ORIGINAL ARTICLE

Loss of oral sensation impairs feeding performance and consistency of tongue–jaw coordination

Jeffrey D. Laurence-Chasen[1] 🄳 | Fritzie I. Arce-McShane[2] | Nicholas G. Hatsopoulos[1] | Callum F. Ross[1]

[1]Department of Organismal Biology and Anatomy, The University of Chicago, Chicago, Illinois, USA

[2]Department of Oral Health Sciences, School of Dentistry, University of Washington, Seattle, Washington, USA

Correspondence
Jeffrey D. Laurence-Chasen and Callum F. Ross, Department of Organismal Biology and Anatomy, The University of Chicago, 1027 E 57th St, Chicago, IL 60637, USA.
Email: jdlaurence@uchicago.edu

Funding information
National Institute of Dental and Craniofacial Research; National Institute on Aging; National Science Foundation

Abstract

Background: Individuals with impaired oral sensation report difficulty chewing, but little is known about the underlying changes to tongue and jaw kinematics. Methodological challenges impede the measurement of 3D tongue movement and its relationship to the gape cycle.

Objective: The aim of this study was to quantify the impact of loss of oral somatosensation on feeding performance, 3D tongue kinematics and tongue-jaw coordination.

Methodology: XROMM (X-ray Reconstruction of Moving Morphology) was used to quantify 3D tongue and jaw kinematics during feeding in three rhesus macaques (*Macaca mulatta*) before and after an oral tactile nerve block. Feeding performance was measured using feeding sequence duration, number of manipulation cycles and swallow frequency. Coordination was measured using event- and correlation-based metrics of jaw pitch, anterior tongue length, width and roll.

Results: In the absence of tactile sensation to the tongue and other oral structures, feeding performance decreased, and the fast open phase of the gape cycle became significantly longer, relative to the other phases ($p < .05$). The tongue made similar shapes in both the control and nerve block conditions, but the pattern of tongue-jaw coordination became significantly more variable after the block ($p < .05$).

Conclusion: Disruption of oral somatosensation impacts feeding performance by introducing variability into the typically tight pattern of tongue-jaw coordination.

KEYWORDS
feeding, mastication, somatosensation, stereognosis, tongue, XROMM

1 | INTRODUCTION

Mastication involves complex sequences of jaw and tongue movements. Cyclic jaw elevation brings the teeth together to reduce the food item into smaller particles while the tongue positions the food between the teeth, forms it into a bolus and transports it into the pharynx.[1–3] Effective coordination of these jaw and tongue movements depends on the integration of information from a dense array of sensory receptors in the oral mucosa.[4]

When oral sensory feedback is disrupted—the hallmark of trigeminal neuropathies—patients may experience difficulty chewing.[5,6] The most common source of trigeminal neuropathy is iatrogenic dental trauma, but many other aetiologies may contribute to loss of oral sensation;[5] in one study, oral numbness was found

to be the most common long-lasting symptom in patients who had experienced non-iatrogenic maxillofacial trauma.[7]

Despite the prevalence of oral numbness, there are few quantitative studies upon which rehabilitative therapies can be based; the basic response properties of the oral cavity's rich array of mechanoreceptors are known,[8] but the kinematics resulting from loss of feeding performance following trigeminal nerve damage are not well understood. In particular, methodological challenges make it difficult to quantify intraoral 3D tongue kinematics.[9]

Lateral-view videofluoroscopy studies have demonstrated the basic sagittal pattern of tongue-jaw movements during chewing in macaques: anteroposterior tongue 'cycles' coordinated with vertical jaw movements.[1,10] This kinematic profile emerges from a brainstem central pattern generator (CPG)[11] whose output is modified by sensory feedback from mechanoreceptors in the tongue, teeth, temporomandibular joint and jaw muscles.[12-14]

It has long been known, however, that the tongue variably deforms along transverse axes to help position and control food on the working side teeth.[15-17] These mediolateral movements are not captured by traditional lateral-view videofluoroscopy and are not well understood. Thus, the extent to which the tongue movements crucial to feeding are affected by loss of oral sensation is virtually undocumented in primates. In a recent study on pigs, unilateral transection of the lingual nerve altered the kinematic pattern of tongue-jaw coordination, but had an inconsistent impact on mandibular kinematics across individuals.[18,19] The extent to which this result generalises to mediolateral tongue movements in humans and non-human primates is unclear. Moreover, given the density of oral innervation, disambiguating the roles of various types of oral mechanosensory feedback, in particular tactile versus proprioceptive afferents, is challenging.

The anatomy of the mouth offers a unique opportunity to selectively disrupt orolingual tactile sensation without impacting motor signals; afferent axons from proprioceptive and tactile mechanoreceptors of the tongue enter the CNS on different nerves. Specifically, tongue muscle efferent and spindle afferents leave and enter the CNS on the hypoglossal nerve,[20,21] while afferents of superficial tactile mechanoreceptors in the oral mucosa (gums, cheeks, palate and anterior 2/3 of the tongue) travel along sensory branches of the trigeminal nerve.[22,23] This anatomical organisation means that oral tactile sensation can be perturbed by an injection-based nerve block with no impact on the efferent motor or proprioceptive signals from the tongue. Moreover, trigeminal nerve blocks, such as those deployed in the dentist's office, are minimally invasive and rapidly acting, minimising the impact of surgery and long-term compensation strategies on results.[18,24]

Here, we employ a nerve block to temporarily silence oral tactile signals during feeding in macaque monkeys (*Macaca mulatta*), leaving motor and proprioceptive signals from tongue and jaw muscles unaffected.[25] We precisely quantify 3D jaw movements and tongue deformations using XROMM (X-ray Reconstruction of Moving Morphology[26]), an innovative imaging workflow for the study of hyolingual and jaw kinematics.[15,27] We compare feeding performance, jaw and tongue kinematics, and tongue-jaw coordination before and after the nerve block. Our results quantitatively demonstrate the impact of the loss of oral sensation on the coordination and performance of feeding.

2 | MATERIALS AND METHODS

2.1 | Subjects

Experiments were performed on three adult male rhesus macaques (monkeys R, Y and B; *Macaca mulatta*, 9–10 kg). All protocols were approved by the University of Chicago Animal Care and Use Committee and complied with the National Institutes of Health Guide for the Care and Use of Laboratory Animals.

2.2 | Behavioural task

Subjects sat calmly and received and consumed food items while head-fixed and seated in a standard primate chair in the University of Chicago XROMM Facility. The experimental paradigm involved two feeding conditions: natural feeding and feeding after an oral tactile nerve block (see below). Each monkey served as its own control and treatment condition; a control data collection session was conducted either one day before or one day after the nerve block session for each monkey. In both conditions, experimental food comprised half grapes and half gummy bears of equal size presented directly to the monkey's mouth via a long stylus. We chose these two foods because both are relatively soft—a common characteristic of foods used in oral rehabilitation--and they possess differential liquid content; grapes have large amounts of liquid, whereas gummy bears have virtually none. The presence of liquid poses an additional challenge in intraoral bolus management. Both foods are also palatable to our study animals, so were likely to be consumed. Food was introduced in semi-random order. Frequent switching was attempted, but at times the monkeys refused a specific food type, necessitating use of the other. Sample sizes of the different food types are provided in Table S1

2.3 | Oral tactile nerve block

To temporarily silence tactile signals from the mouth (while sparing efferent motor and afferent proprioceptive signals from tongue and jaw muscle spindles), a nerve block of sensory fibres was performed via bilateral bupivacaine (2% with 1:100 000 epinephrine) injections to multiple branches of the trigeminal nerve (lingual, inferior alveolar, buccal, palatine; see Appendix S1 methods for specific details of approach). The nerve block

was performed while the subjects were under full sedation, and all experimental data were collected within 90 minutes of the nerve block (well within the effective duration of bupivacaine). Consistent syringe placement was enabled by the creation of individual-specific, 3D-printed needle guides (Figure S7). Nerve block effectiveness was assessed via both behavioural observation (lack of responsiveness to touch in anaesthetised areas), and a global decrease in baseline firing rates of somatosensory neurons recorded using multi-electrode arrays implanted in the primary motor and primary somatosensory areas of the oro-facial cortex (Figure S6).

