Robustness of lateral tongue bracing under bite block perturbation

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Short Title: Robustness of lateral tongue bracing under bite block perturbation

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Number of Tables: 3

Number of Figures: 9

Word count: 8064

Keywords: lateral tongue bracing, bite block perturbation, speech postures

Abstract

Lateral tongue bracing is a lingual posture in which the sides of the tongue are held against the palate and upper molars, and has been observed cross-linguistically. However, it is unknown whether lateral bracing makes adjustments to external perturbation like other body postures. The present study aims to test the robustness of lateral tongue bracing with three experiments. The first baseline experiment was an analysis of an electropalatogram database and the results showed lateral bracing being continuously maintained. The second experiment applied an external perturbation during speech production. A bite block was held between participants' teeth while intra-oral video was used to record contact between the sides of the tongue and upper molars during speech. The results indicated that lateral bracing was maintained most of the time during speech. The third experiment included simulations investigating the activation of tongue muscles relevant to lateral bracing at different degrees of jaw opening. The results show that bracing requires higher activation of bracing agonists and lower activation of bracing antagonists as jaw opening increases. Our results suggest that lateral tongue bracing is actively maintained and robust under external perturbation and further indicate it serves as an essential lingual posture during speech production.

1. Introduction

Lateral tongue bracing is a pervasive lingual posture in which the sides of the tongue are in contact with the hard palate and/or the upper molars (Gick et al., 2017). This posture has been compared to the oral preparatory phase of swallow, both kinematically and in muscle activation (e.g., Mayer et al. 2017). The lateral seal created via such contact separates the central oral tract from the lateral buccal cavities (e.g., Honda, Takano, & Takemoto, 2010; Honda et al., 2004; Perkell, 1979), forming the closed aeroacoustic tube necessary for producing most speech sounds (Gick et al., 2017). Complete loss of lateral tongue-palate contact in English running speech has only been observed in low vowels including /ɑ, aʊ, aɪ, ʌ/, and in lateral consonants, including onset and coda /l/ (Gick et al., 2017). These exceptions to lateral bracing bring alternate bracing postures, such as oropharyngeal for /ɑ/ and central bracing for /l/ (Gauffin & Sundberg, 1978; Gick et al., 2017). In addition to forming the aeroacoustic tube for speech, previous literature suggests that lateral bracing also serves other functions in speech such as facilitating certain kinds of tongue movements and transitions (e.g. Stone, 1990) and providing somatosensory feedback for tongue position (e.g. Stevens & Perkell, 1977).

Lateral tongue bracing is pervasive across different languages. Liu et al. (in press) analyzed tongue vertical movement illustrated by ultrasound imaging during speech and observed the sides of the tongue stayed in a higher region and made less movement across six languages including Akan, Cantonese, English, Korean, Mandarin, and Spanish. Liu et al. (in press) also validated the results from ultrasound imaging data against intra-oral video data where tongue-palate contact could be seen. The validated results suggest that the lateral tongue bracing posture was consistently held cross-linguistically and may have a physiological underpinning (Liu et al., in press).

Gick et al. (2017) used 3-D biomechanical simulations and established that lateral bracing requires active upward movement by the sides of the tongue, which, in turn, requires muscle activation. Gick et al's. (2017) biomechanical simulations showed that contact between the sides of the tongue and the hard palate/upper molars generally requires strong activation of certain intrinsic and extrinsic tongue muscles, including the mylohyoid , the posterior and medial genioglossus, the superior longitudinal, and the verticalis muscles. Other muscles needed to be at low activation levels for bracing outcomes: i.e., the inferior longitudinal, the anterior genioglossus, and the hyoglossus muscles.

Another line of research has investigated lingual compensation to jaw perturbations. While previous (static or dynamic) jaw perturbation studies have tended to focus on acoustic or kinematic effects on specific speech targets, it remains unknown how such perturbations affect the execution of continuous lingual postural control of the kind associated with tongue bracing. McFarland and Baum (1995), for example, examined the effect of bite block insertion (which prevents jaw closure) on vowel formants, comparing large bite block, small bite block and control (no bite block) conditions. Compared to the small bite block and control conditions, the large bite blocks led to higher F1 values for /i, a, u/, higher F2 for /u/, and lower F2 for /i/, with no difference in formants observed between the small bite block and control conditions (McFarland and Baum, 1995). Their results suggest the speakers adjusted the position of their tongue to maintain their vowel formant targets in response to small bite block insertion, but that the adjustments were insufficient to compensate for the larger jaw separation. Dromey et al. (2021) investigated acoustic and kinematic changes during vowel production with 10 mm bite blocks. For monophthongs, they found the fixation of the jaw with the bite block led to a reduced corner space, while diphthongs' formant trajectories remained unchanged; significantly decreased midsagittal mid and back tongue movements were observed for both monophthongs and diphthongs under bite block perturbation (Dromey et al., 2021). These results suggest the front of the tongue showed more flexibility which was sufficient to compensate for producing diphthongs under bite block perturbation. Folkin and Abbs (1975) studied the effect of unexpected jaw perturbation on bilabial production. A jaw loading device was attached to participants' jaws to resist upward jaw movement, and upper and lower lip displacement were recorded (Folkin and Abbs, 1975). The results showed increased downward movement of the upper lip and increased elevation of the lower lip while upward jaw movement was perturbed (Folkin and Abbs, 1975). Kelso et al. (1985) investigated labial and lingual articulatory patterns under unexpected mechanical jaw perturbation. When a downward pull on the jaw occurred during a upward jaw movement (final /b/ closure in /bæb/ and final /z/ in /bæz/), the upper lip was observed to shift downwards for the final /b/ utterance but not final /z/ utterance (Kelso et al., 1985). Moreover, the lower lip exhibited increased displacement and velocity in both final /b/ and /z/ utterances when the jaw was perturbed, and increased tongue muscle activity was observed during /z/ utterances under jaw perturbation (Kelso et al., 1985). The authors interpreted these responses as indicating labial and lingual compensation for jaw perturbation (Kelso et al., 1985). These studies suggest that the lips and the tongue are robust to perturbation during the production of phonemes, achieving the tasks even with the presence of noise (Loeb, 2012).

The present study tests the hypothesis that lateral bracing is an essential posture in the speech motor system (Gick et al., 2017, Liu et al., in press) and is robust under perturbation; as such, we predict that the bracing posture, like other body postures, will adjust in response to varying degrees of external perturbation so as to enable it to be consistently and actively maintained throughout speech. Specifically, we test the robustness of lateral bracing under bite block perturbation, which translates the jaw – and thereby the tongue – downwards, such that additional muscular effort is needed to achieve the tongue elevation sufficient to maintain a lateral bracing posture. We compare the duration and the releases of lateral bracing under both moderate (5 mm) and extreme (10 mm) bite block perturbation.

To establish a baseline of tongue posture, in study 1 we analyzed electropalatography (EPG) data drawn from the MultiCHannel Articulatory (MOCHA) database (Wrench, 2000) which shows a baseline of tongue-palate contact during running speech without bite blocks. For the main behavioural experiment (study 2), we video-recorded participants while they read aloud a passage under two bite block conditions. Releases of lateral bracing were identified, and the durations of tongue-palate contact were measured. Biomechanical simulations (study 3) were conducted to investigate relevant muscle activations with different levels of jaw separation. Implications of the findings will be discussed in relation to speech physiology and models of postural control.

2. Study 1. EPG baseline study

Gick et al. (2017) investigated tongue-palate contact patterns based on 2 participants in the Kay Palatometer Database (Kay Elemetrics Computerized Speech Lab). The database contains EPG data while participants read three short passages, including “the Grandfather Passage” (Van Riper, 1963, see Reilly & Fisher, 2012), “the Rainbow Passage” (Fairbanks, 1960), and “the North Wind and the Sun Passage" (International Phonetic Association, 1949). Gick et al. (2017) analyzed the duration of lateral contact occurring in the back region of the palate (see Figure 2 in Gick et al. (2017)) and found the sides of the tongue maintained bracing constantly (97.5% of the total production duration). They also showed that more movement was observed in the middle of the tongue compared to the sides of the tongue in one sentence (Gick et al., 2017). However, whether the sides of the tongue stayed in contact with the roof of the mouth more than the center of the tongue throughout speech remained unclear. Moreover, Gick et al. (2017) only investigated the lateral tongue bracing pattern in the upper molar region and whether bracing is also maintained in the upper premolar region remains unknown. This baseline EPG study aims to replicate Gick et al. (2017)'s study using EPG data from another database and investigate the duration of contact at different regions at the sides and the center of the tongue without bite block perturbation. Also, this study aims to compare the duration of contact pattern qualitatively with the pattern under bite block perturbation (Study 2).

