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Palatoglossus Activity during Nasal/Nonnasal Vowels of Hindi

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Abstract. Prior electromyographic (EMG) research reveals a lack of agreement as to the role of the palatoglossus muscle in speech. Some reports have concluded that it bears primary responsibility for lowering the velum and that it actively controls velar lowering on nasal sounds in speech, whereas others have concluded that it acts to assist in the tongue-body movements associated with the production of back vowels and linguavelar articulations. To clarify these conflicting claims, EMG recordings were obtained from the palatoglossus (as well as the levator palatini) muscle of a native speaker of Hindi who produced CVC nonsense and meaningful syllables containing a nasal or nonnasal vowel in a symmetric consonantal environment. The results showed the following: Palatoglossus activity for the central and back nasal and nonnasal vowels was moderately to considerably higher than for the front nasal and nonnasal vowels. The levels of palatoglossus activity for the back rounded nasal vowels and for the front nasal vowel /ɛ/ were comparable to those for the corresponding nonnasal vowels, while in all other vowels, the nasal vowels exhibited relatively higher levels of palatoglossus activity than their nonnasal counterparts. In all nonnasal vowels, the increase in palatoglossus activity occurred simultaneously with strong levator palatini activity. On the other hand, in nasal vowels, the increase in palatoglossus activity and the decrease in levator palatini activity were virtually synchronous for the front nasal vowels, while the increase in palatoglossus activity began much earlier than the decline in levator palatini activity for the central and back nasal vowels. This difference in temporal relationship between palatoglossus activation and levator suppression for different vowel types is important since it unambiguously supports the 'gate-pull' model (that is, active velar lowering) for the production of front nasal vowels whereas in the case of central and back vowels, nasal and nonnasal, the palatoglossus appears to be primarily involved in moving the tongue-body.

Introduction

Since the palatoglossus (PG) muscle extends from the oral surface of the velum inferiorly and anteriorly into the sides of the tongue (forming the muscular portion of the anterior faucial pillars), it has potential for lowering the velum, raising and retracting the tongue-body, approximating the tongue dorsum and the velum, and narrowing the passageway between the left and right pillars of the fauces. Various potential modes of PG activity are, however, highly dependent on what other muscles of the velopharyngeal region may be doing, particularly the levator palatini (LP) muscle, which has been shown consistently to be the primary elevator and fixator of the velum.

Although the palatopharyngeus muscle, like the PG muscle, has the potential to lower the velum, it has not been shown to be active during nasal sound production. It has, rather, been found to be active during oral articulations [Fritzell, 1969; Bell-Berti, 1973, 1976; Seaver and Kuehn, 1980; Kuehn et al., 1982].

Accordingly, four different modes of PG activity have been suggested [Lubker and May, 1973; Lubker, 1975]. First, if the velum is fixed by the contracting LP muscle, then the PG may assist in tongue-body movements. Second, if in addition to the velum being fixed, the tongue-body position is also fixed, then the PG may narrow the faucial isthmus. Third, if the tongue is free to move while the velum is fixed, and if the tongue moves downward and/or forward, then the PG may act antagonistically to the muscle(s) producing those tongue-body movements or may act reflexively against the stretching of the anterior faucial pillars (and, thus, the PG itself). Finally, if the LP is relaxing or relaxed, then the PG may lower the velum.

In recent years, several electromyographic (EMG) experiments [Fritzell, 1969; Lubker et al., 1970; Lubker et al., 1972; Bell-Berti and Hirose, 1973; Bell-Berti, 1973, 1976; Benguerel et al., 1977; Seaver and Kuehn, 1980] have been performed to investigate which of the various anatomically possible roles are actually assumed by the PG muscle during speech. The data collected in these experiments appear to be consistent, in that they generally show close association of PG activity with movements of the tongue-body related to the production of velar consonants and back oral vowels. With respect to velum lowering for nasal sounds, however, these data have yielded conflicting results. Fritzell [1969] and Lubker et al. [1970, 1972], for English and Swedish, respectively, reported strong evidence of PG activity associated with lowering of the velum for nasal consonants, suggesting that the velum is actively lowered to open the velopharyngeal port for the production of nasal sounds. This evidence provides the basis for the 'gate-pull' model of nasal sound production, which proposes that '... the levator may relax its activity in an almost gate-like fashion, thus allowing a temporal space during which the palate is easily lowered. At some point in time during the "open" phase of the gate – or during the very early opening phase of it, a slight "pull" is provided by the palatoglossus to facilitate the ease and rapidity of palatal lowering. During this "gating" and "pulling" process the articulators function for the actual production of the nasal phoneme' [Lubker et al., 1972, p. 235].

On the other hand, Bell-Berti [1973, 1976] did not find a relationship between

PG activity and velum lowering for nasal consonants in English, with the exception of the velar nasal. Furthermore, in extensive PG data obtained from 3 subjects, only one showed PG activity for the velar nasal consonant. It was suggested that even in this subject the PG activity was 'associated with linguavelar articulation rather than nasal articulation' [Bell-Berti, 1976]. In another study, Bell-Berti and Hirose [1973] obtained palatoglossus EMG data from 1 speaker of English and 1 speaker of swedish. The Swedish speaker of their study was the same speaker whose data were reported in Lubker et al. [1970, 1972]. The data from the Swedish speaker, as expected, did show a positive relationship between PG activity and velum lowering, but the data from the English speaker did not. (Both English and Swedish speakers, however, showed PG activity associated with linguavelar articulations.) Thus, they concluded that '...while palatoglossus function for nasal articulation may exist for speakers of some languages, this function does not occur for all speakers of all languages' [Bell-Berti and Hirose, 1973; p. 204], which casts serious doubt about the universality of the 'gate-pull' model of nasal sound production.

