Laryngeal Muscle Activity in connection with Thai Tones

Donna Erickson
Department of Speech and Hearing Science
The Ohio State University, Columbus, Ohio 43221, USA

1. Introduction

This paper is a reanalysis of data on laryngeal muscle activity associated with Thai tones, originally recorded at Haskins Laboratories [Erickson, 1976]. Dr. Hajime Hirose performed the electrode insertions and was involved in the data collection and analysis for the original study. His expertise was invaluable. I am appreciative of the opportunity to talk about this research at the symposium in Dr. Hirose's honor.

It is fairly well accepted that the CT is the primary controller of F0; however, it is not clear that the infrahyoid straps can be the primary muscles for lowering F0, even though infrahyoid strap muscle activity has been observed with low F0 [e.g., Ohala & Hirose, 1969; Simada et al., 1990]. The role of the CT in F0 control makes sense physiologically. An increase in CT activity results in the change of longitudinal tension of the folds, and in turn, F0 changes [e.g., Titze, 1991; Fujisaki, 1992; Honda et al., 1980]. But with the infrahyoid strap muscles, a physiological explanation is not obvious. According to Hirose [1992], "There is no established theory about infrahyoid strap muscles and pitch lowering, but it is considered that infrahyoid strap muscles work on the entire framework of the larynx in the direction to reduce the tension of the vocal folds in the front-back direction." It has been suggested [Honda et al., 1993; Hirai, Honda, Fujimoto, & Shimada, 1993] that the physiological curvature of the cervical vertebra may be responsible for the rotation of the cricoid cartilage during F0 lowering. That is, when the larynx is lowered by any of the infrahyoid strap muscles, the cricoid cartilage is rotated in the direction to reduce the length of the vocal folds.

The role of the infrahyoid strap muscles in pitch lowering is complicated by the fact that these muscles are active in connection with segmental articulation, specifically jaw opening and tongue backing, etc. [e.g., Honda, 1983; Atkinson and Erickson, 1976]. The infrahyoid strap muscles also may be involved in initiation of phonation, regardless of pitch height [e.g., Simada et al., 1990; Gårding et al., 1970].

The questions addressed in this study are (1) What is the pattern of laryngeal activity associated with the different Thai tones? and (2) How is F0-lowering accomplished; specifically, what is the role of infrahyoid strap muscles? To answer these questions, the laryngeal muscle activity associated with the five lexical tones in the Central Thai dialect was examined. The primary acoustic correlate of the tones is their underlying F0 contours [e.g., Abramson, 1974; Erickson, 1974]. Generally it is said that there are 3 static tones--the high, mid, and low tones; and 2 dynamic tones--the falling and rising tones [Abramson, 1978].

2. Data acquisition

The subjects were four native Thai speakers of the Central Thai Dialect (students at the University of Connecticut). This study focuses primarily on two of the four speakers--both males. The speakers were asked to produce in random order 16 repetitions of 45 syllables (nine nonsense syllables /baa, bii, buu, paa, pii, puu, phaa, phii, phuu/) spoken on each of the 5 tones in the carrier phrase [ə: __], ("Yes, it is a ____".)

Hooked-wire electrodes [Basmajian, 1974] were inserted into the four laryngeal muscles, the cricothyroid (CT), the sternohyoid (SH), the thyrohyoid (TH), the sternohyoid (ST) , and the vocalis, using the techniques described in Hirose [1971]. The EMG signals were processed and the 16 repetitions of each syllable type were averaged, using the Haskins Laboratories EMG data processing system [Port, 1971; Kewley-Port, 1973].

All muscles had good insertions, although activity levels were low for some muscles. The vocalis activity will not be discussed in this paper.

3. Observations

3.1 Cricothyroid activity and F0

Figure 1 shows the averaged CT and F0 for speaker 1 on each of the 5 tones, on the syllable /buu/. The x axis shows the time in msec, the y axis, F0 in Hz, and EMG activity in microvolts. F0 ranges from 100-200 Hz; CT ranges from 0 to 1000 mv. The line up point--0-- indicates the release of the stop. The focus of the analysis will be the data to the right of the line up point, the vocalic portion of syllable. The F0 is represented by the thin dashed line, the CT by the solid line.

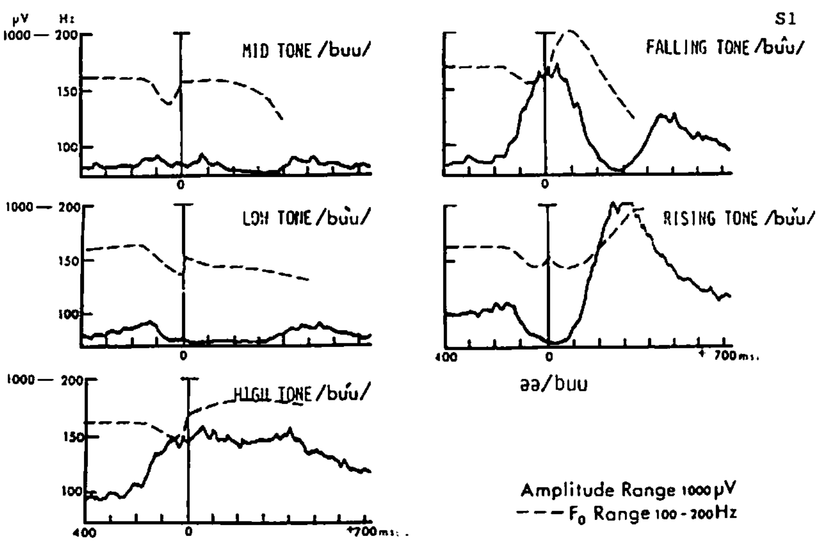

Fig.1. Cricothyroid activity and F0 for Thai mid, low, high, falling and rising tones on the syllable /buu/ for Speaker 1. The CT activity has a range from 0 to 1000 microvolts.