2.1 Methods

2.1.1 Data collection and processing. Baseline EPG data were acquired from the MOCHA database (Wrench, 2000; www.articulateinstruments.com/downloads/) which contains data collected using the Reading palate at a 200 Hz sampling rate for 460 sentences read by two speakers of Southern British English, one male and one female. EPG data files were loaded with EMATOOLS (Nguyen, 2000) using Matlab version R2021a (MATLAB, 2021). The Reading sensors cover the palate but not the teeth. Figure 1 shows a schematic representation of the Reading palate adapted from Gibbon et al. (2010). In line with Gick et al. (2017), we identified the outermost two columns on each side at the last three rows of sensors by the molars (rows 6-8) as the lateral bracing region on the Reading palate (see Figure 1). The central bracing region was defined as the central two columns of sensors (behind incisors). The lateral and central bracing regions are defined as such to be comparable with the regions of interest in study 2. In addition, the outermost two columns on each side of the palate in the premolar region (row 4 and 5) were selected to examine the tongue-palate contact patterns in that area. Lateral or central contact was considered to have occurred if contact was made with at least one sensor in the respective lateral bracing (molar), central bracing, or lateral premolar regions of the Reading EPG palate.

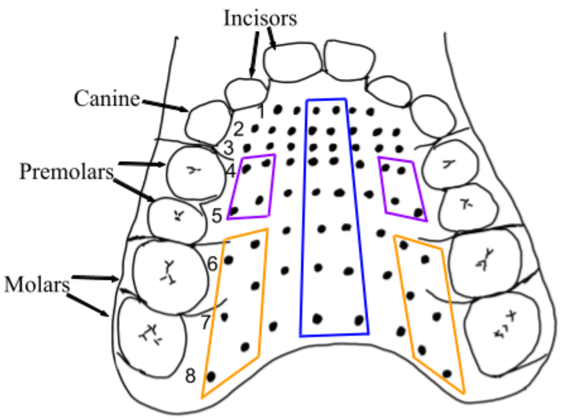


Figure 1. Lateral bracing (yellow boxes), central bracing (blue box), and lateral premolar (purple boxes) regions applied to the Reading palate adapted from Gibbon et al. (2010).

2.1.2 Statistical Analysis: EPG. Statistical analyses were done in R (R Core Team, 2020). For each sentence produced by a speaker, the percentage durations of lateral and central tongue-palate contact were calculated. For example, one sentence had 858 samples of the Reading palate patterns where 829 showed contact in the left bracing (molar) region, 498 in the left premolar region, 133 in the center bracing region, 852 in the right bracing (molar) region, and 653 in the right premolar region. Thus, for this sentence, the percentage duration of lateral and central tongue-palate contact would be 99.6% for the left bracing (molar) region, 58% for the left premolar, 15.5% for the center bracing region, 99.3% for the right bracing (molar) region, and 76.1% for the right premolar. In order to test whether regions (lateral bracing (molar) region, lateral premolar region, and center region) affect percentage contact duration, a Linear Mixed Effects (LME) model was constructed using the “lme4” package (Bates et al., 2014) with regions as a fixed effect and speakers as a random effect with both random slopes and random intercepts, then compared to a null model without regions as a fixed effect (a likelihood ratio test). A post-hoc test of all-pairwise comparisons (the Tukey method) was performed using the “multcomp” package (Hothorn et al., 2008) with p-value set to .05.

Since lateral bracing is primarily associated with the molar region, we next sought to determine the relationship between contact in the premolar region and contact in the molar region. For each sentence, the percentage of concordant tongue-palate contact patterns in the lateral premolar and bracing (molar) regions was calculated. Specifically, for each side, the number of samples where both regions showed contact or non-contact was divided by the total number of samples for each sentence, then averaged between the left and right side. The remaining samples had discordant tongue-palate contact patterns between the lateral premolar and bracing (molar) regions such that the samples showed contact in the bracing (molar) region but non-contact in the premolar region or vice versa.

2.2 Results

Percentage contact durations of different regions of the MOCHA database were processed from a total of 920 sentences, 460 from both speakers (see Figure 2). Mean percentage contact duration for central bracing region was 18.2% (*SD* = 8.19%), left bracing (molar) region was 96.7% (*SD* = 4.56%), left premolar region was 60.5%(*SD*= 13.8%), right bracing (molar) region was 96.6% (*SD* = 5.66%), and right premolar region was 69.5% (*SD*=13.9%). Likelihood ratio test results found that percentage contact duration was affected by the bracing region, $\chi^2[4] = 22.62$, $p < 0.001$. The post-hoc test indicated the percent duration of the central bracing region was significantly lower than both left (*estimate* = -78.51%, $p < 0.001$), and right (*estimate* = -78.38%, $p < 0.001$), bracing regions, yet no difference was observed for contact duration between the left and right bracing regions (*estimate* = 0.13, $p = 0.918$). Moreover, the post-hoc test also showed significantly more percentage contact duration in the left bracing (molar) region than the left premolar region (*estimate* = 36.18%, $p < 0.001$), and more percentage contact duration in the right bracing (molar) region than the right premolar region (*estimate* = 27.12%, $p < 0.001$).

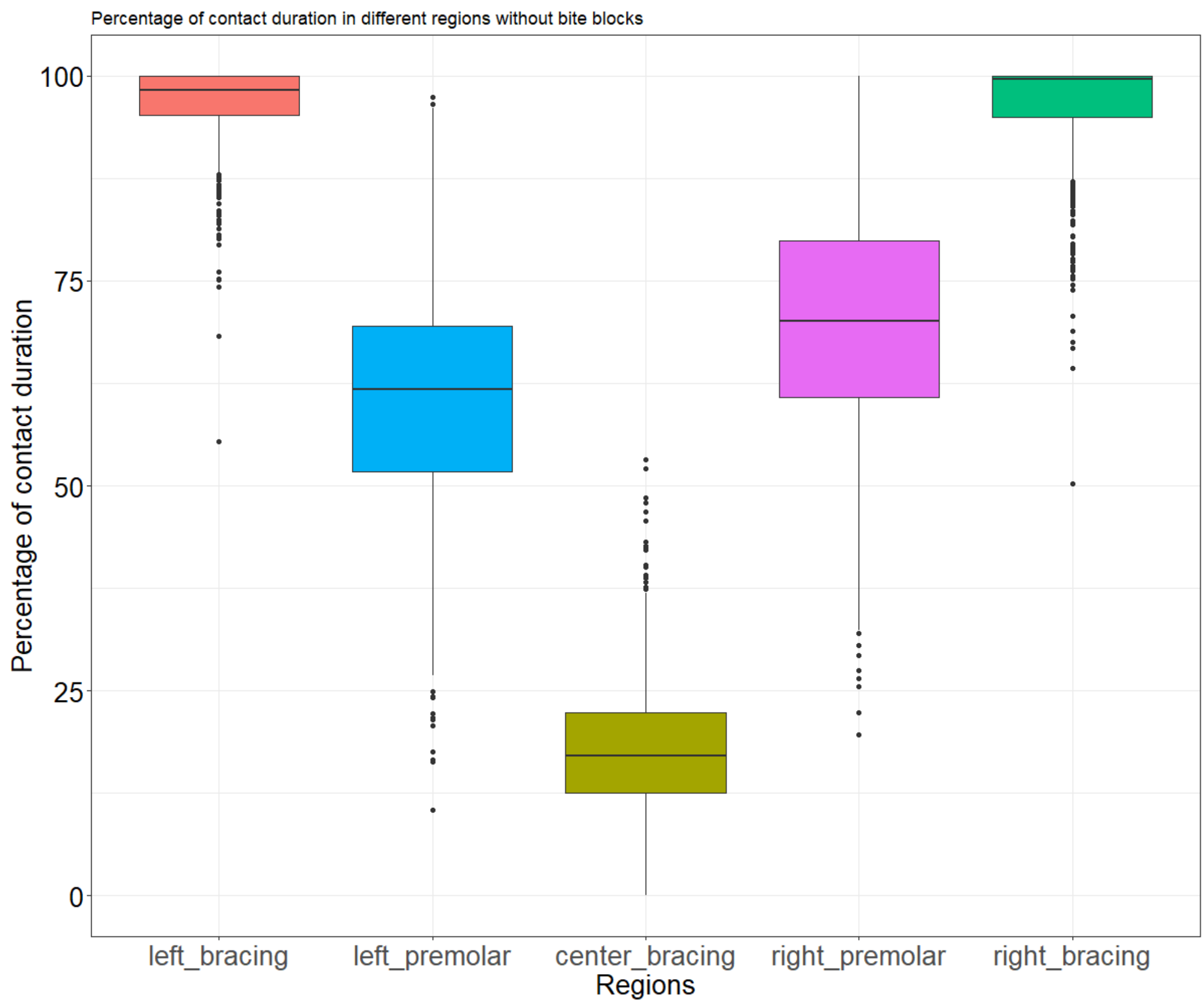


Figure 2. Boxplot of percentage of contact duration between regions of the tongue and the upper teeth/palate without bite blocks illustrated via EPG

For the concordance of the contact patterns in the premolar and the bracing (molar) regions, 2.91% of the samples lacked contact in either the premolar or the bracing (molar) region, 64.88% had contact in both regions, 0.37% had contact in the premolar region but lacked contact in the bracing (molar) region, and 31.84% lacked contact in the premolar region but had contact in the bracing (molar) region.