Unlike English and Swedish, where nasality is contrastive only in consonants, in French it is contrastive in both consonants and vowels. The data from a French speaker reported by Benguerel et al. [1977] contained examples of nasal vowels as well as nasal consonants. Their data revealed strong evidence of a relationship between PG activity and velum lowering for the nasal vowels but not for the nasal consonants. They suggested different modes of velar control of nasality in nasal vowels vis-à-vis nasal consonants in French. (A more de- 1963; Fairbanks and Misra, 1966; McGregor, 1972; Ohala, 1983]. However, the short vowels /ɩ̃, ɩ, ə̃, ə, ʊ̃, ʊ/ are not only short but also qualitatively different from their long counterparts /ĩ, i, ɑ̃, ɑ, ũ, u/ [Dixit, 1963; Kelkar, 1968]. The short/long vowels have also been described as lax/tense [Kelkar, 1968]. Further, the long vowels /ɛ/ and /ɔ/ are monophthongal in the western dialect of Hindi, while in the eastern dialect of Hindi their pronunciation is diphthongal, similar to that of [əɩ ~ əe] and [əʊ ~ əo], respectively. This is also true of their nasal counterparts /ɛ̃/ and /ɔ̃/. In the western dialect of Hindi, moreover, the nasal vowels ẽ and õ (enclosed by parentheses in table I) have merged with the nasal vowels /ɛ̃/ and /ɔ̃/, respectively [Dixit, 1963; Chaturvedi, 1973]. Thus, the western dialect of Hindi has 18 vowels in all: 8 nasal vowels and 10 nonnasal vowels.

Table I. The nasal and nonnasal (oral) vowels of Hindi

ĩ		ũ	i		u
ɩ̃		ʊ̃	ɩ		ʊ
(ẽ)		(õ)	e		o
ɛ̃	ə̃	ɔ̃	ɛ	ə	ɔ
		ɑ̃			ɑ

Traditionally, Hindi has been described as possessing 10 nasal vowels and 10 nonnasal vowels [Guru, 1920, pp. 28, 35–38; Sharma, 1958, pp. 2–4] shown in table I. Comparable vowels in the two sets are said to be produced with similar tongue and lip positions. Recent studies of Hindi [Dixit, 1963; Fairbanks and Misra, 1966; Kelkar, 1968; McGregor, 1972; Chaturvedi, 1973; Ohala, 1983] have either provided tables of

Hindi vowels similar to table I, or have given descriptions of Hindi vowels that generally reflect the articulatory dimensions (such as high–low, front–back, rounded–unrounded) frequently used in formulating such tables.

The terms related to vowel height as used in the present study indicate kinesthetically determined tongue heights which have been traditionally associated with the production of various vowels. Since there are no X-ray data available on Hindi vowels, the propriety of use of tongue-height-related terms in the description of Hindi vowels, unfortunately, cannot be tested. There is, however, some palatographic [Qadri, 1930, pp. 50, 51 and 54] and acoustic [Dixit, 1963, pp. 52 and 54] evidence from which gross tongue heights for Hindi vowels can be inferred. Qadri [1930] has shown that the areas of contact between the sides of the tongue and the alveolar processes of the maxilla progressively increase and proceed forward as the tongue-body moves from /æ to /e/ to /ɩ/ to /i/ position. On the other hand, such areas of contact shown for the back vowels /ɷ/ and /u/ are small and similar. Since the posterior boundary of a false palate falls close to the third molar teeth (wisdom teeth) it can provide only partial information with respect to the contact areas for the vowels /ɷ/ and /u/. Apparently, no contact between the sides of the tongue and the alveolar processes of the maxilla is made for any other back vowels. In Dixit's [1963] formant frequency data, F_1 frequency progressively increases (in steps) from /i/ to /ɩ/ to /e/ to /ɛ, ə/ to /ɑ/ and progressively decreases (in steps) from /ɑ/ to /ɔ/ to /o/ to /ɷ/ to /u/. F_1 frequency of vowels is widely accepted to be inversely related to tongue height or directly related to vocal tract openness. These data, thus, suggest a higher tongue position for /i/ and /u/ than for /ɩ/ and /ɷ/ in high vowels, a higher tongue position for /e/ and /o/ than for /ɛ/ and /ɔ/ in mid vowels, and a low tongue position for /ɑ/ vowel. Tongue position for /ə/ would be expected to be similar to that for /ɛ/ and /ɔ/. We cannot be certain, however, that these above inferences will turn out to be true.

Except for the vowels /ɩ̃, ɩ, ə̃, ə, ɷ̃, ɷ/, all other vowels in the two sets are long phonetically as well as phonologically [Dixit, 1963; Fairbanks and Misra, 1966; McGregor, 1972; Ohala, 1983]. However, the short vowels /ɩ̃, ɩ, ə̃, ə, ɷ̃, ɷ/ are not only short but also qualitatively different from their long counterparts /ĩ, i, ɑ̃, ɑ, ũ, u/ [Dixit, 1963; Kelkar, 1968]. The short/long vowels have also been described as lax/tense [Kelkar, 1968]. Further, the long vowels /ɛ/ and /ɔ/ are monophthongal in the western dialect of Hindi, while in the eastern dialect of Hindi their pronunciation is diphthongal, similar to that of [əɩ ~ əe] and [əɷ ~ əo], respectively. This is also true of their nasal counterparts /ɛ̃/ and /ɔ̃/. In the western dialect of Hindi, moreover, the nasal vowels ẽ and õ (enclosed by parentheses in table I) have merged with the nasal vowels /ɛ̃/ and /ɔ̃/, respectively [Dixit, 1963; Chaturvedi, 1973]. Thus, the western dialect of Hindi has 18 vowels in all: 8 nasal vowels and 10 nonnasal vowels.

Method

The subject (R.P.D.) for the present study is from western Uttar Pradesh in India. He is a native speaker of the western dialect of standard Hindi, and has no history of speech or voice pathology. Although at the time of this study he had lived in the United States for about 20 years, he regularly spoke Hindi at home and with his Hindi-speaking friends.

The speech samples consisted of CVC syllables where C was the voiceless alveolar fricative /s/ and V was one of the 18 vowels indicated above. Thus, the syllables used in the present study were of the form /sɑ̃s/ 'breath', /sas/ 'mother-in-law', /sus/ 'porpoise'. Except for these three syllables, which were meaningful words, all other syllables were nonsense syllables.

Conventional bipolar hooked-wire electrodes were inserted perorally into the PG and LP muscles. EMG recordings were obtained from the LP muscle since they are required for appropriate interpretation of PG muscle data. These LP EMG data are reported elsewhere [Dixit et al., 1985]. For the PG muscle, the electrode was inserted caudocranially into the middle portion of the right anterior faucial pillar; for the LP muscle, the electrode was inserted laterally, superiorly, and posteriorly into the right levator dimple. Electrode placement was verified by the presence of high level of EMG activity in the PG muscle during swallowing and in the LP muscle during /s/ production. EMG channels were monitored oscillographically during the recording session. The EMG signals were recorded simultaneously with the acoustic and synchronization signals using a 14-channel FM tape recorder. EMG calibration signals were recorded on EMG channels. More extensive descriptions of the insertion and verification procedures are provided in Hirose [1971] and Bell-Berti [1973].