For the mid tone, there is a mid level F0 with a fall at the end, and no real CT activity. For the low tone, the F0 contour starts somewhat lower and continues to drop still lower, again with no CT activity. For the high tone, the F0 contour starts somewhat higher and continues to rise. There is a clear increase in CT activity associated with the rise. For the falling tone, there is a rise in F0 followed by a fall. The CT shows a peak of activity just prior to the F0 rise and a decrease in activity just prior to the F0 fall. For the rising tone, there is a drop in F0 followed by a rise. The CT shows a decrease in activity in connection with the drop in F0 and an increase in activity prior to the rise in F0. For speaker 2 (Figure 2) essentially the same pattern is seen. For the mid tone and low tones, there is no CT activity--except at the end of the low tone (which may relate to voice termination maneuvers associated with maintaining creaky phonation at low pitch also reported by Hallé et al., [1990] for Chinese tones in low register). For the high tone, there is increased CT activity, and for the falling and rising tones there are patterns of increased CT activity associated with increased pitch, and decreased CT activity associated with decreased pitch. The other two speakers also show similar patterns [cf. Erickson, 1976].

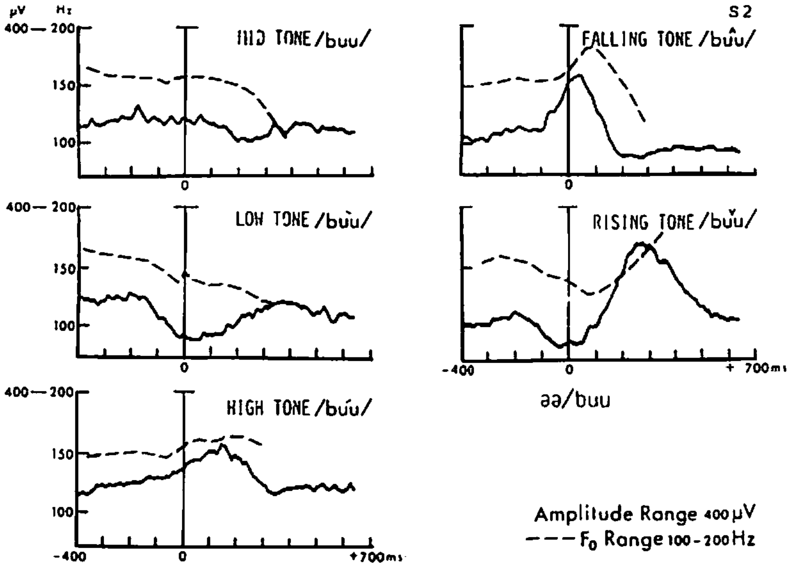

Fig.2. Cricothyroid activity and F0 for Thai mid, low, high, falling and rising tones on the syllable /buu/ for Speaker 2. The CT activity has a range from 0 to 400 microvolts.

This pattern for the CT in relation to F0 has been shown in many studies, for Chinese, [Hallé et al., 1990; Sagart et al., 1986], English, [Atkinson, 1973; 1978], Japanese [e.g., Hirose, 1992; Kiritani et al., 1991,1992; Simada & Hirose, 1971], Swedish [Gårding et al., 1970], Dutch [Collier, 1975], so that it is now generally accepted that the CT is the primary muscle involved in F0 control [e.g., Sawashima & Hirose, 1983].

3.2 Infrahyoid strap muscle activity and F0

Figure 3 shows infrahyoid strap muscle activity for speaker 1's productions. (The F0 is repeated from Figure 1.) The TH is represented by the thin line, and ranges from 0 to 200 mv; the SH is represented by the black line, and also ranges from 0 to 200 mv. The ST is represented by the dotted line, and ranges from 0 to 100 mv. The F0 is the thin dashed line. For the mid tone, there is a peak of infrahyoid strap activity associated with the final fall in F0. For the low tone, there is a peak in infrahyoid strap activity associated with the low F0 of the tone. For the high tone, there is no infrahyoid strap activity. For the falling tone, there is a peak of infrahyoid strap activity associated with the final F0 fall, and for the rising tone, a peak in infrahyoid strap activity associated with the initial F0 fall. Speaker 2 (Figure 4) shows a similar pattern of infrahyoid strap activity, except for the peak F0 of the high tone, which shows increased infrahyoid strap activity possibly related to voice termination maneuvers associated with the glottal constriction sometimes present with this tone. Again, the other two subjects also show similar patterns.

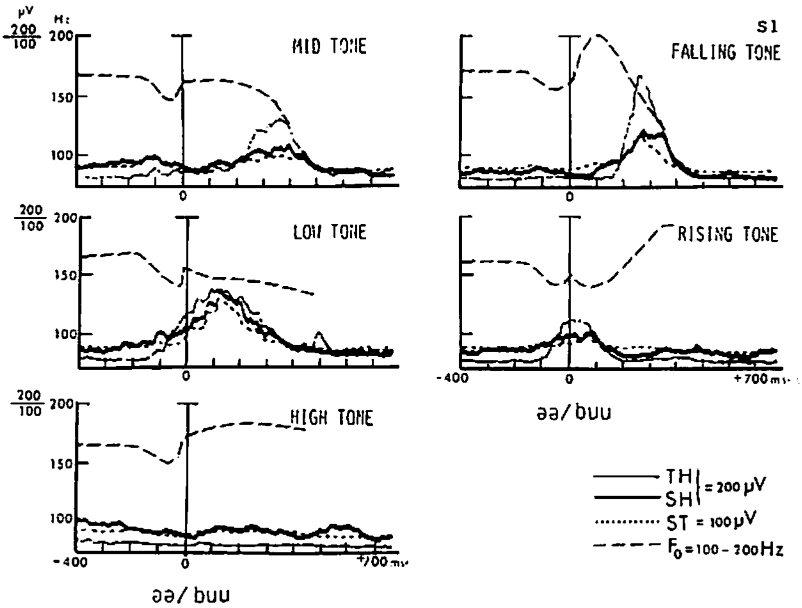

Fig.3. Infrahyoid strap muscle activity and F0 for Thai mid, low, high, falling and rising tones on the syllable /buu/ for Speaker 1. The TH and SH activities have values ranging from 0 to 200 microvolts; the ST activity has a range from 0 to 100 microvolts.

The finding that infrahyoid strap muscles are active during low F0 has been reported in EMG studies of various other languages including Chinese [e.g., Hallé et al., 1990; Sagart et al., 1986], English, [Atkinson, 1973; 1978; Ohala & Hirose, 1969] and various dialects of Japanese [Kori et al., 1990; Sugito & Hirose, 1971; Kiritani et al.,1992; Simada et al., 1990].