3. Study 2. Bite block perturbation experiment

This study tests a) whether the baseline pattern observed in Study 1 is qualitatively observed under bite block perturbation conditions, and b) whether a significant quantitative difference is induced by increasing the size of the bite block. The methods used in this study replicate the validation process in Liu et al. (in press) with more participants and different bite block sizes.

3.1 Methods

3.1.1 Data Collection and Processing. Initially, 49 participants (male = 10, age mean = 20.33, SD = 1.78) were recruited and recorded. All participants gave their signed consent form prior to the experiment, which was approved by the University of British Columbia Research Ethics Board (No. H19-01359). A total of 34 participants were excluded from analysis, 23 because English was not their native language, 10 because tongue-palate contact was not visible for at least one bite block condition, and one participant was excluded for failing to hold bite blocks steady. The remaining 15 English-speaking adult participants (male = 4) were included in the analysis. The task was to read aloud a 130-word passage (see Appendix 1) under two bite block conditions. Since the bite blocks would perturb lip movement (e.g. lip rounding and lip closure), and lip movement would obscure the camera view, the passage was designed with no labial consonants or rounded vowels. Moderate (5 mm) and extreme (10 mm) bite blocks were constructed using wooden tongue depressors, and a small LED light was attached to each bite block to illuminate the oral cavity.

Participants were seated in a chair with their head resting against padded supports. A camera (Sony Cyber-shot DSC-RX100) firmly attached to the same chair was positioned directly in front of the mouth, and was manually focused on the upper molars (shown in Figure 3). By doing this, the camera remained at a stable position to the mouth of the participant. The reading passage was placed on a stand about one meter in front of the participant. Two bite blocks were placed in the mouth, one on each side held by the top and bottom molars. The bite blocks remained static during the experiment, which allowed participants' heads to remain stationary throughout the experiment. The participants were asked to read the passage twice with 5 mm bite blocks, then twice again with 10 mm bite blocks. Individual video clips were collected at 30 frames per second for each repetition, and a total of four video clips were collected for each speaker. A no bite block condition, reading the passage without bite blocks, was omitted in this study as video of the vocal tract is extremely limited without holding bite blocks, and tongue-molar contact is not visible in the camera view.

Figure 3. The experimental setup: Two bite blocks were placed in the mouth, with one on each side held by the top and bottom molars. A camera (Sony Cyber-shot DSC-RX100) was positioned directly in front of the mouth, and was manually focused on the upper molars.

For each participant, within each condition, the recording with better imaging quality was selected and was manually inspected for releases of lateral bracing occurring at either side or both sides of the tongue. The selected videos were then converted into a grey-scale image sequence. The ImageJ software (Schneider et al., 2012) was used to produce videokymograms (Svec & Schutte, 1996) for the left, right, and center of the tongue. Each videokymogram represents the activity over time for one slice of the video. For the middle of the tongue, a vertical slice was taken between the central incisors. Since the sides of the tongue contact the hard palate and upper molars at an approximately 45-degree angle, a 45-degree-angled slice was taken in the molar region for each side of the tongue (shown in black in left panel of Figure 4a). In the videokymograms, light areas correspond to the tongue and teeth, and dark areas correspond to the back of the oral cavity, which is only visible when there is no contact between the tongue and palate/teeth. The videokymograms were cropped to remove the beginning and end of the recording so that the remaining portion corresponded to active speech. Next, sections above the upper teeth and below the lowest position of the tongue surface were removed, such that the remaining areas focused on where tongue bracing occurred. Finally, the videokymograms were converted to black and white images by using ImageJ’s (Schneider et al., 2012) thresholding tool to make clear distinction between light and dark areas (shown in the upper panel in Figure 4a). A small section of the videokymogram that correspond to the production “He has six dogs” was enlarged, and frames corresponding to [i] and [ɑ] were illustrated. Although tongue-premolar contact blocked the view of tongue-molar contact, from the results of study 1 (see above) where tongue-premolar contact without tongue-molar contact was very rare, we are confident that premolar contact entails molar contact the vast majority of the time. Figure 4b shows tongue contact in the premolar and molar region. If tongue-premolar contact were not clearly visible in the video, the participant’s data were excluded (see Figure 4c).

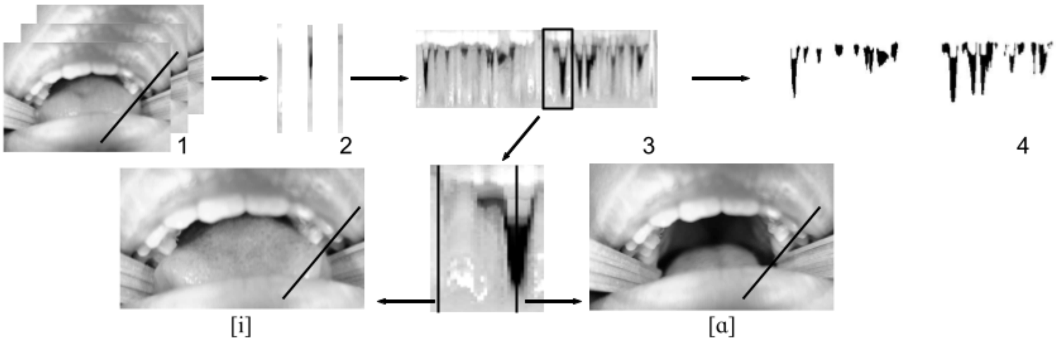
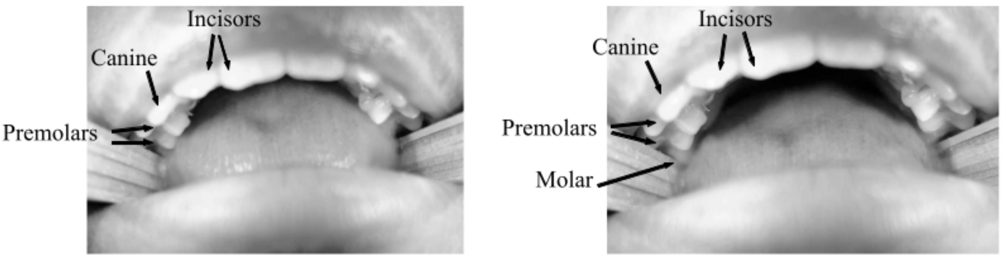


Figure 4a. Videokymogram illustration and two corresponding frames in an enlarged section



Tongue-premolar contact during [ɪ] production Tongue-molar contact during [æ] production

Figure 4b. Two frames showing tongue contacting the premolar region and the molar region


Figure 4c. This participant’s data was excluded due to tongue-premolar contact not being visible

Figure 4. 4a. Conversion from image sequence to videokymogram for one side of the tongue. No.1: a 45-degree-angled slice (shown as black diagonal line) is taken from each image in the image sequence. No.2: these 45-degree-angled slices are placed in temporal order from left to

right. No.3: a cropped videokymogram is formed when 45-degree-angled slices are taken from every image in the image sequence, then temporally ordered from left to right. Light areas correspond to the tongue and teeth, and dark areas correspond to the back of the oral cavity, which is only visible when the tongue is not in lateral bracing position. No.4: a black and white kymography converted from the grey-scale kymograph. Light areas shown in white and dark areas shown in black.

4b. Two frames showing tongue making contact at different regions, premolar and molar.

4c. This participant's data were excluded as tongue-premolar contact not visible in the frame.

3.1.2 Statistical Analysis. A Python (Van Rossum & Drake, 2009) script was used to count the number of columns without black pixels, which corresponds to the duration of bracing. For each speaker, the percentage of bracing duration relative to the duration of active speech in each token was calculated by dividing the number of columns that had no black pixels by the total number of columns in the videokymogram. For instance, among a total number of 1230 columns in the videokymogram of the left side of the tongue, 1080 columns contained no black pixels. Hence, the percentage of bracing duration for the left side of the tongue was 87.8%. The percentage of bracing duration was compared across different regions (left, center, right) and condition (5 mm and 10 mm) using a Linear Mixed Effects (LME) model. The model was constructed using the "lme4" package (Bates et al., 2014) in R (R Core Team, 2020), with regions and bite block condition as fixed effects and speakers as a random effect with both random slopes and intercepts (full model). Further, in order to determine whether regions and conditions showed a significant effect, a likelihood ratio test was conducted to compare the full model to two null models, one without regions as a fixed effect and another without condition as a fixed effect. We further compared the full model with a model without regions and conditions having interactions to determine whether bite block conditions interact with regions of the tongue. A post-hoc test of all-pairwise comparisons (the Tukey method) was conducted on the regions of the tongue in the full model with p-value set to .05 using the "multcomp" package (Hothorn et al., 2008) in R (R Core Team, 2020). Note that instances in which the phoneme /ɛ/ occurred adjacent to a non-laterally-braced production of /l/ were omitted as the status of lateral bracing for /ɛ/ productions was difficult to determine. Also, two allophones of the phoneme /l/, namely light [l] (prevocalic) and dark [ɫ] (postvocalic and syllabic) (Sproat and Fujimura, 1993), were counted. The counts of loss of lateral contact for the segments in different conditions were compared using a Chi square test.

