

Spatiotemporal Visualization of the Tongue Surface using Ultrasound and Kriging

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ABSTRACT

Analyzing the motion of the tongue surface provides valuable information about speech and swallowing. To analyze this motion, two-dimensional ultrasound images are acquired at video frame rates, and the tongue surface is automatically extracted and tracked. Further processing and statistical analysis of the extracted contours is made difficult by: 1) arbitrary spatial shifts and data loss resulting from ultrasound transducer positioning; 2) difference in tongue lengths over time for same utterance (or swallow) and across subjects; and 3) differences in the sampling locations. To address the above shortcomings, we used kriging to extrapolate and resample the tongue surface contours. Kriging was used because it does not lead to wild oscillations associated with traditional polynomial fitting. For our kriging implementation, we used the generalized covariance function and linear drift functions that are used in thin plate splines. Further, we designed a dedicated user interface called “SURFACES” that exploits this extrapolation to visualize the contours as spatiotemporal surfaces. These spatiotemporal surfaces can be readily used for statistical comparison and visualization of tongue shapes for different utterances and swallows.

Keywords: Tongue, Ultrasound, Spatiotemporal surface, Extrapolation, Kriging, Visualization, SURFACES

1. INTRODUCTION

Analysis of the motion of the human tongue surface provides valuable information about speech and swallowing. In this paper, we have used two-dimensional sagittal ultrasound images that are acquired at video frame rates — forming an image sequence in time — to understand the motion of the tongue. In order to compensate for the variability in speech and swallowing, both in a single subject and across subjects, the image sequences are acquired for multiple repetitions of the same utterance or the same kind of swallow. Automatic extraction of tongue surface contours from these ultrasound image sequences and their tracking is accomplished using deformable contours.¹ Applications of these extracted contours include: (1) direct visualization of contours of each word or swallow for qualitative analysis and (2) statistical analysis (eg. principal component analysis) to study inter-subject and intra-subject variability in speech.

There are three difficulties in the further processing and statistical analysis of such extracted tongue surface contours:

1. Occasional changes in ultrasound transducer positioning may result in arbitrary spatial shifts and data loss. These shifts may be different for different repetitions.
2. Both the volume-preserving nature of the tongue and the speaker’s inability to repeat the same word with precision — over time for a single utterance and across repetitions of utterances — lead to differences in actual tongue length. The measured tongue length can also change due to image noise and artifacts.

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3. The deformable contours used to extract the tongue surfaces are not repeatable across different utterances. They vary both in their spatial sampling locations and in their sampling density.

These difficulties make averaging and comparative analysis of different repetitions of an utterance or swallow difficult if not impossible. To address these difficulties, our strategy is to pre-process the contours in order to make them have equal lengths, and then resample them so that they can be averaged and visualized on the same grid. Previous methods have been proposed to extrapolate or to truncate the contours to equal lengths. Typical extrapolation approaches such as polynomial fitting lead to wild oscillations depending on the value of the gradient near the endpoints of the contours. On the other hand, simple data padding can introduce artificial discontinuities in the contours,² leading to incorrect statistical analysis.

In this paper, we present a method to extrapolate and resample the tongue surface contour using kriging.³ Kriging is a statistical estimation technique that uses the statistics of the sampled function to estimate a continuous function that interpolates between the sampled points and also extrapolates beyond the endpoints of the contours. Kriging’s asymptotic properties makes it suitable for pre-processing the contours. (A brief description of the theory of kriging is given in Section 3.) After each contour has been extrapolated and resampled, we stack the contours as a spatiotemporal surface. We analyze and visualize these spatiotemporal surfaces using a dedicated user-interface called “SURFACES”, which we also present in this paper.