In this paper the term "infrahyoid strap muscle" activity is used to mean any one or a combination of the infrahyoid muscles. It was found in this study that all three infrahyoid strap muscles function synergistically in connection with low F0, although there are differences of opinion on this matter. For instance, Sonninen [1956] believed that any of these three muscles could bring about shortening of the vocal folds; Hiki and Kakita [1976] and Collier [1976] report that the TH does not function as a pitch-lowering muscle, while Niimi et al. [1991] show that the ST is active along with the CT for high pitches in singing.

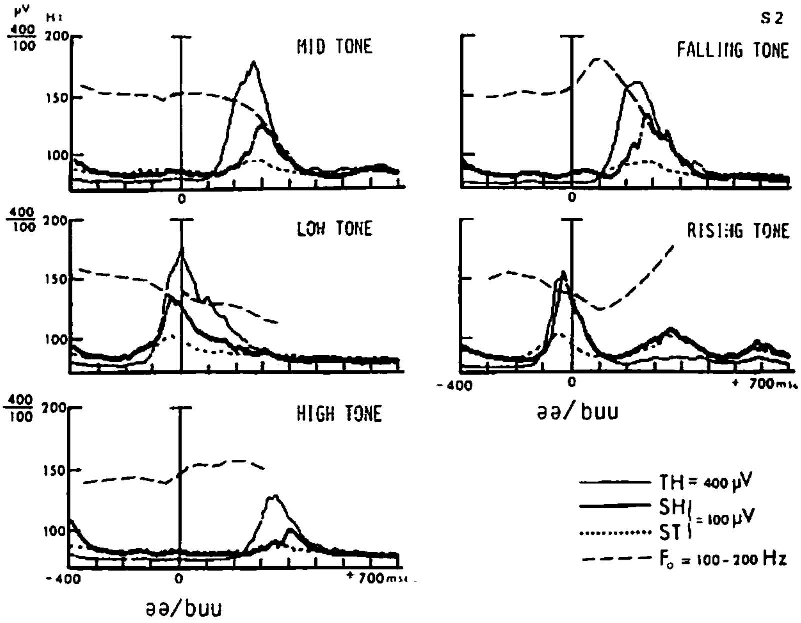

Fig.4. Infrahyoid strap muscle activity and F0 for Thai mid, low, high, falling and rising tones on the syllable /buu/ for Speaker 2. The TH activity ranges from 0 to 400 microvolts; the SH and ST activities have values ranging from 0 to 100 microvolts.

3.3 Cricothyroid and infrahyoid strap muscle activity

It was generally found that the CT and infrahyoid strap activity were inversely related. Figure 5 is an illustration of this, showing the CT and TH for speaker 1 on the syllable /buu/ on each of the 5 tones. The TH is the thin line, the CT, the thick line, and the F0, the thin dashed line. Where a peak in infrahyoid strap activity occurs, there is no CT activity, and where a peak in CT activity occurs, there is no infrahyoid strap activity. Specifically, for mid tone, there is a peak in infrahyoid strap activity, and no CT activity; for low tone, a peak in infrahyoid strap activity and no CT activity; for high tone, no infrahyoid strap activity, and a peak in CT activity; for the falling tone, a peak in CT activity and no infrahyoid strap activity followed by a peak in infrahyoid strap activity, and no CT activity; and for the rising tone, a peak in infrahyoid strap activity, and a decrease in CT activity, followed by a peak in CT activity, and no infrahyoid strap activity.

A reciprocal relationship between decrease of CT activity and increase in SH activity has been reported in many other EMG studies [e.g., Hirose, 1992; Fujisaki, 1992; Sugito & Hirose, 1978; Kiritani et al., 1991,1992; Simada et al., 1991].

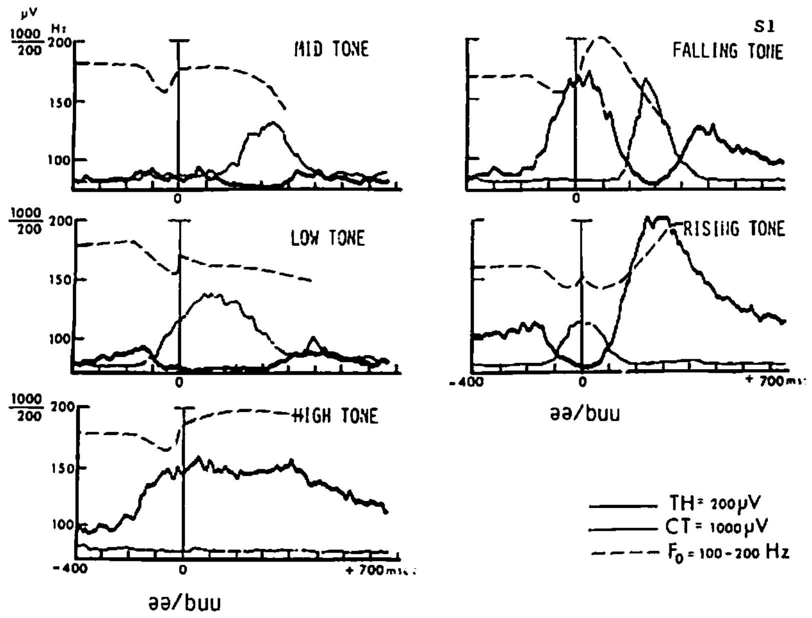

Fig.5. Cricothyroid, infrahyoid strap muscle activity and F0 for Thai mid, low, high, falling and rising tones on the syllable /buu/ for Speaker 1. The TH activity ranges from 0 to 200 microvolts and the CT activity ranges from 0 to 1000 microvolts.

4. Data analysis and discussion

4.1 CT and infrahyoid strap muscle activity in the control of F0

It is fairly well accepted that the CT is the primary controller of F0. An increase in CT is seen with a rise in F0 and a decrease in CT is seen with a decrease in F0 (cf., Figures 1 and 2). In fact, the CT activity mirrors the F0 contour, slightly offset in time. Notice that an increase in CT always precedes the F0 rise, and a decrease in CT always precedes an F0 fall. These figures support the statement that the CT controls F0.

