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Dynamic Aspects of Velopharyngeal Closure[1]

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Introduction

A major question in studies of velopharyngeal closure in speech has been whether the closure is achieved by a sphincteric or a trapdoor mechanism, or by a combination of both actions. Observations of the velum and the lateral pharyngeal walls during speech in the region of velopharyngeal closure have revealed superior and posterior movement of the velum and medial movement of the lateral pharyngeal walls in the port-closing gesture. In some sense, then, the closing gesture is indeed sphincteric, that is, both the velum and the lateral pharyngeal walls move in closing the port. However, the questions of what the relationship between the movement patterns of the velum and lateral walls is and how they are accomplished still remain. More specifically, do the movements result from action of the levator palatini muscle acting alone, essentially a trapdoor mechanism, or from the levator palatini and superior constrictor muscles acting in concert, a more truly sphincteric mechanism?

Several investigators have previously addressed themselves to this question, using a variety of observation techniques, including (a) monitoring of articulator position (including cine- and videofluorography, ultrasonic echo recording, and endoscopy), (b) recording of electromyographic (EMG) potentials from the muscles of the velar region, and (c) analysis of anatomical relationships. These studies have produced conflicting results, but we believe that they can be reconciled. Accordingly, we have begun a series of studies directed toward this goal, and this paper contains the results of our first step.

In a previously reported study, *Bell-Berti and Hirose* [1975] have shown that the pattern of levator palatini EMG activity is reflected in the velar elevation pattern, although the two are offset in time. In addition, *Bell-Berti* [1973, 1976] has shown, for 3 subjects, that the EMG activity patterns of the levator palatini and superior constrictor are not parallel. While the answer to the question of how closure is achieved may only be finally reached by studying the dynamics of port closure from simultaneous measurements of velar and lateral pharyngeal wall motion and EMG recordings from the levator palatini and superior constrictor muscles, we believe that the directly observed movement data presented here, taken together with *Bell-Berti's* [1973, 1976] EMG data for this subject provide strong evidence in favor

[1] A version of this paper was presented at the Third International Congress on Cleft Palate and Craniofacial Anomalies, Toronto, Canada, June 1977.

of the conclusion that the levator palatini is solely responsible for velopharyngeal closure, at least for this speaker.

Methods

A native speaker of American English (one of the authors of this paper) served as the subject for this study. An inventory of 24 disyllables was used in the experiment, containing nasal-oral and oral-nasal consonant oppositions in utterance-medial position, thus using the most extreme contrasts the system is required to make. The nasal consonant was always /m/, and the oral consonants were /p/,/b/,/f/,/v/,/s/, and /z/. The vowels were /i/ and /a/, with the same vowel occurring in both syllables. Each utterance type began with /f/ and ended with /p/; these phone sequences were designed to avoid lingual coarticulation effects, provide clear oscillographic records of the beginning of the first and the end of the second syllable, and insure initial and final oral articulation. All utterances were placed in lists in random order, and the lists were read from six to eight times during the recording session.

A thin plastic sheet with grid markings was inserted into one nostril of the subject, and placed onto the nasal floor (nasal surface of the velum) to enhance the contrast between the edge of the supravelar surface and the posterior pharyngeal wall for subsequent frame-by-frame film analysis. A flexible fiberoptic endoscope (Olympus VF Type 0) was also inserted into the subject's nostril, and positioned with its objective lens tip at the posterior border of the hard palate, providing a view of the vertical excursion of the velum as well as the side-to-side movement of the lateral pharyngeal wall. The subject was able to articulate without any perceptually apparent interference.

A 16-mm motion picture film of the nasopharynx was taken through the fiberscope at the rate of 60 frames per second (fig. 1). Synchronization pulses, which were generated frame by frame, were recorded on the FM data recorder with other acoustic and physiological data, including EMG potentials from velopharyngeal muscles, and intraoral air pressure.

The distances between four monitoring points lying in the velopharyngeal region and a fixed reference point in the field of view were measured frame by frame to expose the relationship between the displacement patterns of the velum and lateral pharyngeal wall above the level of the hard palate. These measurement points, shown in figure 1, included one point on the velum and three points on the lateral nasopharyngeal wall. Velar displacement was measured at the highest visible point on the velum. The lateral wall movements were described at three levels of the lateral pharyngeal wall: at 75, 50 and 25% of the maximum observed vertical excursion of the velum. The maximum excursion was determined by measuring velar height during blowing.

