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Internal Kinematics of the Volume-reduced Tongue: A Longitudinal Microsonometric Study

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Abstract

This study examined tongue internal kinematics during feeding over time after its volume reduction. Six ultrasonic crystals were implanted into the tongue to record distance changes in anterior width (AW), bilateral lengths (LENG), posterior thicknesses (THICK), posterior dorsal (PDW) and ventral (PVW) widths in 5 sibling pairs of Yucatan minipigs (n=10). In each pair, one received tongue volume reduction surgery (reduction) and the other had the identical incisions without tissue removal (sham). Functional deformation of the tongue from pre-implanted ultrasonic crystals was recorded during natural feeding 1 day before, 7–8, 13–15 and 28–30 days after the surgery. The results revealed that feeding behavior and tongue functional deformation were unchanged over time in the sham pigs. However, at day 7–8, more frequent and longer ingestion episodes were seen in the reduction as compared to the sham. Moreover, deformational changes in AW and LENG decreased while those in THICK, PDW and PVW increased significantly ($P < 0.001$). At day 13–15, the reduced deformational changes in LENG ($P < 0.01$) slightly restored and the increased deformation in THICK ($P > 0.05$), PDW ($P < 0.01$), and PVW ($P < 0.05$) diminished. At day 28–30, the restoration of AW and LENG continued ($P < 0.01–0.05$), but previously enhanced deformations in THICK, PDW and PVW were no longer significantly different from the baseline ($P > 0.05$). These results suggest that the tongue volume reduction has significant and persistent impacts on feeding behaviors and tongue internal kinematics, and the restoring capacity of internal kinematics in the anterior tongue is limited and incomplete over time.

Keywords

Tongue kinematics; Tongue Volume Reduction; Ultrasound; Mastication; Pig

By contracting the extrinsic and intrinsic muscles of the tongue, the tongue performs motor functions that exert force through various complex shape changes (Mu and Sanders, 1999; Kayalioglu et al., 2007). These changes include simultaneously lengthening and shortening

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of different regions and a variety of nonlinear movements without altering tissue volume (Kier et al., 1989; Nishikawa et al., 1999; Sokoloff, 2004), which produce kinematic and biomechanical effects (displacement, deformation and load production). Tongue body volume reduction surgery is a valuable approach for treating congenital or acquired macroglossia in growing adolescent, or as an adjunct procedure for surgical correction of craniofacial deformities, such as severe skeletal open-bite and Class III malocclusions (Frohlich et al., 1993; Wolford and Cottrell, 1996; Miyawaki et al., 2000; Hotokezaka et al., 2001; Chau et al., 2011; Chung et al., 2012). Several techniques have been described to reduce the tongue volume, varying from removing an anterior or central wedge of the tongue to excision of the complete anterior and lateral margins of the tongue (Wang et al., 2003).

Given the fact that the tongue is a volume-dependent muscular organ due to its hydrostat nature, significant changes in tongue movement and internal deformation of various dimensions during function are anticipated when the volume is reduced surgically. Our previous short-term study (Shcherbatyy et al., 2008) has demonstrated that tongue volume reduction alters the tongue internal kinematics, and the dimensional losses in the anterior tongue caused by the volume reduction can be compensated by increased deformation in the posterior tongue during mastication. However, those data were collected immediately after the tongue surgery (acute experiment), thus the surgical injury and pain might affect the normal kinematics of the tongue. A number of longitudinal studies (Tomlinson et al., 2007; Chau et al., 2011; Shipster et al., 2012; Heggie et al., 2013) have shown that surgical tongue reduction may not achieve complete normality in tongue function and appearance. However, few studies have been identified regarding whether or not such an altered internal kinematics would be persistent or be recovered over time as a result of surgical wound healing, tongue reshaping or reposition, and functional compensation. Our long-term study revealed that a healed volume-reduced tongue transformed loading regime significantly on its surrounding osseous structures by elevating loading amplitude and altering strain-dominant pattern and orientation (Ye et al., 2013), while the neurovascular bundles of the tongue remained intact (Perkins et al., 2008). However, it is unknown how the load source, i.e., tongue kinematics, alters over time after the tongue volume reduction. For addressing this question, we took a further step to carry out this study, which longitudinally examined the deformational changes of various tongue dimensions during natural mastication following a uniform tongue volume reduction over the period of 4 weeks in the same pig model. We hypothesized that internal kinematics of a volume-reduced tongue would decrease significantly at the region of the anterior tongue, and a compensatory enhancement in the posterior tongue would be persistent over time.