The relation between infrahyoid strap muscle activity and F0 is not as clear (cf., Figures 3 and 4). Infrahyoid strap activity occurs with low F0, but the pattern of infrahyoid strap muscle activity relative to F0 is different from that seen with the CT-F0 and does not suggest necessarily that the infrahyoid strap muscles control F0. Notice that the onset of increased infrahyoid strap muscle activity sometimes precedes the drop in F0 and sometimes follows it (cf. Figures 3 and 4). For instance, increased infrahyoid strap activity in connection with the falling F0 of the **falling tone** begins **after** the onset of the F0 fall. The onset of increased infrahyoid strap activity in connection with the F0 fall of the **mid tone** begins **before** the onset of the F0 fall by about 100 msec. Note the F0 values at the onset of these falls. The F0 fall for the falling tone begins essentially from the top of the speaking range. Note that the F0 fall at the end of the mid tone begins at about the mid point of the speaking range, roughly about 150 Hz.

To corroborate these observations, measurements were made of the delay between onset of infrahyoid strap activity, as defined by the point at which the infrahyoid strap muscles started to increase, and the point at which the F0 begin to drop. The distributions of the delay times between onset of increased infrahyoid strap muscle activity and F0 fall for the mid tone for three Thai speakers are shown in Figure 6. The zero reference point indicates the time at which the F0 begins to fall. Infrahyoid strap muscle activity starts to increase **before** the initiation of the F0 fall. The mean delay between onset of infrahyoid strap activity and onset of F0 mid fall is 96 msec.

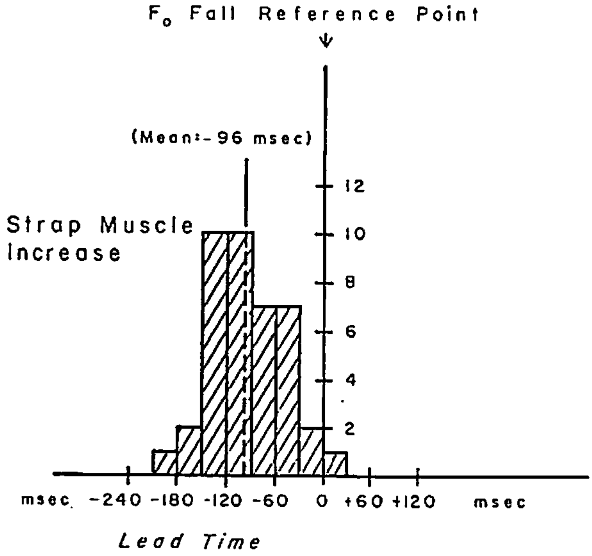

Fig.6. Time delays between onset of increase of infrahyoid strap muscle activity and onset of F0 fall on the **mid** tone. The graph is based on 40 measurements from the averaged muscle activity/F0 of 8 to 16 repetitions of syllables, as produced by 3 Thai speakers, 1-2 muscles per speaker, and 6-9 syllables per speaker (on the vowels /a/, /i/, and /u/, and the consonants /b/, /p/, and /ph/).

This contrasts strongly with the pattern of infrahyoid strap activity seen with high falls, where infrahyoid strap activity **begins after initiation of F0 fall.** Figure 7 shows the distributions of the delay times between onset of increased infrahyoid strap activity and onset of F0 fall in the **high fall** situation of the falling tone. Measurements were made of the delay between onset of infrahyoid strap muscle activity and onset of F0 fall (from a high F0 value) for syllables on the falling tone for two speakers. In this case the infrahyoid strap activity generally occurs **after** the onset of the F0 fall by about 38 msec.

The data suggest that the timing of the onset of increased infrahyoid strap muscle activity is dependent on the value of the F0 at the point it begins to fall, relative to the speaker's F0 range. If the F0 begins to fall from a rather high F0, as in the falling tone, the onset of the infrahyoid strap muscle activity is such that it clearly cannot be considered to initiate the fall. If the F0 begins to fall from a mid range, as in the fall of the mid tone, (or, from the mid F0 point of the fall of the falling tone), the onset of increased infrahyoid strap muscle activity relative to F0 fall suggests that these muscles are involved in either initiating the F0 fall, or in setting up the larynx to allow the low F0 to occur.

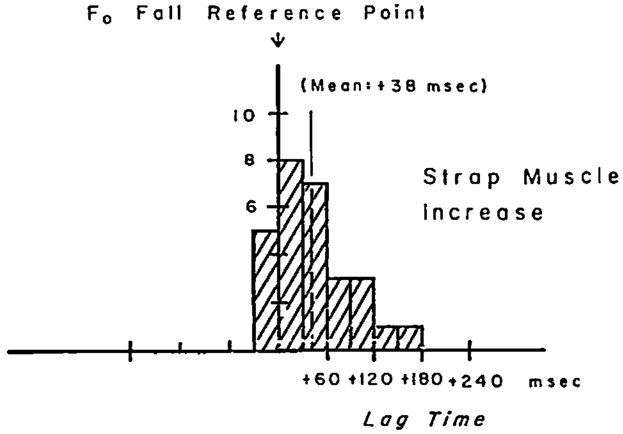

Fig.7. Time delays between onset of increase of infrahyoid strap muscle activity and onset of F0 fall on the **falling** tone. The graph is based on 28 measurements from the averaged muscle activity/F0 of 8 to 16 repetitions of syllables, as produced by 2 Thai speakers, 2 muscles per speaker, and 5-9 syllables per speaker (including syllables on the vowels /a/, /i/, and /u/, and the consonants /b/, /p/, and /ph/).

4.2 Modes of laryngeal control

It has been proposed that *at least* two modes of laryngeal control for F0 are available in speaking [Erickson & Atkinson, 1975; Atkinson, 1978; Erickson et al., 1983]. One mode is used for mid to high F0, and the other for mid to low F0. In the mid to high F0 range, the infrahyoid strap muscles are inactive, and the larynx is in a position to allow the CT to control F0. Within this range, activation of the CT results in pitch-raising, deactivation of the CT results in pitch-lowering. In order to speak in the mid to low F0 range, the infrahyoid strap muscles are activated. It is hypothesized that the infrahyoid strap muscles function to adjust the physical conditions of the larynx to allow the F0 to be low. It is not clear how F0 is controlled in this low F0 range--whether the infrahyoid strap muscles actually control F0, or whether the F0 is controlled by other factors, such as aerodynamic or subglottal pressure mechanisms, or other laryngeal muscles. A correlation analysis by Atkinson [1978] shows subglottal pressure has the highest correlation with F0 in the low F0 range, below 100 Hz, and he suggests that subglottal pressure is primarily responsible for F0 control in this range when the vocal folds are thick and more responsive to pressure variations. Honda [1988, 1980], based on observations that the linear relationship between F0 and vocal fold length is not constant across the entire range of F0, speculated that other laryngeal muscles are involved in controlling F0 below a certain point in the F0 range. He suggested that cessation of the LCA (lateral cricoarytenoid) and activation of the cricopharyngeus may be involved. [See also Honda & Fujimura, 1991; Zenker, 1964.] Simada et al [1990] report that the SH is important in Tokyo Japanese for maintaining low F0, but not necessarily for controlling F0 lowering.