3.2 Results

Sixty tokens of entire video recordings were screened from 15 participants (30 for the 5 mm condition and 30 for the 10 mm condition). The repetition with better imaging quality in each condition was selected then analyzed. We present below results from the 30 tokens collected from the 15 participants.

The percentage of bracing duration across the speakers in different conditions is shown in Table 1 and Figure 5: the sides of the tongue were almost always in contact with the upper teeth/palate across all speakers regardless of the size of the bite block. However, the center of the tongue appeared to have less contact duration compared to the sides.

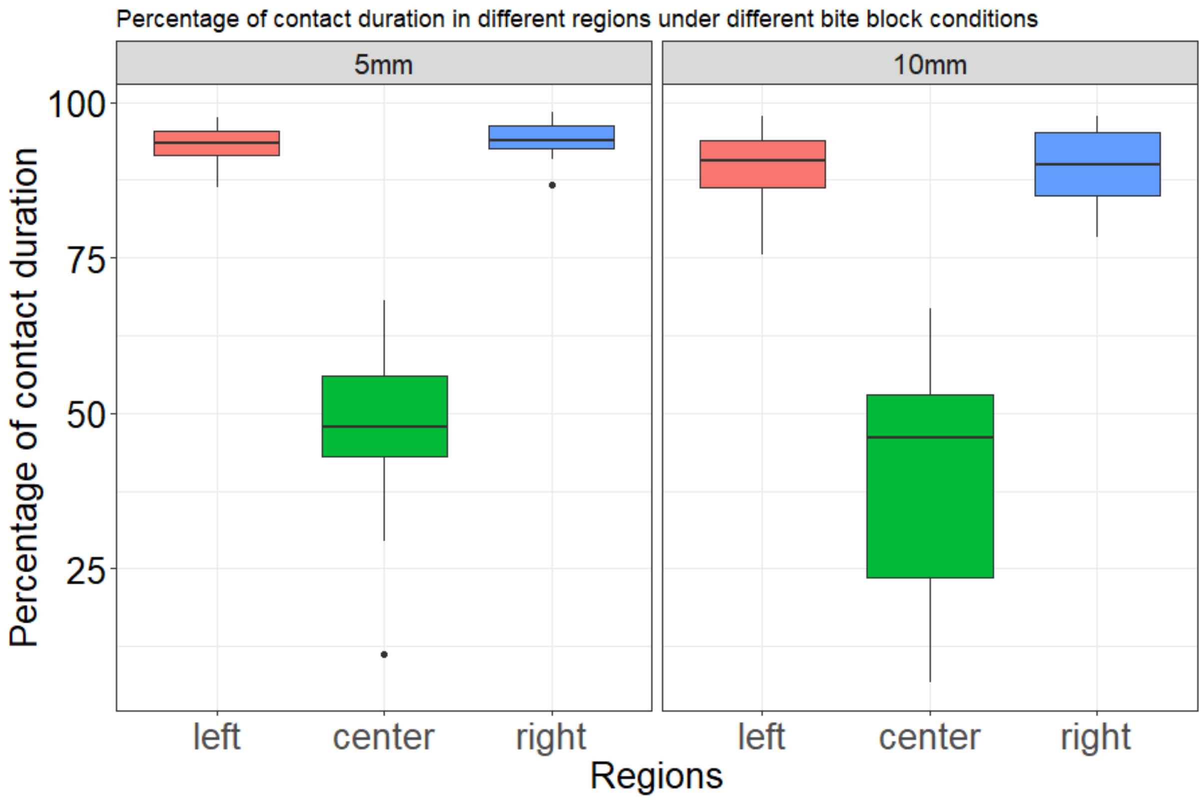


Figure 5. Boxplot of percentage of contact between regions of the tongue and the upper teeth/palate in the 5 mm and 10 mm bite block conditions.

Table 1: Mean and standard deviation (SD) in percentage (%) of lateral bracing across conditions

Condition	Left		Center		Right	
	Mean	SD	Mean	SD	Mean	SD
5mm	92.75	3.09	47.19	14.46	93.21	3.07
10mm	87.49	7.02	39.53	19.72	88.05	6.96

The results of likelihood ratio tests showed the percentage of bracing duration was significantly affected by regions of the tongue ($\chi^2[4] = 42.16$, $p < 0.001$), whereas bite block sizes had no significant effect on the percentage of bracing duration ($\chi^2[3] = 6.64$, $p = 0.084$). Further, there was no region-bite block interaction effect, $\chi^2[2] = 1.66$, $p = 0.435$). The post-hoc comparison results revealed a significant difference in the percentage of contact duration between the center of the tongue and the left (β = -45.91%, z =-12.301, $p < 0.001$) and right (β = -46.72%, z = 11.942, $p < 0.001$) side of the tongue. However, no significant difference in the percentage of contact duration was found between the right and left side of the tongue (β = 0.8%, z = 0.364, $p = 0.716$).

Further, we observed release from lateral bracing during some productions of lateral liquids and some low vowels. A total of 564 releases were visually identified across all speakers in both conditions, which includes 479 releases during phoneme production and 85 releases during interspeech pauses. Among the 479 phoneme releases, 232 releases (155 from /l/ and 77 from vowels) were observed in the 5 mm condition, and 247 releases (162 from /l/ and 85 from vowels) were observed in the 10 mm condition, as shown in Figure 6. Chi square tests found no significant difference between the count of releases in different bite block size conditions for either laterals, $\chi^2[1] = 0.05$, $p = 0.826$, or vowels, $\chi^2[1] = 0.395$, $p = 0.53$.

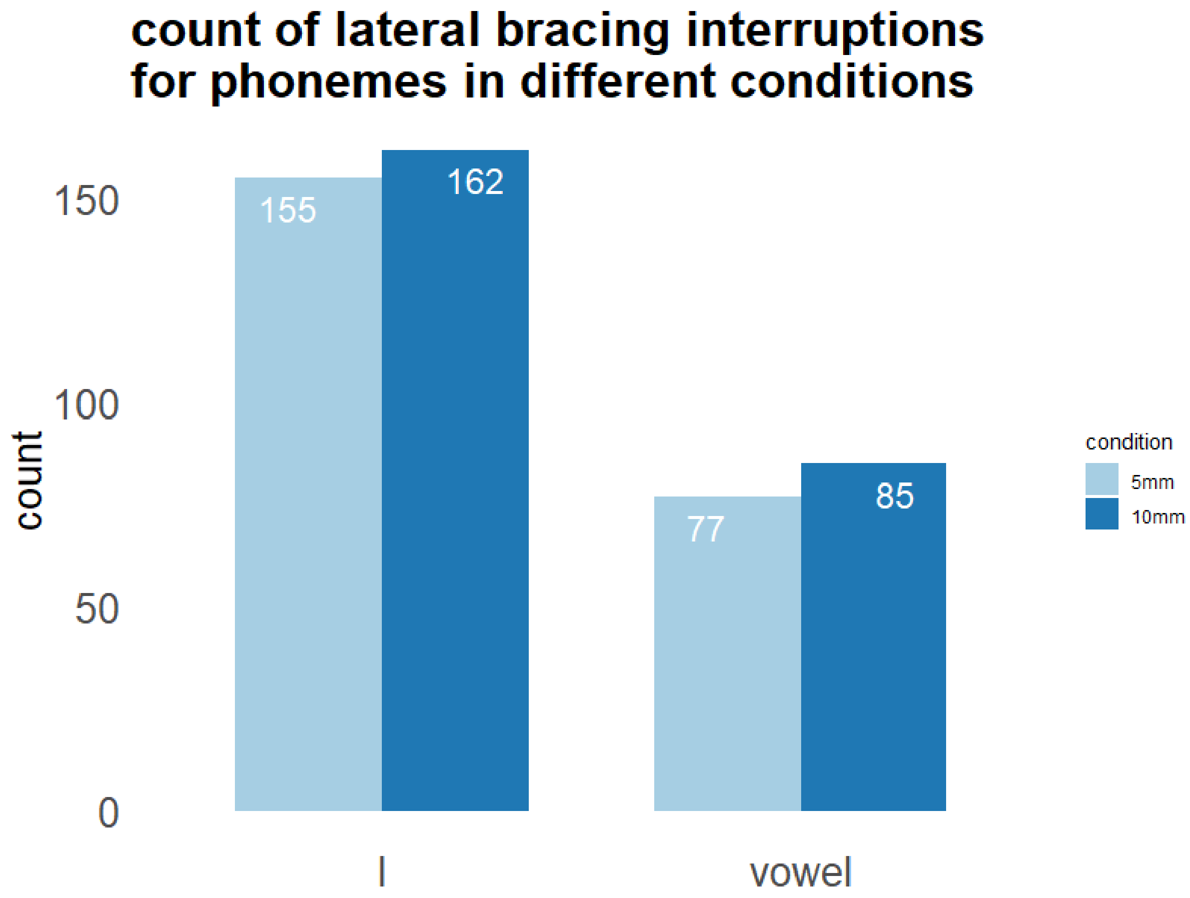


Figure 6. Count of released phonemes in different bite block conditions.