MATERIALS AND METHODS

Animals

Three male and two female sibling pairs (n=10) of 12-week-old Yucatan miniature pigs (body weight: 13 ± 2 kg) were obtained from Sinclair Research Center (Columbia, MO). Daily training and handling for 3–5 days were performed before the experiments for acclimation of the pigs to the laboratory and experimental environment. Body weight was monitored once a week during the entire experimental period of six weeks. All experimental

procedures were approved by the University of Washington Institutional Animal Care and Use Committee (IACUC).

Electromyography and jaw movement videotaping

After 3–5 days training, electromyography (EMG) was acquired using the Biopac system (BioPac Co. CA) during natural feeding. Nickel-chromium wire electrodes (0.05mm in diameter) were inserted into tongue extrinsic and intrinsic tongue muscles and jaw muscles under isoflurane anesthesia, along with the placement of fluorescent jaw markers. The procedures for these EMG recording and synchronized jaw movement videotaping were the same as those previously published (Kayalioglu et al., 2007; Liu et al., 2009).

Ultrasound crystal implantation surgery

Under isoflurane anesthesia through intubation, all pigs received an aseptic surgery to implant ultrasonic crystals with a skin button set (Sonometric Co. London, Canada). A incision along the midline of the submandibular region was made and a long-beak hemostat was used to create a tunnel to reach the designed crystal locations, which were confirmed by manual intraoral palpations. By using another long-beak straight hemostat, six ultrasonic crystals with B-barb (2 mm in diameter) were implanted into the target locations through these tunnels. These six crystals were located in the tongue body (anterior 2/3) to circumscribe a wedge-shaped configuration as illustrated in Fig. 1A: No.1 and No.2 were 15mm posterior to the tongue tip; No.3 and No.4 were 5mm anterior to each circumvallate papilla (CP); No.5 and No.6 were 10–12 mm ventrally deeper to No.3 and No. 4, respectively. Similar to the acute studies published previously (Shcherbatyy and Liu, 2007; Shcherbatyy et al., 2008), the following seven crystal pairs were selected from this configuration to represent dimensional changes of the tongue: anterior width (AW, No.1–2), right and left lengths (RL and LL, No.1–3 and No.2–4, respectively), right and left posterior thicknesses (RT and LT, No.3–5 and No.4–6, respectively), and posterior dorsal and ventral widths (PDW and PVW, No.3–4 and No.5–6, respectively). These crystals functioned as tiny transducers that transmit and receive ultrasound signals and report the real-time distance between two crystals with a claimed resolution of 0.018mm (Fig. 1B). The crystals were stabilized in the place through their barbs and by suturing the proximal end of their leading wire onto the adjacent submandibular tissue using an absorbable suture (Gut 4-0). No intra-oral incision or exposure was made for the crystal implantation. Next, a subcutaneous tunnel was created from the submandibular region to the right back. The leading wires of the implanted crystals were led through this tunnel and were positioned 10cm posterior to the occipital protuberance where a female interface of skin button set (Fig. 2, **inset a**) was secured to the skin using 2-0 silk sutures and its connecting pins were protected by a screwed cover (Fig. 2, **inset b**).

Immediately after all six crystals were implanted and incisions were closed, the tongue was placed in a resting position and the linear distances of each dimension (distance between each designated crystal pairs) were measured using a digital caliper and a needle compass. These measurements were defined as the “implantation lengths”. Antibiotic (Clavamox) was administered with food one day before the surgery and for five days after the surgery.

