THE VELOTRACE: A DEVICE FOR MONITORING VELAR POSITION*

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Abstract. This paper describes the Velotrace, a mechanical device designed to allow the collection of analog data on velar position. The device consists of two levers connected through a push-rod and carried on a pair of thin support rods. The device is positioned in the nasal passage with the internal lever resting on the nasal surface of the velum and the external lever positioned outside the nose. The movements of the external lever reflect the movement of the internal lever as it follows velar movement and are recorded as an analog signal using an optoelectronic position-sensing system. Results of evaluation studies indicate that the Velotrace accurately reflects the relatively rapid movements of the velum during speech.

Introduction

Since the size of the velar port determines the oral or nasal nature of speech sounds, there has long been interest in studying the velopharyngeal region (see Fritzell, 1969, for an extensive historical review). The various techniques used to study the velopharyngeal mechanism have examined a number of its dimensions, one result of which is the recognition that the size of the open velar port is reflected in the position of the velum, although velar position may also vary when the port is completely closed (see, for example, Henderson, 1984; Moll & Daniloff, 1971). These adjustments of velar position above the level at which closure occurs result from the anatomical relationship between the velum and the levator veli palatini (LVP) muscle. That is, since the superior attachment of the LVP muscle lies well above the level at which port closure is complete, increasing contraction of that muscle will continue to raise the velum even after the velopharyngeal port has been closed. As a result, changes in the vertical position of the velum throughout its range of movement may be considered to reflect speech motor control of the velum, and have the additional benefit of not suffering from a boundary effect in the way that velar port size measures do when port closure is achieved (see, for example, Bell-Berti, 1980). Thus, monitoring changes in the vertical position of the velum should allow the discovery of the principles of the (normal) velar motor control, which should increase our understanding of speech production, in general, and also increase our ability to evaluate velar

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control problems in some clinical populations. Thus, and continuing in the tradition of mid-sagittal monitoring of velar function, we have developed a new mechanical device, the Velotrace, that allows the collection of data on velar position in analog form and eliminates the need for X-ray exposure and for frame-by-frame measurements of cine and video recordings.

The Device

The Velotrace (Figure 1) has three major parts: an internal lever, an external lever, and a push-rod between them. The push-rod and levers are carried on a pair of thin support rods. The levers are so connected to the push-rod that when the internal lever is raised, the external lever is deflected toward the subject. The device is loaded with a small spring that improves its frequency response and thus improves the ability of the internal lever to follow rapid downward movements of the velum. The effective length of the internal lever is 30mm (i.e., the linear distance between the fulcrum and tip), that of the external lever is 60mm, and that of the push-rod assembly is 150mm. The height of the device is 4mm and its width is 3mm, making it no larger than many commonly used nasopharyngeal fiberoptic endoscopes.