The remainder of this paper is organized as follows. Section 2 describes both the data acquisition and the method used to extract contours. We also discuss and critique existing methods for pre-processing contours. Section 3 describes the theory of kriging and its application here; this is the main contribution of this paper. We also describe the software tool “SURFACES” in this section. Section 4 demonstrates two applications of this method: to study the effect of gravity on tongue shapes and to study the effect of anterior open bite on swallowing.*

2. BACKGROUND

The motion of three-dimensional human tongue surfaces is of interest because the tongue is a complex system that is critical in speaking, swallowing, and breathing. Being a deformable and volume-preserving object, the tongue can produce a variety of tongue surface shapes through complex activation of its muscles.^{4,5} Imaging techniques are often used to depict the shapes of the tongue and the vocal tract. The imaging techniques include both obtrusive fleshpoint measurements (x-ray microbeam and electromagnetic midsagittal articulator), and non-obtrusive imaging techniques (ultrasound,⁶ X-ray,⁷ and magnetic resonance imaging (MRI)⁷). Compared to the non-obtrusive techniques, the fleshpoint measurements interfere with the natural speech and also introduce the methodological problem of extrapolating the tongue surface between and beyond the fleshpoints.² The non-obtrusive imaging techniques provide a more complete representation of the tongue surface; though each has its limitations. Among the imaging modalities, ultrasound is very attractive for producing an image sequence of the tongue motion because of its real-time capture rates (30 frames per second), its convenience for experimentation, and its cost. Ultrasound has been extensively used to analyze speech production^{7,8} and to understand the act of swallowing.^{9,10}

2.1. Data Acquisition

In this paper, we acquired ultrasound images of the mid-sagittal section of the tongue. A schematic of the mid-sagittal section of the tongue is shown in Fig. 1(a). A sequence of ultrasound images is acquired as the subject either speaks a given utterance or swallows a particular amount of bolus. One of the images in a sequence is shown in Fig. 1(b), with the extracted contour overlaid as white dots. The ultrasound scan rate was set to 30 images per second. The audio data is also recorded, but is not directly useful in the context of this paper. The sequence of images are acquired both in analog and in digital format. The images are then input into the contour extraction program which is described in the next section.

Each subject is made to repeat the utterance several times (usually 5–7 times) in order to account for the intra-subject variability in speech production. Also, in doing statistical analysis on the tongue shapes, it is

*The anterior open-bite, a fairly common problem in children, is considered to be a deviation in the vertical relationship of the dental arches, and is characterized by the incomplete closure of the anterior teeth.

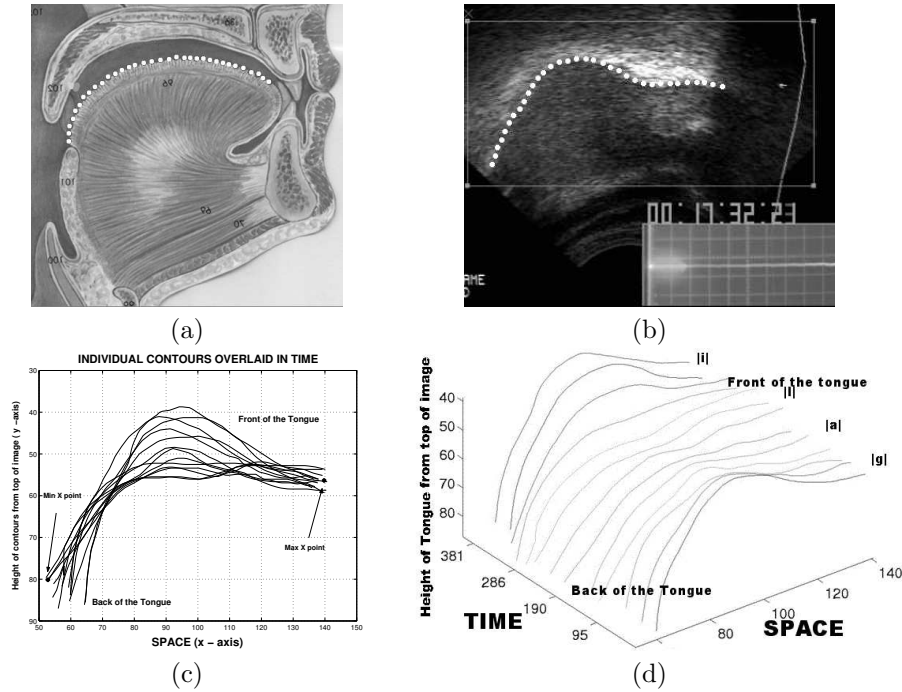


Figure 1. (a) Midsagittal tongue schematic with superimposed surface contours points. (tip of tongue on the right). (b) Midsagittal ultrasound image with tracked surface contour points (c) Sequence of tongue contours in time overlaid on each other. (d) Waterfall display of contours for the word ‘golly’.