Buprenorphine (0.01–0.05mg/Kg, IM) was given every 8–12 hours for five days for post-surgical pain relief. The daily training and handling resumed the next day.

Baseline recording

One week after implantation surgery, the baseline recording of tongue internal kinematics was carried out. To accomplish this, after 24-hours fasting the pigs were first anesthetized for EMG wire electrode insertions and the placement of the jaw movement markers, which were the same as did for the pre-implantation session. Then, the implanted skin button was connected to the microsonometric system through the plug-in cables (Fig. 2, **inset c**). After waking up from anesthesia, the regular pig pellets were offered and the ultrasound signals from implanted crystals during natural feeding were collected at the sampling rate of 250Hz by using SonoLab program (Ver.3.4.26-RC3, Sonometrics Co., London, Canada), along with the simultaneous recordings of EMG and videotaping of jaw movement. The recorded crystal signals served as the baseline of internal kinematics of the tongue, whereas the repeated recordings of EMG and jaw movement were used to verify possible functional interference caused by the crystal implantation.

Volume reduction surgery

One day after the baseline recording, aseptic tongue surgeries took place in each of sibling pairs. One underwent volume reduction (reduction group, n=5), which was performed within the region circumscribed by the six pre-implanted crystals using the uniform mid-sagittal tongue volume reduction (Davalbhakta and Lamberty, 2000). This procedure allows the tissue resections occurring in the anterior two-thirds of the tongue, and reducing not only length and width, but also thickness. The details of this surgery was published previously (Shcherbatyy et al., 2008) (Fig. 3). The other one received the identical incisions and sutures as the reduction pigs but no tongue tissue was removed (sham group, n=5).

After surgery, the tongue was placed in the rest position, and the distances between each crystal pairs were recorded again. By comparing with the “implantation length”, the dimensional losses by the reduction or sham surgeries were calculated as published elsewhere (Perkins et al., 2008). Then anesthesia was ceased, and the pigs were set back to their pen upon regaining consciousness. The administrations of antibiotics and analgesics were the same as performed after surgical implantation described above.

Longitudinal recordings and off-line data analysis

The daily training and handling resumed 2 days after the tongue surgery. Ultrasound signals from implanted crystals during natural feeding were collected longitudinally at the following 3 time points after the tongue surgery: days 7–8, 13–15, and 28–30. The procedures of these longitudinal recordings were the same as the baseline recording (Fig. 2).

Off-line data analyses were performed by selecting stable and consecutive 15–20 chewing cycles from a 3-minute masticatory sequence of each session using SonoView program (Sonometrics Co. London, Canada). Selection standards included signal rhythmicity, regularity and consecutiveness. Outputs of wave data from each designated crystal pairs acquired during rhythmic and stereotyped chewing cycles were exported to an Excel

spreadsheet where a custom-made macro program processed the following values from each chewing cycle at a given crystal pair through the visual-basic edited algorithm: 1) minimal value (valley), the amplitude measured at the starting of distance increase; 2) maximal value (peak), the amplitude measured at the starting of distance decrease. To avoid the confounding effects by the potential variation of distance between each crystal pairs at the implantation and between tracking time points, all measurements of distance changes in various dimensions were converted to the percentages of their corresponding initial distances, which were measured by placing the tongue at the rest position when the pig was under anesthesia for the insertion of wire-EMG electrodes in each session. Due to the fragility of ultrasonic crystals and uncooperativeness of some pigs, not all crystal pairs were operational throughout the entire tracking period, which lasted from one day before the tongue surgery (1 day before the surgery, D-1) to the terminal day (28–30 days after the tongue surgery, D28–30). The actual sample sizes of successful recordings over 4 time points were summarized in Table 1.

