AN ELECTROMYOGRAPHIC STUDY OF VELOPHARYNGEAL FUNCTION IN SPEECH

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Electromyographic (EMG) recordings were obtained from the levator palatini, superior pharyngeal constrictor, middle pharyngeal constrictor, palatoglossus, and palatopharyngeus muscles of three talkers of American English. Bipolar hooked-wire electrodes were used. Each subject read nonsense words composed of three vowels (/i, ɑ, u/), six stop consonants (/p, b, t, d, k, g/), and two nasal consonants (/m, ŋ/) to form various stop-nasal and nasal-stop contrasts. Multiple repetitions of each utterance type were recorded and subsequently processed by computer. The levator palatini was found to be the primary muscle of velopharyngeal closure for each of the subjects. The palatopharyngeus also showed consistent oralization activity for each of the subjects, although the activity of this muscle was strongly affected by vowel environment. Two subjects showed pharyngeal constrictor muscle activity related to oral articulation, but pharyngeal constrictor activity for the third subject was related to vowel quality. Nasal articulation was accomplished by suppression of oral articulation for each subject. Vowel quality affected the strength of EMG signals for lateral and posterior pharyngeal wall muscles. In those cases where activity was different for the three vowels, activity was greatest for /ɑ/.

Phonemes are a product of vocal tract modulation of the glottal airstream (Fant, 1970; Stevens and House, 1955; 1961). For oral segments, the tract may be viewed as a simple tube consisting of the pharynx and oral cavity, while for nasal segments it is a branched tube, with the nasal cavity coupled to the vocal tract below. Effective control of the coupling of the nasal cavity with the vocal tract is essential for production of intelligible speech.

The valving mechanism controlling the coupling and decoupling of these upper branches of the vocal tract is the velopharyngeal mechanism, and understanding how this mechanism functions for speech is necessary for a thorough description of normal speech production. An adequate description of velopharyngeal function requires knowledge of articulator movement patterns, the acoustic and perceptual consequences of different velopharyngeal port sizes, the motor commands to the muscles responsible for the movement patterns, and integration of data collected for each of these types of observation.

A basic question about velopharyngeal function is which muscles are responsible for closing and opening the velopharyngeal port. Studies of the motor commands to the muscles, in the form of electromyographic (EMG) recordings, are important to answering that question. By systematically varying the

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phonetic content of test utterances, we can also discover EMG concomitants of previously observed measurements of velar height and velopharyngeal port size.

In a cineradiographic-EMG study, Lubker (1968) reported variations in velar height to be highly correlated with EMG activity recorded from surface electrodes placed on the oral surface of the soft palate, and that both varied directly with tongue height. However, the utterance set was confined to four isolated steady state vowels, one nasal segment, and eight CV monosyllables, in which the consonant was either an oral or a nasal stop. Fritzell (1969) reported results of an EMG study in which recordings were made from electrodes inserted into the muscles of the velopharyngeal region: levator palatini, tensor palatini, superior pharyngeal constrictor, palatopharyngeus, and palatoglossus, for a varied, but asymmetrical, set of utterances. Although 26 subjects were used, only two muscles were sampled from each subject. Fritzell reported that: (1) levator palatini is the primary muscle used in achieving velopharyngeal closure and that the strength of its contraction varies directly with velar height; (2) superior pharyngeal constrictor activity parallels that of levator palatini; (3) palatopharyngeus activity for speech is inconsistent; (4) tensor palatini is not active for speech; and (5) palatoglossus activity occurs for nasal segments. Finally, Lubker, Fritzell, and Lindquist (1970) reported the results of an EMG study of levator palatini and palatoglossus function. EMG data were recorded from seven speakers with hooked-wire electrodes. The utterance set was a balanced list of minimally contrastive nonsense disyllables, including close and open vowels (/i/ and /ɑ/) and alveolar consonants. Data for only one speaker were presented. The authors proposed a "gate-pull" model of velopharyngeal function, with levator palatini acting to raise the soft palate (that is, close the gate) and palatoglossus acting, in the absence of levator palatini activity, to "pull" the palate down (that is, open the gate).

There are several problems with currently available EMG studies. Lubker's (1968) recordings were from surface electrodes and only from the soft palate, making it difficult to specify which muscles are acting in the palate, and whether other muscles in the velopharyngeal region are active in closing or opening gestures. The limited utterance set does not permit a description of the effect on velopharyngeal function of syllable final consonants, and of consonant clusters. Inspection of Fritzell's (1969) data reveals that palatoglossus activity most often accompanies vowel and consonant tongue movements, and not nasal gestures, except for the velar nasal, /ŋ/. The absence of an appropriately balanced utterance set makes impossible the comparison between oral consonant–nasal consonant and nasal consonant–oral consonant sequences necessary to discern the proposed reciprocity between levator palatini and palatoglossus activity. In addition, one may not, a priori, rule out the possibility of individual differences in velopharyngeal function and not all of the muscles were sampled in any one speaker. The primary problem with the Lubker et al. (1970) study is that the model presented is based on data from only one speaker and may be suspect in view of the doubts raised above about the Fritzell (1969) data, that is, the palatoglossus is not always active for palatal lowering.