2.4 | Sham

To rule out sedation as a possible source of confounding effects on tongue and jaw kinematics, we performed a sham nerve block with monkey Y on a separate day. During the sham, the subject was sedated and the nerve block procedure was performed with saline instead of bupivacaine. There were no significant changes to jaw kinematics following the sham nerve block (Figure S2).

2.5 | XROMM

During feeding, biplanar high-speed (200 Hz) videoradiography data were collected to visualise the movements of 24 radiopaque beads (tantalum, 1 mm diameter) that had been surgically implanted into the tongue, mandible and cranium following our previously described methods.[27,28] The 3D positions of the tongue beads as well as the rigid body transformations of the cranium and mandible were reconstructed using XMALab[29] following the XROMM workflow (see Appendix S1 Methods for a full description). Kinematic data were processed using a modification of the XROMM workflow that incorporates machine learning through DeepLabCut.[30] This yielded what is, to our knowledge, the largest number of frames (by a factor of 10) ever analysed in an in vivo XROMM feeding study.

2.6 | Neural data and electromyography

Jaw and tongue muscle electromyographic (EMG) activity and oro-facial sensorimotor cortical neuronal activity were recorded using chronically implanted EMG electrodes and multi-electrode arrays, respectively. EMG electrodes were implanted bilaterally into the masseter, temporalis and digastric (anterior belly) muscles, as well as multiple intrinsic and extrinsic tongue muscles using our published methods[27] Muscle electrode positions were confirmed with post-mortem CT scans, and only masseter EMG activity was used in the final analysis. Multi-electrode arrays were implanted unilaterally (left hemisphere in all animals) in the oro-facial regions of the primary motor and somatosensory cortices (see Ref. [24,29] for

details).[25,31] Here, cortical neural data were used only to confirm the success of failure of the nerve block, and EMG data were used to quantify number of gape cycles in a feeding sequence.

2.7 | Data analysis

Prior to computational analysis, all trials were inspected and gape cycle types were manually identified using XMALab's biplanar marker tracking interface. Each gape cycle was individually categorised, based on X-ray and light camera video, as either manipulation, stage 1 transport, left chew, right chew, chew (unknown side), stage 2 transport, intercalated swallow or terminal swallow. All subsequent analysis was performed in MATLAB 2020a (Mathworks).

Ecologically relevant[32] feeding performance metrics were calculated following a formal feeding assessment.[33] Based on masseter EMG data and the gape cycle categorisation, we quantified overall feeding sequence duration (from the initial ingestion to terminal swallow) in terms of number of gape cycles, number of manipulation gape cycles prior to the onset of rhythmic chewing, and frequency of swallowing.

Kinematic analysis was performed at the level of individual jaw gape cycles, and gape cycle phases (fast close, slow close, slow open, fast open) were calculated from mandibular pitch following previously established definitions.[34] Mandibular pitch itself was measured using a temporomandibular joint coordinate system--a 6 degree of freedom measure of joint motion.[35,36]

Three tongue kinematic variables (length, width, roll) were computed from the anterior tongue 3D marker positions (Figure 1). Tongue length and width were, mathematically, the Euclidean (straight line) distances of the midline or lateral markers, respectively, and capture deformation of the anterior 1/3 of the tongue (Figure 1A). Roll was calculated as the angle made by the height difference of the two lateral markers, when projected onto a frontal plane (Figure 1B). Importantly, roll represents an inherently mediolateral motion that is important to the tongue's function during feeding.[15,16] To minimise the impact of differences in marker placement between animals, roll angle was zeroed based on a rest frame (after a terminal swallow) for each monkey. Cross-correlation analysis was performed with the MATLAB function xcorr, with inputs being the mean-subtracted jaw pitch and tongue signals, for a given sequence (see Appendix S1 Methods for more information). For an example of baseline (control) jaw and tongue kinematics, see Figure S8.

Previous studies have found large inter-subject kinematic variation in the effect of and compensatory strategies after oral nerve blocks;[18,19,37] thus all analyses were performed at the individual level. Unless otherwise noted, significant differences in magnitude and variance between conditions were assessed with a two-tailed t-test and F-test of equality of variances, respectively. Sample sizes are provided in Table S1. Data were separated by food type when there were significant food type effects (Two-factor ANOVA, with individuals and food type as factors; $p > .1$).
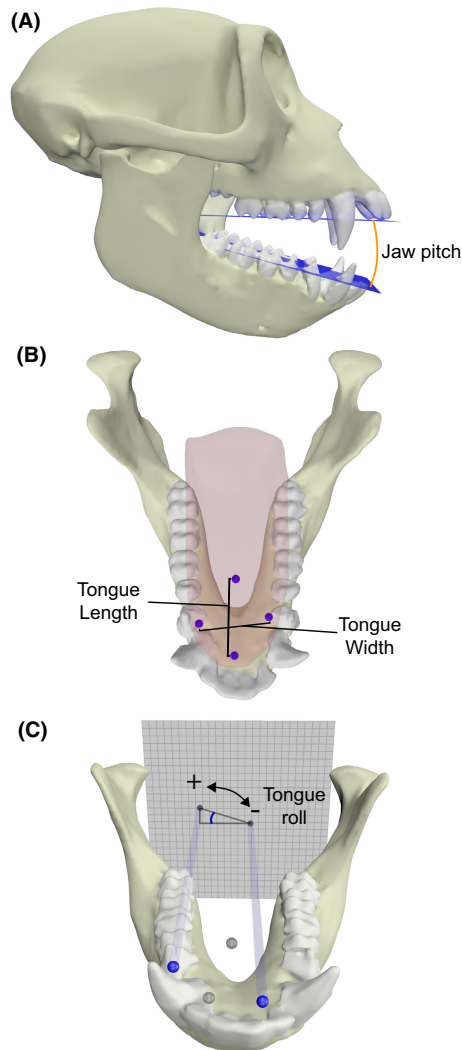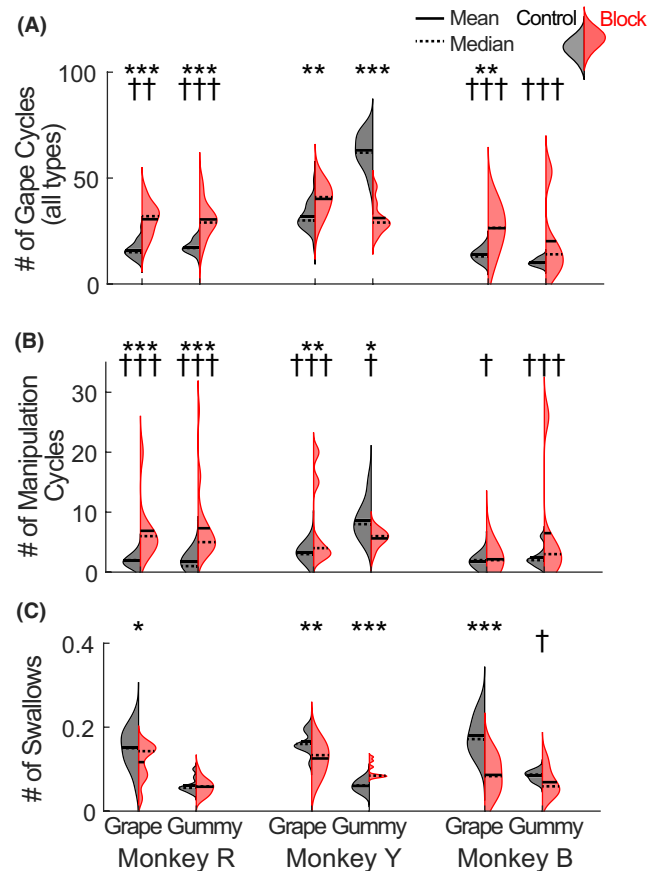
FIGURE 1 Kinematics extracted from XROMM data. (A) Jaw pitch (orange line) is the angle made by theoretical planes fitted to the upper and lower teeth using a joint coordinate system (see Appendix S1). (B) Anterior tongue length and width are the instantaneous Euclidean (straight line) distances between anterior tongue markers. (C) Tongue roll angle (blue line) was derived from the height difference of the two anterior lateral markers projected onto a coronal (frontal) plane. Positive roll is counter-clockwise when looking at the tongue from the front (thus the tongue is negatively rolled as depicted)