Across different bite block conditions and speakers, 56.2% of the releases were triggered by allophones of lateral liquid /l/ (light [l]: 46.6%; dark [ɫ]: 9.6%), 28.3% were triggered by low vowels (/ɑ/: 15.6%; /aɪ/: 10.5%; /æ/: 2 %; /ʌ/: 0.2%), pauses triggered 15.1 % of the releases and 0.5% are triggered by vowel /ɛ/. Furthermore, for each sound, the number of tokens where release occurred among the total number of articulations was compared across different sounds and conditions, as shown in Table 2. No instance of release was observed for any other sounds.

Table 2: Count and percentage of released tokens among articulated tokens for laterals and vowels (*Note.* No release was observed for [ʌ] in the 5mm condition.)

	laterals				vowels									
phoneme	**[l]**		**[ɫ]**		**[ɑ]**		**[aɪ]**		**[ʌ]**	**[æ]**		**[ɛ]**	
Condition (mm)	5	10	5	10	5	10	5	10	10	5	10	5	10
count	345	345	60	60	60	60	150	150	15	420	420	315	315
released count	129	134	26	28	43	45	29	30	1	3	8	2	1
percentage(%)	37	39	43	47	72	75	19	20	7	1	2	0.6	0.3

Lastly, a total of 571 pauses, 284 in 5 mm and 287 in 10 mm condition, were observed in both conditions, and releases were observed in 85 of the pauses. Whereas speech sounds had a balanced distribution of releases across different bite block conditions (shown in Figure 7), the number of the releases during inter-speech pauses doubled between the 5 mm (n = 28) and 10 mm (n = 57) conditions. Chi square test results showed significantly more inter-speech pause releases occurred in the 10 mm condition than the 5 mm condition, $\chi^2[1] = 9.894$, $p = 0.0017$, whereas a similar number of releases occurred in 5 mm (n = 232) and 10 mm (n = 247) condition during phoneme productions, $\chi^2[1] = 0.47$, $p = 0.493$.

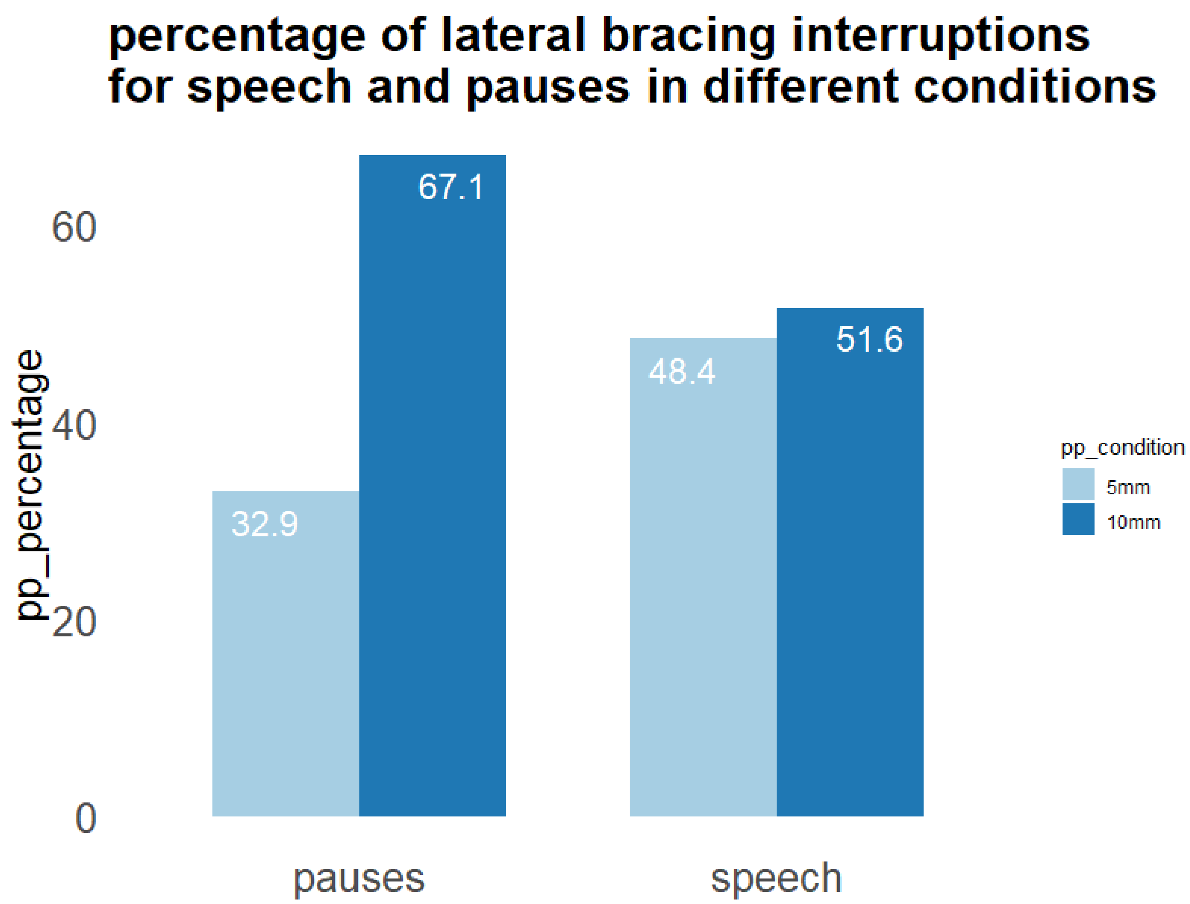


Figure 7. Percentage of release tokens observed in inter-speech pauses and speech in different conditions.

4. Study 3. Biomechanical simulation study

This study[1] investigates the activation of muscles relevant to lateral bracing at different degrees of jaw opening. Opening the jaw increases the distance between the tongue and the palate. If bracing requires active effort to maintain, a lower jaw position should require greater effort to produce bracing, since the tongue has further to travel. One way of quantifying effort is in terms of muscle activation: the strength of the neurological stimulus that causes muscles to contract. Because of the challenges associated with making neurophysiological measurements from speech articulators (e.g., Anderson et al. 2019; Kuehn et al. 1982; Gick et al. 2020), biomechanical simulation techniques are a useful tool for investigating the relationship between muscle activation and movement.

[1] The code for running the simulations can be found at https://github.com/connormayer/artisynth_models/tree/bracing. The output from the simulations and script used for analysis and visualization can be found at https://github.com/connormayer/bracing_simulations.

This study uses the 3D biomechanical simulation platform Artisynth (Lloyd et al., 2012), which allows for accurate models of structures found in the human body using both multibody and finite-element methods. The model used here is the coupled tongue-jaw-hyoid model with finite-element musculature from Stavness et al. (2011). This model was generated based on CT data, and its behavior validated against experimental measurements of vocal tract kinematics. We refer the reader to Stavness et al. (2011) for a more detailed description of the model. Front and back images of the model are shown in Figure 8a and b.

