The Tongue: Two-Dimensional Views of a Three-Dimensional Structure

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Abstract

The research results from three ultrasound investigations are summarized. In the first study, a method for the reconstruction of 3D tongue movement from multiple coronal ultrasound films with metronome-paced speech is presented. Four normal speakers recited a stanza from the poem "Daffodils". An ultrasound transducer was positioned under the participant's mandible and angled at four coronal planes using a lever system. Quantitative data relating to the grooving of the tongue are presented. The second study used a two-dimensional crystal matrix transducer (Philips X3-1) to simultaneously record a coronal and a midsagittal plane during a sentence production task. Data from two female speakers are presented and the biomechanical relationship between lingual protrusion and midsagittal grooving is discussed. In the third study, the X3-1 transducer was used to record seven parallel coronal planes in two female speakers. The speakers recited a sentence with a varied vowel and consonant content. The analysis of lingual grooving revealed distinctly different patterns of tongue movement for the two speakers.

Keywords: Speech, tongue, ultrasound imaging, glossectomy

1. Introduction

The tongue is a complex anatomical structure. While the importance of the tongue for speech and swallowing is obvious, the mechanisms and patterns of tongue movement are not well understood. However, a more complete understanding of the workings of the tongue would be of crucial importance to develop better rehabilitation approaches for patients with conditions such as cancer of the tongue.

Ultrasound imaging is gaining popularity as a research instrument for speech scientists and speech-language pathologists interested in tongue movement. The appeal of ultrasound lies in the simple handling and the appealing visualization of the tongue. Since the data acquisition is relatively easy, potentially 'difficult' subjects such as children and patients can be studied. The image of the tongue is provided almost in real-time. A medical ultrasound machine provides extremely low radiation levels and is safe for the participant [1].

Researchers have used ultrasound to study tongue shapes for different speech sounds [2] - [5] and to assess temporal aspects of speech motor control [6], [7]. A particular benefit of ultrasound imaging is the ability to display the tongue in the coronal plane [8], [9].

Ultrasound has also been used for the assessment of swallowing function [10] - [14]. The method has been used successfully with children [15] and even babies [16], [17]. Swallowing and speech have been studied in pathological populations such as patients with cerebral palsies [18] - [20], strokes [21], [22], glossectomy [23] - [26], and malocclusions [27] - [29].

2. Study 1: Dynamic Multi-Planar Ultrasound Imaging of the Tongue

The current generation of B-mode ultrasound machines can visualize the 2D shape and motion of the tongue. It is also possible to reconstruct static 3D volumes from a sequence of 2D scans but it would be even more interesting if we could obtain information about movement in different anatomical plains in order to appreciate three-dimensional aspects of the tongue. Yang & Stone [30] reconstructed 3D tongue motion from multiple two-dimensional coronal ultrasound scans. The speaker repeated the same sentence multiple times in each scan position. A dynamic programming algorithm was then

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used to identify different acoustic events in the audio signal in order to time-align the different image sequences. The investigation described here used a more pedestrian approach to time-align the signals (metronome pacing) because we were only interested in general aspects of tongue grooving during connected speech. In particular, we wanted to find out how much of the time during a complex speech passage the tongue will be grooved, flat, or convex.

2.1 Materials and Methods

Four normal speakers participated in this study. Two speakers were female (F1 and F2) and two speakers were male (M1 and M2). All participants spoke Canadian English with the standard Southern Ontario accent that is common in Toronto.

A General Electric Logiq Alpha 100 MP ultrasound scanner with a model E72 6.5 MHz transducer with a 114° microconvex array was used to record the participants' tongue movement in four coronal planes. The Comfortable Head Anchor for Sonographic Examinations (CHASE; [31]) was used to make the ultrasound recordings. The transducer holder of the CHASE head holder allowed the experimenter to tilt the transducer to different angles in order to obtain multiple coronal view planes without changing the coupling spot of the transducer on the participant's neck. The ultrasound recordings were made in four coronal planes (10° anterior, 0°, 10° posterior and 20° posterior). The video output from the ultrasound machine was recorded to a digital video camera together with the acoustic signal. The articulatory and acoustic variability of the four repetitions had to be minimized as much as possible. Therefore, a metronome-paced poem was chosen as the speech task. The participants recited the last stanza from William Wordsworth's (1770-1850) poem "I wandered lonely as a cloud" (1815 version, also known as 'Daffodils'). The participants'reading tempo was paced with a metronome set to 108 beats per minute. The participants read the stanza at double time (216 bpm) with the strong syllables on the metronome beats.