useful to stabilize the estimate by averaging over different repetitions. We will see in Section 2.3 that the pre-processing, which is required before faithfully averaging the repetitions is possible, is one of the main motivations for undertaking this research.

2.2. Automatic Contour Extraction and Tracking

Each image in the image sequence is processed using an improved form of the algorithm proposed by Akgul et.al.¹ The algorithm uses a discrete form of the deformable contours and imposes speech, tongue, and ultrasound imaging constraints. The initial contour of the tongue shape is user-defined; it is then used as the initialization for the deformable model. Using the initial contour and the model constraints, the algorithm tracks the tongue surface over the series of images. One of the images with the tracked contour superimposed on it is shown in Fig. 1(b). The algorithm also imposes regularizing constraints on the deformable contours, so that the resulting contour is smooth. Each contour is represented as set of y values, which represents the height of the tongue (calculated from the top of the image) measured at sampling locations determined by the x values (Fig. 1(c)). A dedicated user interface incorporating the algorithm was used to extract and track the contours from the ultrasound image sequences.

2.3. Need for Pre-processing

Applications of the extracted tongue surface contours include:

1. Spatiotemporal visualization of contours for a single repetition, often called a ‘waterfall’ display (Fig. 1(d)).
2. Averaging of different repetitions for single subject and single utterance in order to stabilize the estimate of tongue shape for statistical analysis.
3. Comparative analysis of two repetitions — e.g., overlay of surfaces, difference measures, etc.

While waterfall visualization of the individual contour sequences (item 1 in above list) can be achieved without any pre-processing of contours, both averaging (item 2) and comparative analysis (item 3) need pre-processing. The pre-processing must make the contours equal in length and sample them on the same set of spatial coordinates. But the contours extracted from the algorithm mentioned in Section 2.2 contain the three difficulties that were mentioned in the introduction and are elaborated below.

1. *Shift in transducer position*: Even though the ultrasound transducer is positioned with care using the Head and Transducer Support system (HATS),¹¹ its position may vary across subjects and sessions, resulting in an arbitrary shift in the spatial coordinates. Also in some experiments, like the comparison study of tongue shapes in upright and supine positions,¹² the HATS cannot be used. This makes random spatial shifts more likely and results in data loss.
2. *Change in tongue contour length*: The length of the tongue contours may be different lengths for different repetitions of the same speech-sound due to speaker imprecision. Moreover, the tongue length can change even during one utterance due to the volume-preserving nature of the tongue. For example, vertical expansion or compression must be balanced by an anterior-posterior expansion or compression, respectively, which changes tongue length. Apart from the physical changes in tongue length, the length of the measured contours can be affected by image noise.
3. *Contour extraction effects*: Increasing the gradient of a portion of the extracted contour, increases the density of sampling in that portion. This behavior of the contour extraction algorithm results in differences both in the spatial sampling locations and sampling density.

Hence, it is necessary to pre-process the contours so that they are of equal lengths and are sampled on the same spatial grid.