FIGURE 2 Effects of nerve block on feeding performance variables for three animals eating two food types. Left halves of hemi-violins (black) are control and right halves (red) are nerve block for a single food type for an individual. (A) Total number of gape cycles (all cycle types) per food item, from initial ingestion of food to terminal swallow. (B) Number of gape cycles, manipulation and/or stage I transport, prior to the onset of rhythmic chewing. (C) Swallow frequency, as measured by number of swallows per 10 gape cycles. Results of a two-tailed t-test and F-test of equality of variances (within each subject) are indicated by asterisks and crosses, respectively: $^{*,†}p < .05$; $^{**,††}p < .01$; $^{***,†††}p < .001$. Horizontal solid lines are means and horizontal dashed lines are medians. Sample sizes are provided in Table S1

3 | RESULTS

3.1 | Impaired feeding performance

We first quantified the effect of loss of oral tactile sensation on overall feeding performance[33]—in terms of feeding sequence duration (i.e. number of gape cycles from food ingestion to terminal swallow), number of manipulation cycles and swallow frequency. Feeding performance was adversely impacted by the loss of tactile sensation (Figure 2). Across all animals, it took significantly more gape cycles to eat a grape as compared to the control condition, resulting in a 70% average increase in sequence duration (Figure 2A, $p < .05$,

independent two-tailed t-tests; same for significance results that follow). Monkeys R and Y showed significant changes in sequence duration for gummy bears; monkey R's average sequence duration increased with nerve block, and monkey Y's decreased. A significant increase in the variance of number of gape cycles for both foods was seen in monkeys R and B (Figure 2A, $p < .05$, F-test of equal variance). The increase in total number of gape cycles was driven in some cases by changes to the number of manipulation cycles before the onset of rhythmic chewing (Figure 2B). Monkeys R and Y showed significant changes to number of manipulation cycles, and, notably, there was a significant increase in variance of number of manipulation cycles for all animals for both foods. These results corresponded to qualitative observations of oral incoordination upon receiving a food item; the animals appeared to find handling the food challenging and took

longer to position it from the ingestion point onto the post-canine teeth (stage 1 transport).

After chewing began, there were also significant changes to the frequency of swallowing (Figure 2C). When feeding on grapes, swallows occurred significantly less frequently in all animals after the nerve block. The baseline swallow frequency for gummy bears was substantially lower relative to grapes in all animals, and no consistent pattern of nerve block effect was observed; monkey Y exhibited a significantly higher swallow frequency, and monkey B exhibited higher variance in swallow frequency.

3.2 | Changes to gape cycle kinematics

To understand the source of the marked decrease in feeding performance we measured changes to the gape cycle, the kinematic 'framework' of mastication.[34] All animals exhibited a significant increase in chew cycle duration following the nerve block (Figure 3A; $p < .5$). The longer cycles were found in all subjects when eating gummy bears and in two of three subjects when eating grapes. Moreover, all subjects also showed increased variance in cycle duration while feeding on gummy bears following nerve block. In four of the five cases where there was a significant change in mean cycle duration, there was also a significant increase in cycle duration variance. Thus, not only did the animals chew slower after the nerve block, but cycle durations were more variable. This finding held both for chew cycles pooled across sequences, and for sequence-level means (Figure S1; $p < .05$). To ensure the increased cycle durations were not a side-effect of the sedation required for the nerve block, we performed a sham procedure (see Methods) and found that cycle durations were unchanged (Figure S2, $p > .10$).

To assess how changes to gape cycle duration were effected at the cycle phase-level, we measured the relative duration, in terms of percent of cycle, of the four gape cycle phases (fast close, slow close, slow open, fast open; sensu ref. [34]). Relative phase durations after nerve block differed significantly from their counterpart in the control (Figure 3B); specifically, the relative duration of slow close decreased significantly and the relative duration of fast open increased significantly in all animals. The relative increase in fast open duration was the largest in magnitude of all the changes, and we noted a general pattern of increase in fast phase durations and decrease in slow phase durations.

### 3.3 | Changes to 3D tongue kinematics

The majority of tongue deformation during chewing occurs in the anterior tongue, and most of that deformation occurs during the fast phases of the gape cycle.[15] Accordingly, we measured changes to anterior tongue length, width and roll during right-side chews, from minimum gape to minimum gape (Figure 4A). Overall, the mean trajectories of three tongue kinematic variables remained consistent
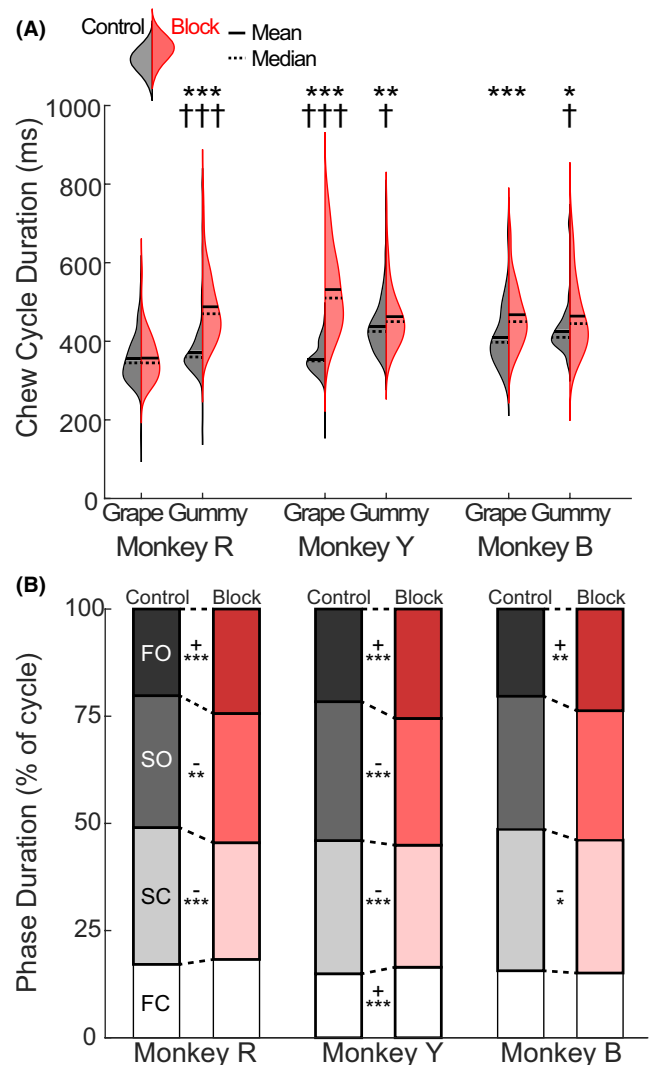