All measurements could not be made for every frame. Figure 1 illustrates the extreme positions, at which certain points are unmeasurable. Figure 1a was taken when the velum was low, i.e., the velopharyngeal port was widely open. In this picture the three measurement points on the lateral pharyngeal wall are visible, but the high point of the velum is below the level of the hard palate, and hence masked. Figure 1b represents the tightly closed velopharyngeal port, in which the velum comes up almost to the 50% level of its maximum upward deflection. In this case, the lateral wall position is undefined at the 25% level, since at levels below the level of the high point of the velum the lateral wall is drawn into the velum. It should be made clear that it was not possible to measure lateral wall displacement at or below the level of the hard palate. However, we know that the level of the closure region extends above the hard palate [*Bjork*, 1961], and that the superior constrictor cannot contribute to closure above the hard palate because of its absence at that level. Thus, we believe that our measurements were made of structures that were involved in closing the velopharyngeal port, at least at and above the level of the hard palate.

Data Reduction Procedures

The displacement of each of the points against time was plotted for each repetition of each utterance type, with the assistance of a small laboratory computer [*Gay*, 1977]. Thus, the movement patterns of four different points for each trial (repetition of each of 24 utterance types) were obtained. For each utterance type, six to eight repetitions were measured, aligned to an acoustic event – the boundary between oral and nasal consonants – and averaged, as in previous studies [*Kewley-Port*, 1973]. Figure 2 displays the component and ensemble-average displacement curves for the four measurement points for two different utter-

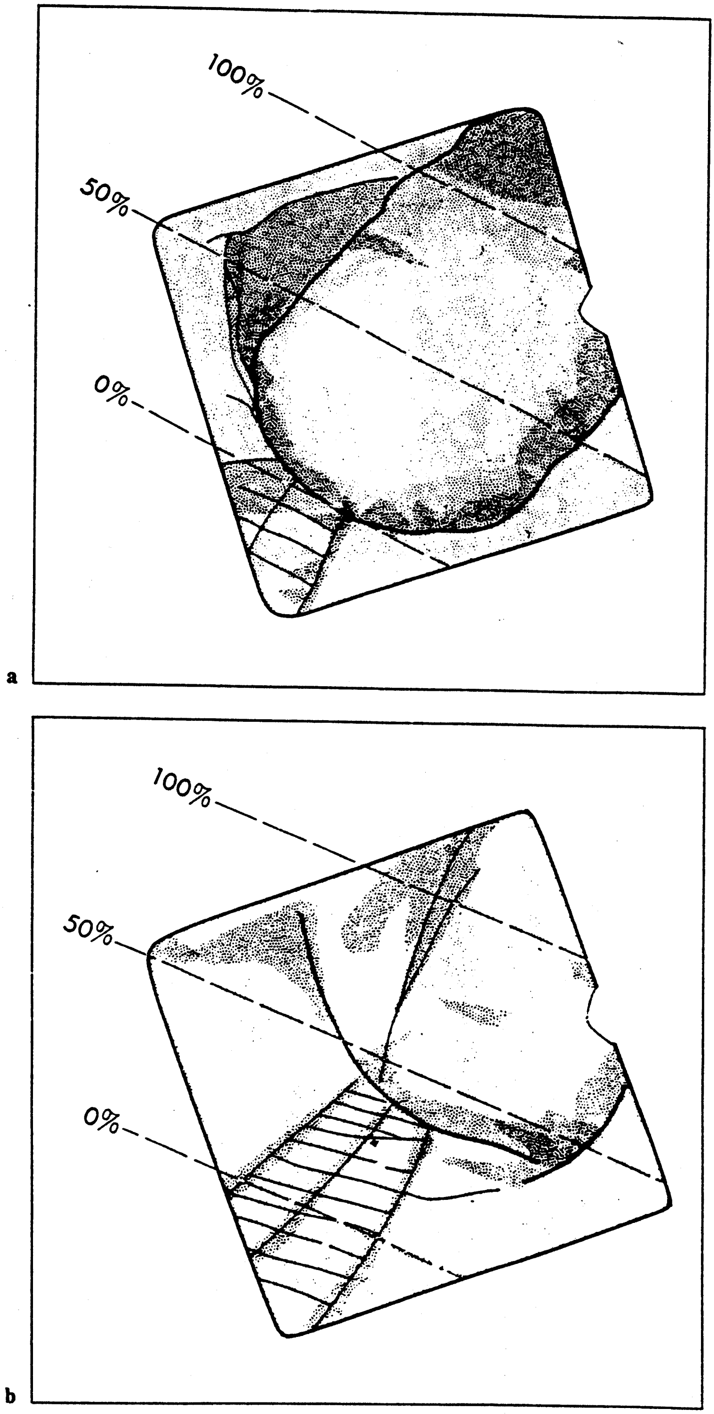


Fig. 1. Frames reproduced from the experimental film, with measurement reference lines superimposed on each frame. **a** The velum is low and out of view. **b** The velum is elevated to nearly 50% of its maximum excursion.