4.3 Hypothetical situation

If at least 2 modes of laryngeal control are available to the speaker for low F0, the relationship between CT - F0 and Infrahyoid Strap Muscle - F0 might look something like the hypothetical plot shown in Figure 8. A positive, probably linear, relation would exist between F0 and CT activity for F0 values above a certain frequency with no activity of the CT in the lower F0 ranges. Conversely, an increase in activity would be seen for the infrahyoid muscles for F0 values below this same frequency but no activity above this frequency.

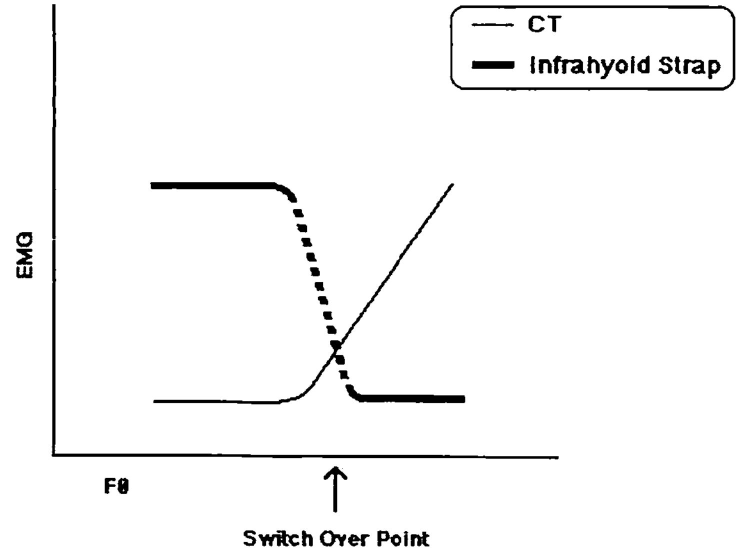

Fig.8. A modal account of F0 control. The hypothetical curve shows the hypothesized relationship between CT and infrahyoid strap muscle activity in the control of F0.

In this hypothetical figure, the relation between CT and F0 is shown to be linear, since it is fairly well accepted that there is a direct relation between CT and F0. However, the relation between the infrahyoid strap activity and F0 is pictured as not linear in this hypothetical graph since it is not clear that the same type of relationship exists between infrahyoid strap muscle activity and F0 as between CT and F0. In this hypothetical figure, the infrahyoid strap muscle activity is drawn to show more of a bimodal-type of relation with F0, i.e., that it is either **on** for low F0 or **off** for high F0.

It is hypothesized that at the point marked by the arrow in this figure, a switch takes place from one mode of operation to another. It is at this point that the infrahyoid strap muscles "kick in" to set the larynx up in a mode to allow low F0.

4.4 Mean Response Time

One way to address the plausibility of the above hypothesis and the relationship between EMG and F0 is to correlate EMG activity with F0. In order to do this, it is necessary to know the delay between onset of muscle activity and change in F0. In fact, the question about causality and laryngeal mode of F0 control hinges on knowing how much time is needed for the contracting muscle to effect a change in the vocal folds, i.e., to bring about a change in F0. The amount of delay between laryngeal muscle event and F0 event is a complex topic, affected by the complicated interaction among numerous linguistic, physiological, and aerodynamic, etc. parameters, as well as the technical aspects of electrode insertion (i.e., location of the electrode relative to the motor firing unit, etc.) and data processing, (i.e., size and type of averaging and smoothing windows). Nevertheless, it may be possible to roughly estimate a mean response time between muscle activity and F0. Atkinson [1973, 1978] devised such a measure which he referred to as "Mean Response Time (MRT)", i.e., the amount of time between the peak of CT activity and peak of F0 activity, assuming a causal relationship between increased CT activity and increased F0. MRT, according to Atkinson, includes not only muscle latency values, which, as mentioned by Sawashima [1974], are dependent on the type of muscle and its size, but also the delay between muscular contraction, and a change in position of the laryngeal structures necessary to change vocal fold dimensions--and F0.

Along the lines proposed by Atkinson [1978], MRT for the Thai data was approximated, using a combination analysis of "cross correlation/ eye-ball matching of peaks" for the EMG and F0 of the falling tone syllables for the two Thai speakers. The analysis was performed in the following way. The averaged CT activity and F0 for 30 utterances on the syllables /baa,bii,buu/ on the falling tone for speaker 1, and 12 utterances on these syllables on the falling tone for speaker 2, were calculated every 5 msec. Correlation coefficients using the Pearson-Product-Moment-formula were calculated for pairs of the F0-CT variables for each speaker offset at 0 msec, at 10 msec, at 20 msec, etc. This was done to ascertain the amount of time shift for which the two sets of data showed a maximum correlation. When the F0 and CT data curves were shifted by 150 to 160 msec for speaker 1, there was a maximum positive correlation of .972; when the F0 and CT data curves were shifted by 100 msec for speaker 2, there was a maximum positive correlation of .940.

An eye-ball matching of CT peak with F0 peak was done by visual inspection of the computer print-out values. The time offsets between the peak CT-peak F0 were identical to the time offset for which there was maximum correlation between CT and F0 for the two speakers. The MRT for the CT was thus determined to be 155 msec for speaker 1, and 100 msec for speaker 2.

Estimating MRT for the infrahyoid strap muscles was done in a similar fashion. The averaged infrahyoid strap activity and F0 values for essentially the same set of 30 falling tone utterances for each of the two speakers were calculated for every 5 msec. Correlation coefficients using the Pearson-Product-Moment-formula were calculated for pairs of the F0-infrahyoid strap muscle variables offset at 0 msec, at 10 msec, at 20 msec, etc. This was done to ascertain the amount of time shift for which the two sets of data showed a maximum negative correlation. When the F0 and SH activity curves were shifted by 110 msec to 200 msec for speaker 1, there was a maximum negative correlation ranging from .896 to .883; when the F0 and TH activity curves were shifted by 70 to 160 msec for speaker 2, there was a maximum negative correlation ranging from .991 to .982. Notice that in the case of the infrahyoid strap muscles, there was a broad range for which there was a high negative correlation.