The present experiment was undertaken in an attempt to resolve these problems, as well as to add information about the effects of the consonant features, place of articulation, and voicing on velopharyngeal function.

METHOD

Electrode Placement

The electrodes and the insertion techniques employed were those described by Hirose (1971). Hooked-wire electrodes were used. Insertions were made after an application of light topical anesthetic to the insertion site. Electrode and subject preparation are described at greater length in Bell-Berti (1973) and Hirose (1971).

Insertions to velopharyngeal muscles were always peroral, using an angulated needle, with the subject in a sitting position. Insertions and verification procedures are described below.

Levator Palatini. The insertion was made into the levator "dimple" on the soft palate while the subject sustained open vowel phonation. The tip of the needle was directed latero-cranio-posteriorly and inserted to a depth of approximately 10 mm from the surface of the mucosa. Verification of electrode placement was assumed from EMG activity noted when the subject produced /s/. Marked activity is observed for this gesture if the electrodes are properly placed.

Superior Pharyngeal Constrictor. The tip of the needle was directed cranially to reach the posterior pharyngeal wall at a position lateral to the midline at the estimated level of velopharyngeal closure. Since the superior constrictor is the only muscle at the insertion site, placement in muscle tissue was assumed to be verified if EMG activity was observed for swallowing.

Middle Pharyngeal Constrictor. The insertion was made using an angulated needle directed caudally into the posterior pharyngeal wall near the level of the tip of the epiglottis, while the subject's tongue was held in a protruded position to improve visualization of the insertion site. Because the pharyngeal constrictor muscles are interlayered in the transition from one to another, precise discrimination of the superior and middle constrictor fibers is impossible. Hence we examined, under the name *middle constrictor*, a topographical representation of the pharyngeal constrictor at the anatomical site described. Placement in muscle tissue was verified if EMG activity was observed for swallowing.

Palatoglossus. The palatoglossus was reached by inserting a needle craniocaudally or caudocranially into an anterior faucial pillar. Placement in muscle tissue was verified if marked EMG activity was observed during swallowing.

Palatopharyngeus. The palatopharyngeus was reached by inserting a needle craniocaudally into a posterior faucial pillar. Placement in muscle tissue was verified if EMG activity was observed for swallowing.

Experimental Utterances

Nonsense disyllables were constructed so that oral and nasal consonants followed each other. The utterances were also designed to investigate the effect of place of articulation of both oral and nasal phonemes (vowels and consonants) on the velopharyngeal mechanism. There were two subsets of test utterances, the first containing a medial stop nasal consonant contrast, the second containing a medial nasal stop consonant contrast.

Labial and velar nasal consonants were included, with the former occurring in both stop nasal and nasal stop contrasts and the latter only in nasal stop contrasts. The six English stop consonants were included, providing two voicing conditions and three places of articulation. Three vowels (/i, u, ɑ/) were included in the stimulus set, with the same vowel occurring in both syllables of each utterance. Each stop consonant was paired with the labial nasal consonant for the stop nasal contrasts and with both nasals for the nasal stop contrasts. In addition, each stop and nasal combination was paired with each of the three vowels. This resulted in 18 utterance types of the form /fVCmVp/ in the stop nasal subset (for example, /fipmip/, /fagmɑp/, /futmup/) and 36 utterance types of the form /FVNCVp/ in the nasal stop subset (for example, /fimkip/, /fŋdp/, /fumbup/).

In electromyographic investigations it is not advisable to attempt to inspect the EMG potentials of the utterance initial gesture because its timing and magnitude both may be affected by a readying of the articulators well before speech begins. Since we wished to study velopharyngeal activity for vowels, the vowel under study had to occur after another phoneme in the experimental utterances. The labial consonant /f/ was selected to give all the utterances an initial oral articulation which did not involve the tongue, and so therefore would minimize coarticulation effects in the following vowel. All of the utterances ended with /p/, a labial consonant, to avoid anticipatory lingual coarticulation effects, to control the length of the final vowel, and to insure a terminal oral articulation. The initial and final consonants were voiceless to facilitate the identification of the vowel onset and termination from an oscillographic record of the speech waveform used to obtain the measurements of segment duration appearing on the data displays below. Four randomizations of the 54 experimental utterances were read four times by each subject, providing 16 repetitions per subject of each utterance type for the subsequent analysis.

Subjects

Each of the three volunteer subjects in this study spoke a different dialect of American English, but was judged to be without speech defect and was trained to maintain stable list articulation. Each subject served twice. The two experimental sessions were separated by six months to one year. Hence, there was a total of six experimental sessions. During the first session an attempt was made to record from each muscle included in the experiment. The second experimental session was used to obtain satisfactory recordings from muscles whose earlier data were unsatisfactory, and to duplicate data from as many muscles as there were remaining recording channels. Thus at least one good recording was obtained from each muscle for each subject. For those cases in which duplicate recordings were made, the patterns, but not the absolute levels of EMG activity were quite similar for the two sessions.

Data Collection and Processing. Data were collected and processed using the system described by Port (1971) and Kewley-Port (1973). The electrodes were connected to differential preamplifiers whose signals were fed to distribution amplifiers having 80-Hz high-pass filters with 24-dB roll-off. The low-frequency filtering was intended to reject noise and movement artifacts. The signals were FM tape recorded on one-inch tape using a 14-channel instrumentation recorder. The subject's speech was recorded with an air microphone, and appropriate clock and code pulses for data processing were recorded as AM signals.