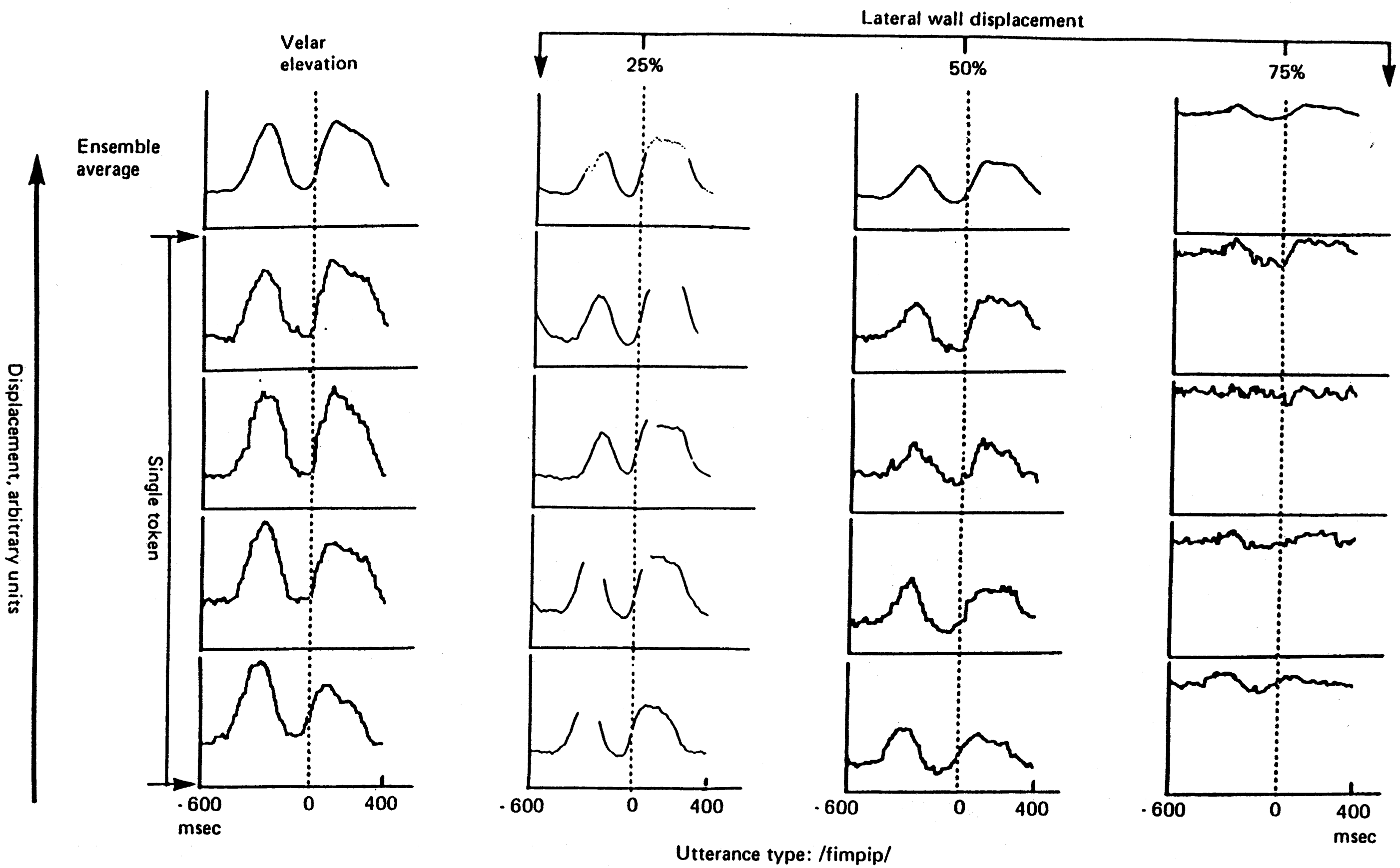


Fig. 2. Ensemble averages and component displacement curves for the utterance type /fazmap/. The ensemble averages of four component displacement curves appear at the head of each column. Four of the eight individual token displacement curves are shown beneath their respective ensemble averages. Velar elevation is displayed in the first column; 25%, 50%, and 75% level lateral wall displacement are shown in the next three columns, respectively.

ance types, which contrast in vowel, medial obstruent consonant, and order of the medial oral and nasal consonant sequence. These curves are followed by examples of the individual tokens.

