An electropalatographic and optoelectronic analysis of Swedish [s] production

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The objective of this study was to evaluate the usefulness of electropalatography (EPG) as a method for diagnostic analysis of the [s] sound and also to make a multiple analysis of the production of the normal Swedish [s] sound in various contexts. Eleven dental students participated. EPG registration, optoelectronic recording of jaw movements, and acoustic registration of a test phrase were made simultaneously. A speech perceptual test was also made. There were four separate recording sessions. Except for at session I, subjects wore an EPG palate. At session II they were not adapted to it, in contrast to the later occasions. The EPG appeared to be a valid method for investigating the [s] sound. In general, EPG and mandibular movement patterns were similar between sessions, and the sound quality normal throughout. At session II, however, the tongue groove was wider, the mandibular movements smaller, and the [s] quality somewhat deteriorated. [s] in various contexts had different tongue groove widths but similar high average mandibular position. To prevent speech and especially [s] sound problems when constructing prosthetic devices, it is important to advance our knowledge of [s] sound production. □ *Electropalatography; mandibular movement; phonetics*

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Fundamental studies are essential to delineate processes of speech production as a part of motor function. In connection with prosthetic rehabilitation, proper motor control of the jaw and tongue is essential to achieve a successful phonetic result. Studies are also necessary to clarify adaptive behavior after rehabilitation with prosthetic appliances. To achieve this, it is important to have good knowledge of normal speech production that involves the dentoalveolar region.

The pronunciation of [s] is often affected by changes in the upper dentoalveolar region. The [s] sound is found in nearly all languages of the world (1, 2). A considerable number of people wear complete dentures or fixed prostheses that influence the incisor region (3). Therefore, mispronounced [s] due to tooth problems is of great clinical importance, and a mispronounced [s] often turns into a lisping sound.

Interpersonal understanding will hardly ever be disturbed by a mispronounced [s] sound alone. Nevertheless, lisping is a handicap from other aspects. Since [s] is frequent and perceptually pregnant, this phenomenon is easily perceived (3). Irrespective of others' reactions, lispers are often embarrassed by their [s] quality and sometimes may avoid speaking in several situations. The attention of many listeners is also easily drawn from what is said to how it is said.

With regard to [s] production requirements with prosthesis, dentists follow the line of trial and error. As an example, a common but not proven and perhaps even false opinion among dentists is that the interdental spaces in fixed prosthesis on osseointegrated implants (FPOI) may affect the [s] quality (4). To increase our knowledge in this field, a description of not least the aerodynamic aspects of [s] production is anticipated (5–7).

Objectives

The objectives of this study were, first, to evaluate the usefulness of electropalatography (EPG) as a diagnostic method of analysis of the [s] sound and, secondly, to make a multiple analysis of the production of the normal Swedish [s] in various contexts, achieved by simultaneously recordings of the tongue contact pattern and mandibular movements.

Materials and methods

Materials

Eleven dental students participated, five men and six women (mean age, 26 years; range, 21–46 years). All had normal speech without a foreign accent or hearing deficits, a full arch of natural teeth, no signs or symptoms of cranomandibular disorders, and good health.

The material consisted of a phrase and a text. The phrase was 'å sadist' [osa'dɪst], meaning 'oh sadist'. This was uttered three times at each session with half a minute's pause or more in between. It was chosen to