The recorded signals were played back through the distribution amplifiers and routed through a section of the 80-Hz high-pass filter, resulting in 36-dB total roll-off. The overall frequency response of the system was flat between 80 to 1250 Hz, with a signal-to-noise ratio of about 40 dB for the FM channels.

The electromyographic voice and code tracks were input to an 18-channel visicorder whose oscillographic records were used for visual editing of the signals and determining the segment durations of the vowels and medial consonants of the experimental utterances. The point in the audiosignal selected for lining up the utterances for computer sampling and averaging was the beginning of the acoustic signal for /m/ in the stop nasal utterances, and the end of the acoustic signal for /m/ and /ŋ/ in the nasal stop utterances. In subsequent figures, this point is always referred to as time zero.

The EMG data tape was played back on the 14-channel tape recorder under computer control. The analog EMG signals were full wave rectified and passed through a resistance capacitance (RC) circuit that performed a running integration at a time constant of 22 msec. The signals were sampled at 5 msec intervals. The stored digital sample values were converted to microvolt values by comparison with the 300 μv calibration signal. The conversion factors were calculated and stored on the digital tape along with the digital sample values for the experiment. The sums and sums of squares for each utterance type were computed and stored on the digital tape. Means were calculated and printed for the 5 msec intervals at which the analog data were sampled.

RESULTS

Levator Palatini

Inspection of the averaged EMG potentials recorded from the levator palatini muscle of each of the three subjects in this study revealed a peak of activity associated with the articulation of the initial consonant /f/ of each utterance in the region of −600 to −500 msec (see Figure 1). The data reveal

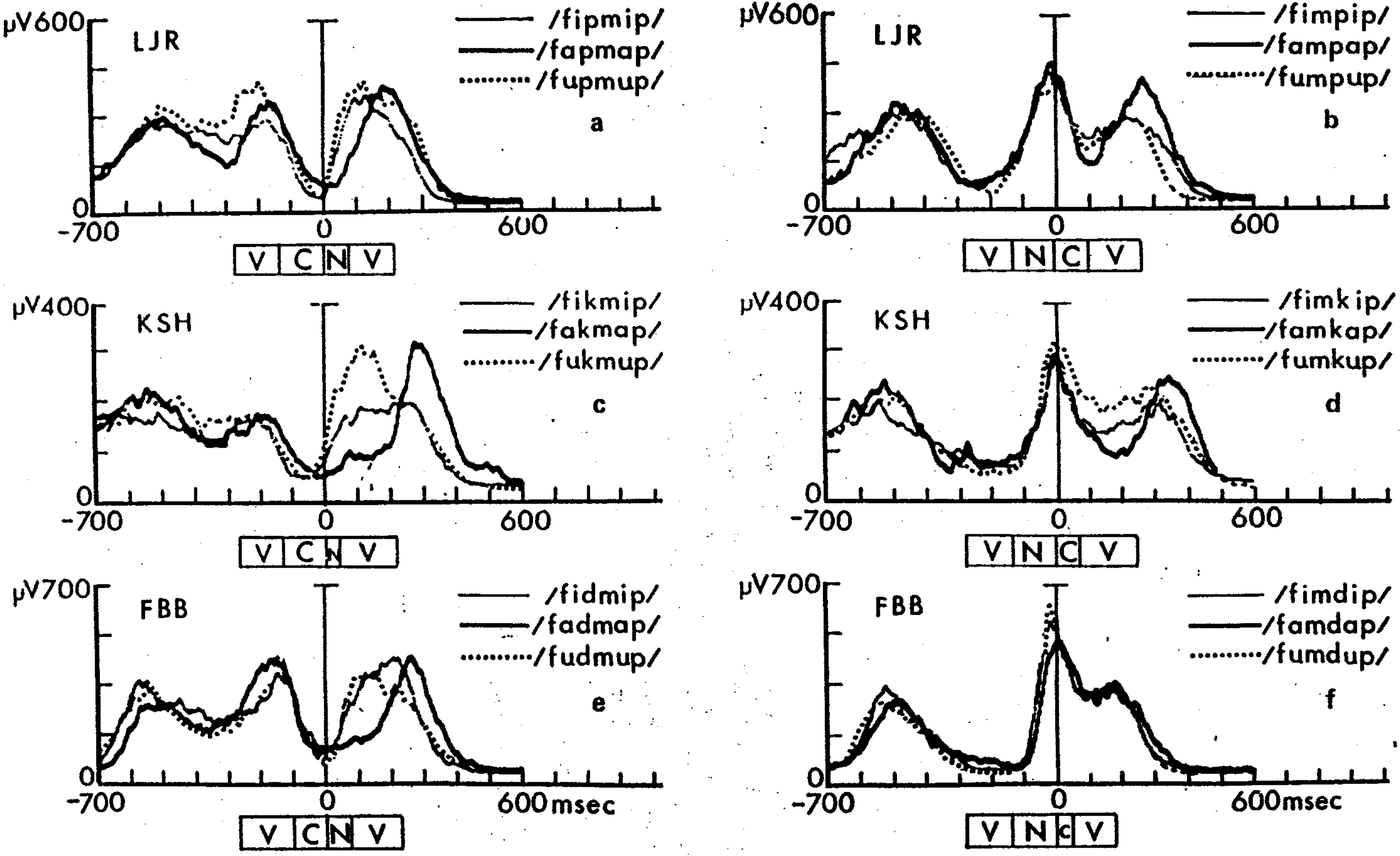

Figure 1. Representative examples of levator palatini activity for all subjects for all vowel conditions for both stop nasal and nasal stop utterance types. Average acoustic segment durations are indicated: V, vowel segments; C, stop segments; and N, nasal segments.