The subject produced five blocked (i.e., nonrandomized) repetitions of each of the 18 utterance types. Vowel onset was selected as the reference, or line-up, point for subsequent ensemble averaging of the EMG data. This point was identified as the first glottal pulse following initial /s/ frication. The EMG and acoustic signals were rectified, integrated (using 5-ms linear reset integrators), and digitized. Individual token data were software-smoothed (25-ms triangular window) and ensemble averages calculated from the five artifact-free tokens of each utterance type. Vowel duration was measured for each token from an oscillographic waveform display. Graphic displays of the ensemble-averaged EMG and acoustic signals were generated under computer control, and are presented in figures 1 through 5. Although these EMG data are based only on five tokens of each test syllable, they are quite comparable to those reported from English, French and Swedish in which more than five tokens of each test utterance were used.

Results

In general, two peaks of PG activity are found for each utterance type, with the first peak occurring during the initial consonant before the onset of the vowel and the second peak occurring near the end of the test syllables. Since the increase in PG activity for this second peak begins so late in the test syllables (at about the same time as the utternace-final decrease in LP activity), it cannot be associated with test-syllable articulation, because EMG activity must precede the resulting movements [see Harris, 1982, for example, for a more complete discussion]. Rather, it appears to be associated with velum lowering to open the velopharyngeal port at the end of the utterance and we will not be concerned with this second burst of PG activity any further. Instead, our primary concern will be with the first peak of PG activity.

We must also note that LP activity is relatively high for the nonnasal vowels and covaries with the traditionally identified vowel heights (the higher the vowel the stronger the LP activity, and vice versa). With respect to nasal vowels on the other hand, the LP exhibits baseline activity for the long vowels and somewhat greater than baseline activity for the short vowels. Furthermore, the decrease in LP activity for both the nasal and nonnasal vowels in the target CVC begins during the preceding (oral) consonant, and the increase in LP activity for the (oral) consonant following the vowel begins during the vowel. (This is not surprising, since EMG activity must precede the resulting movements as indicated earlier). We will refer to these LP activity patterns in our presentation of PG muscle EMG data.

Figure 1 presents the EMG results for the nasal and nonnasal front unrounded high vowels /ĩ/, /i/ and the lower-high vowels /ɩ̃/, /ɩ/. In this figure, the peak height and duration of PG activity are considerably greater for the nasal vowels than for the nonnasal vowels. The EMG peak for the long nasal vowel /ĩ/ is somewhat lower than for the short nasal vowel /ɩ̃/, but the

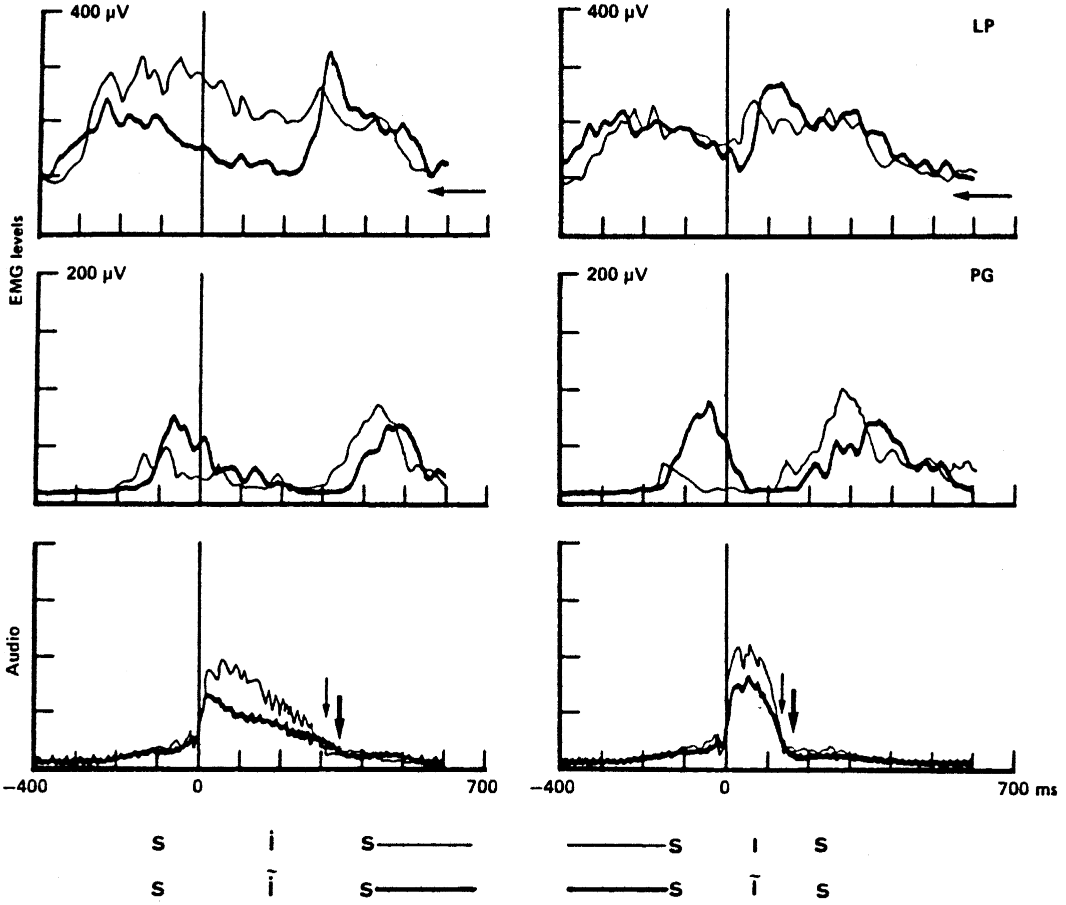

Fig. 1. Superimposed curves of ensemble average: LP (upper panels) and PG (middle panels) EMG potentials and audio amplitude envelope (lower panels) for the nasal and nonnasal vowels /ĩı,/ – /i/ (on the left) and /ɪ̃/ – /ɪ/ (on the right). EMG and audio signals were rectified and integrated before ensemble averaging. The heavy lines represent data for the utterances containing nasal vowels; the light lines represent data for the utterances containing nonnasal vowels. Signal amplitudes are represented along the ordinate: EMG signal in microvolts, audio signal in arbitrary units. Time (in milliseconds) is represented along the abscissa. Zero (0) on the abscissa marks the line-up point for ensemble averaging. The horizontal arrow to the right of the LP curves represents the baseline level of LP activity. The vertical arrows over the audio curves mark the offset of the vowels.