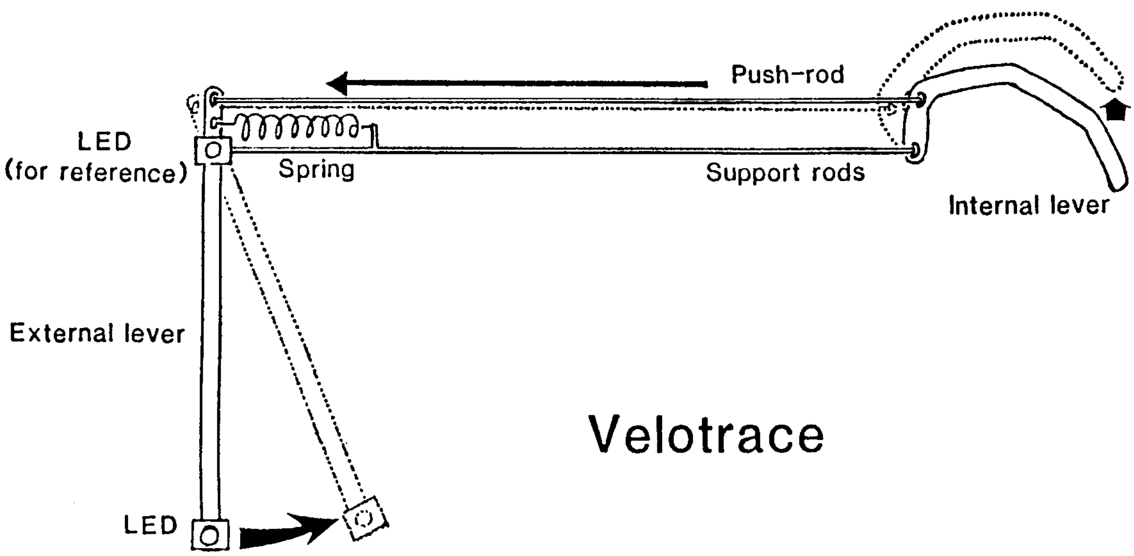

Figure 1. Schematic diagram of the Velotrace.

The device is positioned after topical anesthetic and decongestants have been applied to the nasal mucosa, if necessary, and the posterior pharyngeal wall has become visible through the nasal passage; the Velotrace is inserted using a procedure similar to that used for nasal catheterization. Although the Velotrace is a rigid device (unlike fiberoptic endoscopes), the insertion is easy unless the subject has serious pathologies or deformities in the nasal passage (e.g., substantial deviation of the nasal septum, nasal polyps, etc.).

None of our four subjects (three males and one female) for the evaluation study has complained of any discomfort from the device.

The fulcrum of the internal lever of the Velotrace is positioned at the end of the hard palate, with the internal lever resting on the velum and the support rods resting on the floor of the nasal cavity (Figure 2). An external clamp, which is attached to a headband positioned on the subject's head, is used to stabilize the position of the Velotrace against his/her head during recording sessions.

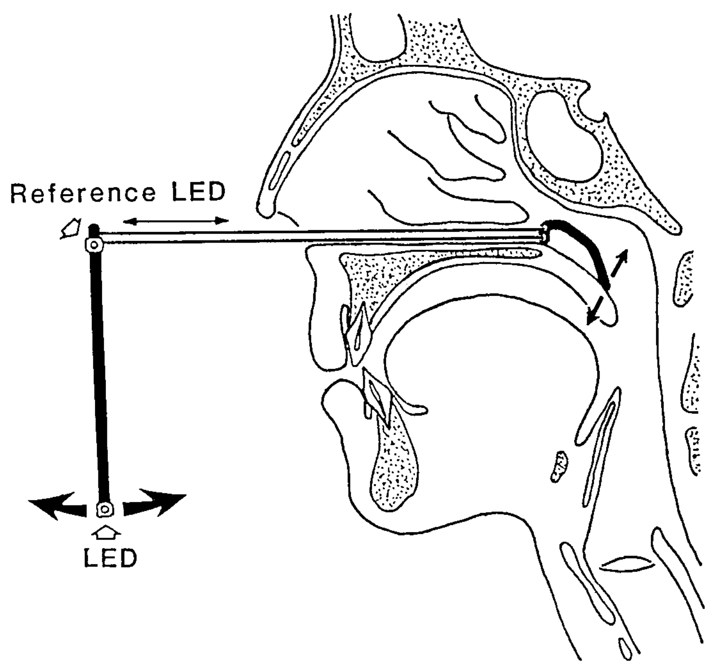

Figure 2. A mid-sagittal schematic drawing of the Velotrace in position with the internal lever resting on the velum.

The Recording System

Monitoring the movements of the external lever can be accomplished in a number of different ways. For example, one might use a velocity-displacement transducer, which would make the Velotrace a convenient stand-alone device for the clinical evaluation of velar movement. Another approach would be to use an optoelectronic tracking system, such as the one we have been using, to monitor the movements of the external lever using infrared Light Emitting Diodes (LEDs) attached to the Velotrace. In our system, one LED is attached to the end of the external lever and allows us to monitor the movement of the lever about its fulcrum. A second LED is positioned at the fulcrum of the external lever and serves as a reference point against which the movements of the end of the external lever can be described. The positions of the LEDs are tracked in two-dimensional space. The acoustic speech signal and a timing signal are recorded simultaneously with the LED-position signals on a multi-channel instrumentation data recorder. The position signals may also be monitored with an oscilloscope in real time. The data acquisition system is represented in Figure 3.