The methods of pre-processing — registering, smoothing, extrapolating, and interpolating — of data is a necessary step in many statistical applications.¹³ A variety of pre-processing methods have been suggested by Stud et.al in Ref. 2 and Stone et.al in Ref. 14, for application of principal component analysis (PCA) on coronal tongue contours. Methods to equalize the lengths of the contours include combinations of the following three approaches: 1) truncation of the longer contours beyond a defined region; 2) extrapolation of shorter contours to the size of longer ones through linear or spline extension; and 3) padding shorter curves with constant values. The truncation approach, although good for certain kinds of data, discards interesting and valid data from the longer curves. Slud et. al² discarded the attempt to extrapolate using splines, because of unacceptably wild swings in the extrapolated contours[†]; instead they used the “padding” approach, padding the shorter curves with endpoint averages. They argue that, even though padding will introduce artificial discontinuities, they did not affect the PCA methods. But, these artificial discontinuities can be a problem in other statistical analysis.

3. METHODS

In order to extrapolate the contours without explicit data padding and without the wild swings characteristic of polynomial extrapolation approaches, we use kriging to extrapolate and resample the contours. To illustrate the problem, Fig. 2 shows a typical extracted tongue surface contour. The data corresponding to the extracted contour is represented in the form of a stem plot descending from the top of the plot. Note that the sampling density is higher in locations where the slope is larger, such as at the back of the tongue (on the left). This occurs because the contour itself is sampled somewhat uniformly, but the slope of the contour increases the density with respect to the x -axis. The dark contour in Fig. 2(a) is the result of extrapolation using cubic splines, while that in Fig. 2(b) is the result of kriging. Clearly, there is a non-intuitive, extreme fluctuation in the extrapolation using cubic splines, which is absent in the kriging result. The key to kriging’s improved performance in extrapolation is its spatial asymptotic properties, which is similar to the asymptotic properties of the thin-plate splines.¹⁷ Also, given the sample data points and their statistics, kriging estimates a continuous functions that best fits the data points. Therefore, the resulting continuous function can be resampled at any given spatial grid. In the following section, we summarize the derivation of kriging and give its final solution.

[†]Wild swings in the extrapolated values are a characteristic behavior of polynomial-based extrapolation techniques when there are large gradients among the values near the end of the contours. See Ref. 15 and Ref. 16 for more details.

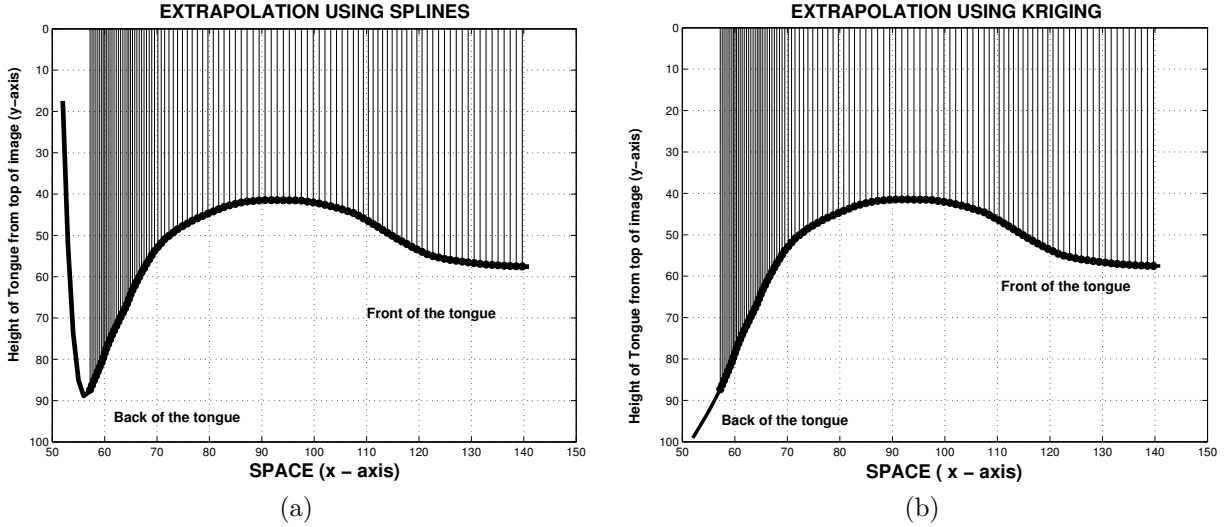


Figure 2. (a) Extrapolation using cubic splines; note the anomalous behavior in the back of the tongue. (b) Extrapolation using kriging; note the improved performance of kriging at the back of the tongue.

