A New Approach To Pressure-Sensitive Palatography Using A Capacitive Sensing Device

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ABSTRACT

In this work we report on a new type of pressure sensor and its application to palatography. The device is a flexible sheet sensitive to pressure-induced changes in capacitance with a spatial resolution of 2 mm. When mounted to a plastic palatal plate thermoformed off a subject's dental cast we have used it to record lingual palatal contact pressure from 25 distributed locations at a 40 Hz/sensor sampling rate. Because of pervasive noise and problems with calibration our results obtained using the device are preliminary, though consistent with previous work in this area.

1. INTRODUCTION

Electro-palatography (EPG) is a well-established technique for investigating patterns of tongue contact with the hard palate during running speech production (cf. [1] for review). In a typical arrangement, at least 60 contact measuring electrodes are distributed over a thin acrylic 'pseudopalate' which has been constructed from a dental cast for use with a particular subject to obtain the best fit and least interference with articulation. The electrodes are scanned at rates ranging from 60 to 200 Hz, with contact results usually grouped functionally for data reduction and analysis (e.g. [2]).

Because conventional EPG is limited to on/off binary contact information, a number of researchers have investigated ways of making the distributed contact points sensitive to pressure. For example, Matsumura and colleagues developed a prototype system incorporating five piezoelectric strain gauges, each about 1 mm in height and diameter [3]. These were mounted midsagittally at 6 mm intervals on a .5 mm plastic palatal plate. Measurements obtained from one male speaker of Japanese on the sequences /ta/, /da/, and /na/ show highest pressure and longest contact duration for /t/, and least pressure and shortest duration for /n/. Wakumoto and colleagues took an approach closer to standard EPG by distributing up to 16 resistive-film sensors on .5 mm thick subject-specific palatal plates manufactured from dental casts [4]. Each sensor was 3 mm in diameter and .1 mm thick. They observed 10 Japanese subjects producing /ata/ and /ada/ sequences, and reported higher pressure for the unvoiced stop.

Our group has made use of a new pressure sensing technology based on changes in capacitance. As implemented in a commercially available flexible sensing sheet [5], two orthogonally oriented sets of parallel electrodes are separated by a compressible membrane, in which the sensels (pressure sensing points at the electrode intersections) are uniformly distributed at 2 mm intervals (Figure 1a).

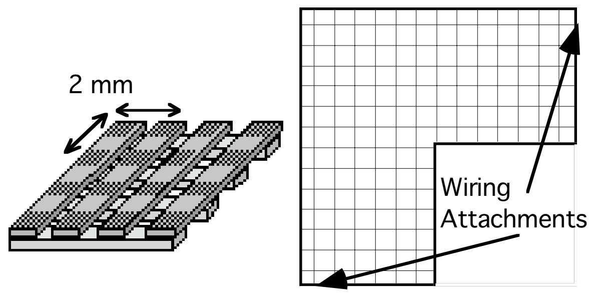

Figure 1: **a)** Capacitive sheet forms sensels at electrode overlap points; **b)** Trimmed layout showing approximate locations of potentially addressable sensels

This has several advantages in the context of a palatography system: The sheet is thin (1 mm) and sufficiently flexible to provide a minimally intrusive fit to the palate, it can potentially be reused by multiple subjects, and it has a distribution of potential contact positions approaching the density of conventional EPG.

2. DESCRIPTION

In our application, a .5 mm palatal plate is made from plastic thermoformed to a dental impression of the upper teeth and palate, extending over the buccal and labial surfaces of the upper teeth to provide adequate retention. To facilitate attachment to the plate the capacitive sensing sheet is trimmed by the manufacturer to remove approximately one quarter of the initial square (Figure 1b). The sheet is then glued to the surface of the template with

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a silicone adhesive, with the two wires providing electrical connectivity passed along channels fit to the exterior sides of the upper molars. We refer to the resulting PREssure Measuring Unit as the PREMU.

The PREMU device is operated by specifying one of 256 potential sensel locations under computer control and sampling the returned analog signal that gives the currently transduced pressure at that location. Although the manufacturer electronics operate with a .192 millisecond (5208.3 Hz) clock, we have found that the latency associated with switching addresses limits us to an effective 1 kHz sampling rate partitioned across all sampled locations (in practice data are collected at 5 kHz, with 5 samples per sensel contributing to each output data point). A reasonable balance between sampling rate and palatal coverage is given by circular addressing of 25 sensels, which allows us to obtain pressure data for each sampled location at an effective 40 Hz rate.