Statistical Analysis

SPSS (Version 11.0.1) for Windows was used for the statistical analysis. Descriptive statistic was performed for all means, standard deviations (SD), and ranges of distance changes. Further exploration was done to examine their normal distribution through skewness calculations. One-way analysis of variance (ANOVA) was used, followed by Tukey post-hoc tests. Non-paired t-test was performed to compare distance changes of each crystal pair between the two groups at each time point. Probability of 0.05 or less was considered to indicate statistical significance. For Tukey pair-wise comparisons over time in each group, the significance levels were adjusted by Bonferroni correction.

RESULTS

No noticeable functional impairment was identified by comparing EMG and jaw movement data acquired before and after crystal implantation. However, as compared to the sham pigs, significant modifications in feeding behavior were observed in the reduction pigs throughout this longitudinal investigation. Typically, a reduction pig utilized the mandible, instead of the anterior tongue, to shovel food into the mouth for ingestion, then moved and shook the head intentionally for chewing and swallowing as a way to take an advantage of gravity (inertial pattern). The feeding session lasted significantly longer than that of the sham pigs. The food leaking from the mouth corners during feeding was often seen at the initial 1–2 weeks after the surgery in the reduction pigs. However, the amount of daily food consumption of the reduction pigs was similar to that of the sham pigs, and both groups showed significant body weight gain over time ($P < 0.01$) but no significant difference of body weight between the two groups at any time points was identified (Fig. 4).

Because statistical analyses did not show any significant differences of dimensional changes between right and left lengths (RL and LL) and thicknesses (RT and LT), values of the lengths and thicknesses from the two sides were combined. Therefore, the total of 5 parameters, i.e., anterior width (AW), length (LENG), posterior thickness (THICK),

posterior dorsal (PDW) and ventral (PVW) widths, were used to examine the characteristics of tongue internal kinematics during natural feeding between the reduction and sham groups.

Longitudinal recordings indicated that tongue functional deformation was unchanged over time in the sham pigs as compared to the normal unoperated control pigs previously reported (Shcherbatyy and Liu, 2007). However, significant distortions were observed over time in the reduction pigs. At days 7–8 after the surgery (D7–8), more frequent and longer ingestion episodes interposed in masticatory sequence as compared to the baseline (D-1). The difference of tongue deformational pattern between chewing and ingestion episodes seen at D-1 became less distinct, particularly in the body length changes (Fig. 5). Furthermore, dimensional changes in AW and LENG significantly decreased (20%–35%) while those in THICK, PDW and PVW increased significantly (10%–20%) for both chewing and ingestion as compared to D-1 (Figs. 5 and 6). At days 13–15 after the surgery (D13–15), the reduced deformational capacities in AW and LENG were slightly restored with better regularity of stereotypical chewing cycles than those seen at D7–8. However, the increased deformation in THICK, PDW and PVW diminished as compared to those seen at D7–8 (Fig. 6). At D28–30, while the feature of ingestion episode in the reduction pigs existed and the restoration of AW and LENG deformation continued, the deformational ranges in THICK, PDW and PVW further decreased (Fig. 6).

As summarized in Fig. 7, in both reduction and sham groups, the largest deformational change relative to the initial distances was seen in AW ($30.5\% \pm 2.3\%$), and the smallest in PVW ($14.8\% \pm 1.5\%$) and LENG ($16.4\% \pm 1.4\%$) at D-1. As compared to the sham pigs, deformational changes during chewing in the reduction pigs significantly decreased in AW ($16.7\% \pm 1.3\%$, $P < 0.001$) and LENG ($12.24\% \pm 0.7\%$, $P < 0.001$), but changes in the posterior tongue body (THICK: $24.2\% \pm 1.7\%$, PDW: $22.3\% \pm 2.1\%$, and PVW: $20.2\% \pm 1.9\%$) enhanced significantly ($P < 0.001$) at D7–8. At D13–15, the reduced deformational capacity in AW ($18.2\% \pm 1.8\%$; $P < 0.001$) and LENG ($12.53\% \pm 1.5\%$; $P < 0.01$) slightly restored with the better regularity of stereotypical chewing cycles than those seen at D7–8. However, the increased deformation in THICK ($22.4\% \pm 1.7\%$; $P > 0.05$), PDW ($21.2\% \pm 1.2\%$; $P < 0.01$) and PVW ($19.1\% \pm 1.5\%$; $P < 0.05$) diminished as compared to those seen at D7–8. At D28–30, the restoration of anterior tongue body deformation continued despite still significantly lower than those of the sham pigs ($P < 0.01$ – 0.05), but the deformational ranges in the posterior tongue body further decreased and were not significantly different from those of the sham pigs and the baseline level at D-1.