Evaluation Studies

The experimental utterance set was composed of three groups of disyllables (Table 1). The eight items of Utterance Group 1 each contained a medial oral-nasal consonant contrast that was used to insure that maximum stress was placed on the velar lowering mechanism (because the nasal consonant immediately follows a very strongly oral articulation). These utterances allowed us to examine the ability of the Velotrace to follow very rapid downward movements of the velum. Conversely, the eight items of Utterance Group 2 each contained a medial nasal-oral consonant contrast, used to insure that maximum stress was placed on the velar raising mechanism (because a very strongly oral articulation immediately follows a nasal one). These utterances allowed us to examine the ability of the Velotrace to follow very rapid upward movements of the velum. The six items of Utterance Group 3 contained high and low vowel contrasts with medial oral consonant sequences of varying length, and allowed us to examine the ability of the Velotrace to reflect the smaller velar excursions of entirely oral speech. All of the utterances used also had the advantage of having been used in some of our previous work, thus providing the opportunity of comparing the Velotrace data, albeit for different subjects, with endoscopically recorded data.

In the first evaluation study, Velotrace data were compared with previously collected endoscopic data. The endoscopic data used for comparison with the Velotrace data were obtained from two experiments in which frame-by-frame measurements of velar position were made of cine films photographed through a nasally positioned fiberoptic endoscope (Bell-Berti, 1980; Bell-Berti, Baer, Harris, & Niimi, 1979). The subject for the endoscopic studies was a speaker of educated Greater Metropolitan New York City English. In those experiments a long thin plastic strip with grid markings was inserted into the subject's nostril and placed along the floor of the nose and over the nasal surface of the velum, to enhance the contrast between the edge of the supravelar surface and the posterior pharyngeal wall. Then a flexible fiberoptic endoscope was inserted into the subject's nostril, and positioned so that it rested on the floor of the nasal cavity with its objective lens at the posterior border of the hard palate, providing a view of the velum and lateral pharyngeal walls from the level of the hard palate to above the maximum elevation of the velum (observed during blowing). Cine films were taken through the endoscope at 60 frames/sec. The position of the high point of the velum was then tracked, frame-by-frame, with the aid of a small laboratory computer.

The subject for the first Velotrace experiment was a normal speaker of educated Middle Atlantic American English who produced between 7 and 12 repetitions of each of the 22 experimental utterances. The 16 disyllables of Groups 1 and 2 were produced in isolation. The six disyllables of Group 3 were produced in the carrier phrase "It's a (test word) again." Within each group, the utterances were read from randomized lists. The speech acoustic signal and the positions of the LEDs were recorded simultaneously using the system described above. The speech acoustic signal was subsequently digitized at 10,000 samples/sec and the Velotrace signals were digitized at 200 samples/sec.