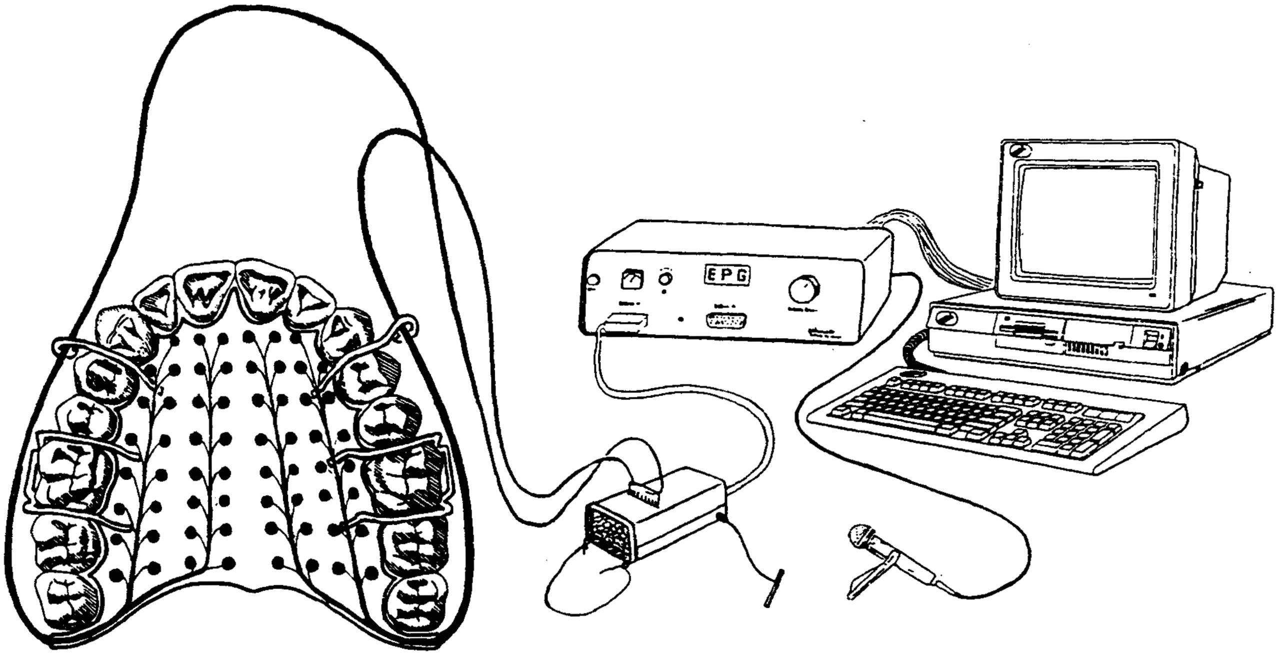

Fig. 1. The test set-up for the electropalatographic (EPG) registration with the palate, the interface, and the IBM computer.

study [s] in two very different contexts (A and B). In the A position the [s] context was two non-close vowels; in the B position the context was the fairly closed frontal vowel [I], and [t], both with front tongue positions more similar to [s]. The relation to stress also differed in the onset of an unstressed syllable (A) versus in the corda (end part) of a main stressed syllable (B).

A tape recording was also made of each subject reading a part of a short text often used for standardized perceptual evaluation of pronunciation: 'Nordanvinden och solen' ('The north wind and the sun').

Methods

All recordings, simultaneous EPG registration, optoelectronic recording of jaw movements, and acoustic registration of the production of the test phrase were made at the Department of Prosthetic Dentistry, Göteborg University.

The recordings of the short text and the phrase were randomly mixed and judged by four speech pathologists. These experts judged each [s] sound on the basis of a 4-point scale, where 0 = perfect, 1 = acceptable, 2 = slightly distorted, and 3 = definitely distorted.

The main acoustic registration was made with a microphone and tape recorder. The microphone was placed about 10 cm from the speaker's mouth, about 45° to the side of the midline. This signal was used for perceptual analysis of sound quality. The audio signal was also fed into a computer synchronically with the optoelectronic registration and later presented as a low-pass filtered oscillogram in parallel with the mandibular curves. This audio registration was used for identifying the sound segments in the jaw movement curves.

Each subject was audiologically tested at the Otorhinolaryngological Department, Sahlgren's Hospital, Göteborg. A standard test was used to examine whether the hearing was normal within the speech sound domain.

The EPG equipment has been described in detail and compared with other types of EPG devices elsewhere (8, 9). In short, it consisted of a system of 62 electrodes inserted in an individually made acrylic palate (Fig. 1). It covered the whole palatal vault from the teeth back to palatum molle. Its thickness varied between 0.5 and 1.5 mm. The palate was connected to the EPG main unit via a signal processing device (the multiplexer) (Fig. 1). The electrodes were scanned and detected tongue contacts registered at a frequency of 100 Hz. The data acquired by the EPG unit were saved and processed in a computer. The processed information was displayed in frames, each showing tongue contact pattern every 10 msec (Fig. 2).

The optoelectronic equipment for monitoring mandibular movements at a frequency of 400 Hz was based on light-emitting diodes and a computer program (10) (Fig. 3). The movements can be presented as calibrated curves and/or quantitative data giving values for displacement amplitudes, cycle duration, velocity, and velocity changes. In this study the movement of only one diode attached to the chin was registered. Calibrated curves of vertical and sagittal movements of this point were produced.