Results

There is a striking similarity in the movement pattern of the three measurement points on the lateral pharyngeal wall. The differences between the medial displacement of the several levels are primarily differences in the extent, rather than the time-course, of the excursions.

This point is illustrated in figure 2, which shows four single tokens of the utterance /fazmap/. An inspection of the figure shows that medial movement is very small at the 75% point, which is nearest the 'hinge' of the lateral wall, and that medial movement is substantially greater at the 50% and 25% points. The data illustrate very well the indeterminate state that occurs when the velum is high. In forming the average curves, we have excluded the regions of the tokens which are undefined, leaving gaps in those curves. Since the movements of all three points are so similar, we have chosen the 50% point of the lateral wall movement to compare with velar movement.

In utterances having oral-nasal sequences (fig. 3) both velar elevation and medial displacement of the lateral pharyngeal wall increase for the initial fricative, /f/ (thus decreasing velopharyngeal port size), decrease for the first vowel, increase for the medial oral consonant, decrease markedly for the nasal consonant (to open the port and enhance nasal coupling), and then increase again for the final vowel and stop consonant, /p/. In utterances having nasal-oral sequences after the velar elevation and medial displacement of the lateral pharyngeal wall to reduce port size for the initial fricative, there is a marked decrease in both displacements for the first vowel and the nasal, followed by a rapid increase in displacement for the oral consonant, a decrease for the second vowel and, in some utterances, an increase for the final /p/. (We might note, in this light, that it is apparently quite usual for velar elevation to vary during connected speech, with changes in velar position, and thus in velopharyngeal port size, produced to enhance or prevent nasal coupling, as needed, for the segments in the phonetic string. It has been shown previously that velar elevation varies directly with the oral cavity constriction of oral segments [*Bjork*, 1961; *Lubker*, 1968; *Fritzell*, 1969; *Bell-Berti and Hirose*, 1975; *Bell-Berti*, 1976]. Thus, the observation that there are variations in velar position during connected speech in some speakers with velopharyngeal incompetence [*Shprintzen* et

Table I. Correlation coefficients: velar elevation versus lateral pharyngeal wall displacement

fVCmVp	r	fVmCVp	r
fapmap	0.94	fampap	0.95
fabmap	0.93	fambap	0.97
fafmap	0.89	famfap	0.96
favmap	0.87	famvap	0.92
fasmap	0.89	famsap	0.98
fazmap	0.91	famzap	0.97
fipmip	0.94	fimpip	0.97
fibmip	0.96	fimbip	0.96
fifmip	0.93	fimfip	0.99
fivmip	0.96	fimvip	0.96
fismip	0.86	fimsip	0.95
fizmip	0.96	fimzip	0.96