reverse is true for the corresponding nonnasal vowels. Generally, longer EMG activity occurs for the long vowels than for the short vowels, regardless of their nasality. It is of interest to note that PG activity for the nasal vowels occurs during the vowel-associated decline in LP activity, whereas comparable peaks of PG activity for the nonnasal vowels occur simultaneously with rather high level of LP activity. Furthermore, PG

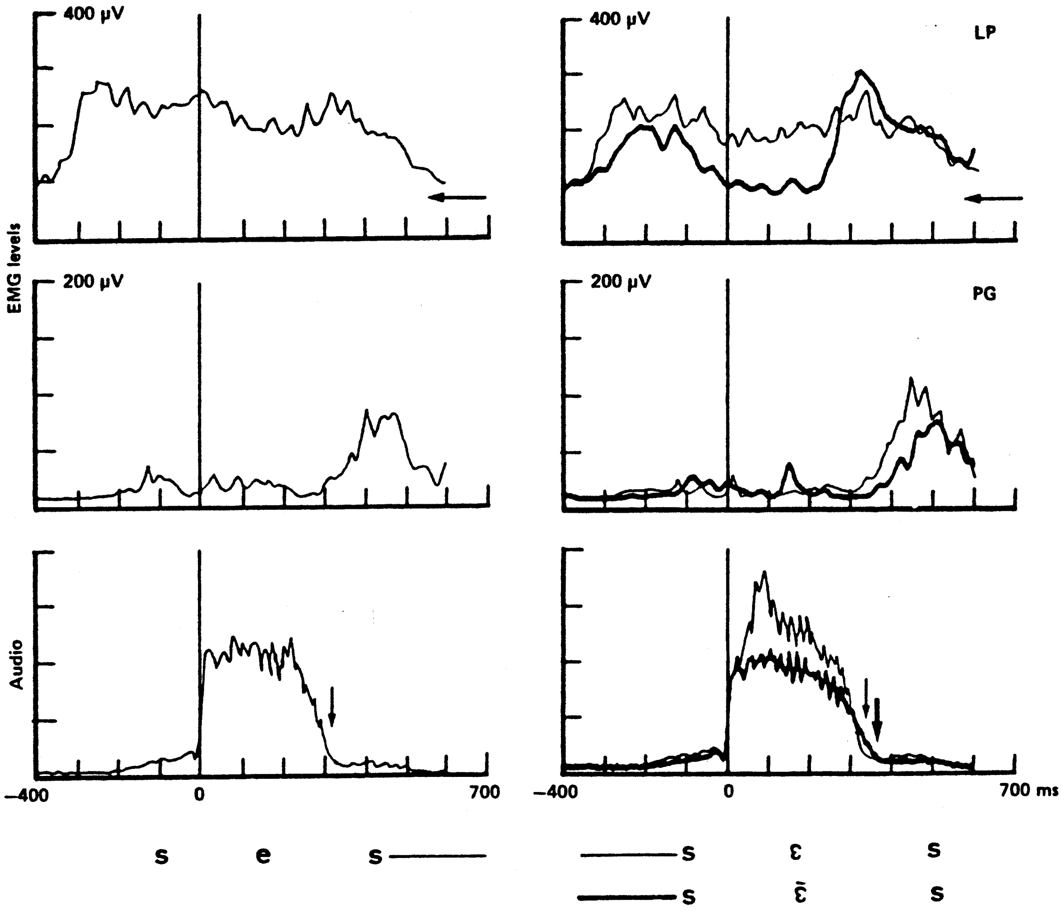

Fig. 2. Superimposed curves of ensemble average: LP (upper panels) and PG (middle panels) EMG potentials and audio amplitude envelope (lower panels) for the nonnasal vowel /e/ (on the left) and nasal and nonnasal vowels /ɛ̃/ – /ɛ/ (on the right). Other details as specified in figure 1.

activity occurs later (in relation to the vowel onset) for the nasal vowels than for the nonnasal vowels, a temporal relationship that does not exist for the central and back vowels. It should also be noted that the increase in PG activity for the nonnasal vowels begins only after a fairly high level of activity has been reached in LP.

Figure 2 presents the EMG data for the front unrounded higher-mid nonnasal vowel /e/ and the lower-mid nasal and nonnasal vowels /ɛ̃/ and /ɛ/. Clearly, PG activity for all of the three vowels is very low, being minimal for /ɛ/, slightly higher for /ɛ̃/, and highest for /e/. It should be observed that PG activity for /e/ is of about the same magnitude as that for the short vowel /ɪ/, but it is of longer duration for /e/ than for /ɪ/ (fig. 1). With respect to the timing of the onset and peak PG activ-