In order to select a specific MRT from this range, an eye-ball matching of strap muscle peak with F0 minimum was done by visual inspection of the computer print-out values. The time offset between the peak SH-minimum F0 for speaker 1 was 165 msec, which fell in the middle of the range for which there were high correlation coefficients; the time offset between peak TH-minimum F0 for speaker 2 was 130 msec, which fell in the middle of the range for which there were high correlation coefficients. These values were determined to represent the MRT for these speakers for the infrahyoid strap muscles.

Using these rough MRT estimates, the relation between the EMG activity and the F0 delayed by that MRT value can be plotted, as was done in the hypothetical situation (cf. Figure

8), in which CT activity showed a linear relationship to F0, at high F0 values, and infrahyoid strap activity, an inverse relationship to F0 at low F0 values.

Figure 9 plots the average EMG activity with average F0 values for the 30 utterances on the falling tone, for the syllables /baa, bii, buu/ for speaker 1. F0 is plotted on the x axis, with values ranging from 70 to 180 Hz. EMG activity is plotted along the y axis; the values have been normalized to facilitate comparison with data from the other speaker. The F0 measurements were made at every 5 msec throughout the syllable; the corresponding CT measurements were made at 155 msec prior to each of the F0 measurements, using the above-approximated MRT value. The corresponding infrahyoid strap muscle measurements, were made at 165 msec prior to each of the F0 measurements, using the above-approximated MRT value.

In the low F0 range, the infrahyoid strap muscle (filled diamonds) shows increased activity that drops off to very low level activity in the higher ranges. The infrahyoid strap activity, the SH, which has strong activity for this speaker, drops off about after 120 Hz. The CT, on the other hand, (unfilled squares) shows very low level activity in the low F0 range, and a marked increase in activity in the high F0 range. In fact, after about 120 Hz, the CT seems to show a regular increase with F0 which is virtually linear between 120 to 150 Hz, with some scatter in the region above 150 Hz.

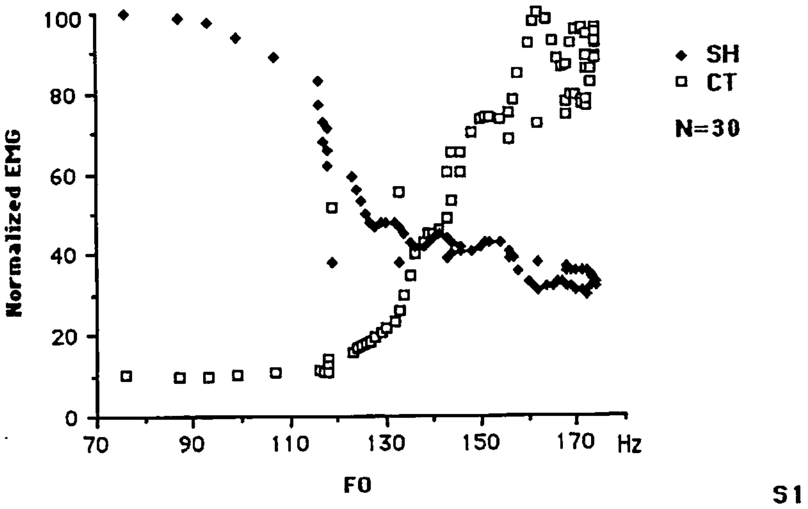

Fig.9. F0 and EMG activity for Speaker 1. An averaged F0 contour was calculated from 30 utterances on the falling tone for the syllables /baa, bii, buu/. F0 measurements made every 5 ms throughout the tone are plotted against corresponding EMG measurements offset by the appropriate MRT value. The MRT for the CT is 155 ms, and the MRT for the SH is 165 ms.

To a certain extent, this figure resembles the hypothetical data. The switch-over point is not as clear as in the hypothetical data; however, a switch over point may occur between 110-120 Hz. Above this point, there is an increase in CT, and below this point, there is increased infrahyoid strap muscle activity. The lowest level of activity of the CT in this region (below 120 Hz) , and of the infrahyoid strap muscle in this region (above 120 Hz), is most likely in the noise level, and the variations cannot be said to have significant effects on the F0.

Figure 10 shows corresponding data for Speaker 2, for both CT and infrahyoid strap muscle. The infrahyoid strap muscle is the TH, which had the strongest level of activity for this speaker. The CT is plotted against the F0 offset by a 100 msec delay. The infrahyoid strap is plotted against the F0, offset with a 130 msec delay. The CT measurements are based on the average of 12 utterances on the falling tone on the syllables /baa, bii, buu/; the infrahyoid strap measurements are based on an average of 30 utterances on the falling tone on the syllables /baa, bii, buu/. The F0 measurements were made at every 5 msec throughout the syllable, and the infrahyoid strap measurements were made at 165 msec prior to each of the F0 measurements.

Looking at the infrahyoid strap activity (filled diamonds), increased activity occurs in the low F0 range, and decreased activity occurs in the high F0 range. Looking at the CT (unfilled squares) , relatively little activity occurs in the low F0 range, and increased activity occurs in the high F0 range. Above 140 Hz, the CT shows a roughly linear relation with F0. Thus, a pattern of high infrahyoid strap activity, and low CT activity occurs below approximately 140 Hz, and high CT activity and low infrahyoid strap activity occurs above 140 Hz.