3. CHARACTERISTICS

Because not all sensels respond equally, especially after deformation to the palatal plate, the following procedure was used both to identify useful sensels and to provide a baseline calibration of their response: The PREMU was inserted into a balloon which was then inflated (in fact a latex surgical glove rather than a balloon was used because of its relatively wide neck).

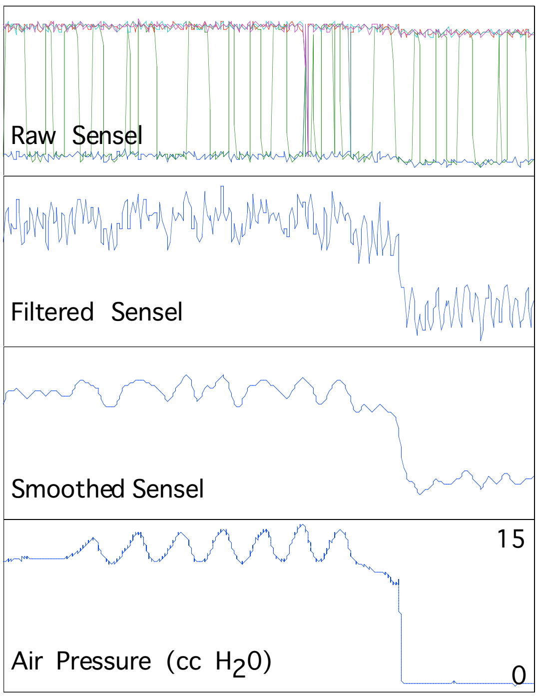

Figure 2: Sample balloon calibration data for one sensel. Smoothed data tracks pressure with reasonable fidelity.

While first varying compression on it and then permitting air to escape, a water column calibrated pressure transducer was used to sample air pressure within the balloon at the same time that data were collected from PREMU sensels.

The PREMU data were collected from 25 sequentially ordered locations per trial, and the sampled addresses were incremented each trial until the entire address space had been reviewed. Figure 2 shows an example sensel response from this procedure.

It will be immediately apparent that PREMU data are noisy. In part this is due to our use of a small portion near the low end of the 24 kPa range claimed by the manufacturer, and also because of the settling time latency associated with changing addresses. In addition, sensels are prone to saturation; that is, applied pressure exceeding some level effectively shorts out the capacitance at that point, and this problem is exacerbated by the stress imposed by deformation to the palate.

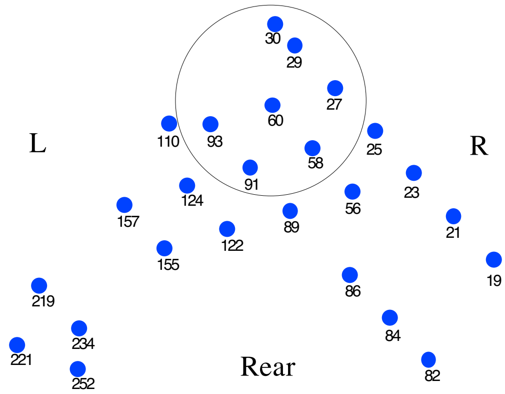

Figure 3: Sampled sensel map used for experiment. Circled sensels averaged to characterize alveolar contact.

We attempt to address these problems during post-processing: After first unpacking and grouping data from the continuously sampled device, the five samples per sensel data point (see top panel "Raw" of Figure 2) are first scanned for values in the range associated with saturation and tagged as missing data if necessary. They are then median-filtered, mean-centered, and averaged ("Filtered"). Output data are obtained by fitting a cubic interpolating spline ("Smoothed"), which is then calibrated with air pressure data. However, since the pressures exerted by tongue contact exceed those obtainable using air pressure calibration techniques, pressure values over the full observed range must be obtained by extrapolation, and thus rely on the untested linearity characteristics of the device (claimed to be within 1% of the output signal by the manufacturer).