FIGURE 3 Effect of nerve block on jaw kinematics. (A) Chew cycle duration. Left halves of hemi-violins (black) are control and right halves (red) are nerve block for a single food type for an individual. Results of a two-tailed *t*-test and *F*-test of equality of variances (for each food type, within each subject) are indicated by asterisks and crosses, respectively: $^{*,\dagger}p < .05$; $^{**,\dagger\dagger}p < .01$; $^{***,\dagger\dagger\dagger}p < .001$. Horizontal solid lines are means and horizontal dashed lines are medians. (B) Relative duration of gape cycle phases. Grey-scale bars are control durations and red-scale bars are nerve block durations. FC is fast close, SC is slow close, SO is slow open, and FO is fast open. See *Methods* and ref. [34] for definitions of gape cycle phases and rhythmic chews. Asterisks and signs (+/−) indicate the significance level and the direction of a significant change, respectively. There were no significant food type effects, thus chews on both grapes and gummy bears were pooled for the phase analysis. Sample sizes are provided in Table S1

across the two experimental conditions (Figure 4B–D). We found no significant variation between food types in terms of mean trajectories, and thus pooled foods for this analysis. The most consistent and substantial nerve block effect was on tongue width; in all three animals the tongue was narrower during jaw opening after nerve block (Figure 4C). In 8 out of 12 measured variables (jaw pitch and

FIGURE 4 Effect of nerve block on tongue deformation trajectory during rhythmic right chews. See Figure 1 for definitions of shape variables. (A) Jaw pitch, for reference. (B) Anterior tongue length. (C) Anterior tongue width. (D) Anterior tongue roll, where positive roll is the rotation of the dorsum of the tongue to the right. Lines are mean ± 1 SD for right chews; black is control and red dashed is treatment (nerve block). Cycles are from minimum gape to minimum gape, and scaling was performed independently on opening and closing phases to control for shifting phase durations (see Methods section and Figure 4); thus, 50% of cycle is always maximum gape. Sample sizes are provided in Table S1
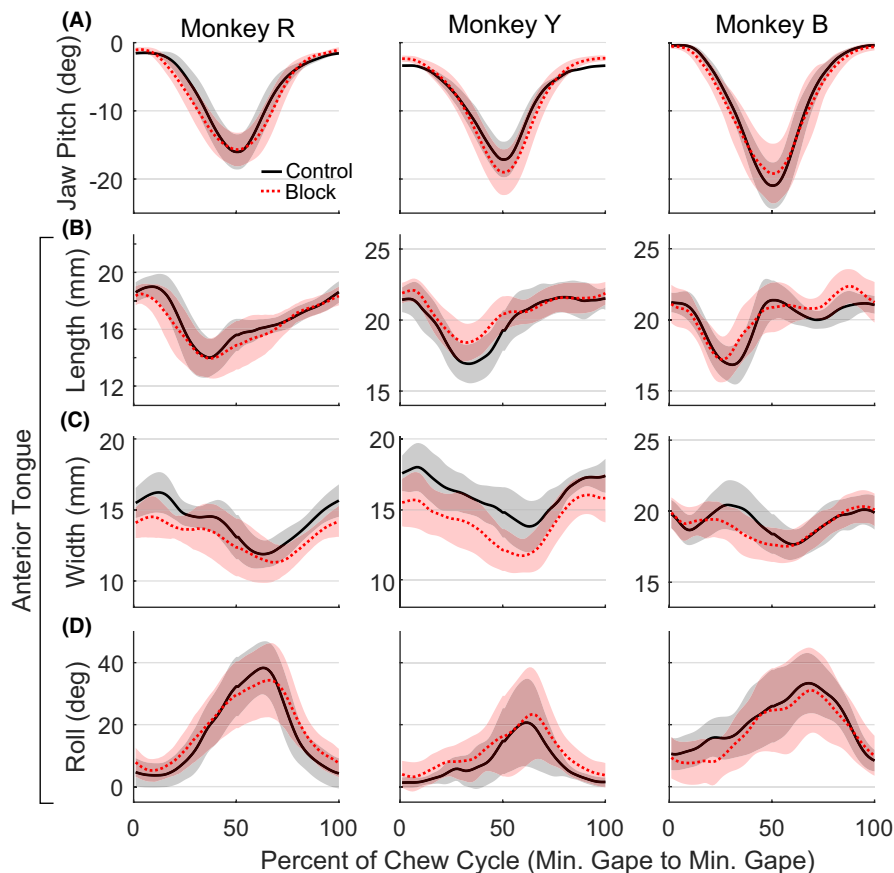
FIGURE 5 Representative kinematic traces of tongue movement relative to jaw pitch in control (A, black) and nerve block (B, red) conditions. The upper ball-and-stick plots depict the lag of jaw pitch (black lines) and anterior tongue length (i, orange), width (ii, teal) and roll (iii, pink). Lags correspond to the maximum of the cross-correlation function of the two signals for a 300-frame range centred at that position. Note that in A, the correlation between jaw pitch and tongue width remains temporally consistent over the course of 10 chews and two intercalated swallows. In B, the initial lags are similar to A, but then shift substantially at ~2.5 s. Swallows are indicated by black arrows.
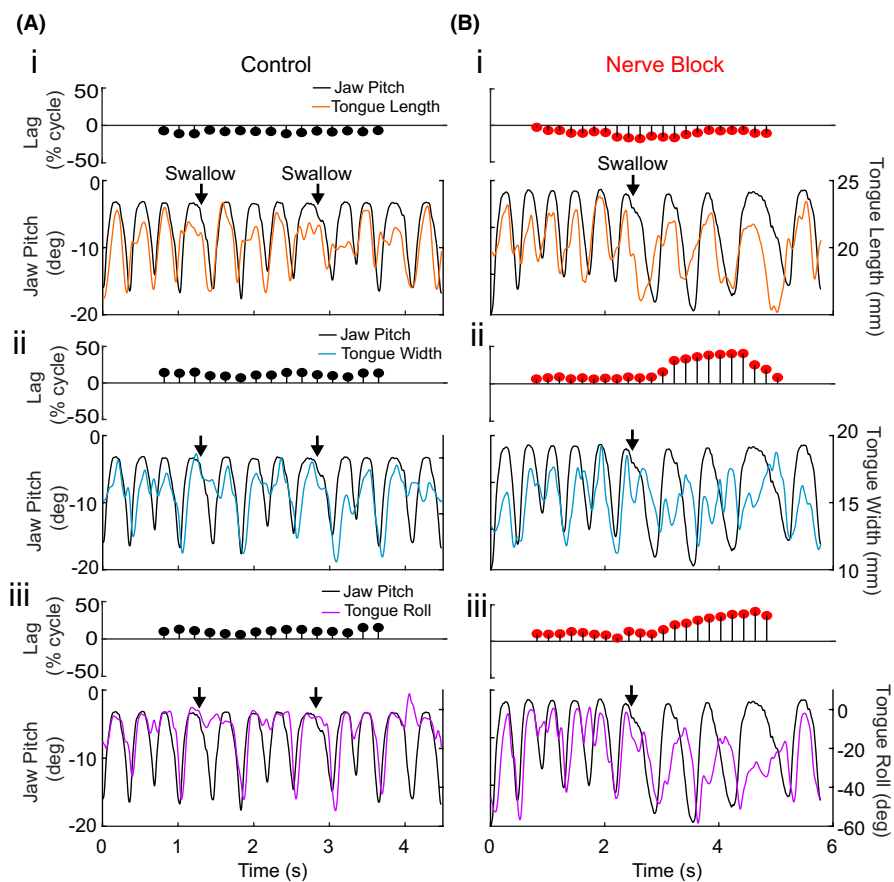
3 tongue variables in 3 animals), the variance of the trajectory increased significantly after the nerve block (Figure S3). Only monkey Y's tongue length and monkey B's tongue width showed significant decreases in variance. In short, the tongue moved and deformed in similar ways after the nerve block, but there was increased variation in the shape trajectories.