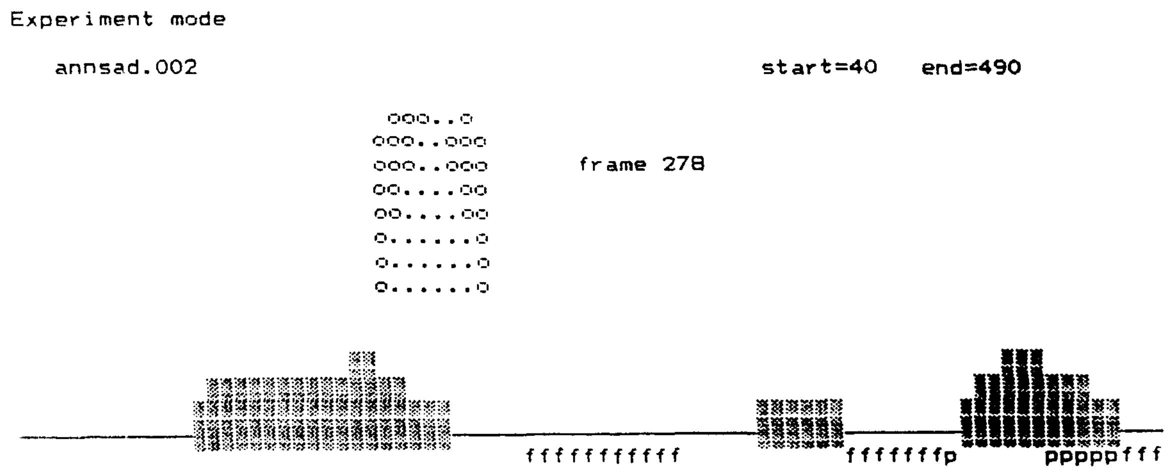

Fig. 2. Electropalatographic (EPG) printout for one of the frames registering [s]. Points denote untouched electrodes, zero denotes electrodes with lingual contact. f = fricatives; p = plosives. The shaded parts on the line are vowels.

Procedures

In total, there were four recording sessions (Fig. 4). At session I a clinical examination was performed and a questionnaire delivered. It contained questions concerning medical history and speech items. Optoelectronic and acoustic recordings were also made. At session II the first round of registrations were made with the EPG equipment, simultaneously with optoelectronic and acoustic recordings. To achieve adaptation, the subjects were given a dummy palate to wear day and night until session III, 2 weeks later.

Sessions III and IV were performed on the same day, with 4 h in between. The same registrations as at session II were made. During the 4 intermediate hours, the subjects did not wear the dummy palate, to evaluate the effect of sensorimotor memory.

EPG registration analysis. The main part of [s] is produced with a narrow groove made by the upper front part of the tongue against the alveolar crest. In the EPG registration frame this corresponds to lateral contacts and a narrow medial opening in one or often more of the front three electrode rows (Fig. 2). Measurements were made in the constriction phase for all occurrences of [s].

For practical purposes the constriction phase of [s] was operationally defined as consisting of all EPG frames with four or less free (untouched) electrodes in at least one of the front four rows (Fig. 2). Measurements were made of the number of EPG frames in this constriction phase with maximally four, three, two, and one free electrodes in at least one row.

In addition to the measurements, systematic observations of EPG features of the [s] groove and of other sounds of the test phrase were made.

Mandibular movement curve analysis. In the mandibular movement curves measurements were made of the vertical and sagittal amplitudes of the first and second [s]—called A and B—in the test phrase 'å sadist' and also of the vertical and sagittal amplitude differences

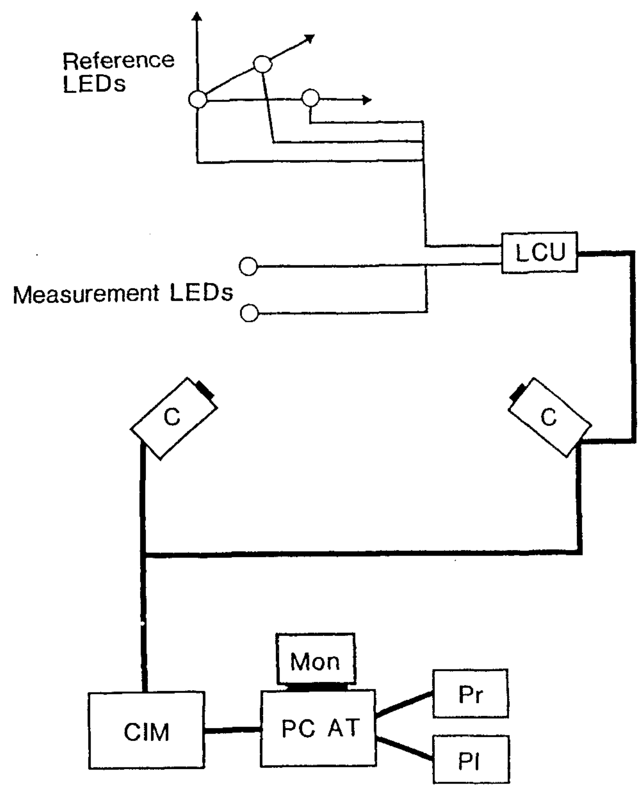

Fig. 3. Optoelectronic test set-up. LED = light-emitting diode; LCU = LED control unit; C = camera; CIM = camera interface module; MON = monitor; PC AT = personal computer; Pl = plotter; Pr = printer.