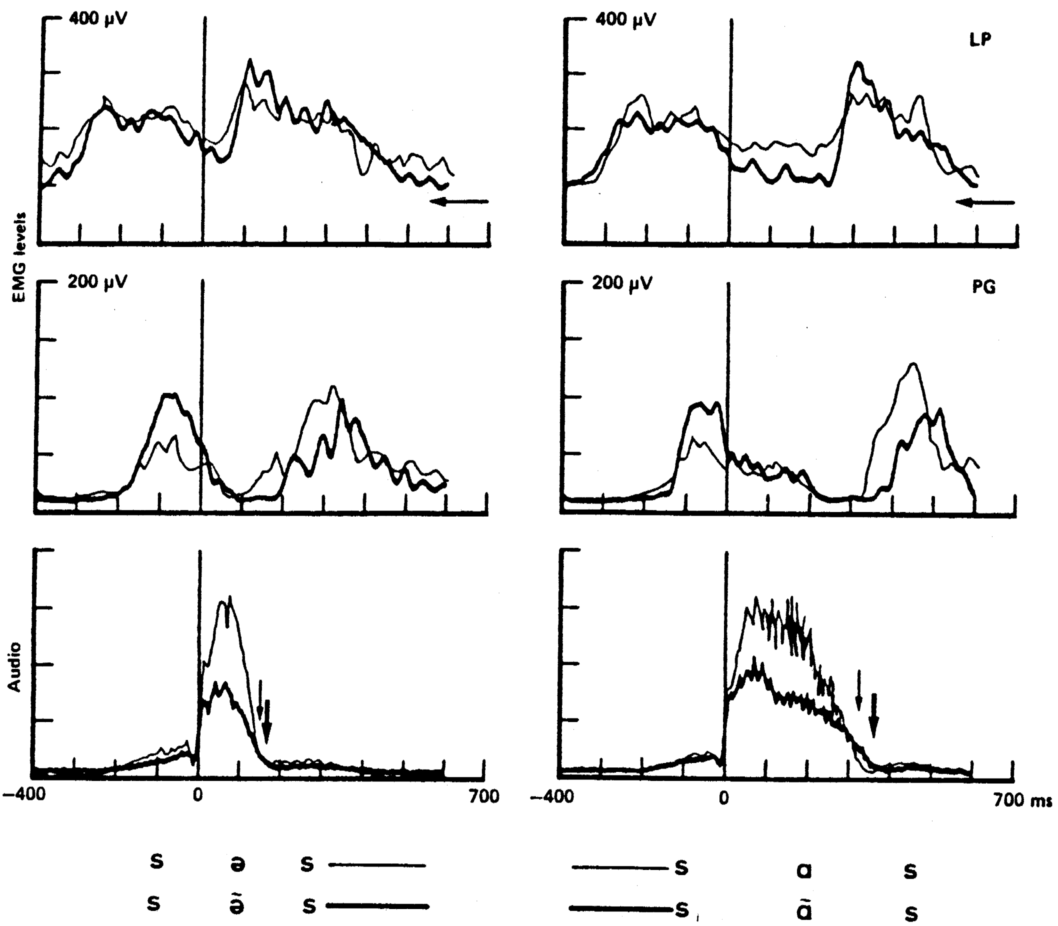

Fig. 3. Superimposed curves of ensemble average: LP (upper panels) and PG (middle panels) EMG potentials and audio amplitude envelope (lower panels) for the nasal and nonnasal vowels /ə̃/ – /ə/ (on the left) and /ɑ̃/ – /ɑ/ (on the right). Other details as specified in figure 1.

ity, we observe the same patterns for these vowels as for the long vowels /ĩ/ and /i/ (fig. 1).

Figure 3 displays the EMG data for the nasal and nonnasal lower-mid central unrounded vowels /ə̃/ and /ə/ and the low back unrounded vowels /ɑ̃/ and /ɑ/. It is quite evident that peak PG activity is moderately higher for the nasal vowels /ə̃/ and /ɑ̃/ than for their nonnasal counterparts /ə/ and /ɑ/. PG activity is of approximately equal magnitude within this pair of nasal vowels; similarly, it is also of approximately equal magnitude within this pair of nonnasal vowels. The activity peaks occur at about the same time before the onset of the vowel for both the nasal and nonnasal vowels. Again, the peak PG activity for the nonnasal vowels occurs during relatively high level LP activity, and coincides with

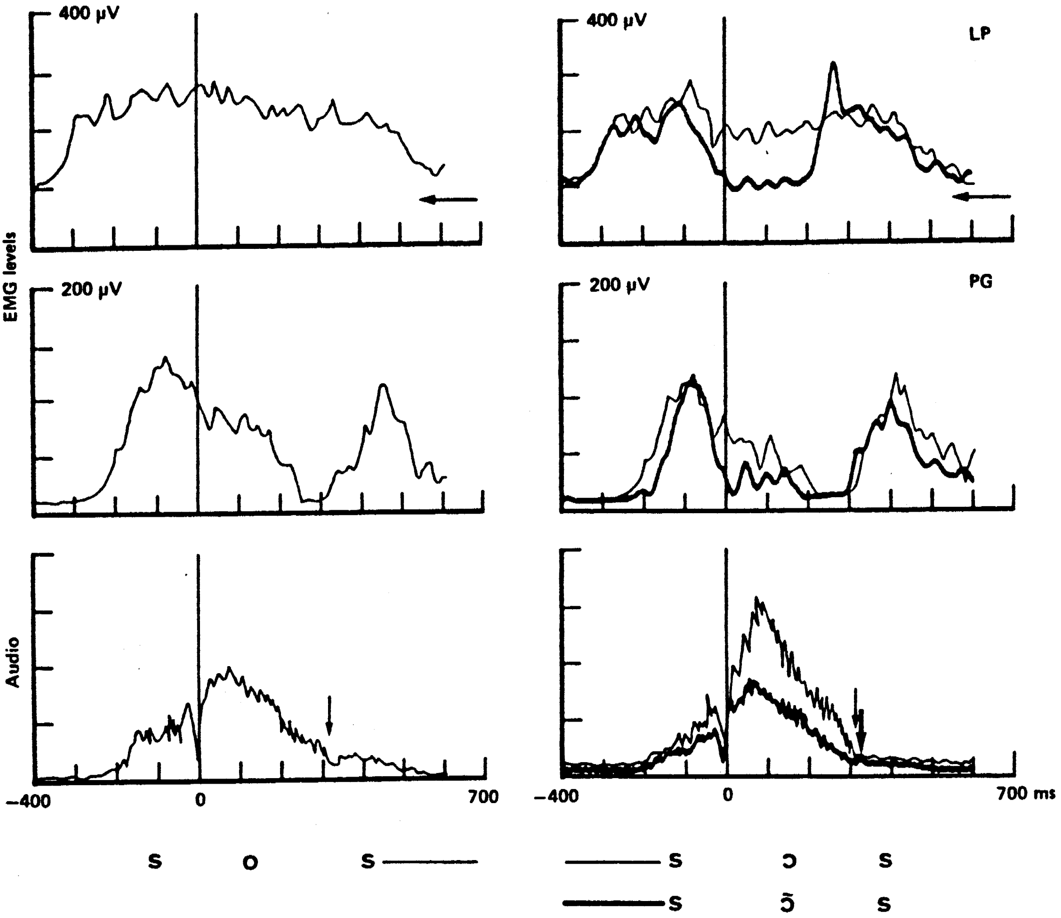

Fig. 4. Superimposed curves of ensemble average: LP (upper panels) and PG (middle panels) EMG potentials and audio amplitude envelopes (lower panels) for the nonnasal vowel /o/ (on the left) and nasal and nonnasal vowels /ɔ̃/ – /ɔ/ (on the right). Other details as specified in figure 1.

decreased LP activity for the nasal vowels. We would also note that the increase in PG activity for the central and back vowels (both nasal and nonnasal) begins earlier than it does for the front nasal vowels /ĩ/, /ɪ̃/, and ɛ̃/ where the onset of PG activity is almost synchronous with the decrease in LP activity. Moreover, peak PG activity for the nasal and nonnasal vowels /ə̃, ə/ and /ɑ̃, ɑ/ is greater than that for the front nasal and nonnasal vowels (fig. 1, 2).