3.4 | Strength and consistency of tongue-jaw coordination

We quantified tongue-jaw coordination with event and cross-correlation-based analyses. In our event-based analysis, we used a conventional metric of tongue-jaw coordination[3]: the temporal lag between the anterior-to-posterior reversal of tongue-tip movement and the preceding minimum gape, that is tongue-tip reversal (Figure S4). To account for changing gape cycle duration (Figure 3A), we measured lags in both milliseconds (Figure S4A) and in percent of cycle (Figure S4B). Results were consistent between the two different measurement approaches; after nerve block, tongue-tip reversal relative to minimum gape was more variable, but the magnitude or direction of the lag was not consistent.

We used cross-correlation analysis as a second means of quantifying tongue-jaw coordination. Figure 5 depicts representative sub-sequences from monkey Y in which we calculated, on a rolling basis, the relative lag of jaw pitch and anterior tongue length, width and roll (lag corresponding to maximum value of cross-correlation function). In the control condition (Figure 5A), all dimensions of tongue movement remained consistently temporally correlated with jaw pitch over the course of 10 chews and 2 swallows. After the nerve block (Figure 5B), patterns of temporal correlation were less consistent over the duration of sequences. During the chews at the beginning of the sub-sequence, tongue-jaw lag appears to resemble

the control, but then at approximately 3 s, the lags of jaw pitch and tongue width and length changed substantially. Noticing these shifting patterns of coordination, we quantified the mean tongue-jaw lag (via cross-correlation) for bouts of 3–10 rhythmic chews (Figure 6). Half of the measured correlation lags showed significant shifts in magnitude; however, the direction of the changes was not consistent; sometimes the tongue shifted earlier relative to the jaw after the nerve block, sometimes it shifted later. In contrast, 10 of 18 lags exhibited a significant increase in variance after the nerve block, with no significant decreases. Thus, between bouts of rhythmic chews, the pattern of tongue-jaw coordination was more variable after the nerve block.

Was this change in temporal correlation reflected in a change in strength of correlation? We took the magnitude of the maximum (absolute value) correlation coefficient for the same chewing sub-sequences (Figure S5). Interestingly, there were no consistent patterns in change to correlation strength or variance in correlation strength. Of the 18 correlations, 5 exhibited a significant change after the nerve block, and the direction of the changes was not consistent. Thus, lack of tactile sensation changes the consistency of the pattern of tongue-jaw coordination during feeding, but not the instantaneous strength of that pattern.

4 | DISCUSSION

The goal of this study was to quantify the impact of loss of oral tactile sensation on 3D tongue movement and tongue-jaw coordination during feeding. We found that, after the loss of tactile feedback, all animals exhibited impaired feeding performance and more temporal variability in the pattern of tongue deformation and tongue-jaw coordination, though the average trajectory of tongue deformation during chews remained largely unchanged.
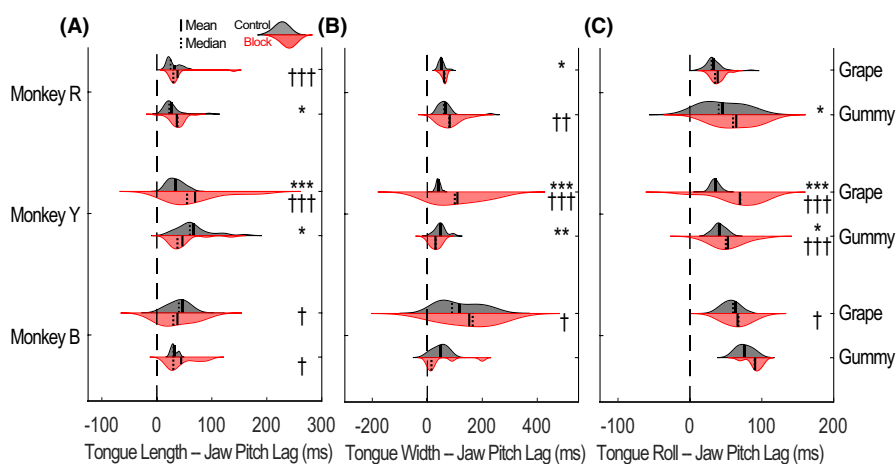
FIGURE 6 Effects of nerve block on temporal correlation of jaw pitch and anterior tongue (A) length, (B) width and (C) roll. Violins depict the lag (in ms) corresponding to the maximum cross-correlation coefficient for bouts of 4–10 rhythmic chews. Thus, a positive lag indicates the tongue variable *follows* jaw pitch when optimally correlated. Top halves of hemi-violins (black) are control and bottom halves (red) are nerve block for a single food type for an individual. Results of a two-tailed *t*-test and *F*-test of equality of variances (for each food type within each subject) are indicated by asterisks and crosses, respectively: $^{*,\dagger}p < .05$; $^{**,\dagger\dagger}p < .01$; $^{***,\dagger\dagger\dagger}p < .001$. Vertical solid lines are means and vertical dashed lines. Sample sizes are provided in Table S1

4.1 | Feeding performance

We used ecologically relevant metrics drawn from comparative studies and a recently formalised feeding assessment[32,33] to quantify feeding performance. We found that feeding sequence duration increased after the nerve block (Figure 3A), except in the case of one food type for one individual (monkey Y, gummy bears), where it decreased. While an increase in sequence duration is consistent with previous findings,[38] we propose that deviation from normal values in either direction is indicative of impaired performance; more chews on a food item indicates difficulty in processing or difficultly sensing when processing is sufficient, while fewer chews on a given food item could indicate that the item is not adequately processed before swallowing. The latter presents a particular concern in regard to swallowing safety[39] but can also affect digestive efficiency. Analysis of the material properties of the swallowed bolus would be necessary to determine whether the increased sequence durations were driven by incoordination (bolus would be under-chewed), or poor estimation of bolus properties (bolus would be over-chewed). Given the effect of loss of tactile feedback on tongue-jaw coordination and swallowing, it seems likely that a combination of the two is responsible for the change in feeding sequence durations. The marked increase in number and variance of manipulation cycles (Figure 3B) suggests that tactile feedback plays an especially important role in the initial ingestion stages of the feeding sequence.