3.1. Kriging

Kriging is a statistical estimation technique that estimates the value of a scalar function $s(\mathbf{x})$, given observations at the points $\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_p$. In our case, the observations are the “ y_i ” values that measure the height of tongue contours from the top of the ultrasound image at sampling points “ x_i ”. Since the x_i ’s are one-dimensional, we let $\mathbf{x} = x$, a one-dimensional variable. Kriging assumes that the estimated function $s(x)$ consists of two components

$$s(x) = u(x) + \mathbf{f}^T(x)\mathbf{d},$$

where $u(x)$ is a zero-mean random function with known covariance function $k(x_a, x_b)$.¹⁸ The term $\mathbf{f}(x)$ is $r \times 1$ vector of known “drift functions” and \mathbf{d} is the $r \times 1$ vector of unknown “drift coefficients”. The mean of the function $s(x)$ is deterministic, but unknown. Usually the drift functions are taken to be monomials of degree less than or equal to a chosen value q . Given the shape of the tongue contours, we have selected $q = 1$, which leads to the linear drift functions,

$$\mathbf{f}(x) = [1 \ x]^T.$$

Given this statistical model for the data, kriging produces the best linear unbiased estimate (BLUE), which consists of a linear combination of the observations.

$$\hat{s}(x) = \mathbf{a}^T \mathbf{y},$$

where \mathbf{y} is a vector of the observations (“ y ” values) at x_1, x_2, \dots, x_p and $\mathbf{a}(x)$ is a $p \times 1$ vector of coefficients, which we want to estimate. The constraint of unbiasedness of the estimate leads to the constraint on the coefficients,

$$F\mathbf{a}(x) = \mathbf{f}(x),$$

where

$$F = [\mathbf{f}(x_1) \dots \mathbf{f}(x_p)], \tag{1}$$

an $r \times p$ matrix. The kriging estimate is then obtained by finding $\hat{s}(x)$ that minimizes the expected squared error

$$E[(s(x) - \hat{s}(x))^2]$$

subject to the unbiasedness constraint. The constrained minimization problem can be solved using the method of Lagrange multipliers and the solution depends only on $\mathbf{f}(x)$, F , data covariance matrix

$$K = \begin{bmatrix} k(x_1, x_1) & \dots & k(x_1, x_p) \\ \vdots & \ddots & \vdots \\ k(x_p, x_1) & \dots & k(x_p, x_p) \end{bmatrix} \quad (2)$$

, and the covariance vector

$$\mathbf{k}(x) = [k(x, x_1) \dots k(x, x_p)]^T. \quad (3)$$

The solution is

$$\hat{s}(x) = \mathbf{k}^T \mathbf{w} + \mathbf{f}^T(x) \hat{\mathbf{d}}, \quad (4)$$

where

$$\begin{aligned} \mathbf{w} &= K^{-1}[I - F^T(FK^{-1}F^T)^{-1}FK^{-1}]\mathbf{y}, \\ \hat{\mathbf{d}} &= (FK^{-1}F^T)FK^{-1}\mathbf{y}. \end{aligned}$$

Thus, the solution is a continuous function, which can be resampled on an arbitrary spatial grid. Notably, the spatial grid can include extrapolated points that are beyond the original range of x_i 's over which the data was collected.

The above solution presents kriging used as an interpolator — i.e., the final continuous function passes through all the data points. Kriging methods have also been derived to spatially smooth the estimate, addressing observations that are subject to noise. Since noise appears in our model, we have used the spatial smoothing version of kriging in this paper. The final form of the smoothing version is essentially the same as in Eq. (4), except that K in the expressions for \mathbf{w} and $\hat{\mathbf{d}}$ is replaced by $(K + \Sigma)$, where Σ is the noise covariance matrix that characterizes the statistics of the noise in the data. A detailed derivation of the smoothing form of kriging can be found in Ref. 18.