The EMG data for the higher-mid back rounded nonnasal vowel /o/, and the lower-mid back rounded nasal and nonnasal vowels /ɔ̃/ and /ɔ/ are presented in figure 4. Both magnitude and duration of PG activity are quite similar for the nasal and nonnasal vowels /ɔ̃/ and /ɔ/, but the PG

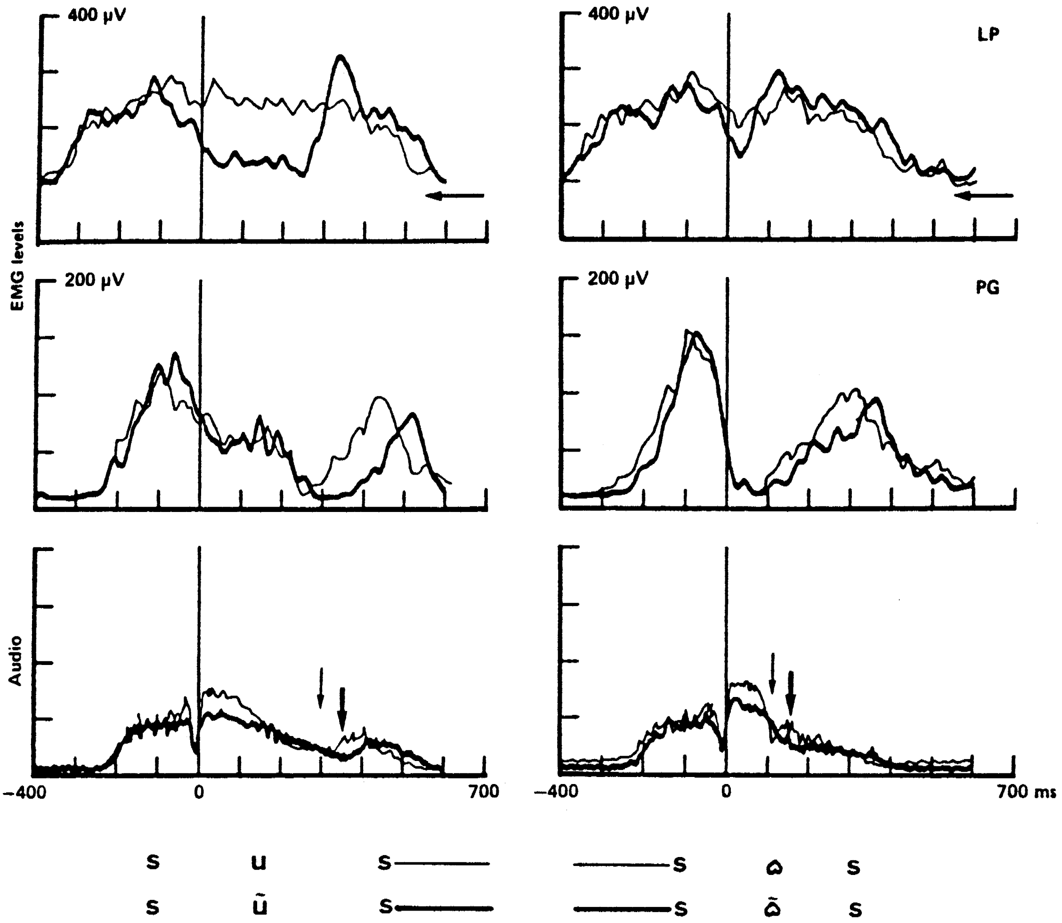

Fig. 5. Superimposed curves of ensemble average: LP (upper panels) and PG (middle panels) EMG potentials and audio amplitude envelope (lower panels) for the nasal and nonnasal vowels /ũ/ – /u/ (on the left) and /õ/ – /o/ (on the right). Other details as specified in figure 1.

activity magnitude is smaller and the duration shorter for these vowels than for the nonnasal vowel /o/. Furthermore, peak PG activity is greater for these vowels than for the vowels /ə̃/, /ə/, /ɑ̃/, and /ɑ/ (fig. 3), and peak PG activity for these vowels (/o/, /ɔ̃/, and /ɔ/ occurs at about the same time before vowel onset. Again, and as we have seen for /ə̃/, /ə/, /ɑ̃/, and /ɑ/ (fig. 3), peak PG activity co-occurs with high levels of LP activity for the nonnasal vowels, and with low LP activity for the nasal vowels. Moreover, the increase in PG activity begins earlier for these vowels than for the front vowels (fig. 1, 2).

Figure 5 presents the EMG data for the nasal and nonnasal back rounded high vowels /ũ/, /u/ and the lower-high vowels

/ɷ̃/, /ɷ/. With respect to peak amplitude and duration, PG activity is comparable within the nasal and nonnasal vowels of the pair /ũ/ and /u/, and for those of the pair /ɷ̃/ and /ɷ/. Moreover, PG peak magnitude for these four vowels is similar to that for /o/ (fig. 4), but greater than for any of the other vowels studied (fig. 1–4). The timing of PG activity for these vowels is similar to that for the other back and central vowels. That is, it begins before vowel onsets and reaches its peak for the nonnasal vowels during the high levels of LP activity and the peak for the nasal vowels is reached during decreasing LP activity.