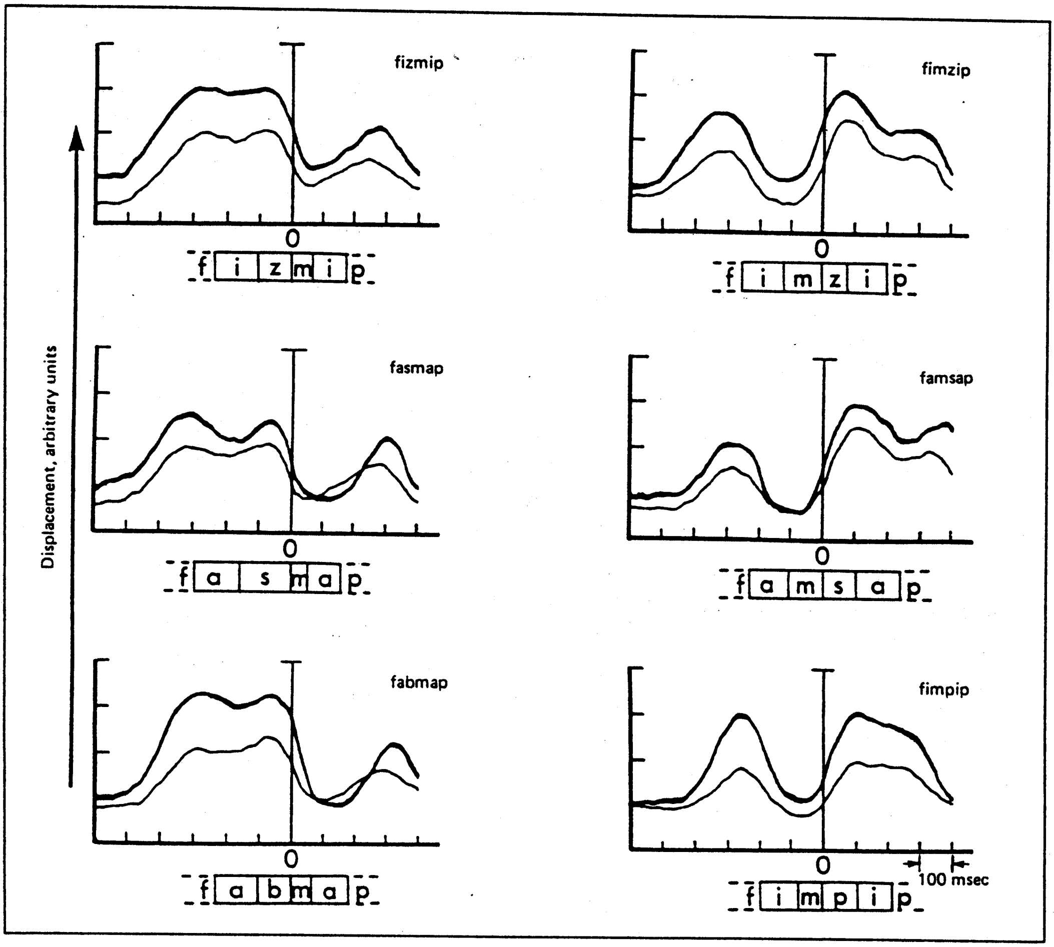


Fig. 3. Ensemble average time-course of velar (—) and lateral (—) wall displacement (50% level) for six utterance types. Zero on the abscissa represents the acoustic reference point for averaging. Displacement is in arbitrary units, with velar elevation and mesial lateral wall displacement increasing in the direction of the arrow at the left of the figure. Average audio segment durations are displayed beneath each graph.

al., 1977] should not necessarily be considered a pathological articulatory pattern: Such individuals may be using a normal articulatory strategy which fails because of anatomical defect.)

In order to quantify the temporal parallelism of lateral wall and velar movement, we have correlated averages as a function of time for the 24 utterances [*Kewley-Port,* 1973]. These values are shown in table I. The values range between $\underline{r} = 0.86$ and $\underline{r} = 0.99$; there are no obvious systematic, phonetically based trends in the $\underline{r}$ values.

The comparison of velar and lateral wall movement data for pairs differing only in vowel quality may give us some insight into