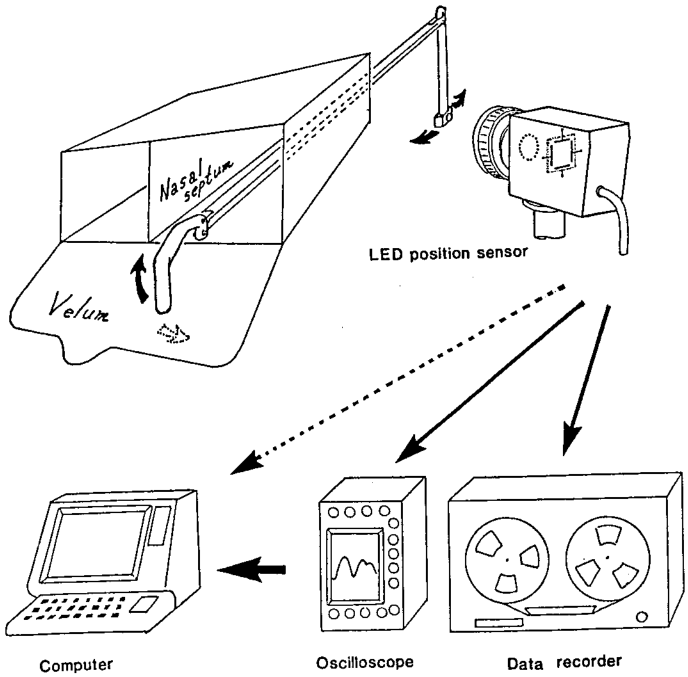

Figure 3. Schematic diagram of the recording and processing system.

Table 1

Experimental Utterance List

Utterance Group 1 (oral-nasal contrast)	Utterance Group 2 (nasal-oral contrast)	Utterance Group 3 (vowel contrast)
/fipmip/	/fimpip/	/flisɑp/
/fɑpmɑp/	/fɑmpɑp/	/flitsɑp/
/fibmip/	/fimbip/	/flistsτɑp/
/fɑbmɑp/	/fɑmbɑp/	/kɑsiz/
/fismip/	/fimsip/	/kɑtsiz/
/fɑsmɑp/	/fɑmsɑp/	/kɑststiz/
/fizmip/	/fimzip/	
/fɑzmɑp/	/fɑmzɑp/	

An acoustic event identified in the waveform of each token of each utterance type served as a reference point for that token in subsequent data analysis. The choice of acoustic reference point depended upon the phonetic structure of the utterance.[1] These reference points have two functions: First, they allow us to examine the physiological signals for repetitions of an utterance type with reference to the same acoustic event. Second, they provide a reference point for aligning tokens of an utterance for calculating an ensemble average of the signals for the repetitions of an utterance type.

The endoscopically collected velar position data had been reduced to ensemble averages and their standard deviations (Bell-Berti, 1980; Bell-Berti et al., 1979). Since the individual token data were no longer available, it was necessary to calculate the equivalent ensemble averages for the Velotrace data. However, before comparing ensemble averages of the Velotrace data with the endoscopic data, we examined the Velotrace token data and averaged data. Samples of both ensemble-average and individual token Velotrace data are shown in Figure 4. The velar movement patterns recorded with the Velotrace are very similar for the tokens of each utterance type, and the individual tokens are also strikingly similar to the ensemble averages. Thus, we conclude that the ensemble averages are representative of the constituent token data, and may be used for comparison of Velotrace data with existing ensemble-average endoscopic data.

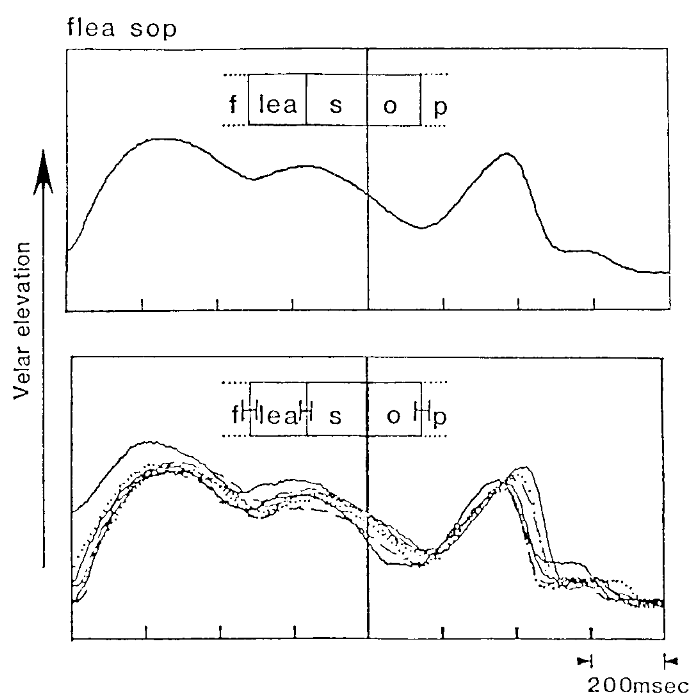

Figure 4. Ensemble-average (above) and individual token (below) Velotrace data for one utterance type. Zero on the abscissa identifies the reference point for aligning tokens of an utterance type for computer sampling and averaging.