The nerve block had a food-dependent effect on swallow frequency (Figure 3C). For grapes, swallows occurred significantly less frequently after the nerve block. For gummy bears, there was no consistent change to swallow frequency. Notably, grapes had a higher baseline swallow frequency, which after the nerve block decreased to approach that of gummy bears. A higher frequency of intercalated swallows with foods that have a liquid component has been noted previously,[40] thus, we infer that the reduction in swallowing events reflects an impaired ability to sense or handle the liquid component of the food in the oral cavity sensu stricto. Importantly, sensory feedback from the valleculae was preserved in our study, so the effects reported here reflect decreased efficiency of bolus handling and/or changes in the impact of oral sensations on reflexive components of jaw and tongue movement.[41] As many foods differ in their material properties and demand different jaw kinematics,[42] this result illustrates the importance of including multiple food types in future nerve block and transection feeding studies.

4.2 | Jaw kinematics

We found that chew cycle duration increased after the loss of tactile sensation (Figure 3A). This result is consistent with clinical findings that in neuromuscular disorders impairments to sensorimotor integration can result in slowing of movement.[43,44] Relatedly, both computational and in vivo experiments have shown that CPGs operate at lower frequencies in the absence of sensory feedback.[38,45-47]

Our results corroborate these results, showing that tactile feedback is important for the maintenance of the natural chewing frequency.

The increases in chew cycle duration are not evenly distributed across the gape cycle phases; the relative duration of the fast open phase increased after the nerve block (Figure 3B). During fast open, the tongue performs one of its principle sensorimotor tasks: the gathering of new information about bolus properties while simultaneously repositioning it onto the tooth row.[9] An elongation of this phase after the loss of tactile feedback suggests that performance of this task depends heavily on ongoing tactile feedback. Additionally, fast open is immediately followed by the closing phases of the gape cycle, where the risk of a tongue bite is highest. Thus, in a situation where stereognosis and manipulation of the bolus is impaired, a prolonging of the opening phase could reduce the chance of the tongue being bitten while those processes are still occurring.

4.3 | Tactile feedback enables consistent tongue-jaw coordination

Our findings suggest that tactile feedback from the oral cavity plays a key role in regulating the pattern of tongue-jaw coordination, but not necessarily in the generation of the pattern itself. After the nerve block, there was more variation in the correlation lag between the tongue and the jaw (Figure 6). This result held for multiple dimensions of tongue kinematics—both internal deformation (length and width) and positional change (roll). While the example sequence depicted in Figure 5B contains a shift in coordination corresponding to the first intercalated swallow, we did not find statistically significant ($p > .1$) patterns in the change of temporal coordination related to swallows or to any particular time point in the feeding sequences; the increased variance in tongue-jaw temporal correlation was distributed throughout the feeding sequence. Importantly, in two of three animals this increased temporal variance was not reflected in a change to the strength of the correlations (Figure S5). In other words, the tongue and jaw were not 'less' tightly synchronised, but rather differently synchronised.

How did this difference in coordination relate to the tongue movements themselves? We found an increased variance in the trajectory of tongue deformation (Figure S3), as well as some changes to the average trajectory of tongue deformation during chews—in particular anterior tongue width (Figure 4). But those changes were minimal, in that the tongue assumed approximately the same shapes at the same times in the gape cycle. This result stands in opposition to the findings of a recent study that observed differential hand postures in subjects with a chronic loss of tactile feedback.[48] We believe this difference could be due to the inherent differences between chewing and grasping—both in terms of cyclicity and role of vision in the behaviour. Given that cycle-to-cycle variation in tongue kinematics is expected as the tongue responds to changing bolus properties, how does the increase in variance after the loss of tactile feedback relate to impaired feeding performance? We suspect that deviations from the tongue's average kinematic trajectory in normal feeding

are relatively subtle in magnitude, in part so they do not disturb the overall masticatory rhythm in which they are contextualised. Indeed, responses to perturbations or changing extrinsic factors in limbed locomotion are often rapid and result in little change to the overall gait cycle.[49] Thus, while some variation in kinematics is required to account for a dynamic environment (or bolus, in the case of feeding), it seems that temporal resilience of the overall motor pattern in the face of changing external factors is a hallmark of coordinated, cyclic behaviours in mammals.[50,51] Our results demonstrate that when the tongue and jaw are deprived of tactile feedback that consistency is impaired. That the strength of the correlations between the tongue and jaw is not degraded suggests that the generation of the pattern itself does not depend on tactile feedback. Further studies are needed to test whether proprioceptive feedback from muscle spindles is involved in the emergence of the motor pattern, as has been found in locomotion.[52] Finally, our understanding of the role of the sensorimotor cortex in the control of tongue-jaw coordination is still rudimentary and constitutes an important avenue for future research.[53]

4.4 | Comparison with previous studies

Several previous studies have used nerve blocks or transections to clarify the role of sensory feedback in mastication. Inoue and colleagues[38] found that bilateral transection of the maxillary and inferior alveolar nerves in rabbits resulted in increased and more variable feeding sequence duration, slower chewing cycles and irregular patterns of jaw movements. Similarly, Huang and colleagues[54] reported that, in minipigs, a unilateral block of the superior and inferior alveolar nerves induced increased variance in feeding sequence duration, slower chewing cycles and an overall reduction in the ability to 'regulate muscle force and the coordination of jaw movements'. These results are consistent with several findings reported here (Figures 2A,B & 3A). At the level of individual chewing cycles, however, our finding of a decrease in relative slow close phase duration and a commensurate increase in fast open (Figure 3B) have not previously been documented. Montuelle and colleagues[18] unilaterally transected the lingual nerve in pigs but noted wholly inconsistent changes to relative gape cycle phase durations at the individual level. Their study highlighted the high incidence of inter-subject variation in oral perturbation experiments. Future work that builds upon the present study would but ideally involve a larger number of subjects to account for this phenomenon. However, logistical constraints (i.e. cost, time investment) render large-sample non-human primate studies challenging to execute.

In a separate study Montuelle and colleagues[19] also quantified changes to tongue-jaw coordination after unilateral lingual nerve transection in pigs. They found that, on average, anteroposterior movements of the tongue occurred earlier in the gape cycle, but they did not provide an analysis of the variance in these altered patterns of the coordination. We did not observe a consistent shift in the relative timing of tongue and jaw movement across individuals

in this study (Figure S4), but we did find consistent increases in the variance of tongue-jaw timing (Figure 6). Whether or not other oral structures in addition to the tongue are anaesthetised is likely an important factor in emergent motor changes.[55] On the whole, differences in experimental design (unilateral vs. bilateral treatment; lingual nerve vs. inferior alveolar nerve, etc.) abound in the literature and complicate interpretation. That oral tactile feedback plays a key role in mastication is incontrovertible; disruption of oral tactile afferents leads to changes in jaw kinematics, tongue kinematics and tongue-jaw coordination in various taxa. But the manner in which the central nervous system integrates altered sensory information into ongoing motor commands (to the tongue, in particular) remains challenging to parse.