3.2. Algorithm

Given a contour in terms of x_i (spatial sampling locations) and y_i (height of the point from the top of the image), the problem is to estimate the value of a continuous function $s(\cdot)$ at arbitrary spatial position $x \in \mathbb{R}$. The smoothing form of the kriging algorithm is applied on the contour to estimate $\hat{s}(x)$. The detailed algorithm is given below.

ALGORITHM 1.

1. Form the data vector, $\mathbf{y} = [y_1 \dots y_p]$.
2. Select the drift function $\mathbf{f}(x)$ and calculate F as defined in Eq. (1).
We used the linear drift function, $\mathbf{f}(x) = [1 \ x]^T$.
3. Select the covariance function for the data, $k(x_a, x_b)$ and calculate the matrix K and vector $\mathbf{k}(x)$ as defined in Eqs. (2) and (3) respectively. We used the generalized covariance function, $k(x_a, x_b) = \|x_a - x_b\|^2 \ln \|x_a - x_b\|^2$.
4. Select the noise covariance matrix Σ , a $p \times p$ matrix that characterizes the statistics of the noise in the data.
We assumed the noise was white and zero-mean with variance equal to 10 mm^2 . Hence, $\Sigma = 10I$, where I is the $p \times p$ identity matrix[‡].

[‡]The noise variance of 10 mm^2 is justified by the fact that the surface of the tongue is relatively smooth and any sharp discontinuities in the contour has to be smoothed out. The use of the noise variance parameter makes this algorithm different from thin-plate splines, which is an interpolator that uses generalized data covariance function and linear drift functions.

5. Calculate the matrices

$$\begin{aligned} L &= (K + \Sigma)^{-1} \\ M &= (FLF^T)^{-1}FL \\ G &= KL(I - F^T M) \end{aligned}$$

6. Calculate the coefficient vectors

$$\begin{aligned} \hat{\mathbf{d}}_s &= M\mathbf{y} \\ \mathbf{w}_s &= K^{-1}G\mathbf{y} \end{aligned}$$

7. Calculate the desired estimate using

$$\hat{s}(x) = \mathbf{k}^T(x)\mathbf{w}_s + \mathbf{f}^T(x)\hat{\mathbf{d}}_s.$$

■

After each contour has been extrapolated and resampled, we stack the contours as a spatiotemporal surface [see Fig. 3(b)]. Similar processing can be done on different repetitions of the same speech utterance or swallow, and resulting surfaces averaged to yield an average spatiotemporal surface. The details of the software “SURFACES”, which we designed to implement the kriging of contours and their subsequent visualization, is given in the next section.

3.3. “SURFACES” Software

Fig. 3(a) shows a snapshot of the graphical user interface (GUI) for “SURFACES”. The GUI and the algorithm were implemented in MATLAB Version 6 (Mathworks, Natick MA, USA). The GUI has three main parts. The first part reads in the initial contours and allows the user to select a maximum and minimum values of x , within which each contour will be smoothed (estimated) using kriging and resampled. The “*Krige and Show Surface*” button kriges all the contours in one repetition resulting in a spatiotemporal surface, as shown in Fig. 3(b).

The spatiotemporal surfaces that are derived from the kriged contours can be used to qualitatively analyze a speech utterance. For example, Fig. 3(b) shows the spatiotemporal surface for the word ‘golly’. Noting that the front of the tongue is on the right, the nearest contour shows the ‘g’, which is arched in the middle [see 1 in Fig. 3(b)]. As time advances, the tongue flattens and the tip rises for the ‘l’ [see 2 in Fig. 3(b)]. Finally the tongue arches again for ‘y’ [see 3 in Fig. 3(b)].

Part 2 of the software is for averaging different repetitions of the same utterance that have been kriged and resampled in Part 1. The result is an *averaged* spatiotemporal surface and a variance surface, which can be used for further statistical analysis. Part 3 of the software is used for comparison of two spatiotemporal surfaces. These spatiotemporal surfaces can be either individual repetitions or average surfaces (see Fig. 4 for an example of an overlay of two such surfaces.).