Figure 5 displays ensemble averages of two different test words, (one each from Groups 1 and 2) recorded with an endoscope for one subject and with the Velotrace for the other subject. It is clear that the ensemble-averaged Velotrace data display the same patterns as do the frame-by-frame measurement data obtained from the cine films, although the subject, speech rate, and duration of the individual speech sounds are different. We also observe strikingly similar patterns for endoscopic and Velotrace data in which the test words were embedded in a carrier phrase (Figure 6). (See Bell-Berti, 1980, for a description of the experimental design and results of the second endoscopic study.)

For the second evaluation study, cine-radiographic films were taken of a third subject, also a speaker of educated Greater Metropolitan New York City English. The experimental utterances were two tokens each of a subset of six of the utterances used by Bell-Berti et al. (1979) and in the first evaluation study. For this experiment, the Velotrace was positioned in the subject's nasal cavity, with the internal lever resting on the nasal surface of the velum. A thin gold chain was inserted through the other nasal passage and positioned along the velum and into the oropharynx to improve visualization of the nasal surface of the velum in the X-ray images.[2] The films were taken at 60 frames/sec.

Figure 7 represents the film frame image, with the measurement points indicated with numbers on the figure. We measured the position of the tip of the internal lever of the Velotrace (1), the point on the velum that would be tracked by the Velotrace (2), the Velotrace internal fulcrum (3), and two reference points: an upper molar (4) and a lead pellet on the upper incisor (5). Visual inspection of the data on the vertical position of the Velotrace lever and of the velum (see Figure 8) suggests that movements of the Velotrace clearly reflect the movements of the velum itself. In order to quantify the relationship between these measures, we calculated the correlation coefficient between our measures for each of the twelve tokens. The very high linear correlation between these two measurements is reflected in scatterplots of the data (e.g., Figure 9) and in correlation coefficients of between 0.982 and 0.995.

We also compared velocity measures derived from these Velotrace movement data with equivalent velocity measures reported in the literature. To do this, we calculated the velocity of the vertical component of the velar and Velotrace movements. The velocity functions were calculated from successive central difference scores for each sample point. Maximum upward velocity, occurring in the transition between a nasal and a fricative consonant (/fimzip/), may be as high as 130mm/sec; maximum downward velocity, occurring in the transition between fricative and nasal consonants (/fismip/), may be as high as 100mm/sec. These values are similar, but not identical to Kuehn's (1976) data, in which he reports downward velocities as high as 132mm/sec.[3] We also calculated the linear correlation between the velar and Velotrace velocity functions for each token; all are within the range of r=0.90 to r=0.97. On the basis of visual inspection of the functions, the very high positive linear correlations between the two positional measures for each of the 12 tokens in our experimental set, and the equally high correlation between the velocities of these movements, we conclude that the internal lever accurately follows movements of the velum.