In summary, then, we would make several points: (1) PG activity for the central and back nasal and nonnasal vowels is moderately to considerably higher than for the front nasal and nonnasal vowels. (2) All nasal vowels except /ɛ̃/ exhibit high levels of PG activity. (3) PG activity for the back nasal vowels /ɔ̃/, /ɷ̃/, /ũ/ and the front nasal vowel /ɛ̃/ is comparable to that for the corresponding nonnasal vowels, whereas PG activity for the back nasal vowel /ɑ̃/, central nasal vowel /ə̃/, and front nasal vowels /ĩ/ and /ɪ̃/ is greater than that for the corresponding nonnasal vowels. (4) Peak PG activity occurs at about the same time for the central and back nasal and nonnasal vowels, whereas the timing of peak PG activity in the front vowels occurs earlier for the nonnasal vowels than for the nasal vowels. (5) For the front nasal vowels PG activity increases as LP activity decreases, whereas PG activity for the central and back vowels begins before LP activity decreases. (6) Peak PG activity for the nasal vowels always occurs at times of decreasing LP activity. (7) For all nonnasal vowels, the increase in PG activity begins after a high level of LP activity has begun, and peak PG activity occurs simultaneously with strong LP activity. (8) Patterns of PG activity for the long vowels differ from those for the short vowels, irrespective of their being nasal or nonnasal.

Discussion

The results of this study reveal the presence of at least some PG activity for all nasal and nonnasal vowels of Hindi, with the level of PG activity increasing from low to high and from front to back in varying degrees. This result is consistent with reports of PG activity for a limited number of nasal and nonnasal vowels of French [Benguerel et al., 1977] and nonnasal vowels of English [Bell-Berti and Hirose, 1973; Bell-Berti, 1973, 1976; Seaver and Kuehn, 1980] and of Swedish [Lubker et al., 1970; Lubker and May, 1973]. But, since Hindi has a relatively richer set of nasal vowels and since there exists a strong parallel between nasal and nonnasal vowel sets, it is possible to distinguish among various potential modes of PG activity suggested by Lubker and May [1973] and Lubker [1975], and described in the 'Introduction' of this paper. We will examine PG function in Hindi nasal and nonnasal vowels in terms of those potential modes, beginning with a discussion of the nonnasal vowels, and then turning to the nasal vowels.

It is well-known that the LP muscle is the primary elevator and fixator of the velum. Appropriately, then, we find relatively high levels of LP activity during all the nonnasal vowels included in the present study. And, in agreement with previously reported data LP activity level covaries with traditionally identified vowel heights (the higher the vowel the greater the LP activity). In addition, there is some evidence that velar height also covaries with vowel height in both Hindi and English [Henderson et al., 1982; Bell-Berti et al., 1983]. Thus, the relatively fixed position of the velum provides an anchorage against which the PG may function during all the nonnasal vowels.

Although LP activity level and velar height covary with vowel height, both these parameters show only small differences among /i/, /ɩ/, /e/; the differences, moreover, are not always in the same direction. These above parameters, however, show relatively larger differences between /i, ɩ, e/ and /ɛ/, and between /ɛ/ and /ɑ/. Similar trends, with respect to LP activity level and velar height, occur between /u, o, o/ and /ɔ/, and between /ɔ/ and /ɑ/.

Although there are no X-ray data for Hindi vowels, it has been shown in other languages that the tongue-body (in accompaniment with the jaw) moves upward and forward toward the hard palate during the production of front vowels [see X-ray tracings in Fant, 1961, 1970; Ladefoged, 1962, 1964; MacNeilage and Scholes, 1964; Lindblom and Sundberg, 1969, 1971; Ladefoged et al., 1978; Lindau, 1978, 1979; Wood, 1979; Alfonso and Baer, 1982]. Moreover, Qadri's [1930] palatographic data on Hindustani (a variety of Hindi) vowels and Dixit's [1963] formant frequency data on Hindi vowels suggest a similar tongue-body movement as above for the front vowels (see 'Introduction'). In accordance with these, in Hindi the PG shows a low level of activity for the front nonnasal vowels, increasing from /ɛ/ to /e–ɩ/ to /i/. However, one cannot attribute the presumed movement of the tongue-body toward the hard palate for these vowels to PG activity because its points of attachment and the orientation of its fibers preclude its participation in the tongue-body fronting necessary for these vowels. Rather, this forward movement of the tongue-body results from contraction of the posterior fibers of the genioglossus (GG) muscle [MacNeilage and Scholes, 1964; Harris, 1971; Smith 1971; Miyawaki et al., 1975; Raphael and Bell-Berti, 1975; Hirose et al., 1977; Alfonso and Baer, 1982; Alfonso et al., 1984]. The concomitant upward movement of the tongue-body during front vowels may result from the coordinated contraction of the intrinsic muscles of the tongue [Raphael and Bell-Berti, 1975] and of mylohyoid muscle [Alfonso et al., 1984], in addition to the GG posterior contraction [Raphael et al., 1979; Wood, 1979; Collier et al., 1982]. The PG activity observed during the front nonnasal vowels in Hindi would seem to be antagonistically related to the tongue-body fronting by the GG muscle, possibly reflexively, in response to the forward pull exerted by the GG muscle for these vowels. (It is interesting to note that EMG activity of the GG muscle is generally observed to increase from /ɛ/ to /i/, in parallel with the PG activity levels reported in this study.) Lubker and May [1973] and Lubker [1975] have hypothesized the presence of such a stretch reflex in the PG muscle under similar conditions.

In contrast, the levels of PG activity during the production of central and back nonnasal vowels, activity that increases from /ə-ɑ/ to /ɔ/ to /o-o-u/, would seem to be associated with the upward and/or backward movement of the tongue-body, since during these vowels the velum is relatively elevated and fixed by the high level of LP activity (which varies with vowel height). In the absence of X-ray data on Hindi vowels, we will assume that the tongue-body movements during these vowels are similar to those described by Wood [1979]. Thus, during Hindi vowels /o, u/ and /ɔ, o/, the tongue-body would move toward the velum and upper posterior pharyngeal wall, respectively. The styloglossus (SG) is considered to be the primary muscle of upward and backward movement of the tongue-body [Harris, 1971; Smith, 1971; Raphael and Bell-Berti, 1975; Alfonso et al., 1984] and the superior pharyngeal constrictor (SC) muscle has been implicated in backward movement of the tongue-body [Smith, 1971; Bell-Berti, 1973, 1976]. In addition, the hyoglossus (HG) muscle [Alfonso et al., 1984] and the posterior portion of the GG muscle [MacNeilage and Scholes, 1964; Harris, 1971; Smith, 1971; Miyawaki et al., 1975; Raphael and Bell-Berti, 1975; Hirose et al., 1977; Alfonso et al., 1984] are reported to be active for the production of /u/ and /o/. We have found the PG to be highly active during all central and back vowels of Hindi and assume that this activity is associated with upward and/or backward movement of the tongue-body. One might also conclude that the PG plays a role in the formation of the velar constriction for /o/ and /u/, by preventing unrestricted movement of the tongue-body toward the upper posterior pharyngeal wall, movement that might result from the activity of the SG if the PG were inactive. It would appear, then, that two muscles – the posterior GG and the PG – guide the tongue-body toward the velum for /o/ and /u/, while the SG pulls the tongue-body upward and backward. The HG may be a counterbalance to the posterior GG and the PG in the above maneuver.