DISCUSSION

Several surgical procedures for anterior resection of the tongue have been described (Wang et al., 2003; Balaji, 2013). All the techniques aim to reduce the bulk of the tongue such as length, width, thickness or all of them and to preserve the neurovascular bundles. Clinically, tongue volume reduction surgery is performed as part of the total treatment in acquired macroglossia, or orthodontic and orthopedic treatment for skeletal Class III malocclusion or anterior open bite. This is because the relatively enlarged tongue after mandibular set-back or Lefort osteotomy is not only potential source of relapse but also results in various functional disorders (Miyawaki et al., 2000; Hotokezaka et al., 2001). A number of long-

term studies have shown the impacts of tongue reduction surgery on speech, sensation, taste, psychology, feeding, and drooling (Van Lierde et al., 2010; Shipster et al., 2012; Matsumoto et al., 2014). However, few studies have been identified with regard to the effect of a volume-reduced tongue on its motor function over time. Our previous study reported for the first time that tongue volume reduction alters the tongue internal kinematics significantly (Shcherbatyy et al., 2008). Unfortunately, that study was unable to address the question about if these negative effects on the tongue internal kinematics are transient or relatively permanent consequences following the tongue volume reduction.

The present study demonstrated that both feeding behavior and deformational pattern of the tongue are not significantly affected by the sham surgery as compared to the results from normal unoperated pigs previously reported (Shcherbatyy and Liu, 2007), and the period of 6-week rapid growth has no apparent influences on the tongue internal kinematics. However, significant modifications in feeding behavior was clearly observed over time in the reduction pigs, indicating the persistent impact on the ability of food ingestion, transportation, chewing, and possibly swallowing due to the loss of anterior tongue mass. Of course, these kinematic alterations in the reduction pigs might also partially result from the post-surgically pain, in particularly during the initial 1–2 weeks after the surgery. However, given the fact that the sham pigs received the same surgical incisions as the reduction pigs but showed similar features of feeding behavior and tongue internal kinematics to those seen on normal unoperated animals in the current study, the influences of post-surgical pain on tongue internal kinematics should be considered moderate or minor (Shcherbatyy and Liu, 2007).

The longitudinal tracking further revealed that both rhythm and amplitude of tongue dimensional changes during feeding modified over time in the reduction pigs. At D7–8, the basic features of functional deformation during chewing still remained, but more frequent and longer ingestion episodes interposed in masticatory sequence with the decrease in the regularity and amplitudes of AW and LENG and increased amplitudes in THICK, PDW and PVW. These results suggested that changes in the posterior tongue (both widths and thickness) were significantly enhanced to compensate for the loss in the anterior width and body length. In addition, from D13–15 to D28–30, the amplitude of AW and LENG increased but THICK, PDW and PVW decreased. While the recovery of deformational capacity in the anterior tongue body did not reach the level of baseline or the sham pigs, the compensatory enhancement of deformational capacity in the posterior tongue body gradually vanished and almost returned to the level of the baseline at D28–30. These time-course changes in tongue body functional deformation clearly indicate that although the tongue deformational capacity subjects to a short-term loss in the anterior part and a compensatory enhancement in the posterior part, these distorted features are diminishing over time. It is worthy to note that although there was some recovery, the restoration of the deformational capacity in the anterior part at the end of this experiment (D28–30) was still significantly smaller than that of baseline (D-1). This relatively long-term negative impact might stem from the fact that the healing after the tongue volume reduction surgery is not a process of myogenic regeneration, but fibrosis and formation of the scar tissue, as evidenced by our histological studies (Perkins et al., 2008; Ye et al., 2010). Since the performed tongue volume reduction surgery was only involved in the anterior and middle parts of the tongue