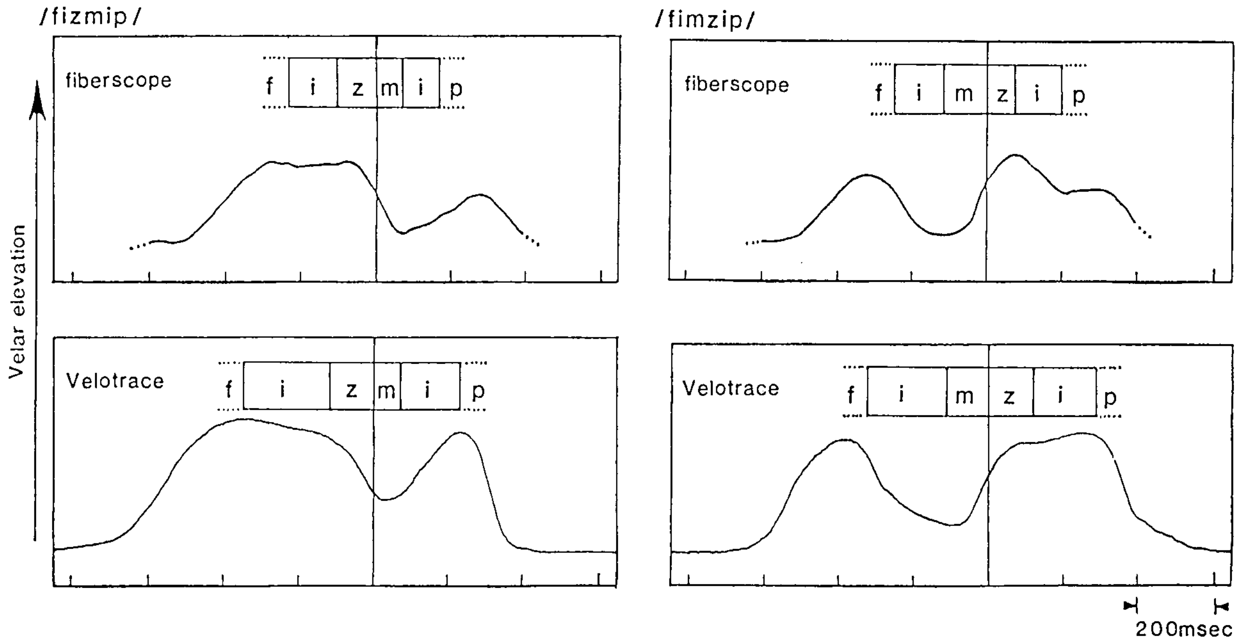

Figure 5. Ensemble-average endoscopic data from one subject (above) and Velotrace data from a second subject (below) for two utterance types (produced in isolation). Zero on the abscissa identifies the reference point for aligning tokens of an utterance type for computer sampling and averaging.

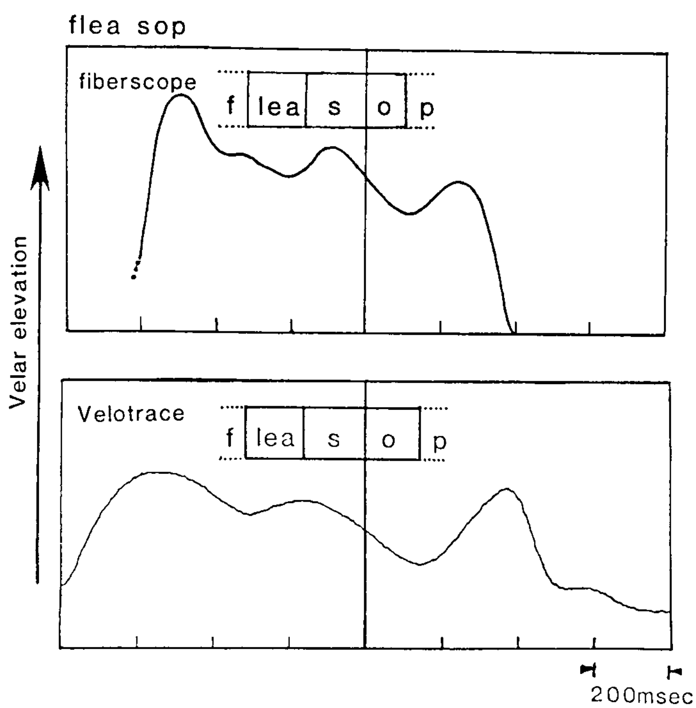

Figure 6. Ensemble-average endoscopic data from one subject (above) and Velotrace data from a second subject (below) for one utterance type (produced in a carrier phrase). Zero on the abscissa identifies the reference point for aligning tokens of an utterance type for computer sampling and averaging.