two basic EMG activity patterns, one for the 18 stop nasal contrast utterances, another for the 36 nasal stop contrast utterances.

In the stop nasal contrasts, a second peak of activity corresponding to stop consonant articulation occurred between −200 and −150 msec. This burst of activity was followed by reduction of levator palatini activity, which reached a minimum near 0 msec, the point corresponding to the onset of nasal consonant articulation. There was a subsequent increase in levator activity in all utterances although the point of onset of the increase varies with the height of the vowel following the nasal consonant: the increased activity begins earlier for the high vowels /i/ and /u/ than for the low vowel /ɑ/ (Figure 1a, c, e). The place of articulation does not appear to have any systematic effect on the peak EMG level achieved for oral stop consonant articulation (Figure 2a; Table 1).

In nasal stop utterances the initial peak at −500 msec was followed by a steady decline in EMG activity to a minimum level at about −200. This minimum was followed by a steep increase in the EMG activity, reaching a maximum at 0 msec, the point corresponding to the beginning of stop closure

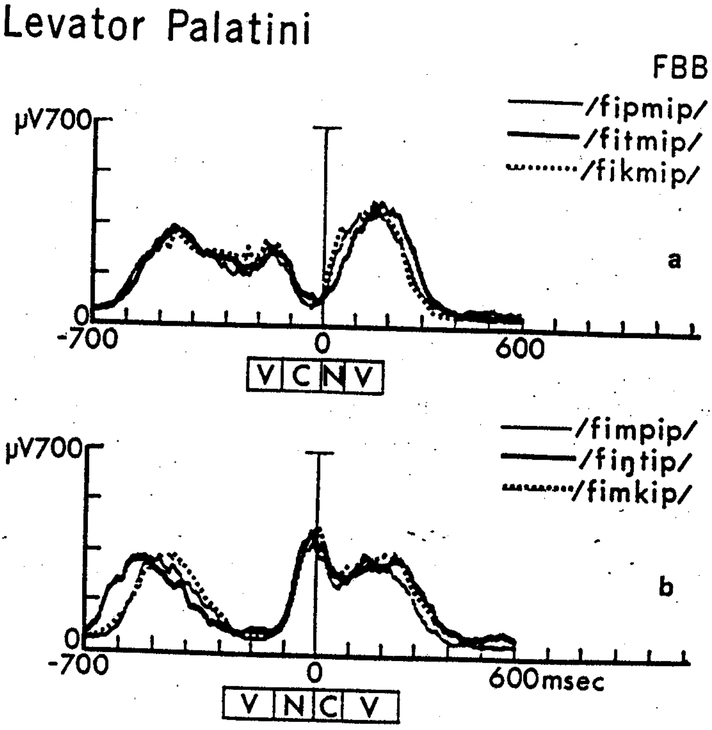

Figure 2. Representative examples of levator palatini activity for one subject (FBB), showing activity for different places of consonant articulation. Average acoustic segment durations are indicated: V, vowel segments; C, stop segments; and N, nasal segments.

TABLE 1. Peak EMG values (in microvolts) from the levator palatini for the medial oral consonant in stop nasal and nasal stop contrasts. Peaks are inspected to see if those in nasal stop contrasts are greater than peaks in stop nasal contrasts.

Subject	*FBB*			*KSH*			*LJR*		
Vowel *Contrast*	i	ɑ	u	i	ɑ	u	i	ɑ	u
pm	300	410	326	174	224	167	300	351	406
mp	392	445	396	326	306	407	431	458	406*
ŋp	374	394*	414	383	326	383	457	431	406*
tm	284	305	286	175	248	155	261	230	370
mt	448	355	514	337	325	364	458	456	494
ŋt	429	433	467	300	287	333	444	389	421
km	316	350	264	173	176	182	406	442	419
mk	449	424	493	288	292	322	472	485	523
ŋk	417	449	437	309	276	285	470	431*	432
bm	323	476	339	160	204	213	353	335	363
mb	565	531	660	332	363	337	464	357	477
ŋb	466	541	512	328	392	400	384	353	397
dm	402	443	460	187	286	248	345	346	286
md	573	496	629	340	384	317	464	362	528
ŋd	443	533	493	345	327	339	368	335*	328
gm	266	364	200	162	258	205	343	321	352
mg	517	496	580	307	302	314	472	372	492
ŋg	496	484	546	315	315	357	423	374	375

*Failing contrasts.