5 | CLINICAL IMPLICATIONS

Impaired oral tactile sensation, a hallmark of trigeminal neuropathy, is highly prevalent[5] and may result in difficultly chewing and swallowing. In most but not all clinical cases, numbness is unilateral and/or localised. For this reason, many previous studies have used unilateral nerve transection or blocks in their experimental design. A consequence of unilateral perturbation is that subjects typically chew on the unaffected side, ostensibly relying on the intact sensory afferents to safely process food. Such experimental paradigms are clinically plausible and provide insight into compensatory masticatory kinematics after nerve damage. But the fact that, in unilateral perturbation, at least half of the oral cavity retains its sensory function introduces confounds that limit our ability to relate results to a broader, mechanistic framework of sensorimotor integration during feeding. Such a framework is crucial for understanding the consequences of oral neuropathy, and for informing therapeutic approaches.

This study provides evidence for the key role of oral tactile feedback in supporting the tight patterns of tongue-jaw coordination that underlie the performance of feeding. Consequently, for patients experiencing disrupted oral sensation, foods that require the rapid modulation of tongue and jaw kinematics may be inadvisable. A general category that fits this description is hard foods, which fragment into many small pieces demanding rapid modulation of tongue kinematics to form and control the bolus. Furthermore, at higher chewing frequencies variance in the relative timing of tongue-jaw coordination may result in greater risk of tongue bites. In sum, our data suggest that slower chewing, with an emphasis on homogenous, minimally fragmenting food may be beneficial for rehabilitation of patients experiencing oral anaesthesia or paraesthesia.

CONFLICT OF INTEREST

N.G.H. serves as a consultant for BlackRock Microsystems, Inc., the company that sells the multi-electrode arrays implanted in sensorimotor cortices.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Jeffrey D. Laurence-Chasen https://orcid.org/0000-0001-6192-175X

REFERENCES

1. Palmer JB, Hiiemae KM, Liu J. Tongue-jaw linkages in human feeding: a preliminary videofluorographic study. *Arch Oral Biol.* 1997;42(6):429-441. doi:10.1016/S0003-9969(97)00020-4
2. Franks HA, Crompton AW, German RZ. Mechanism of intraoral transport in macaques. *Am J Phys Anthropol.* 1984;65(3):275-282. doi:10.1002/ajpa.1330650307
3. Hiiemae KM, Hayenga SM, Reese A. Patterns of tongue and jaw movement in a cinefluorographic study of feeding in the macaque. *Arch Oral Biol.* 1995;40(3):229-246. doi:10.1016/0003-9969(95)98812-D
4. Capra NF. Mechanisms of oral sensation. *Dysphagia.* 1995;10(4):235-247. doi:10.1007/BF00431416
5. Smith JH, Cutrer FM. Numbness matters: a clinical review of trigeminal neuropathy. *Cephalalgia.* 2011;31(10):1131-1144. doi:10.1177/0333102411411203

6. Lecky BRF, Hughs RAC, Murray NMF. Trigeminal sensory neuropathy. *Brain.* 1987;110:1463-1485. doi:10.1136/bmj.1.5691.301-a
7. Sen P, Ross N, Rogers S. Recovering maxillofacial trauma patients: the hidden problems. *J Wound Care.* 2001;10(3):53-57. doi:10.12968/jowc.2001.10.3.26062
8. Haggard P, de Boer L. Oral somatosensory awareness. *Neurosci Biobehav Rev.* 2014;47:469-484. doi:10.1016/j.neubiorev.2014.09.015
9. Hiiemae KM, Palmer JB. Tongue movements in feeding and speech. *Crit Rev Oral Biol Med.* 2003;14(6):413-429. doi:10.1177/154411130301400604
10. Nakamura Y, Iriarte-Diaz J, Arce-McShane FI, et al. Sagittal plane kinematics of the jaw and hyolingual apparatus during swallowing in *Macaca mulatta. Dysphagia.* 2017;32(5):663-677. doi:10.1007/s00455-017-9812-4
11. Lund JP, Kolta A. Generation of the central masticatory pattern and its modification by sensory feedback. *Dysphagia.* 2006;21(3):167-174. doi:10.1007/s00455-006-9027-6
12. Yoshida A, Moritani M, Nagase Y, Bae YC. Projection and synaptic connectivity of trigeminal mesencephalic nucleus neurons controlling jaw reflexes. *J Oral Sci.* 2017;59(2):177-182. doi:10.2334/josnusd.16-0845
13. Komuro A, Morimoto T, Iwata K, et al. Putative feed-forward control of jaw-closing muscle activity during rhythmic jaw movements in the anesthetized rabbit. *J Neurophysiol.* 2001;86(6):2834-2844. doi:10.1152/jn.2001.86.6.2834
14. Tsuboi A, Takafuji Y, Itoh S, Nagata K, Tabata T, Watanabe M. Response properties of trigeminal ganglion mechanosensitive neurons innervating the temporomandibular joint of the rabbit. *Exp Brain Res.* 2009;199(2):107-116.
15. Feilich K, Laurence-Chasen JD, Orsbon CP, Gidmark NJ, Ross CF. Twist and chew: three-dimensional tongue kinematics during chewing in macaque primates. *Biol Lett.* 2021;17(12):20210431.
16. Abd-El-Malek S. The part played by the tongue in mastication and deglutition. *J Anat.* 1955;89(2):250-254.
17. Tomura Y, Ide Y, Kamijo Y. Studies on the morphological changes of the tongue movements during mastication by x-ray TV cinematography. *Oral-Facial Sensory and Motor Functions.* Quintessence Publishing Co. Inc; 1981:45-52.
18. Montuelle SJ, Olson RA, Curtis H, Sidote JV, Williams SH. The effect of unilateral lingual nerve injury on the kinematics of mastication in pigs. *Arch Oral Biol.* 2019;98:226-237. doi:10.1016/j.archoralbio.2018.11.024
19. Montuelle SJ, Olson RA, Curtis H, Williams SH. Unilateral lingual nerve transection alters jaw-tongue coordination during mastication in pigs. *J Appl Physiol.* 2020;128(4):941-951. doi:10.1152/JAPPLPHYSIOL.00398.2019
20. Kubota K, Negishi T, Masegi T. Topological distribution of muscle spindles in the human tongue and its significance in proprioception. *Bull Tokyo Med Dent Univ.* 1975;22(3):235-242.
21. Fitzgerald MJ, Sachithanandan SR. The structure and source of lingual proprioceptors in the monkey. *J Anat.* 1979;128(Pt 3):523-552.
22. Trulsson M, Essick GK. Low-threshold mechanoreceptive afferents in the human lingual nerve. *J Neurophysiol.* 1997;77(2):737-748. doi:10.1152/jn.1997.77.2.737
23. Biedenbach MA, Chan KY. Tongue mechanoreceptors: comparison of afferent fibers in the lingual nerve and chorda tympani. *Brain Res.* 1971;35(2):584-588. doi:10.1016/0006-8993(71)90507-5
24. Adachi K, Lee JC, Hu JW, Yao D, Sessle BJ. Motor cortex neuroplasticity associated with lingual nerve injury in rats. *Somatosens Mot Res.* 2007;24(3):97-109.
25. Arce-McShane FI. The association between age-related changes in oral neuromechanics and Alzheimer's disease. *Adv Geriatr Med Res.* 2021;3(2):e210011.