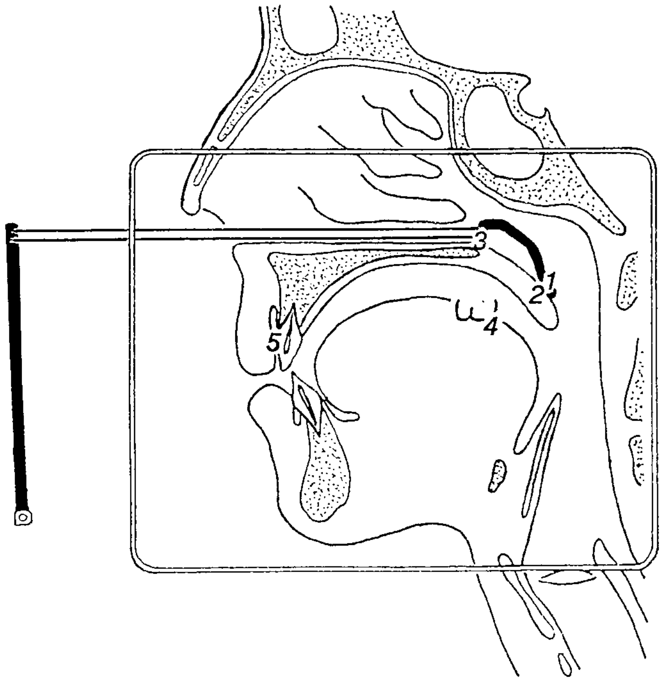

Figure 7. Schematic drawing of lateral cine X-ray film frame image with the Velotrace in place and measurement points indicated: (1) tip of the Velotrace internal lever; (2) the point on the velum that would be tracked by the Velotrace; (3) Velotrace internal lever fulcrum; (4) upper molar reference point; (5) upper incisor reference point.

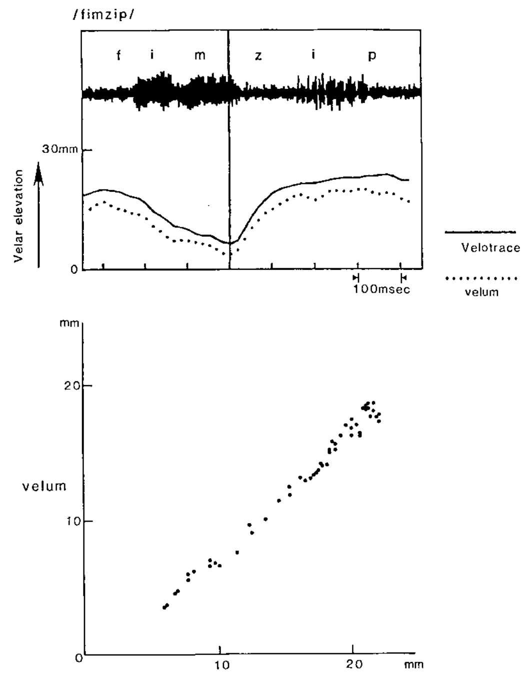

Figure 8. Comparison between the actual vertical movement of the velum and the movement of the tip of the internal lever of the Velotrace. The time function for one token is shown in the upper panel, with the acoustic waveform at the top and the Velotrace tip elevation (solid line) and velar elevation (dotted line) data below. A scatterplot of velar elevation and Velotrace tip elevation for each sample point in one token is shown in the lower panel.

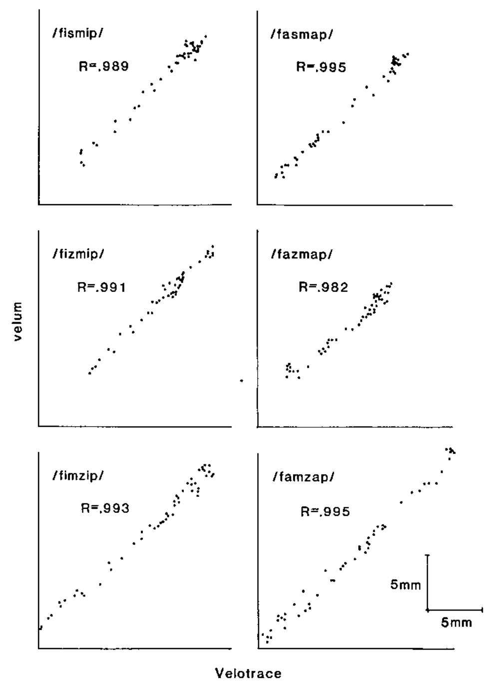

Figure 9. Scatterplots of vertical velar position vs. Velotrace position data for one token of each utterance type.