(Figure 1b, d, f). The timing of the levator palatini suppression was unaffected by the place of the consonant articulation and the magnitude of the oral consonant activity burst was unaffected by the place of articulation of either the nasal or the stop consonant (Figure 2b; Table 1).

The highest microvolt value for the medial oral stop for each utterance for each subject is tabulated in Table 1. Peak activity for stop consonants preceding nasal consonants (for example, /fɑpmɑp/) was usually lower than peak activity for stop consonants following nasal consonants (for example, /fɑmpɑp/). This pattern was not dependent on the place of the stop consonant occlusion—all failures occurred in the environment of back vowels. This result is not surprising since when a stop follows a nasal consonant the palate must be moved through a greater distance than when the stop follows a vowel. Hence, the EMG values for stop consonants should be greater for stops following nasals than for stops following vowels (Berti and Hirose, 1972).

We noted previously that when a vowel followed a nasal consonant there was a difference in the timing of the increase in EMG activity that depended on vowel quality: the EMG activity increase began earlier when the vowel was /i/ or /u/ than when the vowel was /ɑ/ (Figure 1a, c, e). When these vowels occurred between oral consonants they showed different EMG activity levels, with /i/ and /u/ having higher potentials than /ɑ/.

Superior Pharyngeal Constrictor

Recordings from the superior constrictor generally were of low amplitude for two subjects, LJR and KSH, and failed to reach a maximum peak value of 100 μv. Both of these subjects had peaks of activity corresponding to oral consonant production (Figure 3a, b). The third subject, FBB had peak values greater than 250 μv with activity corresponding to the vowel articulations (Figure 3c). The data in Figure 3 separate depending upon the vowel: the peaks were largest for /ɑ/ and smallest for /u/. The /i/ curve was lower than the /ɑ/ curve.

Middle Pharyngeal Constrictor

The EMG recordings obtained from middle constrictor electrode placements paralleled those obtained from the superior constrictor placements. Middle constrictor recordings were of low amplitude for all subjects with a maximum peak of 130 μv. Again, two subjects, LJR and KSH, had small peaks of activity for oral consonants (Figure 4a, b), although the third subject, FBB had activity for vowels (Figure 4c). Subject FBB showed clear peak separation, with changes in the vowel exhibiting the same activity pattern in the middle constrictor as in the superior constrictor.

Palatoglossus

Palatoglossus activity for Subject LJR appeared to be related to the place and not to the manner of consonant articulation. For example, in Figure 5a, peaks of palatoglossus activity were seen at −200 msec for /fukmup/ and /fuŋpup/, and at −50 msec for /fumkup/. That is, the palatoglossus peak occurred earlier in utterances in which a velar consonant preceded a labial consonant than in utterances in which the velar followed a labial. The palatoglossus peak was associated with linguavelar articulation rather than with nasal articulation in this subject.

Palatoglossus activity appeared to be related primarily to vowel quality for subjects FBB and KSH: the minimum points in the EMG curves were between −100 and 0 msec for both the stop nasal and the nasal stop utterances. For both subjects, while the differences in peak size were small, the largest and most consistent peaks occurred for /ɑ/ (Figure 5b, c). The data of Subject FBB included several averaged potential curves in which palatoglossus activity was of equal magnitude for /i/ and /u/, but /u/ was generally of greater amplitude than /i/ if they were different (Figure 5b). Subject KSH showed some activity for /i/ and /u/. This activity was either of equal magnitude or was greater for /i/ than /u/ (Figure 5c). Subject KSH tended to have peaks of greatest magnitude associated with velar stop production (Figure 5d).