4. RESULTS, APPLICATIONS AND DISCUSSION

Application of the “SURFACES” software is demonstrated here in two studies: 1) the effect of gravity on the tongue during speech, analyzed by comparing speech during upright and supine head orientations¹²; and 2) the effects of anterior-open bite on swallowing.¹⁹

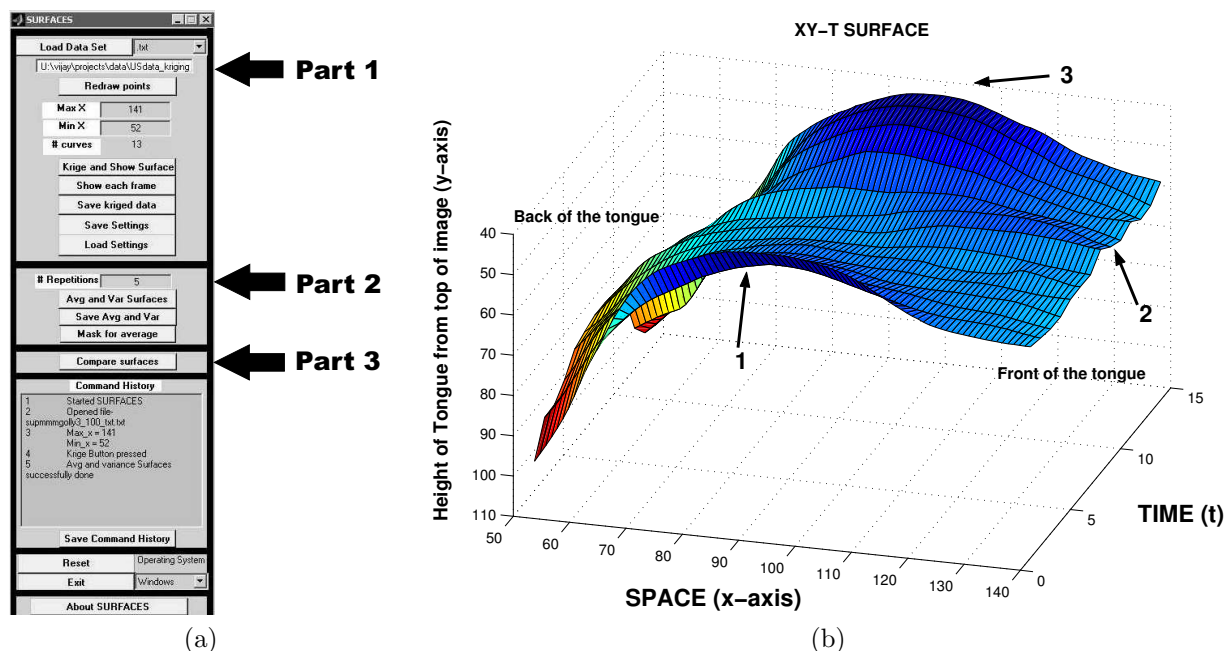


Figure 3. (a) A snapshot of the “SURFACES” software and (b) a spatiotemporal surface of the word ‘golly’.

4.1. Upright Supine Study

This experiment studied the effects of gravity on the tongue during speech. In particular, it is not known how and to what degree the tongue changes shape during speech uttered in the supine position versus that uttered in the upright position. It is scientifically important to understand this phenomenon in order to register imaging studies of tongue motion during speech acquired in a magnetic resonance scanner, which generally requires a supine position, to conventional studies acquired in the upright position.

In this study, the subjects were asked to repeat the same utterances in upright position first and then in supine position. Tongue contours were extracted from the ultrasound data, kriged, and visualized using SURFACES. The overlaid surfaces in Fig. 4(a) shows a typical result during the utterance of the word ‘golly’. We see that the supine surface (colored surface) is rotated backward from the upright surface (white mesh) during the entire word. A secondary effect that can also be observed is that tongue tip is elevated in the supine study during the ‘l’ (see arrow). It is likely that the tip is being held more firmly against the palate in the supine position, probably to counteract the gravitational pull while still making the correct sound.