26. Brainerd EL, Baier DB, Gatesy SM, et al. X-ray reconstruction of moving morphology (XROMM): precision, accuracy and applications in comparative biomechanics research. *J Exp Zool A Ecol Genet Physiol.* 2010;313(5):262-279. doi:10.1002/jez.589

27. Orsbon CP, Gidmark NJ, Ross CF. Dynamic musculoskeletal functional morphology: integrating diceCT and XROMM. *Anat Rec.* 2018;301(2):378-406. doi:10.1002/ar.23714

28. Orsbon CP, Gidmark NJ, Gao T, Ross CF. XROMM and diceCT reveal a hydraulic mechanism of tongue base retraction in swallowing. *Sci Rep.* 2020;10(1):1-16. doi:10.1038/s41598-020-64935-z

29. Knörlein BJ, Baier DB, Gatesy SM, Laurence-Chasen JD, Brainerd EL. Validation of XMALab software for marker-based XROMM. *J Exp Biol.* 2016;219(23):3701-3711. doi:10.1242/jeb.145383

30. Laurence-Chasen JD, Manafzadeh AR, Hatsopoulos NG, Ross CF, Arce-McShane FFI. Integrating XMALab and DeepLabCut for high-throughput XROMM. *J Exp Biol.* 2020;223(17):jeb226720. doi:10.1242/jeb.226720

31. Arce-McShane FI, Ross CF, Takahashi K, Sessle BJ, Hatsopoulos NG. Primary motor and sensory cortical areas communicate via spatiotemporally coordinated networks at multiple frequencies. *Proc Natl Acad Sci.* 2016;113(18):5083-5088. doi:10.1073/pnas.1600788113

32. Ross CF, Washington RL, Eckhardt A, et al. Ecological consequences of scaling of chew cycle duration and daily feeding time in primates. *J Hum Evol.* 2009;56(6):570-585. doi:10.1016/j.jhevol.2009.02.007

33. Huckabee ML, McIntosh T, Fuller L, et al. The test of masticating and swallowing solids (TOMASS): reliability, validity and international normative data. *Int J Lang Commun Disord.* 2018;53(1):144-156. doi:10.1111/1460-6984.12332

34. Ross CF, Iriarte-Diaz J. What does feeding system morphology tell us about feeding? *Evol Anthropol.* 2014;23(3):105-120. doi:10.1002/evan.21410

35. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng.* 1983;105(2):136-144. doi:10.1115/1.3138397

36. Menegaz RA, Baier DB, Metzger KA, Herring SW, Brainerd EL. XROMM analysis of tooth occlusion and temporomandibular joint kinematics during feeding in juvenile miniature pigs. *J Exp Biol.* 2015;218(16):2573-2584. doi:10.1242/jeb.119438

37. Schaerlaeken V, Meyers JJ, Herrel A. Modulation of prey capture kinematics and the role of lingual sensory feedback in the lizard *pogona vitticeps. Fortschr Zool.* 2007;110(2):127-138. doi:10.1016/j.zool.2006.09.002

38. Inoue T, Kato T, Masuda Y, Nakamura T, Kawamura Y, Morimoto T. Modifications of masticatory behavior after trigeminal deafferentation in the rabbit. *Exp Brain Res.* 1989;74(3):579-591. doi:10.1007/BF00247360

39. Mayerl CJ, Myrla AM, Gould FDH, Bond LE, Stricklen BM, German RZ. Swallow safety is determined by bolus volume during infant feeding in an animal model. *Dysphagia.* 2021;36(1):120-129. doi:10.1007/s00455-020-10118-x

40. Hiiemae KM, Crompton AW. Mastication, food transport, and swallowing. *Functional Vertebrate Morphology.* Harvard University Press; 1985:262-290.

41. Thexton AJ, Crompton AW. Effect of sensory input from the tongue on jaw movement in normal feeding in the opossum. *J Exp Zool.* 1989;250(3):233-243.

42. Iriarte-Díaz J, Reed DA, Ross CF. Sources of variance in temporal and spatial aspects of jaw kinematics in two species of primates feeding on foods of different properties. *Integr Comp Biol.* 2011;51(2):307-319. doi:10.1093/icb/icr072

43. Patel N, Jankovic J, Hallett M. Sensory aspects of movement disorders. *Lancet Neurol.* 2014;13(1):100-112. doi:10.1016/S1474-4422(13)70213-8

44. Abbruzzese G, Berardelli A. Sensorimotor integration in movement disorders. *Mov Disord.* 2003;18(3):231-240. doi:10.1002/mds.10327

45. Hatsopoulos NG. Coupling the neural and physical dynamics in rhythmic movements. *Neural Comput.* 1996;8(3):567-581. doi:10.1162/neco.1996.8.3.567

46. Morimoto T, Inoue T, Nakamura T, Kawamura Y. Characteristics of rhythmic jaw movements of the rabbit. *Arch Oral Biol.* 1985;30(9):673-677. doi:10.1016/0003-9969(85)90154-2

47. Huang CS, Hiraba H, Murray GM, Sessle BJ. Topographical distribution and functional properties of cortically induced rhythmical jaw movements in the monkey (*Macaca fascicularis*). *J Neurophysiol.* 1989;61(3):635-650.

48. Miall RC, Rosenthal O, Ørstavik K, Cole JD, Sarlegna FR. Loss of haptic feedback impairs control of hand posture: a study in chronically deafferented individuals when grasping and lifting objects. *Exp Brain Res.* 2019;237(9):2167-2184. doi:10.1007/s00221-019-05583-2

49. Daley MA, Biewener AA. Running over rough terrain reveals limb control for intrinsic stability. *Proc Natl Acad Sci.* 2006;103(42):15681-15686. doi:10.1073/pnas.0601473103

50. Ross CF, Blob RW, Carrier DR, et al. The evolution of locomotor rhythmicity in tetrapods. *Evolution (N Y).* 2013;67(4):1209-1217. doi:10.1111/evo.12015

51. Ross CF, Baden AL, Georgi J, et al. Chewing variation in lepidosaurs and primates. *J Exp Biol.* 2010;213(4):572-584. doi:10.1242/jeb.036822

52. Akay T, Tourtellotte WG, Arber S, Jessell TM. Degradation of mouse locomotor pattern in the absence of proprioceptive sensory feedback. *Proc Natl Acad Sci.* 2014;111(47):16877-16882. doi:10.1073/pnas.1419045111

53. Bollu T, Ito BS, Whitehead SC, et al. Cortex-dependent corrections as the tongue reaches for and misses targets. *Nature.* 2021;594:82-87. doi:10.1038/s41586-021-03561-9

54. Huang X, Zhang G, Herring SW. Effects of oral sensory afferents on mastication in the miniature pig. *J Dent Res.* 1993;72(6):980-986.

55. Ernberg M, Serra E, Baad-Hansen L, Svensson P. Influence of topical anaesthesia on the corticomotor response to tongue training. *Arch Oral Biol.* 2009;54(7):696-704. doi:10.1016/j.archoralbio.2009.04.004

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.