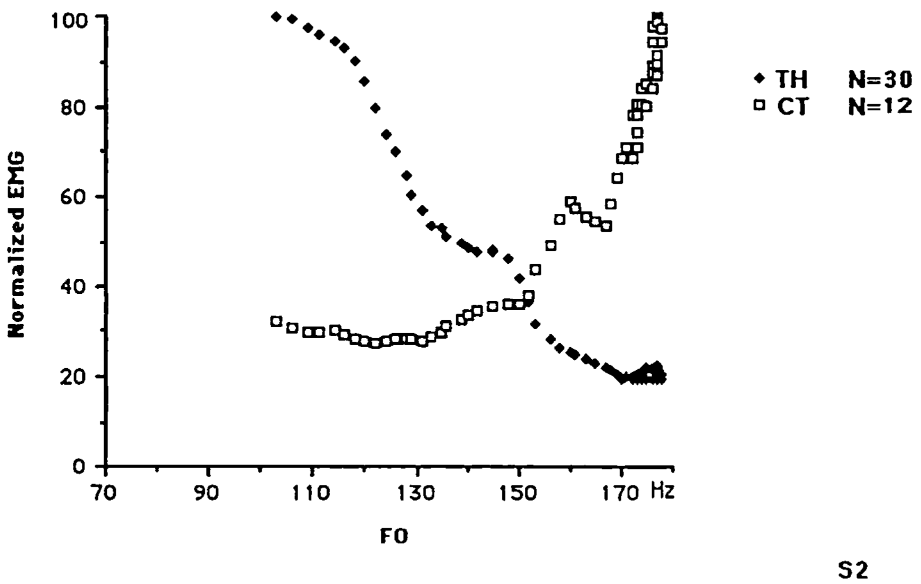

Fig.10. F0 and EMG activity for Speaker 2. An averaged F0 contour was calculated from 30 utterances on the falling tone for the syllables /baa, bii, buu/. F0 measurements made every 5 ms throughout the tone are plotted against corresponding EMG measurements offset by the appropriate MRT value. The MRT for the CT is 100 ms, and the MRT for the TH is 130 ms. The TH measurements are based on 30 utterances, and the CT measurements are based on 12 utterances.

For speaker 2, a "switch-over point" in infrahyoid strap activity is more difficult to pinpoint than for speaker 1. However, both speakers show patterns of increased activity of the infrahyoid strap muscle in low ranges and in increased activity of the CT in high ranges.

A similar phenomenon was found for English by Atkinson [1978]. He found that in the mid-low range (between 100-120 Hz), "the SH shows a much higher correlation with F0 than any other factor" and at high F0 (above 120 Hz) the CT shows a high correlation." He suggests that "different combinations of physiological factors appear to be involved for different ranges of F0," including subglottal pressure especially in the low F0 range.

4.5 Modal control of F0

These figures encourage a theory of **Modal Control of F0** in speaking. Essentially the infrahyoid strap muscles act as a "laryngeal adjustor" which "kicks in" around the speaker's mid-voice range to allow low F0. It "kicks off" at this range to allow high F0. A first approximation for a "speaker's handbook" for controlling F0 might read as follows:

(1) When speaking in the mid to high F0 range, the infrahyoid strap muscles are inactive (except in their segmental articulation/jaw opening function) . To control F0 in this range, the CT is predominant. To increase F0, activate CT; to decrease F0, deactivate CT.

(2) To get into the mid to low F0 range, use the infrahyoid strap muscles. To control F0 in this range, a normal candidate is the subglottal pressure, aided perhaps by other laryngeal muscles.

There are probably more than two modal ranges involved in speaking, but the Thai data presented here do not show this, and this is not discussed here. Sonninen [1956] reports that "The sternothyroid muscle has a dual effect on the length of the vocal cords: In low tones it may shorten the cords..., but in high tones it participates in lengthening of the cords" (p. 96). Prior work by Erickson et al., [1976] and Honda [1983] suggest that the infrahyoid muscles cooperate with the suprahyoid muscles, and the CT, for raising the F0 in the region above the mid F0 speaking range in certain situations, and possibly for purposes of linguistic prominence.

5. Summary

In summary, this study on laryngeal activity in connection with Thai tones shows that (1) each tone has a distinct pattern of EMG activity, (2) infrahyoid strap muscles are active at low F0 but inactive at high F0, and (3) there may be at least two modes of F0--one for mid to high F0 and one for mid to low F0. Within the mid to high F0 range, control of F0 primarily involves the CT: to raise F0, the CT is activated, to lower F0, the CT is deactivated. The infrahyoid strap muscles act as a "laryngeal adjustor" which adjusts the physical condition of the larynx to allow F0 to drop below the mid level. Within the mid to low F0 range, it is not clear from the data analyzed here how F0 is controlled, but subglottal pressure, as well as other laryngeal muscles, may be involved.

Complicating the picture is the relation between segmental articulation and these muscles. For example, infrahyoid strap muscles have been implicated for jaw opening for low vowels, among other things. Ultimately, the mechanism for controlling F0 should have enough redundancy to allow implementation of prosodic rules, in spite of the various articulatory gestures required for speech.

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References

Abramson, A.S. (1974). The tones of Central Thai: Some perceptual experiments. *Haskins Laboratories Status Report on Speech Research* , SR-39/40, 91-104.

Abramson, A.S. (1978). Static and dynamic acoustic cues in distinctive tones. *Language and Speech*, 21, 319-325.

Atkinson, J.E. (1973). *Aspects of intonation in speech: Implications from an experimental study of fundamental frequency*. Ph.D. dissertation, University of Connecticut.

Atkinson, J.E. (1978). Correlation analysis of the physiological factors controlling fundamental voice frequency. *J.Acoust.Soc.Am.*, 63, 211-222.

Atkinson, J.E. & Erickson, D. (1976). The function of strap muscles in speech: Pitch lowering or jaw opening? *J.Acoust.Soc.Am.*, 60, S65.

Basmajian, J.V. (1974). *Muscles alive. Their function revealed by electromyography.* 3rd edition, Baltimore: The Williams and Wilkins Co..

Collier, R. (1975). Physiological correlates of intonation patterns. *J. Acoust. Soc.Am.*, 58, 249-255.

Erickson, D. (1974). Fundamental frequency contours of the tones of Standard Thai. *PASAA*, 4, 1-25.

Erickson, D. (1976). *A Physiological Analysis of the Tones of Thai.* Ph.D. dissertation, University of Connecticut.

Erickson, D. & Atkinson, J.E. (1975). The function of the strap muscles in speech. *J. Acoust. Soc.Am.*, 58, S12. (Also in Haskins Laboratories Status Report on Speech Research, SR-45/46 (1976), 205-210.)

Erickson, D., Liberman, M.Y., & Niimi, S. (1976). The geniohyoid and the role of the strap muscles in pitch control. *J.Acoust.Soc.Am.*, 60, S63.

Erickson, D., Baer, T., Harris, K.E. (1983). The role of the strap muscles in pitch lowering. In D.M. Bless & J.H. Abbs (Eds.), *Vocal Fold Physiology: Contemporary Research and Clinical Issues*. (pp 279-285). San Diego, CA: College-Hill Press.