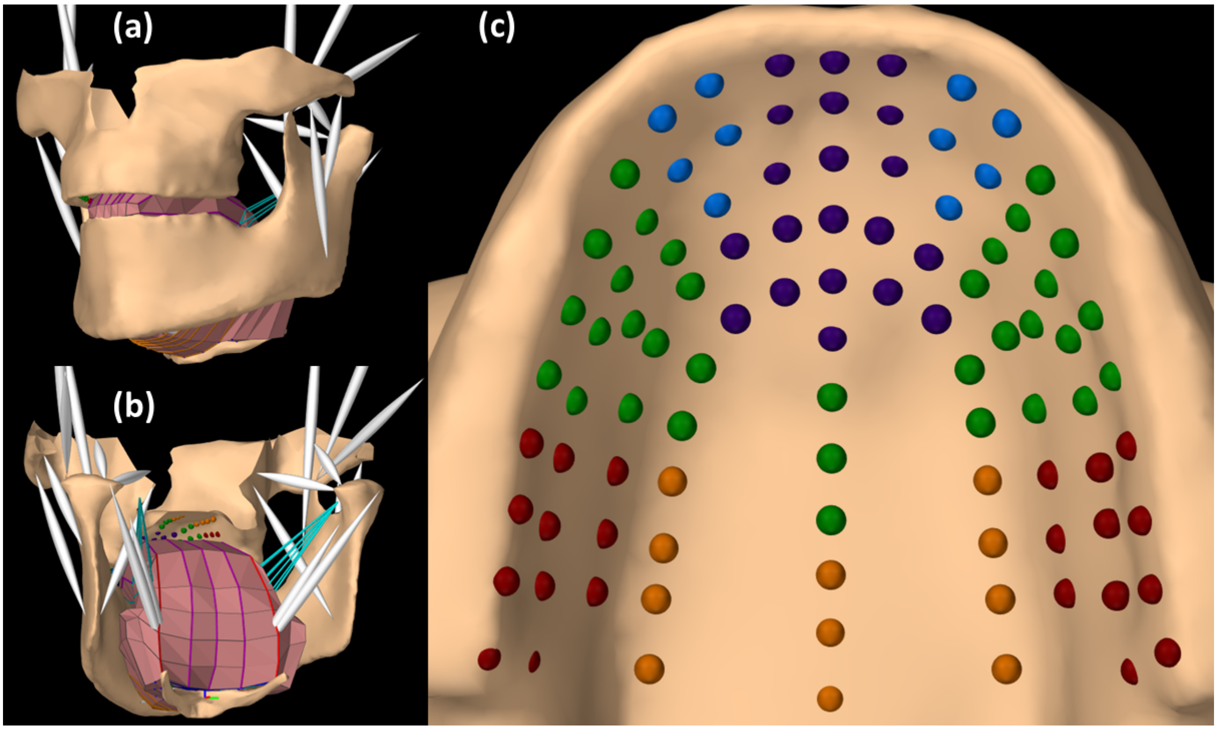


Figure 8. (a) Front and (b) back images of the jaw-tongue-hyoid model used in the simulations. (c) The layout of the contact sensors on the palate. The colored regions are coronal (purple), front (light blue), mid (green), back (orange), and lateral (red).

Artisynth allows models to be used in muscle-driven, feed-forward dynamic simulations by providing input in the form of muscle activations, which Artisynth represents as proportions of maximum activation that range from 0-1. Activations can be varied over time and relevant outcome variables tracked. The simulations described in this study investigate the relationship between muscle activation and lateral bracing: specifically, which kinds of muscle activations are sufficient to produce lateral bracing, and do these activations differ as a function of jaw height?

4.1 Methods

The simulation study uses similar methodology to Mayer et al. (2017) and Gick et al. (2017), which also used biomechanical simulation to relate muscle activation to bracing outcomes (see also Gick et al. 2020 for a similar study looking at labial postures). A set of ten intrinsic and extrinsic tongue muscles were chosen to be activated in the simulations: Superior (SL) and inferior (IL) longitudinal; transverse (TRANS); verticalis (VERT); posterior (GGP), medial (GGM), and anterior (GGA) genioglossus; styloglossus (STY); mylohyoid (MH); and hyoglossus (HG).

Simulations were run in two conditions which correspond roughly to the conditions in study 2: one where the mid-sagittal aperture of the jaw was 5 mm, and one where it was 10 mm. The jaw opening at rest position (incorporating the effects of gravity) was roughly 8mm. The 5 mm aperture was achieved by activating the bilateral jaw closer muscles (anterior, medial, and posterior temporalis; deep and superficial masseter; and medial pteryogoid) to a level of 0.15%, while the 10 mm aperture was achieved by activating the bilateral jaw opener muscles (lateral pterygoid and anterior belly of digastric muscles) to a level of 1%. These values were determined based on trial and error.

Each simulation was one (simulated) second long. The process for each simulation was:

1. 0-100ms: Increase jaw opener/closer activation linearly to maximum activation level.
2. 100-800ms: Increase tongue muscle activation linearly to maximum activation level.
3. 800ms-1000ms: Hold at maximum activation level.
4. Record tongue-palate contact.

Contact between the tongue and palate was detected using 96 contact sensors placed on the palate in a similar configuration to the electrodes in the Kay Electropalatogram. This is the same configuration used in previous work (Stavness et al. 2011; Mayer et al. 2017; Gick et al. 2017). The sensors were divided into five regions: front, middle, and back, as well as left and right lateral bracing regions. A "contact" outcome was defined as any instance of contact between the tongue and a sensor, while a "bracing" outcome was restricted to the subset of contact outcomes that had contact in both the left and right lateral bracing regions. The layout of these sensors is shown in Figure 8c.

The maximum activation levels for each muscle were varied across simulations based on grid-based sampling of the muscle activation space (Mayer et al. 2017; Gick et al. 2017). Each of the ten tongue muscles listed above were activated at all possible combinations of 0%, 10%, and 25% activation, leading to a total of 3^{10} = 59,049 simulations. A maximum overall activation value of 25% was chosen because it was sufficiently high to produce bracing outcomes, but low enough to limit the rate of numerical errors such as element inversion, which become more frequent at high activation levels and produce invalid results. A grid-based sample over muscle activations allows us to consider strategies for achieving bracing in aggregate, rather than individually. In general, there are many different but functionally-equivalent motor strategies that result in the same outcomes (e.g., Ting et al. 2015). Identifying a single strategy for producing bracing does not guarantee that that specific strategy is the one that is typically used by humans. Considering a range of activations allows us to get a sense of which muscles contribute consistently to particular outcomes, which in turn delimits the space of strategies that humans are likely to adopt.

Simulations were run using Artisynth's BatchSim feature, which facilitates the running of large-scale simulations such as these. Analysis of the simulation results was done using R (R Core Team, 2020).

4.2 Results

Of the 59,049 simulations in each condition, 57,767 were successful in the 5 mm condition and 55,780 in the 10 mm condition. The remaining simulations (5 mm: 1282; 10 mm: 3269) produced numerical errors and were discarded.

Of the successful simulations in the 5 mm condition, only 1438 (2.5%) resulted in tongue-palate contact, and 632 (1%) resulted in bilateral bracing. The proportion of contact and bracing outcomes in the 10 mm condition was lower: only 323 simulations (0.5%) resulted in contact and 217 (0.3%) in bilateral bracing. This indicates that many of the activations that are sufficient to achieve contact/bracing in the 5 mm condition are not sufficient in the 10 mm condition. Interestingly, the activations that successfully produced bracing in the 10 mm condition were not a strict subset of those that produced bracing in the 5 mm condition: 70 activations produced bracing in the 10 mm condition but not the 5 mm condition.

Figure 9 shows the mean activation level for each muscle in simulations that produced bilateral bracing. Two facts are apparent from this graph. First, some muscles tend to be strongly activated in bracing outcomes (particularly GGP, MH, and SL) while others tend to be weakly activated or not activated at all (particularly HG, STY, and TRANS). Second, muscles that are strongly activated in bracing outcomes tend to be activated more strongly in the 10 mm condition, while muscles that are weakly activated tend to be more weakly activated in the 10 mm condition. This suggests that bracing in the 10 mm condition requires a greater contribution from muscles that facilitate bracing, and less disruption from muscles that hinder it.

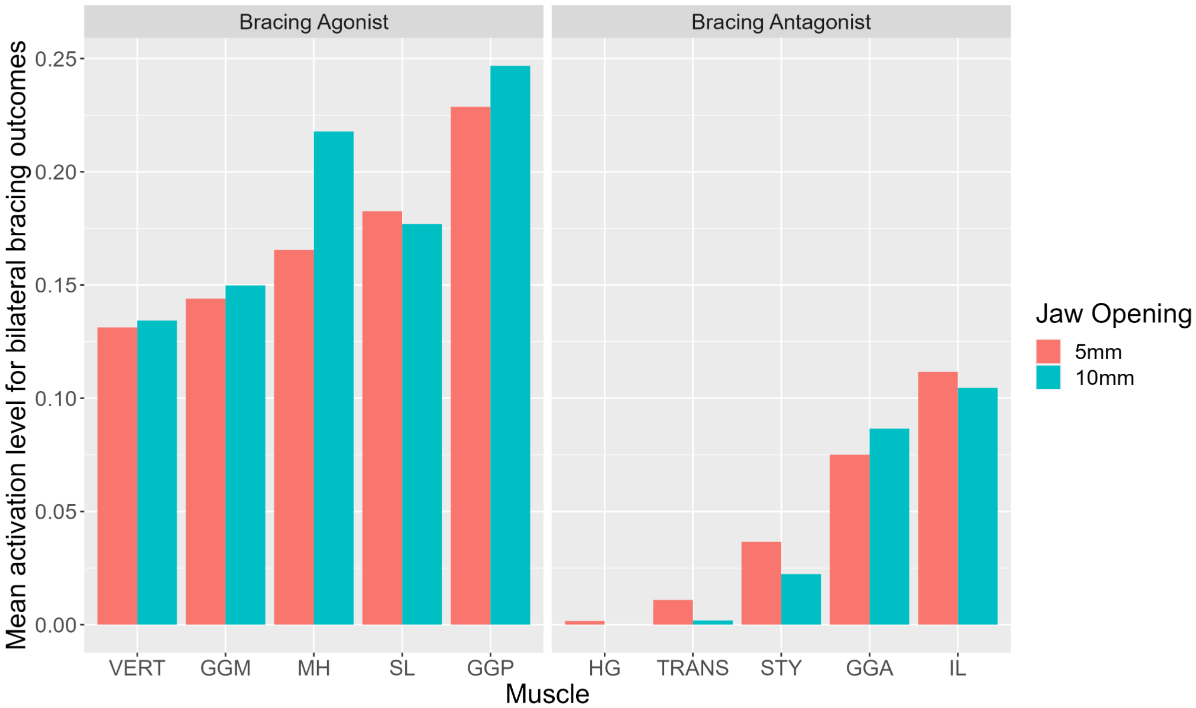


Figure 9. The mean muscle activation across simulations that produced bilateral bracing, for both the 5 mm and 10 mm jaw height conditions. The division of muscles into bracing agonists and antagonists is motivated based on the analysis below.