The digital movie clips with the individual repetitions of the metronome-paced poem were analyzed using the Ultrasonographic Contour Analyzer for Tongue Surfaces software (Ultra-CATS; [31]). The Ultra-CATS allows the experimenter to extract individual frames from a movie to make semi-automatic measurements of the tongue height with a drawing tool.

In order to assess aspects of the intrinsic deformation of the tongue, a measure of lingual concavity was calculated [25], [26]. The concavity measure was calculated for each of the four view planes by calculating an average of the tongue height at the lateral free margins at 15° left and 15° right and then subtracting the tongue height in the midsagittal plane.

2.2 Results

The concavity values were calculated for each individual frame in each coronal plane for each speaker. Positive values indicated concavity and negative values indicated convexity. The data were recoded for the analysis. Concavity values that were larger than 1 mm were taken to indicate concavity, values between 1 mm and -1 mm indicated a flat tongue surface, and values below -1 mm indicated convexity. The distributions of concavity, flatness, and convexity were transformed into percentages. Sample results for the speaker F1 are shown in Figure 1.

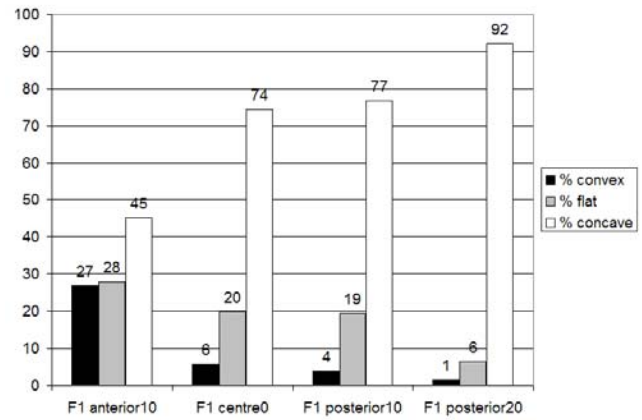

Figure 1a. Distribution of concavity for participant F1.

2.3 Discussion

The purpose of this study was to investigate global characteristics of coronal tongue grooving, based on multiple coronal ultrasound recordings during the metronome-paced recital of a poem. In all participants, it was observed that the centre of the tongue travelled greater distances than the lateral free margins. This finding was in agreement with previous research by McGlone & Proffit [32] and Stone [9] who described lateral bracing as the most important function of the lateral free margins of the tongue in speech. The concavity measure demonstrated that all participants had a marked amount of grooving throughout the paced recital of the poem stanza. At the most posterior coronal plane at 20º, all participants exhibited grooving for between 86% and 98% of the ultrasound frames. The degree of flatness and convexity was more variable for the coronal planes between 10º anterior and 10º posterior. M1's tongue was the most grooved tongue. Even at the 10º anterior coronal plane, his tongue was concave in 80% of the ultrasound frames. All other participants showed some degree of flatness or convexity at the 10º anterior plane. Similar to M1, the participant F2 showed pronounced grooving of the tongue, while F1 had an overall flatter tongue up to the 10º posterior plane. While the participant M2 had the flattest tongue in this group, it should be noted that his tongue was still mainly concave for the planes between 0º centre and 20º posterior.

3. Study 2: Cross-Plane Imaging of Tongue Movement

The 4D ultrasound technology is particularly popular in pre-natal imaging in Obstetrics and Gynaecology. While the technology is sometimes derided as ‘baby TV’, the current 4D ultrasound machines are able to visualize up to 30 volumes per second. Most 4D ultrasound machines use transducers that are a combination of array and sector scanners. The piezoelectric crystals are arranged in a line and moved by a motor, which limits the speed and accuracy of the data acquisition. The newest generation of ultrasound transducers uses crystal matrix arrays. The company Philips markets the X3-1 matrix transducer, which allows the examiner to acquire two scan planes in real-time (x-planes mode). Figure 2 displays parallel coronal and sagittal views of the tongue. The real-time display of two scan planes offers exciting new possibilities for speech researchers.

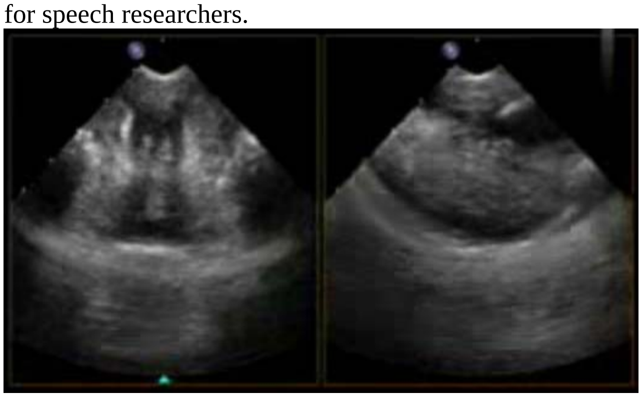

Figure 2. Screenshot of coronal and sagittal tongue shapes using the x-planes mode.