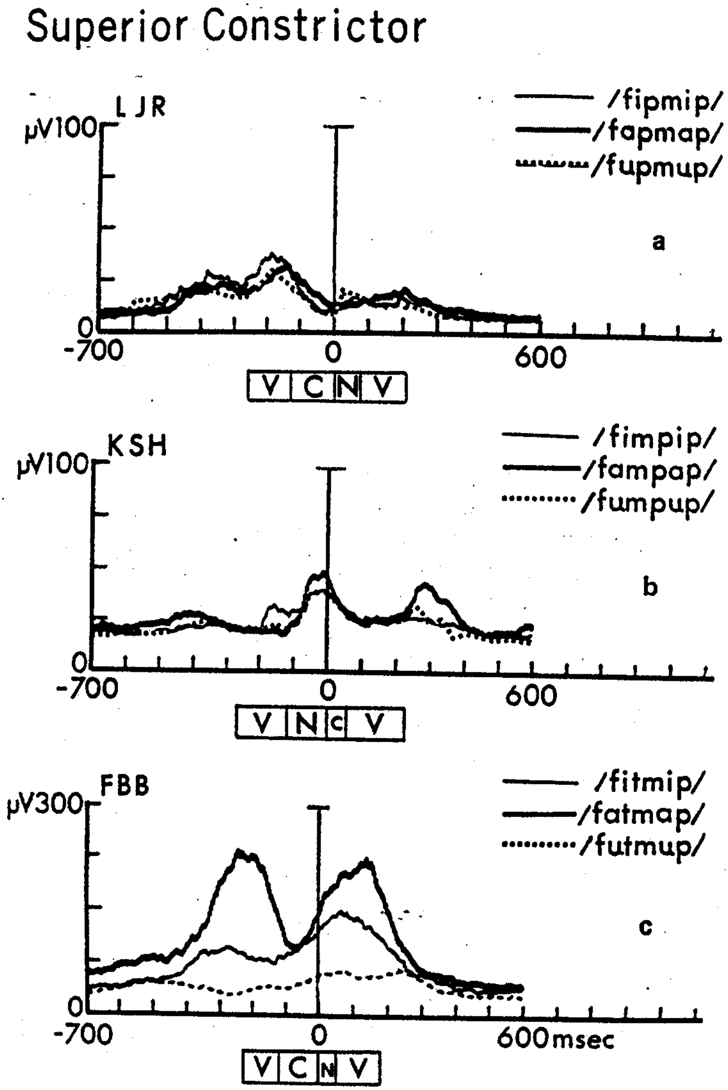

FIGURE 3. Representative examples of superior constrictor activity for all subjects. Average acoustic segment durations are indicated: V, vowel segments; C, stop segments; and N, nasal segments.

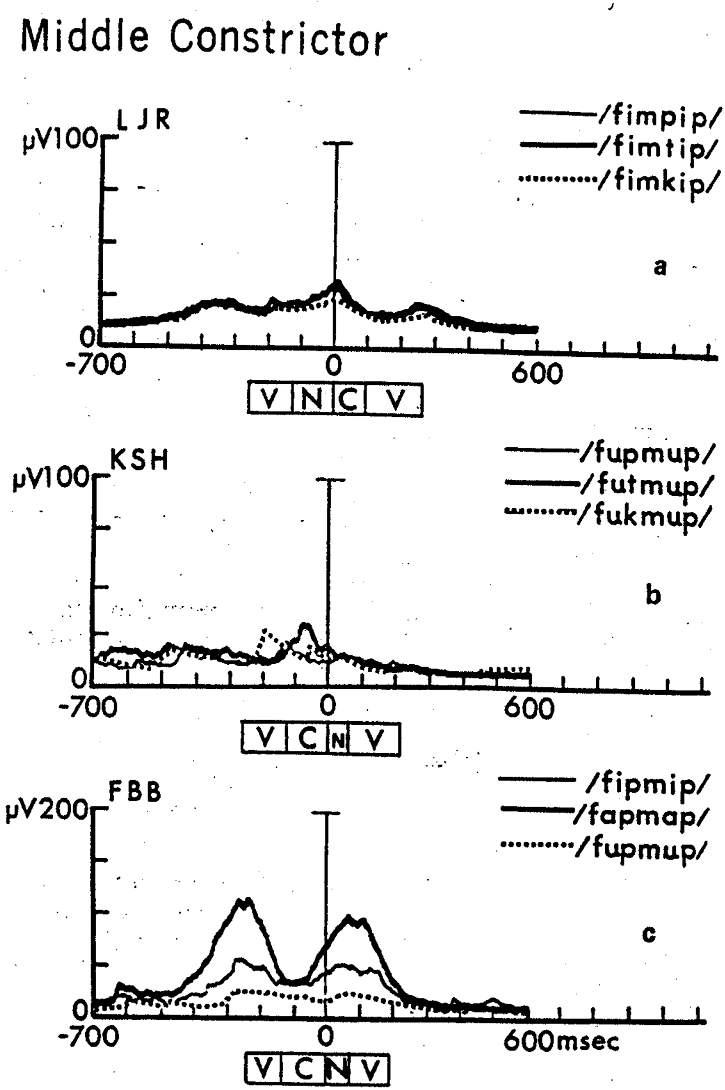

FIGURE 4. Representative examples of middle constrictor activity for all subjects. Average acoustic segment durations are indicated: V, vowel segments; C, stop segments; and N, nasal segments.