(tongue blade and body) with little invasion close to the region of the two circumvallate papillae, the observed changes in tongue internal kinematics are most likely derived from the loss of the tongue mass. It is also worthy to note that because the midline area of the tongue is made of fibrous septum, bundles of the bilateral muscle group of tongue are often approximated when the tip is reconstructed. This newly formed structure may fail to provide synchronous function as does an intact tongue (Ye et al., 2010). Based on all of these morphological and histological alterations, maladaptation of tongue internal kinematics may be initiated due to the natures of muscular plasticity and the consequence of motor learning, as seen in the present longitudinal observations. Apparently, this type of maladaptive internal kinematics in a volume-reduced tongue does not result in a functional performance as good as an intact tongue, evidenced by behavior alterations and reduced deformational capacity in the anterior tongue during feeding, and potentially negative consequences on craniofacial growth and occlusal development (Liu et al., 2008).

Although successful, the implantable microsonometric technique for the longitudinal and dynamic tracking of tongue internal kinematics should be considered as a challengeable and demanding approach because of the frangible nature of implanted ultrasonic crystals and the difficulty of infection control around the skin button implanted area. These disadvantages limited that the current study was only able to do the longitudinal tracking for about 4 weeks after the tongue surgery. Therefore, it is premature to state that this type of maladaptation of the internal kinematics of a volume-reduced tongue would persist over months or years. The other limitation of the current study is that only one surgical method of tongue volume reduction was applied with the identical reduction rate of 18–20% (Perkins et al., 2008). Therefore, it is unknown that if other surgical approaches with different volume reduction rates would result in different changes in internal kinematics of the tongue.

In conclusions, the present results suggest that in the pig: 1) the tongue internal kinematics is not subject to significant changes over time during the rapid growth period; 2) the tongue body volume reduction has significant and persistent impacts on both feeding behavior and tongue internal kinematics over time; 3) the restoring capacity of internal kinematics in the anterior tongue after the reduction surgery is limited and incomplete over time; 4) the tongue internal kinematics should be considered volume-dependent, and may subject to maladaptation.

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Fig. 1. Implantation of six ultrasonic crystals in the tongue body

A: Wedge-shaped configuration of implanted crystals array. Numbers indicate the location of each crystal, and a given dimension of the tongue is represented by a pair of crystals. 1–2: anterior width (AW); 3–4: posterior dorsal width (PDW); 5–6: posterior ventral width (PVW); 1–3 and 2–4: right and left length (RL and LL); 3–5 and 4–6: right and left thickness (RT and LT). Arrows indicate two circumvallate papillae (CP). Please note that the crystals No.5 and No.6 (dotted circles) were implanted 10–12mm ventrally deeper to the crystals No.3 and No.4. **B:** A pair of 2mm B-barb ultrasonic crystals. *This figure was modified from the one previously published at The Anatomical Record 290:1288–1299, 2007.*

Fig. 2. A cephalometric radiograph showing the implanted crystals array and a skin button set The white-dashed line outlines the tongue shape and the black-solid lines depict the wedge-shaped configuration of six implanted crystals (white dots). Numbers indicate the location of crystals. **A:** The tongue and ultrasonic crystal array; **B:** Leading wires of implanted crystals; **C:** Skin button. **Inserts:** A skin button set. **a:** Female connector; **b:** Screwed cover; **c:** Male connector and plug-in cables. Refer to the captions of Fig. 1 for numbers and dimensions in the crystal array.