The PG is also capable of narrowing the velar constriction transversely. Wood [1979] has reported some indirect evidence that supports this view: second formant frequency for /u/ is well below 1,000 Hz for his Arabic subject, and such low formant values result from extreme narrowing of the velar constriction. F_2 frequency measurements of 700–1,000 Hz for /u/ have been reported for the same speaker [Dixit, 1963] whose PG data are reported here. It seems plausible to assume, then, that the low F_2 frequency for /u/ in this subject was, at least in part, a consequence of the sphincteric action of the PG muscle.

MacNeilage and Scholes [1964] and Alfonso et al. [1984] have reported antagonistically related activity of the HG and SG muscles during /o/ and /ɔ/. In the production of /o/ and /ɔ/, the PG may be a counterbalance to the HG, working in concert with the SG and glossopharyngeal portion of the SC in guiding the tongue-body toward the upper posterior pharyngeal wall. (Since the SG and PG move the tongue upward and backward it does not seem implausible to suppose that the PG activity observerd here for /o/ and /ɔ/ and that of the HG reported in the studies by MacNeilage and Scholes [1964] and Alfonso et al. [1984] represent the same antagonistic relationship.

MacNeilage and Scholes [1964] and Alfonso et al. [1984] have also reported antagonistic activity between the SG and HG muscles during /ʌ/ and /ɑ/, and Wood [1979] has suggested that the tongue-body moves toward the back wall of the lower pharynx during [ə]-, [a]-, and [ɑ]-type vowels. One might, therefore, assume that there is antagonistic activity of the PG and HG during these and similar vowels. Smith [1971] and Bell-Berti [1973, 1976] reported considerable activity of the SC during [a] and [ɑ]. In the present study, the PG was quite active during /ə/ and /ɑ/, and many other reports have shown high levels of PG activity during /ɑ/. (In Hindi, /ə/ may often seem to approach the quality of a higher-low central unrounded or even higher-low back unrounded vowel similar to [ʌ].) Thus, one might speculate that a combination of PG, SG, HG, and SC muscle activity is involved in achieving the appropriate positioning of the tongue-body in the lower pharynx for the /ə/ and /ɑ/ vowels of Hindi, with the HG and SC acting against the upward pull of the SG and PG to guide the tongue-body toward the lower posterior pharyngeal wall during /ə/, /ɑ/, and similar vowels.

Our results for Hindi nasal vowels are similar, but not identical, to those reported by Benguerel et al. [1977] for French nasal vowels. In both languages, the PG was active and the LP was suppressed for all nasal vowels, but the increase in PG activity and the decline in LP activity were almost synchronous for all nasal vowels of French, whereas this was not true for all nasal vowels of Hindi. (We are not suggesting that the observed differences in PG activity between Hindi nasal vowels as against French nasal vowels are language-specific; they may simply be differences between speakers. The PG data reported from these languages is, unfortunately, only from 1 speaker of each language.) The presence of PG activity during LP suppression suggests that this muscle was functioning to lower the velum to open the velopharyngeal port for the production of nasal vowels, supporting the 'gate-pull' model [Lubker and May, 1973; Lubker, 1975] that velar lowering for the production of nasal sounds is actively controlled. The EMG data reported here, however, do not provide unqualified support for this model. That is, although peaks of PG activity generally occurred at the same time, with regard to vowel onset, for all nasal vowels, the timing of the onset of PG activity in relation to the decrease in LP activity differed between front nasal vowels, and central and back nasal (and nonnasal) vowels. For the front nasal vowels, the onset of PG activity and the offset of LP activity were virtually synchronous, providing strong support for the 'gate-pull' model of nasal sound production. However, the situation was quite different for the central and back vowels of Hindi. Contrary to the observations for the front vowels, for the central and back vowels (nasal as well as nonnasal) the increase in PG activity began much earlier than the suppression of LP activity. This suggests that the activity of the PG muscle for the central and back nasal vowels, like that for the central and back nonnasal vowels, was primarily associated with tongue-body movements, and that the velar lowering for the nasal vowels was a by-product of the PG activity. That is, the PG may contribute to velar lowering for the central and back nasal vowels because it continues to be active during suppression of LP activity. However, the PG data for the central and back vowels do not provide unqualified support for the 'gate-pull' model of nasal sound production, suggesting that a model of active lowering of the velum for such sounds is suspect. In this respect, recall that according to Lubker et al [1972] PG activity during nasal sound production occurred at some point in time either during LP suppression or during declining LP activity. However, in our PG data on the central and back nasal vowel sounds, the situation as to the timing of PG activation with respect to the timing of LP suppression and velar lowering was quite different to that predicted by the 'gate-pull' model.

Conclusions

The results of the present study suggest that the PG muscle functions in all four modes [enumerated in Lubker and May, 1973, and Lubker, 1975] during the production of Hindi vowels. During the front nonnasal vowels, the PG appears to function antagonistically and possibly reflexively in response to the forward pull exerted by the GG muscle for these vowels, whereas during the central and back nonnasal vowels, the PG seems to be involved in tongue-body movements (presumably in concert with such extrinsic muscles of the tongue as the SG, HG, GG, and SC). The PG may also constrict the isthmus between the anterior pillars of the fauces during low F_2 vowels like /u/.

During the front nasal vowels, the PG activity appears to be associated with active velar lowering, whereas during the central and back nasal vowels (as during their nonnasal counterparts), the PG activity seems to be primarily related to the tongue-body movements rather than to the active velar lowering. But, since the PG continues to be active during LP suppression, it may contribute to lowering of the velum.

The temporal relationship that exists between PG activation and LP suppression is quite different in the front nasal vowels as against the central and back nasal vowels. In the former it unambiguously supports the 'gate-pull' model of nasal sound production, whereas in the latter it does not do so.

Since the EMG data on the PG muscle reported in the present study are from a single speaker of Hindi, the conclusions based on these data should be considered tentative.

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