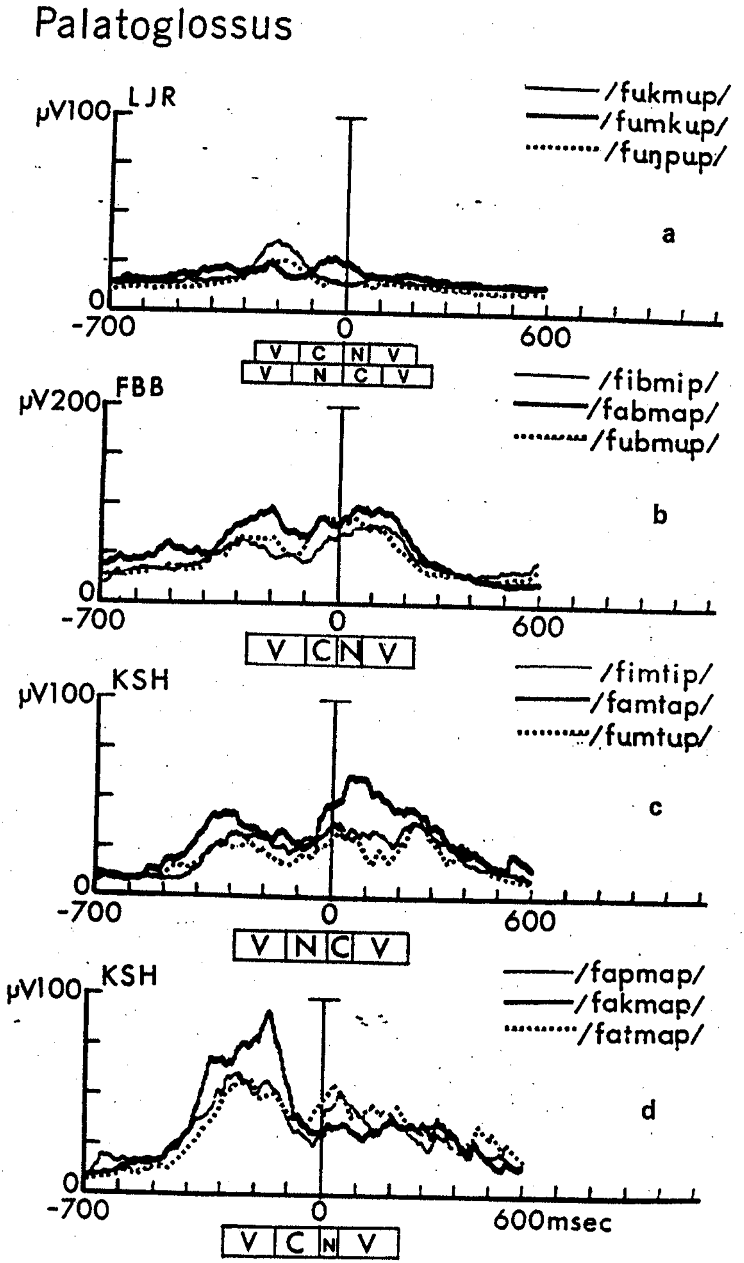

FIGURE 5. Representative examples of palatoglossus activity for all subjects. Average acoustic segment durations are indicated: V, vowel segments; C, stop segments; and N, nasal segments.

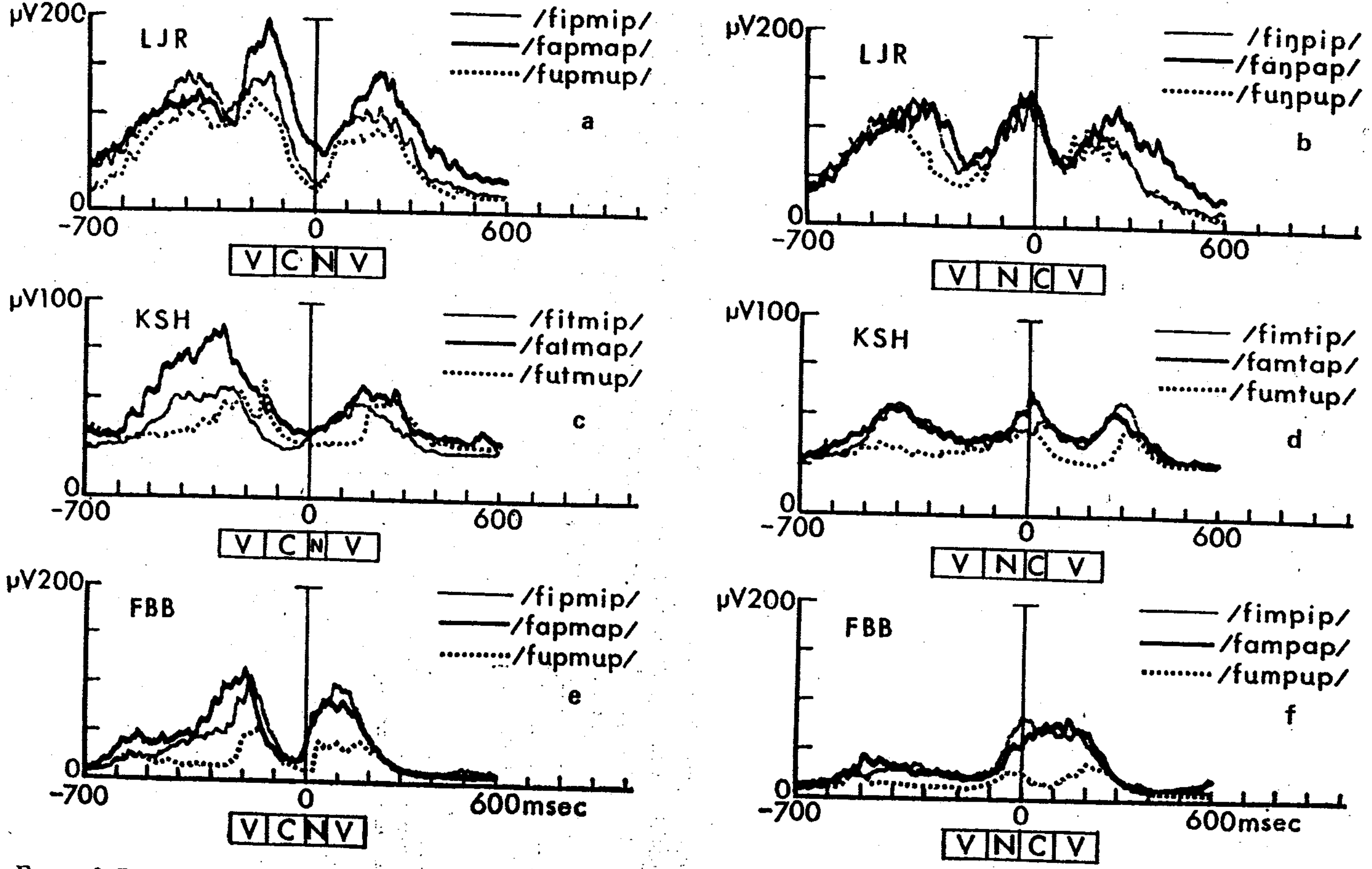

FIGURE 6. Representative examples of palatopharyngeus activity for all subjects for all vowel conditions for both stop nasal and nasal stop utterance types. Average acoustic segment durations are indicated: V, vowel segments; C, stop segments; and N, nasal segments.

