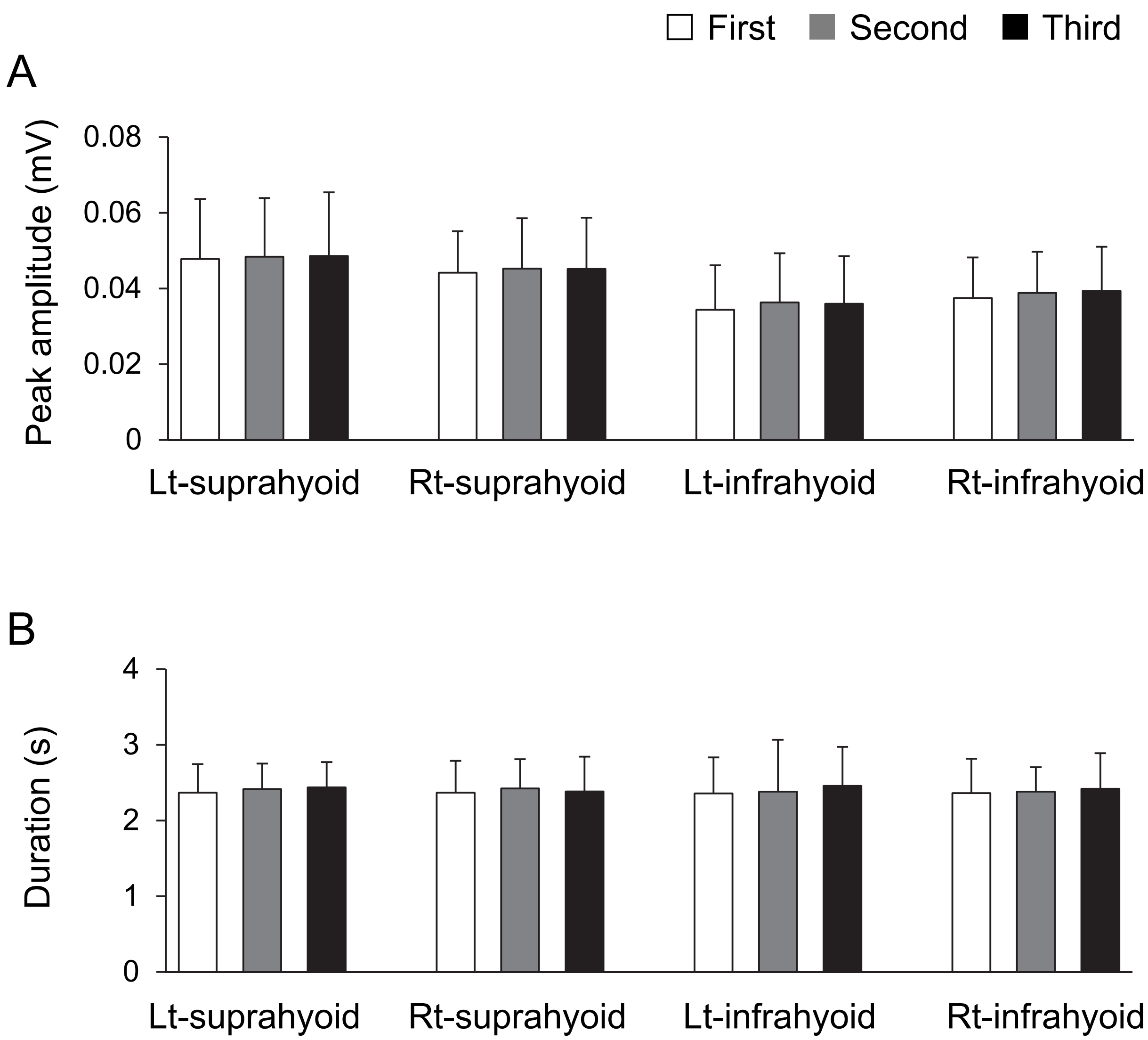

First
Second
Third
A
0.08
0.06
0.04
0.02
0
Peak amplitude (mV)
Lt-suprahyoid
Rt-suprahyoid
Lt-infrahyoid
Rt-infrahyoid
B
4
3
2
1
0
Duration (s)
Lt-suprahyoid
Rt-suprahyoid
Lt-infrahyoid
Rt-infrahyoid

Fig. 11