Conclusion

In evaluating the Velotrace, we compared data collected with the Velotrace with data obtained from frame-by-frame measurements of cine films (both endoscopic and radiographic) and found that the Velotrace signal accurately reflects the relatively rapid movements of the velum during speech. Among the advantages of the Velotrace as a device for monitoring the velum during speech are the elimination of X-ray exposure for the subject, and of frame-by-frame measurement for the investigator. Furthermore, the elimination of both of these drawbacks makes possible the collection and analysis of substantial quantities of data that should allow the development of a more complete understanding of velar motor control. In addition, the analog Velotrace signal can be sampled at a sufficiently high frequency to allow calculation of the highly accurate velocity and acceleration functions of velar movement patterns.

The Velotrace has a number of potential applications, among them the study of velar kinematics in normal speakers. Additionally, it may be used to monitor velar function in a number of different speech pathologies. For example, by carrying out clinical studies of individuals suffering from neuromuscular pathologies that affect velar function during speech and swallowing, one should be able to provide objective descriptions of the nature of the disruptions of speech and swallowing, although the Velotrace does not provide information about lateral pharyngeal wall movement. Such information should also provide further insight into the nature of the organizational patterns of velar motor control. Another application would be to the study of velar movement patterns in persons with velopharyngeal insufficiency, to examine the ways in which vertical movements of the velum differ from, or are similar to, those of normal speakers: That is, do they use "normal" or nearly normal articulatory strategies that fail because of anatomical and/or physiological limitations? Similar studies could be conducted with persons having mobile repaired clefts, to identify their articulatory strategies. Finally, the Velotrace may serve as a biofeedback device for training individuals with a variety of velar function problems, including pre-lingual hearing impairment, as well as the disorders mentioned above. We would note, however, that extending the use of the Velotrace to studies of children's speech depends upon considerations of instrumental and anatomical size, as well as interference of the adenoids with the function of the internal lever. Furthermore, the use of this device to study velopharyngeal function in persons with anatomical anomalies may require modification of the device.

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Footnotes

[1]For Group 1 utterances, the beginning of [m] was chosen as the reference point (voicing onset following [p]; voicing onset or end of frication following [s]; increased amplitude following [b]; end of frication following [z]). For Group 2 utterances, the end of [m] was chosen as the acoustic reference point (voicing offset before [p]; voicing offset or beginning of frication before [s]; amplitude reduction or voicing offset before [b]; beginning of frication before [z]). For Group 3 utterances, the end of the medial consonant-sequence occlusion was chosen as the acoustic reference point (end of frication for [...sV] and the stop burst for [...tV] utterances).

[2]As a result of field-size limitations and because we were primarily interested in knowing how well the internal lever follows movements of the velum (rather than how well the external lever reflects movements of the internal lever), the external lever was not included in the viewing field.

[3]Kuehn's displacement-versus-time data, taken from the constant velocity portion of displacement-versus-time curves, are not directly comparable with our data for two reasons. First, his data are measures of Euclidean

distance, whereas ours are of vertical distance only. Second, his data are an index of the velocity during the relatively constant velocity portion of the gesture, whereas ours are the peak values in the first derivatives of our displacement-versus-time functions. However, using the angular factor that he reported, we have estimated the maximum y-trajectory velocities for each of his two subjects. The maximum y-trajectory upward velocities are 54mm/sec and 90mm/sec; downward velocities are 38mm/sec and 83mm/sec.