To more precisely investigate the relative contribution of individual muscles to bracing outcomes, and how these contributions differ based on jaw aperture, we fit a logistic regression model to the simulation data. The binary outcome was whether bracing was observed. The independent variables were the activation level of each of the 10 muscles and the jaw height condition (5 mm vs. 10 mm). The model also contained an interaction term between each of the muscle activation levels and the jaw height condition, based on the assumption that the effect of jaw height on the contribution of a muscle to a bracing outcome will differ depending on whether that muscle serves to raise or lower the tongue. This model is a simplification because it does not encode any interactions between different muscles, but it is sufficient to get a picture of their aggregate contribution.

Details from the model are shown in Table 3**.** The *Main* column contains the model's estimate for the coefficients associated with each of the main effects, as well as the intercept. The *Interaction* column contains the estimates for the coefficients associated with each interaction term between a muscle and the jaw height condition.

Term	**Main (std err)**	**Z**	**p**	**Interaction (std err)**	**Z**	**p**
Intercept	*-7.94 (0.30)*	*-26.25*	*< 0.001*	n/a	n/a	n/a
Jaw Opening (ref. 5mm)	*-6.96 (1.05)*	*-6.60*	*< 0.001*	n/a	n/a	n/a
GGP	*21.51 (0.91)*	*23.75*	*< 0.001*	*14.27 (3.46)*	*4.12*	*< 0.001*
GGM	*4.83 (0.54)*	*8.95*	*< 0.001*	1.82 (1.13)	1.60	0.1
GGA	*-7.59 (0.61)*	*-12.48*	*< 0.001*	2.31 (1.20)	1.93	0.5
STY	*-17.34 (0.86)*	*-20.05*	*< 0.001*	*-7.17 (2.34)*	*-3.07*	*< 0.005*
MH	*8.38 (0.58)*	*14.56*	*< 0.001*	*10.73 (1.50)*	*7.15*	*< 0.001*
HG	*-55.18 (3.41)*	*-16.19*	*< 0.001*	-136 (2710.16)	-0.05	0.96
TRANS	*-33.15 (1.58)*	*-20.92*	*< 0.001*	*-21.55 (5.69)*	*-3.79*	*< 0.001*
VERT	*2.65 (0.53)*	*5.00*	*< 0.001*	0.73 (1.09)	0.67	0.5
SL	*11.24 (0.62)*	*18.02*	*< 0.001*	-0.98 (1.27)	-0.77	0.44
IL	-0.85 (0.54)	-1.60	0.11	-1.62 (1.11)	-1.46	0.15

Table 3: Coefficients, Z scores and p values for the logistic regression model. Significant results are italicized and underlined. Note that the large estimate and standard error for the HG intercept coefficient results because there are no cases of bracing in the 10mm condition where HG is activated.

The coefficients in this model are expressed in terms of the log odds of a bracing outcome. A positive value indicates that a bracing outcome is more likely than a non-bracing one, while a negative value indicates the opposite. The coefficient for the intercept tells us the log odds of a bracing outcome in the 5 mm condition when all muscle activations are 0. The relatively large negative value (-7.94) indicates a non-bracing outcome is much more likely. The coefficient for the categorical variable jaw height tells us how the log odds change when we move from the 5 mm condition (the reference level) to the 10 mm condition: the relatively large negative value here (-6.96) indicates that, all else being equal, the odds of a bracing outcome decrease substantially in the 10 mm condition.

For a continuous variable like muscle activation, the coefficient corresponds to the change in log odds associated with a unit increase in the variable in the 5 mm condition. A positive value indicates that as muscle activation increases, the odds of a bracing outcome increase, while a negative value indicates the opposite. The estimates for these coefficients all come out as significant, with the exception of IL, whose activation seems to have a negligible effect on bracing outcomes. Based on this, we can use the model's estimates to classify muscles into those whose activation increases the odds of a bracing outcome (*bracing agonists*; GGP, GGM, MH, VERT, SL) and those whose activation decreases it (*bracing antagonists*; GGA, STY, HG, TRANS, IL; we include IL in this category based on the sign of its coefficient, even though it was not significant).

This division into agonists and antagonists broadly aligns with the functional role of these muscles (see, e.g., Dotiwala and Samra, 2022; Jang, 2022). Agonists tend to be muscles that advance/raise the tongue (e.g. GGP, MH) or widen it (VERT, SL), while antagonists tend to be those that retract/lower the tongue (HG, STY) or narrow/protrude it (TRANS, GGA).

The Interaction column in Table 3 contains the coefficients associated with the interaction terms between muscle activation and jaw opening. These can be interpreted as the difference between the change in log odds associated with a unit increase in muscle activation in the 10 mm condition and in the 5 mm condition. For example, a unit increase in GGP activation in the 5 mm condition results in an increase of 21.51 to the log odds of a bracing outcome. The interaction coefficient indicates that in the 10 mm condition, the log odds of a bracing outcome should increase by a further 14.27 for each unit increase in GGP activation (so in the 10 mm condition the overall change in log odds corresponding to a unit increase in GGP is 21.51 + 14.27 = 35.78).

The sign of this coefficient tells us whether the activation of the muscle is more predictive (positive) or less predictive (negative) of a bracing outcome in the 10 mm condition than in the 5 mm condition: that is, whether bracing outcomes are more/less likely to occur at higher activations of the muscle in the 10 mm condition. Here only four of these estimates come out as significant: GGP, MH, STY and TRANS. GGP and MH are bracing agonists, while STY and TRANS are bracing antagonists. In the 10 mm condition, GGP and MH activation becomes even more strongly predictive of bracing outcomes, while STY and TRANS activation becomes more strongly predictive of a non-bracing outcome. The remainder of the muscles appear to make similar contributions to bracing outcomes in both conditions. This indicates that in order to achieve bracing in the 10 mm condition relative to the 5 mm condition, certain bracing agonists must be activated more and certain bracing antagonists must be activated less.

With this analysis in hand, we can refine the hypothesis that bracing will require more effort in lower jaw positions into two different proposals: the activation levels for bracing agonists (GGP, GGM, MH, VERT, SL) should be higher in the 10 mm condition, because more effort is needed to move the tongue to contact the palate, while the activation for bracing antagonists (GGA, STY, HG, TRANS, IL) should be lower in the 10 mm condition since it requires less effort to prevent the tongue from reaching the palate. This is borne out in the results: the mean activation of bracing agonists for a bracing outcome is 17% in the 5 mm condition, and 18.5% in the 10 mm condition. For bracing antagonists, the mean activation in bracing outcomes is 4.7% in the 5 mm condition and 4.3% in the 10 mm condition.

In addition to bracing outcomes being less common and requiring greater effort in the 10 mm condition, they also resulted in less contact between tongue and palate: the mean number of sensors contacted in the lateral regions in bracing outcomes was 3.27 in the 5 mm condition and 2.72 in the 10 mm condition.

5. Discussion

In order to investigate the robustness of lateral tongue bracing posture under external perturbation, we conducted three studies: an EPG study to establish a baseline of lateral bracing posture, an oral video study that investigated how the bracing posture responds to bite block perturbation, and biomechanical simulations to examine the degree of muscle activation needed to respond to jaw perturbation. Our analysis of the MOCHA EPG database showed that lateral bracing was consistently maintained throughout running speech. The results of the bite block experiment/study (see Table 1) indicate that lateral bracing posture was robust under both 5 mm and 10 mm bite block perturbation. The biomechanical simulations demonstrate that achieving bracing in the 10 mm condition requires bracing agonists to be activated more strongly, and bracing agonists less strongly, relative to the 5 mm condition. Taken together, these results indicate the lateral bracing posture is robust and makes adjustments to external perturbation, responding with increased lingual muscle activity, suggesting that lateral bracing is an intentionally and actively maintained lingual posture that is necessary for producing speech.

Our lateral tongue-palate contact results from the MOCHA EPG database replicates Gick et al. (2017)'s findings that a lateral bracing posture is maintained throughout speech. Our overall lateral bracing duration percentage is 96.7%, which is comparable to the overall 97.5% reported in Gick et al. (2017). Additionally, our results indicate similar tongue-palate contact duration patterns are observed with and without bite block perturbation. Results of study 1 also suggest that lateral bracing is pervasively maintained in the molar region, while less consistent tongue-palate contact pattern is observed in the premolar region. This finding further supports Gick et al. (2017)'s observation that lateral bracing occurs in the upper molar region. The results of concordance of tongue-premolar and tongue-molar contact patterns indicate that premolar contact occurred with molar contact the majority of the time. Further, premolar contact without molar contact was very rare (0.37% of EPGs), indicating that tongue-molar contact can be assumed to be present whenever premolar contact is made.