4. EXPERIMENTATION

The PREMU was put to use in an investigation contrasting pressure differences in English lingual obstruent production. The subject was a male native speaker of American English. The sequence "say /aCa/ for me" was produced with ten repetitions of each of the phonemes /t d n tʃ dʒ s z ʃ ʒ/. Ten repetitions each of "say /bVb/ for me" were also collected for the vowels /i/ and /ɪ/. In

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addition, closed mouth air pressure calibration trials were recorded in which the subject was instructed to manipulate oral pressure to obtain a full-scale reading on an inserted probe. After preparing the PREMU device from a dental cast, 25 active sensels were selected based on their sensitivity and distribution using the balloon calibration technique, and a 'map' of sensel addresses was produced (Figure 3). The anterior-most sensel (30) was located at the base of the alveolar ridge, and the posterior-most (252) was at the level of the (left side) 2nd molar.

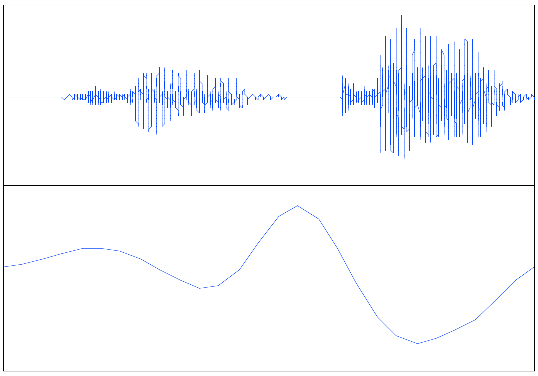

Figure 4: Sample utterance ("say ata for me") showing uncalibrated smoothed data from alveolar sensel 30.

A custom software application [6] was used to control sensel addressing and sampling, concurrent audio and air pressure data acquisition, and visual stimulus presentation. Audio was recorded at a 20 kHz rate, PREMU at 5 kHz (for a 40 Hz/sensel rate as described above), and pressure at 5 kHz.

5. RESULTS

Because our efforts to quantify the smoothed sensel data using the mouth closed calibration trials have to date produced inconsistent values when extrapolated beyond the range of the air pressure transducer, we present our results in terms of uncalibrated relative values.

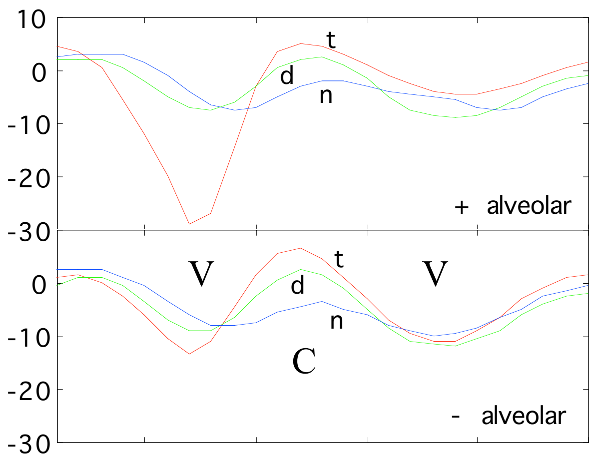

Figure 5: Averaged relative pressure for /ata/, /ada/, /ana/. At offset C, t > d > n.

As a means of reducing noise and emphasizing salient pressure differences, we used ensemble averaging [7] across repetitions, aligned by the smoothed audio RMS onset associated with the vowel of "say." Sensel values were also grouped by region: either within the alveolar region (circled in Figure 3) or exterior to it.

Figure 5 shows a comparison of grouped /aCa/ data for /t/, /d/, and /n/. At the aligned maximum pressure point associated with obstruent contact we observe the expected t > d > n ordering consistent with the previous Japanese data. The large dip preceding closure for /ata/ is probably an artifact of unfiltered noise.

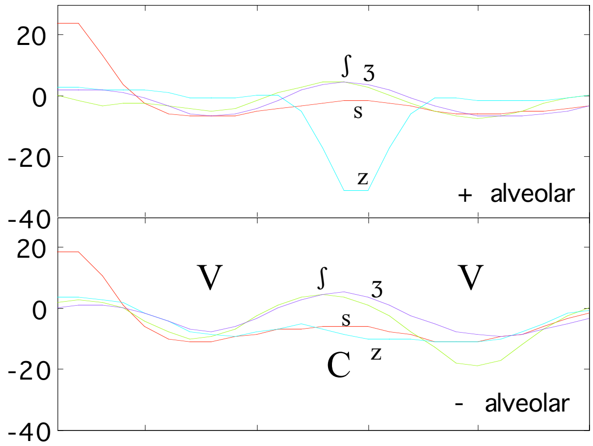

Figure 6: /asa/, /aʃa/, /aza/, /aʒa/. At C, ʃ,ʒ > s > z.