Fig. 3. Diagram of the uniform tongue volume reduction surgery

Shaded areas represent surgical incisions and removed tongue tissue for the volume reduction. Arrows indicate two circumvallate papillae (CP). **A:** Dorsal view of the entire tongue. Circles and numbers indicate implanted crystal sites. **B:** Cross-sectional view at the junction of anterior 1/3 and 2/3 of the tongue. **C:** Cross-sectional view at the location 5mm anterior to the two CPs of the tongue. Refer to the captions of Fig. 1 for numbers and dimensions in the crystal array. *This figure was modified from the one previously published at The Anatomical Record 291:886–893, 2008.*

Fig. 4. Comparison of body weight gains over 6-week experimental period

W-1: 1 week before the tongue volume reduction or sham surgeries; **W0:** day of the tongue surgery; **W1, W2, W3 and W4:** 1, 2, 3 and 4 weeks after the tongue surgery, respectively. F values and superscripted asterisks indicate overall significance over 4 time points in each group by ANOVA. $**P < 0.01$. The asterisks above the data points indicate significant difference as compared to the baseline (W-1) in each group by Tukey post-hoc tests with Bonferroni correction. $*P < 0.01$. Please note that there is no significant difference between the two groups at each time point. *This figure was modified from a supplemental figure previously published at Otolaryngology–Head and Neck Surgery 139, 291–297, 2008.*

Fig. 5. Raw microsonometric tracings of the deformational changes during natural feeding from the pig #25

A: Before the reduction surgery; **B:** One week after the reduction surgery. Dotted vertical lines separate chewing and ingestion episodes of a masticatory sequence. Refer to Fig. 1 for dimensional captions.

Fig. 6. Zoomed microsonometric tracings of chewing in a reduction pig over time
D-1, D7, D15 and D30 indicate the time point 1 day before and 7, 15, and 30 days after the tongue volume reduction surgery, respectively. Refer to Fig. 1 for dimensional captions.

Fig. 7. Comparisons of deformational ranges of each dimension over time during chewing between the reduction and sham groups

The left two panels indicate the anterior width (AW) and lengths (LENG), and right three panels indicate the posterior widths (PDW and PVW) and thickness (THICK). F_s and F_r represent F values of ANOVA tests in the sham and reduction group, respectively. Asterisks superscripted at F values indicate overall significance across 4 time points. $**P < 0.01$; $***P < 0.001$. Asterisks superscripted at the data points indicate significantly difference of deformational changes at each time point between the two groups by non-paired t tests. $*P < 0.05$; $**P < 0.01$; $***P < 0.001$. All values were converted to the percentages of rest-position distance of each dimension. D-1, D7-8, D13-15, and D28-30 represent the time point 1 day before and 7-8, 13-15, and 28-30 days after the tongue volume reduction or sham surgeries, respectively.

Table 1

Sample Sizes of Successful Microsonometric Recordings

Time	Group	AW	RL	LL	RT	LT	PDW	PVW
D-1	Sham	4(89)	4(89)	4(92)	4(89)	4(90)	4(89)	5(113)
	Reduction	4(94)	4(94)	4(94)	4(95)	5(119)	4(95)	5(119)
D7-8	Sham	4(92)	3(70)	4(92)	4(92)	4(92)	3(70)	4(92)
	Reduction	4(91)	4(91)	4(91)	4(91)	4(91)	4(91)	4(91)
D13-15	Sham	4(87)	3(65)	4(87)	4(87)	4(87)	3(65)	4(87)
	Reduction	3(68)	4(89)	4(89)	4(89)	4(89)	4(89)	4(89)
D28-30	Sham	4(90)	3(68)	4(90)	4(90)	4(90)	3(68)	4(90)
	Reduction	3(64)	3(65)	4(87)	4(87)	4(87)	3(65)	4(87)

Numbers in parentheses represent sampled chewing cycles; D-1, D7-8, D13-15, and D28-30 represent the time point one day before and 7-8, 13-15, and 28-30 days after the tongue volume reduction or sham surgeries, respectively. AW: anterior width; RL and LL: right and left lengths; RT and LT: right and left thicknesses; PDW and PVW: posterior dorsal and ventral widths.