The research goal of the present study was to obtain more information about the interaction between the sagittal and the coronal movement of the tongue. The midsagittal grooving of the tongue is attributed to the contraction of the genioglossus muscle. The genioglossus is compartmentalized into inferior, middle and superior segments. The inferior fibres pull the tongue forward in the pharynx, raise it in the oral cavity and groove the base of the tongue. The middle fibres of the genioglossus muscle fan into the oral part of the tongue and serve to depress and groove the dorsum of the tongue. The present study used x-plane mode ultrasonography to look at dynamic tongue movement in a phonetically varied sentence. We also introduced a mild speech perturbation condition to assess possible effects of a bite block on tongue movement.

3.1 Materials and Methods

The participants were the two female speakers I (33 years) and T (28 years). The CHASE head anchor [31] was used to make the ultrasound recordings with the X3-1 transducer. The video output from the ultrasound machine was recorded to a digital video camera together with the acoustic signal. Both participants recorded three repetitions of the sentence ‘The tide was nice and cool at shore’ without and with a bite block (a wooden tongue depressor held between the premolars and molars). The sentence was designed to contain a varied selection of vowels and consonants of Canadian English.

The digital movie clips with the individual repetitions of the metronome-paced poem were analyzed using the Ultrasonographic Contour Analyzer for Tongue Surfaces software (Ultra-CATS; [31]).

3.2 Results

In the first step, a principal component analysis was completed, which arrived at 3-component solution, explaining a total of 92% of the variance in the data set. The components delineated the anterior tongue, dorsum of tongue, and base of tongue, as in previous papers. The measurement points in the coronal plane clustered with the dorsum of the tongue between 15° posterior and 5° anterior. The solutions were identical in the conditions with and without the bite block.

In the next step, the amount of concavity was calculated as described in the previous section, and frequencies were calculated. The results can be found in Table 1. Pearson correlation coefficients between different sagittal segments of the tongue and the concavity index were calculated. The results are displayed in Tables 2 and 3.

Table 1. Frequencies for concavity and convexity of the tongue

	Normal condition	**Bite block condition**
% tongue concave	34.4	31.1
% tongue flat	57.4	59.9
% tongue convex	8.2	9

Table 2. Correlations between the concavity measure and different segments of the tongue in the normal condition

	Posterior 35°	**Sagittal 0°**	**Anterior 30°**	**Concavity**
Posterior 35°		-.492**	-.350**	.048
Sagittal 0°	-.492**		.051	-.626**
Anterior 30°	-.350**	.051		.228**
Concavity	.048	-.626**	.228**	

Table 3. Correlations between the concavity measure and different segments of the tongue in the bite block condition

	Posterior 35°	Sagittal 0°	Anterior 30°	Concavity
Posterior 35°		-.364**	-.352**	.044
Sagittal 0°	-.364**		.056	-.641**
Anterior 30°	-.352**	.056		.180**
Concavity	.044	-.641**	.180**	

3.3 Discussion

The present study aimed to shed light on the relationship between the sagittal movement of the tongue and the grooving of the oral parts of the dorsum of the tongue. The principal component analysis in the present study had a solution that was comparable to results that Bressmann et al. [24], [26] have found for static 3D ultrasound volumes. As in our previous research, the lateral margins of the tongue clustered with the sagittal measurement points on the tongue. The introduction of the bite block did not change the functional associations between the different segments of the tongue.

The frequency analysis of the concavity index demonstrated that the tongue tended to be mostly flat (ca. 57-59%) or concave (31-34%) during the repeated production of the sentence. In contrast to the results of the first study presented here, the two speakers in this study had mostly flat tongue shapes. This may have been a consequence of differences in orofacial morphology or the different phonetic materials. There was no noticeable difference between the normal and the bite lock speaking conditions.

The correlation coefficients showed no association between the protrusion of posterior tongue and the grooving of the tongue dorsum. There was only a moderately strong negative correlation between the depth of the groove and the height of the tongue at the 0° measurement point, which may be taken as further evidence for the independence of the different segments of the genioglossus muscle in speech. The presence of a mildly intrusive bite block did not change the global aspects of tongue movement.