Our oral video results (study 2) show that the lateral bracing posture is robust across bite block conditions. The percentage of contact duration of the sides of the tongue was significantly greater than for the center regardless of bite block conditions, and bite block size did not influence the percentage of contact duration between the sides and the center. In other words, lateral bracing is robust even when the degree of jaw perturbation is doubled - the behavior of the sides of the tongue stays consistent relative to the hard palate/upper molars rather than relative to the floor of the mouth, and similar release events are observed compared to moderate perturbation.

With regard to releases from the lateral bracing posture, we observed systematic releases during the production of laterals (allophones of /l/) and low vowels (/æ/, /ɑ/, /ʌ/, and the first portion of the diphthong /aɪ/) in both bite block conditions, which is consistent with findings in Gick et al. (2017). Additionally, we observed three instances of release of bracing during /ɛ/ production, but only in the name "Dex". It is unclear whether this is a lexical effect or whether the lateral bracing of /ɛ/ was somehow influenced by phonetic context (though both adjacent sounds are normally produced with lateral bracing). We note that /ɛ/ is backed and lowered in Canadian English due to Canadian Shift (Labov et al., 2006), which might contribute to the observed effect. Future investigations examining the status of lateral bracing for specific speech sounds should take into account local and long-distance phonetic environments, as well as dialect variation.

Our results also show that significantly more releases occurred during interspeech pauses in the 10 mm condition than the 5 mm condition while there was no difference in the number of releases for speech sounds. This observation underscores the view that a special effort must be made to get the tongue into a braced posture for speech – particularly under bite-block perturbation – while this requirement can be relaxed during inter-speech pauses (ISPs; see Gick et al. 2004).

Study 3 results show that increased activation of certain bracing agonists and decreased activation of certain bracing antagonists is necessary to maintain bracing posture under downward jaw perturbation. This increased activation is consistent with our proposal that, in the perturbation study, lateral tongue bracing was actively maintained even under external perturbation, supporting the view of lateral bracing as an essential lingual posture for speech.

Bracing the sides of the tongue against the hard palate/upper molars provides a stable, structured reference frame for coordinating movements of other parts of the tongue, thereby reducing the degrees of freedom in the tongue and facilitating motor control. An analogous mechanism can be found in whole-body posture and movement: under one view of posture, musculature in the center of the body serves as a stable support structure that allows peripheral parts of the body to perform movements such as reaching, grasping, and lifting (Kuypers, 1981). This property of the lateral bracing posture is thus not unique to speech production, but is comparable to that of other non-speech-related postures, including those that operate laterally.

Although the lateral bracing posture is consistently maintained during speech and requires muscle activation, each of the various muscles involved in achieving and maintaining the lateral bracing posture may fluctuate in activation in response to tongue movements for producing specific sounds. In other words, in order to maintain lateral bracing, posture-related activations likely coactivate in response to movement-related activations. This is analogous to mechanisms of whole-body posture: for instance, during reaching movements, posture-related muscle activations involved in maintaining a standing, erect posture coactivate in response to movement-related muscle activations involved in executing the reaching movement (Pienciak-Siewert et al., 2020). There is much room for future work to examine this interplay between postural and transient activations in speech.

There are multiple possible mechanisms that could result in the observed releases from lateral bracing: (a) release is achieved via inhibition or reduction of activation of muscles responsible for lateral bracing, (b) release is achieved via activation, or increase of activation, of muscles that actively pull downward on the sides of the tongue while activation of muscles responsible for lateral bracing is maintained, or (c) release is achieved via a combination of both (a) and (b). The relevant mechanism of release may depend on the specific movements being produced when the release occurs. These speculations are inspired by Benguerel et al.'s (1977) electromyographic findings that nasality in French is not a "one muscle – one parameter" system. In particular, the speaker in the study used two different mechanisms to produce nasals in different contexts: (a) suppression of levator veli palatini activation (allowing gravity and elasticity to pull down on the velum), and (b) suppression of levator veli palatini activation complemented by palatoglossus activation (actively pulling down on the velum), with the relevant mechanism dependent on the type and context of the nasal sound being produced. The mechanism of releases of lateral bracing posture is unclear, and future biomechanical simulation studies could examine the effect of inhibiting muscles required for lateral bracing or activating muscles that pull the tongue downwards.

In terms of limitations, the first study was based on an analysis of the MOCHA EPG database which is based on two speakers, and the Reading palate does not have sensors for the molars. Secondly, in Study 2, though our video analysis illustrated tongue-palate contact clearly and showed tongue shape for each frame, it failed to show the area of the contact, and required separate methods for the bite-block and non-bite-block conditions. To address this, future studies could employ a combination of methods such as EPG and 3-D ultrasound. Another limitation that Study 2 has is that size of head/oral capacity or dental arch was not controlled, and these anatomical differences across participants might also contribute to different degrees of compensation under jaw perturbation. Future studies could use bite blocks in various sizes to reflect similar jaw openings based on participants' mouth size.

There are also limitations to the simulations in Study 3. Although the results indicate that greater jaw opening requires greater activation of bracing agonists and lower activation of bracing antagonists, it's unclear whether this is due to the increased distance between tongue and palate, interference between jaw opener muscles and the tongue muscles, or a combination of the two. One of the jaw opener muscles, the anterior belly of the digastric (ABD), connects indirectly to the hyoid bone, which in turn connects to the tongue. It may be the case that activation of the ABD impedes the ability of other muscles to raise the tongue.

6. Conclusion

This paper investigated the robustness of lateral tongue bracing under moderate (5 mm) and extreme (10 mm) bite-block jaw perturbation conditions. Our results show that lateral tongue bracing is maintained during speech, regardless of the size of the bite block. The results suggest that lateral tongue bracing is robust under even extreme static external perturbation, supporting the view that lateral tongue bracing behaves like other body postures and is a required lingual posture for speech production.

Statements

Acknowledgement

This study was conducted at the Integrated Speech Research Laboratory (ISRL) at the University of British Columbia under the supervision of Bryan Gick. We thank volunteer research assistant Sylvia Mott at the ISRL. The simulations in Study 3 were run at the Speech Science Lab at the University of California, Irvine.

Statement of Ethics

In this research, Study 1 and Study 3 do not involve collection of new data from human subjects. Specifically, Study 1 analyzed a previously collected database (the MOCHA database) and permission to use the database was granted by the Department of Speech and Language Sciences of Queen Margaret University College. Study 3 ran biomechanical simulation via the ArtiSynth platform. Signed consent forms were obtained from all participants recruited in Study 2, and the experiment was approved by the University of British Columbia Research Ethics Board (No. H19-01359).

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Funding Sources

This study was made possible by funding from NIH Grant DC-002717, NSERC RGPIN-2015-05099, and RGPIN-2021-03751. Monika Łuszczuk's stay at the University of British Columbia as a visiting scholar was financed by the Polish National Science Center (NCN), MINIATURA 2, no. 2018/02/X/HS2/00838.

Author Contributions

Yadong Liu was the leading investigator and contributed to the conception of this work, as well as the design and running Study 1 and Study 2. Yadong Liu also contributed to the writing and revision of all sections of this paper. Sophia Luo contributed to the conception of this research, and the design and running of Study 2. Additionally, Sophia Luo contributed to the writing and revision of all sections except for Study 3 of this paper. Monika Łuszczuk contributed to the conception, design and running of Study 2. Monika Łuszczuk also contributed to the writing of the Methodology section of Study 2 and the revision of other sections. Connor Mayer contributed to the conception, design, and execution of Study 3, as well as the writing/revision of Study 3 and writing/revision of other sections of the paper. Arian Shamei contributed to the conception of Study 3 and writing and revision to all sections of the paper. Gillian de Boer contributed to the conception of Study 1, and to the writing and revision of all sections except for Study 3 of the paper. Bryan Gick contributed to the conception of all three studies, as well as the writing and revision of all sections of the paper.

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Appendix

Below is the reading passage used in the experiment. It was designed with no labial sounds in order to avoid the lips obstructing the camera view.

> Today is a nice day. I decided to take a taxi to the city to see Alex. Alex is a dentist. He has six dogs.
>
> I saw Alex at a diner and had tea and cake. Then, Alex and I headed to the clinic. He said that there's a kid, Dan, that hates the dentist. He gets sad and yells a lot and doesn't let Alex clean his teeth.
>
> Today, Dan is at the clinic again.
>
> "I hate the dentist!" Dan yells at Alex, and he still doesn't let Alex clean his teeth. Suddenly, Alex's dog, Dex, sits next to Dan and licks his hand. Dan giggles and says to Alex, "Dex has nice teeth! I need teeth like that!" Then, he lets Alex clean his teeth. Alex is stunned.