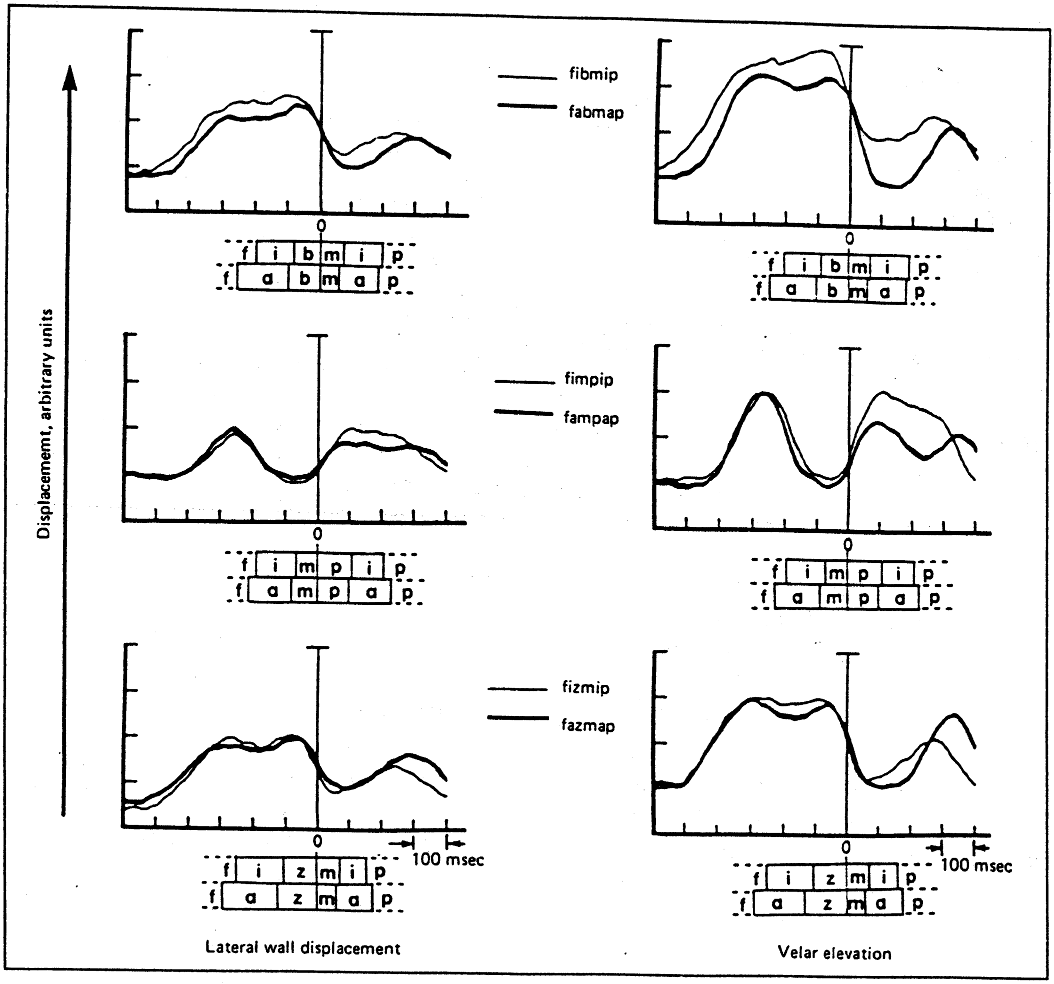


Fig. 4. Lateral wall displacement and velar elevation for three minimal pairs contrasting in vowel quality. Utterances with /i/ are represented by the thin line; utterances with /a/ are represented by the heavy line. Zero on the abscissa represents the acoustic reference point for averaging. Displacement is in arbitrary units, with velar elevation and mesial lateral wall displacement increasing in the direction of the arrow at the left of the figure. Average audio segment durations are displayed beneath each graph.

the muscular forces acting on the lateral wall. Measurements of lateral wall movement with ultrasound [*Kelsey* et al., 1969; *Minifie* et al., 1970] have shown that at levels on the pharyngeal walls below the hard palate, the walls move inward far more for /a/ than for /i/ to narrow the faucial isthmus. In a later study, *Zagzebski* [1975] suggested that the vowel differences were reduced or nonexistent for a probe 'approximately at the level of the hard palate' (p. 315).

The effect of vowel quality on velar eleva-

Table II. Sign test: comparison of velar and lateral pharyngeal wall positions for utterances minimally contrasting in vowel quality

	Velum	Lateral wall		Velum	Lateral wall
fipmip-fapmap	+	+	fimpip-fampap	+	+
fibmip-fabmap	+	+	fimbip-fambap	+	+
fifmip-fafmap	+	−	fimfip-famfap	+	+
fivmip-favmap	+	+	fimvip-famvap	+	+
fismip-fasmap	+	−[1]	fimsip-famsap	+	+
fizmip-fazmap	+	+	fimzip-famzap	+	+

Inspection was made at the time point corresponding to articulation of the vowel associated with the medial oral consonant. '+' indicates greater displacement for the utterance containing /i/; '−' indicates greater displacement for the utterance containing /a/.

[1] Maximum velar height exceeded the 50% level for some tokens, making impossible measurement of the lateral pharyngeal wall at that point. The average value for the /i/ utterances in these cases is depressed because of the removal from the average of those tokens having the greatest velar elevation.

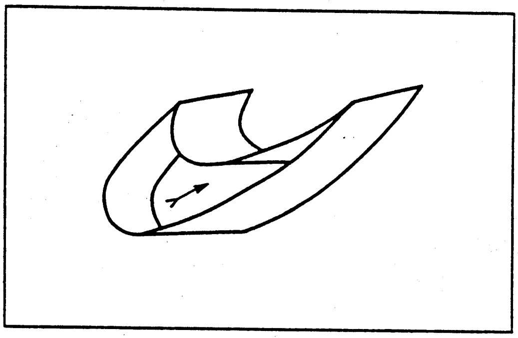
tion has been well documented, using various techniques over a hundred-year period [*Czermak,* 1869; *Subtelny* et al., 1961; *Lubker,* 1968; *Fritzell,* 1969; *Sawashima and Ushijima,* 1971; *Bell-Berti and Hirose,* 1975]. The velum is found to be higher for high vowels (such as /i/) than for low vowels (such as /a/). Results are shown in figure 4 for three utterance types. In general, our data reveal a small tendency for excursions to be greater both in velar elevation and in medial movement for /i/ than for /a/.