4. Study 3: A Tale of Two Tongues

The Philips iU22 allows capturing volumetric data at an acquisition speed of over 40 Hz. To capture tongue movement, it is necessary to choose a wide and deep view angle. The large scan area will usually slow the volume acquisition rate to around 10Hz. Because of the large amount of data that are acquired, it is not possible to view the 3D tongue movement in real-time. The volumes can be displayed in a post-processing program (Philips QLab software). Figure 3 shows a screenshot of the QLab software with 7 parallel coronal slices of the tongue. This technology currently has limitations for speech research because the speech signal cannot be recorded. In the present study, the X3-1 matrix transducer was used to further investigate the phenomenon of midsagittal grooving of the tongue in speech.

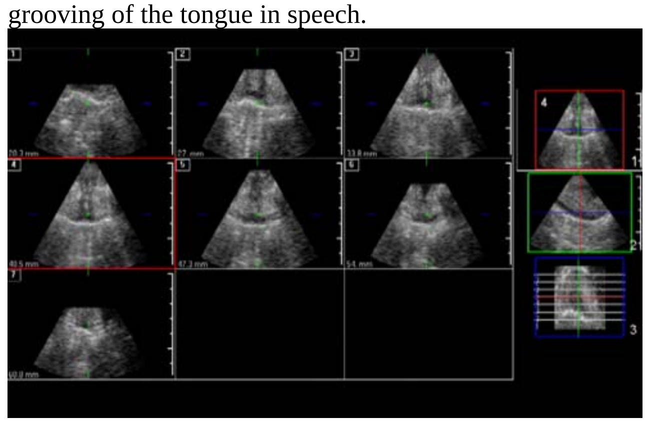

Figure 3. Multiple viewplanes obtained with the X3-1 crystal matrix transducer.

4.1 Materials and Methods

The participants were the two female speakers E (23 years) and I (22 years). The CHASE head anchor [31] was used to make the ultrasound recordings with the X3-1 transducer. The participants recorded the sentence ‘The tide was nice and cool at shore’. The sentence contained a varied selection of vowels and consonants of Canadian English. The QLab software was used to segment the volumes into seven equally spaced coronal slices. Videos of the individual slices were exported and analyzed using the Ultra-CATS software.

4.2 Results

In a first step, the convexity of the tongue between the measurement angles 20° left and 20° right was calculated, and the frequencies for concave, flat, and convex tongue shapes were obtained. The results are displayed in Table 4.

In a second step, two principal component analyses were conducted to evaluate the relationship between the different measurement points. In the first analysis, the measurement points for each of the seven slices were entered as separate variables into the analysis. The resulting solution for the two participants explained 89% of the variance in three components. The three components represented the anterior tongue (slices 1 and 2), the dorsum of the tongue (3 and 4), and the posterior tongue (slices 5, 6, and 7).

A second principal component analysis was used to evaluate the associations between the different coronal segments of the tongue. The resulting solution explained 98% of the variance and differentiated between the parasagittal measurement angles between 10° left and 10°

right and the lateral free margins of the tongue from 15° to 25°.

Table 4. Distribution of concavity and convexity in the different slices of the ultrasound volumes

		Slices:						
Subj		**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	% convex	1	2	2	7	22	19	14
	% flat	44	36	16	18	7	9	14
	% concave	55	62	82	76	71	72	72
2	% convex	70	73	38	1	0	0	0
	% flat	12	14	26	15	5	3	2
	% concave	18	13	36	85	95	97	98

4.3 Discussion

The present study demonstrated the applicability of the crystal matrix ultrasound transducer technology to speech research. Using this technology, it was possible to capture a rich three-dimensional data set of tongue movement in speech. The data demonstrated different patterns of tongue grooving for the two participants. While participant 1 had a flat tongue surface in the anterior slices, she showed marked convexity in the posterior segments. On the other hand, participant 2 showed most of her convexity in the anterior regions of the tongue, while her posterior tongue was consistently concave. Participant 2 was overall consistent with the patterns observed in the participants of Study 1, while participant 1 showed a different pattern.

The principal component analysis in the present study had a solution that was comparable to that of Study 2 and to previous results for static 3D ultrasound volumes [24], [26]. When the data were arranged to evaluate the coronal aspects of tongue movement, the analysis differentiated between the parasagittal and the lateral aspects of the tongue. The current analysis was based on only one sentence spoken by two participants. Further analyses of this data set are currently in the works.

5. Conclusions

Ultrasound offers exciting new opportunities for speech scientists and Speech-Language Pathologists. Patients and research participants generally tolerate ultrasound examinations very well. The real-time visualization on the screen is often interesting and motivating for research subjects. Currently, ultrasound is probably the most cost-effective instrumentation for the acquisition of 3D tongue shapes. New technologies such as the crystal matrix transducers have the potential to add significantly to the information that can be obtained about tongue movement in speech.

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