Fujisaki, H. (1992). The role of quantitative modeling in the study of intonation. In *Proceedings of International Symposium on Japanese Phonetics, (Nara, Japan)* pp. 163-174.

Gårding, E., Fujimura, O., and Hirose, H. (1970). Laryngeal control of Swedish word tones. *Ann. Bull. RILP*, 4, 45-54.

Hallé, P.A., Niimi, S., Imaizumi, S. & Hirose, H. (1990). Modern standard Chinese 4 tones: EMG and Acoustic patterns revisited. *Ann. Bull. RILP*, 24, 41-58.

Hiki,S., & Kakita, S. (1973). A study on laryngeal control for pitch change by use of anatomical structure model. *Conference Record, IEEE International Congress on ASSP*, 43-46.

Hirai, H., Honda, K., Fujimoto, I. , & Shimada.Y. (1993). Analysis of magnetic resonance images on the physiological mechanisms of fundamental frequency control. *ATR Technical Report*, TR-A-0166.

Hirose, H. (1971). Electromyography of the articulatory muscles: Current instrumentation and technique. *Haskins Laboratories Status Report on Speech Research*, SR-25/26, 73-86.

Hirose, H. (1992). Physiological mechanisms for speech production. In *Proceedings of International Symposium on Japanese Phonetics, (Nara, Japan)* pp.131-140.

Honda, K. (1983). Relationship between pitch control and vowel articulation. In D.M. Bless & J.H. Abbs (Eds.), *Vocal Fold Physiology* (pp. 286-299). College Hill Press, San Diego.

Honda, K. (1988). Various laryngeal mechanisms in controlling voice fundamental frequency. *J.Acoust.Soc.Am.*, 84, S82.

Honda, K., Hibi, S., Kiritani, S., Niimi,S., and Hirose, H. (1980). Measurement of the laryngeal structures during phonation by use of a stereoendoscope. *Ann. Bull. RILP*, 14,

73-78.
Honda, K. & Fujimura, O. (1991). Intrinsic vowel F0 and phrase-final lowering: Phonological vs biological explanations. In J. Gauffin & B. Hammarberg (Eds.), *Vocal Fold Physiology, 3,* (pp.149-157). San Diego, CA:Singular Publishing Group.
Honda, K., Hirai, H., & Kusakawa, N. (1993). Modeling vocal tract organs based on MRI and EMG observations and its implication on brain function. *Ann. Bull. RILP, Festschrift for Professor Hajime Hirose,* 27.
Kewley-Port, D. (1973). Computer processing of EMG signals at Haskins Laboratories. *Haskins Laboratories Status Report on Speech Research* ,SR-33, 173-183.
Kiritani, S., Hirose, H., Maekawa, K., Kawashima, H., & Sato, T. (1991). Electromyographic studies on the production of pitch contour in accentless dialects in Japanese. *Ann. Bull. RILP,* 25, 1-15.
Kiritani, S., Hirose, H., Maekawa, K., Sato,T. (1992). Electromyographic studies on the production of pitch contour in accentless dialects in Japanese. *Proc. I.C.S.L.P.,Banff, Canada,* pp 783-785.
Kori, S., Sugito, M., Hirose, H., Niimi, S. (1990). Participation of the sternohyoid muscle in pitch lowering: Evidence from Osaka Japanese. *Ann. Bull. RILP,* 24, 65-75.
Niimi, S., Horiguchi, S. and Kobayashi, N. (1991). F0 raising role of the sternohyoid muscle--an electromyographic study of two tenors. In J. Gauffin and B. Hammarberg (Eds.), *Vocal Fold Physiology. Acoustic, Perceptual, and Physiological Aspects of Voice Mechanisms,* (pp. 129-138). San Diego, CA: Singular Publishing Group, Inc.
Ohala, J. & Hirose,H. (1969). The function of the sternohyoid muscle in speech. *Reports of the 1969 Autumn Meeting of the Acoustical Society of Japan,* 359-360.
Port, D.K. (1971). The EMG data system. *Haskins Laboratories Status Report on Speech Research,* SR-25/26, 67-72.
Sagart, L., Hallé, P., De Boysson-Bardies, B., Arabia-Guidet, C. (1986). Tone production in modern Standard Chinese: An electromyographic investigation. *Paper prepared for the 19th Annual Meeting of the International Conference on Sino-Tibetan Languages and Linguistics. (Columbus, Ohio, September, 1986).*
Sawashima, M. (1974). Laryngeal research in experimental phonetics. In T.A. Sebeok et al (Eds.), *Current Trends in Linguistics,* 12, (pp.2303-2348).The Hague: Mouton.
Sawashima, M. & Hirose, H. (1983). Laryngeal gestures in speech production. In P. MacNeilage (Ed.),*The Production of Speech* (pp. 11-38). New York: Springer.
Simada, Z., & Hirose, H. (1971). Physiological correlates of Japanese accent patterns. *Ann. Bull. RILP,* 5, 41-49.
Simada, Z.B., Horiguchi, S., Niimi, S., Hirose,H. (1990). Sternohyoid muscle activity and pitch control at the onset of utterances. *Proc I.C.S.L.P., Kobe,* 449-452.
Simada, Z.B., Niimi, S., & Hirose, H. (1991). On the timing of the sternohyoid muscle activity associated with accent in the Kinki dialect. *Ann.Bull.RILP,* 25, 39-45.
Sonninen, A.A. (1956). The role of the extrinsic laryngeal muscle in length-adjustment of the vocal cords in singing. *Acta Otolaryngol.,* 130
Sugito, M. & Hirose, H. (1978). An electromyographic study of the Kinki accent. *Ann. Bull. RILP,* 12, 35-51.
Sugito, M. & Hirose, H. (1988). Production and perception of accented devoiced vowels in Japanese. *Ann. Bull. RILP,* 22, 21-39.
Titze, I.R. (1991). Mechanisms underlying the control of fundamental frequency. In J. Gauffin and B. Hammarberg (Eds.),*Vocal Fold Physiology. Acoustic, Perceptual, and Physiological Aspects of Voice Mechanisms* (pp. 129-138).San Diego, CA: Singular Publishing Group, Inc.
Zenker, W. (1964). Questions regarding the function of external laryngeal muscles. In "Research Potentials in Voice Physiology", State University of New York Press, 20-40.