4.2. Swallow Study

This study considered the effects of anterior open bite (AOB) on swallowing stability. AOB is a fairly common problem in children, sometimes due to thumb sucking, and is characterized by incomplete closure of anterior teeth when the molars are occluded. This experiment studied the effects of this malocclusion on tongue’s propulsion of food and liquid. AOB was simulated by placing a bite block between the first molars of normal subjects. Fig. 4(b) shows the spatiotemporal surface of a 20 cc water swallow. We observe that the water is initially contained anteriorly, with the tongue tip depressed and the back elevated to protect the airway. Subsequently, the tongue deforms around the bolus as it is propelled backwards. Finally, the tongue elevates from front to back to make contact with the palate after the water’s passage.

5. CONCLUSION

We described the use of kriging to extrapolate the tongue surface contours which are extracted from ultrasound image sequences of the tongue. The resulting kriged contours can then be stacked and visualized as a spatiotem-

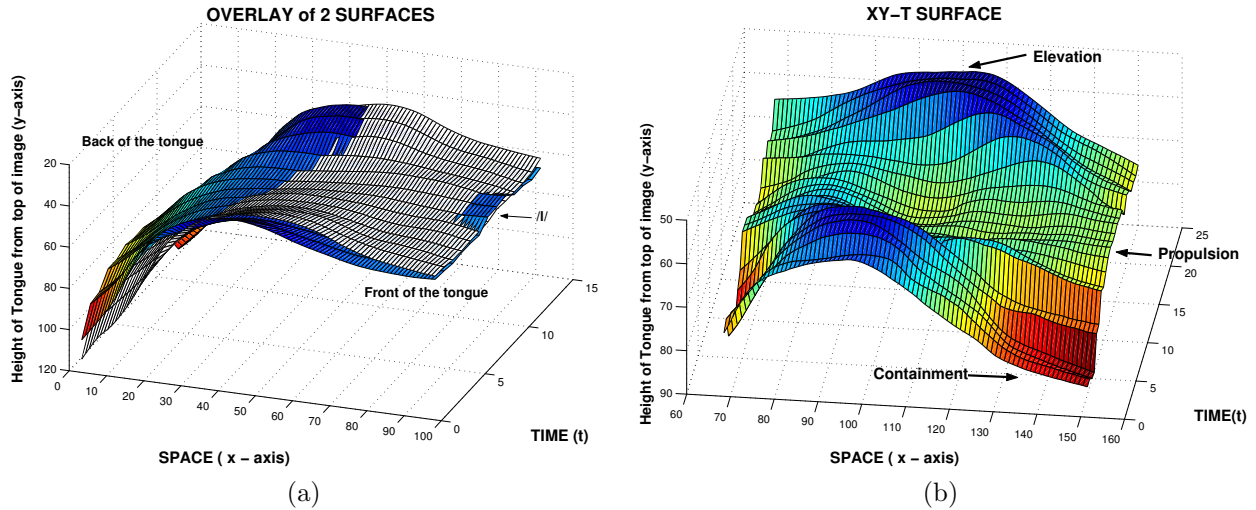


Figure 4. (a) Overlay of 2 spatiotemporal tongue surfaces of the word ‘golly’. Mesh surface is the ‘upright’ surface and the colored surface is the ‘supine’ surface. (b) Spatiotemporal surface of 20cc swallow. Notice that the water is contained in front of tongue, propelled backwards and tongue surface elevates after the water’s passage.

poral surface. A dedicated user interface, “SURFACES,” was described. SURFACES implements the kriging algorithm and is used for averaging and comparative analysis of different tongue shapes.

The calculation and visualization of spatiotemporal mid-sagittal tongue surfaces helps in understanding tongue deformations during speech and swallowing. It is hoped that this methodology will further help in quantification and statistical comparison of complex tongue motion.

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