In order to make a rough quantitative estimate of the magnitude of the effect for all minimal pairs, we compared the curves at the point of the vowel associated with the medial oral consonant. The comparisons were tabulated as '+' or '−' in table II. In all 12 cases velar elevation was higher for /i/ than for /a/; lateral wall movement was greater for /i/ than for /a/ in 10 out of 12 cases. Hence, the data support the hypothesis that both velar elevation ($p < 0.0005$) and lateral wall movement ($p < 0.011$) are greater for /i/ than for /a/.

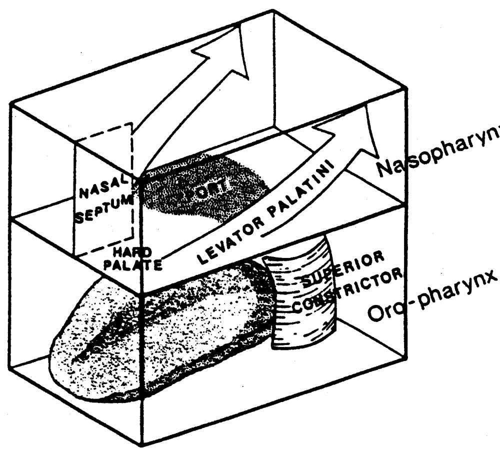
Discussion

There is general agreement that the velum is elevated and retracted primarily by the levator palatini muscle [*Lubker,* 1968; *Fritzell,* 1969; *Lubker* et al., 1970; *Bell-Berti,* 1976]. The point of controversy revolves around the putative role of other muscles in the velopharyngeal port region in bringing about movement of the lateral pharyngeal walls at various levels relative to the point of velopharyngeal closure. Essentially two points of view have been advanced.

The first of these views is that of *Skolnick* and his colleagues [*Skolnick,* 1970; *Skolnick* et al., 1973; *Shprintzen* et al., 1975; *Skolnick* et al., 1975]. On the basis of measurements of frontal and lateral videofluoroscopic films, *Skolnick* has suggested that the observed lateral pharyngeal wall movement toward the midsaggital line observed during speech cannot be due to the action of the levator palatini, because maximal medial excursion occurs below the level of the levator eminence on the nasal floor.



a



b

Fig. 5. a Schematic representation of the unitary action of the velum and lateral nasopharyngeal walls. **b** Drawing showing the anatomical relationships among the levator palatini, superior constrictor, and hard palate.

The second point of view is that of *Dickson* [1972, 1975; *Dickson and Dickson,* 1972], whose recent anatomical studies of the velopharyngeal region have shown that the superior margin of the superior constrictor muscle is at the level of the hard palate. Thus, while the superior constrictor might act in velopharyngeal closure, it can do so at, but no higher than, the level of the hard palate. The muscle in the lateral nasopharyngeal walls which might effect the medial displacement of the walls above the hard palate is the levator palatini, which runs infero-antero-medially from its origin on the Eustachian tube to its insertion in the velum (fig. 5). *Dickson* [1972] has proposed that maximum medial movement of the lateral walls, during speech, is at the level of the torus tubarius, and results from contraction of the levator palatini, which lies laterally to the torus. The *Dickson* argument excludes the superior constrictor from participation in displacing the lateral pharyngeal walls at the level of closure on two grounds: first, that the superior constrictor does not normally extend above the level of the hard palate, as we mentioned above; and, second, that there is no anteriorly directed movement of the posterior pharyngeal wall at any level during velopharyngeal closure for speech – a movement which would be expected since the constrictor attachment to the medial pharyngeal raphe is a very loose one. A third possibility does exist, however, although it has not been widely suggested. It is that velopharyngeal closure is accomplished by both sphincteric and trapdoor mechanisms, with the contribution of each differing among speakers.

EMG studies have shown that velar elevation and retraction are accomplished by contraction of the levator palatini muscle [*Lubker,* 1968; *Fritzell,* 1969; *Lubker* et al., 1970; *Bell-Berti,* 1973, 1976]. However, the contradictory reports of *Fritzell* [1969] and *Bell-Berti* [1973, 1976] on the role of the superior constrictor in velopharyngeal closure serve to illustrate the controversy over the nature of the closure mechanism: sphincteric, trapdoor, or, perhaps, a combination of the two.