A similar comparison is shown in Figure 6. In this case, palato-alveolar sibilants /ʃ/ and /ʒ/ show higher relative pressure than the more anterior /s/ and /z/, probably due to greater tongue contact with available sensels. Once again, the anomalous dip for the alveolar-grouped /z/ is likely noise-related.

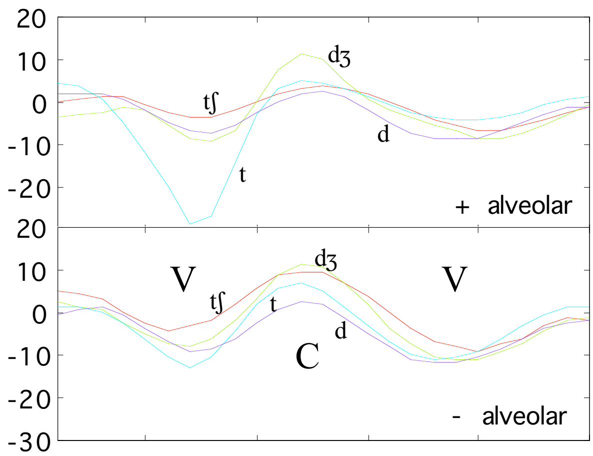

Figure 7: /atʃa/, /adʒa/, /ata/, /ada/. At C, dʒ > t,tʃ > d.

The comparison of stops with affricates shown in Figure 7 shows a somewhat surprisingly low relative value for /tʃ/ in the alveolar grouping, which may reflect a more anterior place of contact relative to /dʒ/. Alternatively, the

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higher value for /dʒ/ may reflect an increase in intraoral pressure required to maintain voicing. Overall, affricates show higher relative pressure.

A final comparison contrasts the greater contact for tense /i/ with that found for lax /ɪ/, shown in Figure 8. The tense vowel shows higher relative pressure, which is consistent with the tongue bracing observed by MRI [8].

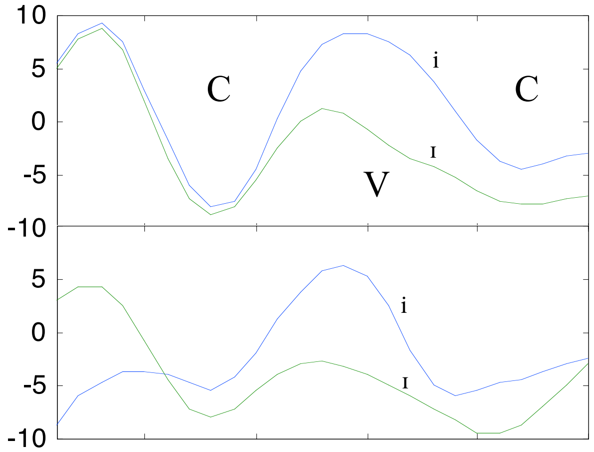

Figure 8: /bib/, /bɪb/. The tense vowel shows higher relative pressure consistent with tongue bracing.

6. DISCUSSION

The capacitive device described here remains a considerable distance from real usefulness in the task of quantifying lingual contact pressure. Pervasive noise and inconsistencies in repeated measurements raise questions of reliability, and the lack of a means of calibration over the full range of expected pressures limits the obtained results to relative comparisons. Another liability is the lack of a clear contact signal, which makes it likely that air pressure is confounded with tongue pressure to some degree.

But this system's potential is substantial. Subjects adapt readily to the PREMU palate, and the flexible sensing sheet is sufficiently robust in our own experience to permit reuse by different subjects. The manufacturer now offers improved and faster electronics which we have not obtained that could potentially decrease noise associated with address changes, and permit sampling a greater density of distributed sensels. Even in the necessarily preliminary form taken by our results, the observed hierarchies of relative pressure (t > d > n, i > ɪ) are consistent both with previous work in this area and with our expectations for lingual pressure required to maintain occlusion/bracing in the different contexts.

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