Palatopharyngeus

All three subjects had patterns of palatopharyngeus activity associated with oral articulation (Figure 6), with the patterns generally paralleling those of the levator palatini. There was a peak of activity between −200 and −100 msec for stop nasal contrast utterances (Figure 6a, c, e) followed by suppression of activity reaching a minimum at, or just before, 0 msec. Inspection of the nasal stop contrast utterances (Figure 6b, d, f) reveals peaks of activity near −400 msec, 0 msec, and near +300 msec, with a minimum near −200 msec. Palatopharyngeus activity levels were somewhat more affected by vowel quality than were those of the levator palatini, for all three subjects, with /ɑ/ generally displaying the greatest potential amplitude. In all cases, /u/ had the lowest EMG potentials of the three vowels.

DISCUSSION

The results of this study confirmed those of Fritzell (1969) in revealing the levator palatini as the primary muscle of velopharyngeal closure. However, Fritzell's description of superior constrictor, palatopharyngeus, and palatoglossus function were not confirmed. Velopharyngeal closure was achieved by raising and retracting the soft palate with the levator palatini, and possibly additional narrowing in the region of the port by contraction of palatopharyngeus. However, this latter action was highly dependent on vowel quality, being much greater for open vowels than for close vowels. Contrary to Fritzell's results, the superior constrictor (and the middle constrictor, which was not included in Fritzell's study) contributed relatively little to closure, and then not for each speaker; it was strongly active only for vowel production, being more active for open than for close vowels, as was palatopharyngeus. The palatoglossus was found to be active for tongue body movements and

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[1] After the experiment reported here was completed, we had an opportunity to hold an additional experimental session in which the subject was a native speaker of Swedish. The experiment was not a part of the design of this investigation which dealt only with speakers of American English and addressed itself to a broader series of questions than did the experiment was not a part of the design of this investigation which dealt only with speakers subject whose data were reported in detail by Lubker et al. (1970), and the results correspond to their reported findings. EMG recordings were obtained from the palatoglossus and levator palatini muscles of the subject. The data were obtained and processed using the EMG system described above. The 36 stimuli used were a subset of the stimuli of this larger experiment involving both stop nasal and nasal stop contrasts, three places of stop articulation, one stop consonant voicing condition, and labial and velar nasals. In addition, nine stimuli were added to the nasal stop group in which the nasal was alveolar. The subject BG showed peaks of palatoglossus activity corresponding to nasal consonant articulation. However, he also showed peaks of palatoglossus activity corresponding to velar stop articulation and /u/ and /ɑ/ production. The palatoglossus activity was of greatest magnitude for /ɑ/. Palatoglossus activity was greater for velar nasals than for labial or alveolar nasals. Based on the results of the experiment with the Swedish speaker, we cannot tell whether the difference in function of the palatoglossus is one of intersubject anatomical variation or idiosyncratic behavior. In either case, Fritzell's hypothesis of a universal nasal mechanism, paralleling a universal oral mechanism, can be rejected since not all speakers use it.

pharyngeal narrowing and not for palatal lowering, as Fritzell reported. The picture of the mechanism that emerged from these data was closure achieved essentially by raising and retracting the soft palate with levator palatini. Other muscles of the region were primarily active for the pharyngeal cavity adjustments that accompany differences in vowel quality, that is, narrowing the pharynx for open vowels. Opening of the velopharyngeal port was accomplished by suppressing activity in levator palatini and any other muscles that may have been contributing to closure. Opening of the port results from the natural tendency of tissue to return to its rest position, and not from increased activity in any muscle.[1]

The study supports the reports of Lubker (1968), Fritzell (1969), and Lubker et al. (1970), that the velopharyngeal closure mechanism is not a binary, on/off one, since the strength of the EMG potentials recorded from levator palatini varied as a function of the identity of the segment produced and its phonetic environment. Inspecting levator palatini EMG potentials for oral phonetic segments in minimally contrastive utterance types, we observed that they were greater for close vowels than for open vowels, and greater for stop consonants than for close vowels. Or as Lubker (1968) suggested, levator palatini activity for oral segments varies directly as a function of oral cavity constriction. Since the strength of levator palatini EMG potentials in the same phonetic environment is highly correlated with velar height (Bell-Berti and Hirose, 1975; Fritzell, 1969), and velar height is highly correlated with velopharyngeal port area (Ushijima and Sawashima, 1972), we might conclude that the area of the velopharyngeal port varies directly as a function of oral cavity constriction for oral segment production.

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