EMG data reported elsewhere [*Bell-Berti,* 1973, 1976] on the activity patterns of the levator palatini, palatopharyngeus, and superior constrictor indicated that both the levator palatini and the palatopharyngeus are more active for consonant than for vowel articulations, although palatopharyngeus activity is highly influenced by vowel quality, so that palatopharyngeus is most active in low-vowel environments, helping to narrow the faucial isthmus for such vowels [*Bell-Berti,* 1973, 1976]. That finding amplifies *Fritzell's* [1969] earlier report that palatopharyngeus activity is most evident for the articulation of /a/. *Fritzell* [1969] and *Bell-Berti* [1973, 1976] have reported conflicting data from the superior constrictor, with the former reporting consonant-dependent activity and the latter reporting vowel-dependent activity, with the greatest EMG potentials recorded for the articulation of /a/. *Bell-Berti* [1973, 1976] also reported that the EMG potentials from the middle constrictor, recorded at the level of the tip of the epiglottis, mirrored those from the superior constrictor, recorded at the estimated level of velopharyngeal closure.

We believe that the levator palatini is the muscle primarily responsible for the medial movement of the lateral pharyngeal wall from the level of velopharyngeal closure (which varies with the type of phonetic segment produced) to the superior limit of that movement. That the interpretation that the levator palatini is responsible for both the lateral wall and velar movements is a valid one is supported by the data presented here, as well as by the data of other investigators, including *Harrington* [1944], *Skolnick* [1969], *Zagzebski* [1975], and *Honjo* et al. [1976], who have also described lateral pharyngeal wall movement, from the level of velopharyngeal closure upward, as paralleling velar movement. Since *Bell-Berti's* [1973, 1976] EMG data for this subject show different effects of phonetic environment on the levator palatini and superior constrictor, and the levator palatini data parallel the velar and lateral wall movement data, we believe that the weight of evidence supports the conclusion that this subject's mechanism is essentially trapdoor in nature.

The data of *Skolnick* et al. [1973] and of *Shprintzen* et al. [1974], which show the presence of a bulge in the lateral pharyngeal wall above the hard palate and below the levator eminence, might be an artifact of the videofluoroscopic focal plane: A vertical slice through an oblique ridge would look very much like a localized bulge (fig. 5b). In any case, in normal speakers having no history of anatomical or physiological anomaly, the ridge observed by *Skolnick* et al. [1973] and by *Shprintzen* et al. [1974] cannot result from action of the superior constrictor, simply because it is not present at that level. The question of whether this bulge is actually a point on the levator sling could be resolved using mutliplane tomography, a technique in which X-rays are taken simultaneously in multiple planes.

Finally, we must also expect some individual differences, even among normal speakers, and thus it may be that some speakers use the superior constrictor in addition to the levator palatini when they constrict the velopharyngeal port; in such speakers, the vertical dimension of the port should increase directly with velar elevation, since the lower level of closure will not shift its vertical position.

Zusammenfassung

In einer Untersuchung des normalen velopharyngalen Verschlussmechanismus wurden Filmaufnahmen des Velums und der lateralen Rachenwand gemacht. Dazu wurde ein flexibles Endoskop eingeführt, das die Beobachtung des Velums und der lateralen Rachenwand im Nasopharynx ermöglichte. Die Bild-für-Bild-Analyse des sich hebenden Velums und der Bewegung der Rachenwand während des Sprechens zeigte, dass drei Punkte auf der Rachenwand sehr ähnliche Bewegungsmuster hatten. Sie unterschieden sich mehr in der Stärke als im Zeitverlauf der Bewegung. Die Rachenwandbewegungen und die Velumbewegungen liefen parallel. Diese Beobachtung unterstützt die Hypothese, dass die beiden Bewegungen ihren Ursprung in einem einzigen Muskel haben, dem Levator palatini, und nicht in der kombinierten Aktion dieses Muskels und des oberen Schlundmuskels.

Résumé

Dans une étude des mécanismes normaux de la fermeture vélo-pharyngienne nous avons filmé le voile du palais et la paroi pharyngienne latérale. A cet effet un endoscope flexible a été introduit dans le nasopharynx de façon à permettre une vue simultanée du voile du palais et de la paroi pharyngienne latérale. L'élévation du palais et les mouvements de la paroi pharyngienne ont été mesurés image par image alors que le sujet parlait. Les mouvements de trois points de la paroi se faisaient selon sensiblement le même schéma, plutôt dans leur ampleur que dans leur évolution temporelle. Les mouvements de la paroi latérale étaient parallèles à ceux du voile du palais, ce que soutient l'hypothèse selon laquelle ces mouvements résultent de l'action d'un seul muscle, le levator palatini, et non de l'action combinée du levator palatini et des muscles constricteurs supérieurs.

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