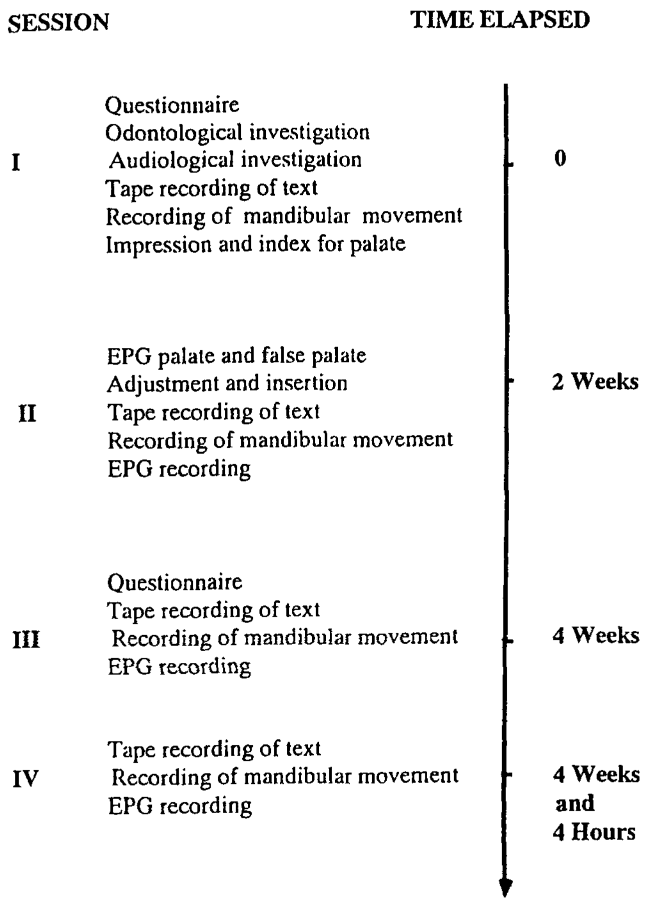

Fig. 4. Experimental model—sessions and registrations.

between [s]A and [a], and [s]B and [I] (Fig. 5). Reference was the mandibular position before the phrase, when the subjects were asked to close their mouth to the intercuspal position. In addition to those measurements, systematic observations of mandibular curve features in [s] were carried out.

Statistical analysis. Wilcoxon's signed rank test for nonparametric values was used. Statistical calculations were made to analyze contrasts and similarities between the different sessions and the two different [s]A and [s]B. The relations between two or more simultaneous variables were also calculated, such as EPG and mandibular curve correlates of perceived [s] quality differences.

Results

Questionnaire

All subjects declared that they were healthy. Eight of them considered themselves to have a regional dialectal variant of standard Swedish.

Nine subjects thought their speech had become fairly normal after 1 week's permanent palate-wearing, whereas two found it difficult to adapt to their palate. Seven subjects considered themselves lispers when first wearing their dummy palate. Three others noted that their palate fitted badly. Two persons reported increased salivation during the 1st week.

Audiologic examination

All subjects passed the audiologic examination with results within the range of normal variation.

Auditory judgement of pronunciation

Listening analysis showed that all the subjects had a constant flawless pronunciation (Fig. 6). The average quality of [s] varied between 'acceptable' and 'perfect' at all sessions. However, the general speech quality was somewhat deteriorated at session II ($p < 0.01$) (Fig. 6). There was also a change between sessions III and IV ($p < 0.05$).

EPG pattern data

The general [s] contact pattern in all EPG recordings was similar: a longitudinal, central—or fairly central—tongue groove configuration was seen in one or more of the front three rows—that is, in the incisor region. The duration of the tongue contact was typically 100–170 msec.

In all [s] sounds there was also a dynamic change in the groove width. Thus three phases were generally found: a narrowing first phase, a fairly stable middle phase, and a final phase. The duration of the middle phase was generally longer than the added durations of the peripheral ones ($p < 0.05$). In addition, the duration of the first phase tended to be longer than the final one in both [s] sounds ($p < 0.05$). The first two phases had similar character in [s]A and [s]B, but the final phase was different. In [s]A it consisted of a widening to the following [a], but in [s]B it was a narrowing into the total occlusion of [t]. Only the first two phases are dealt with here.

The two [s] sounds had also different groove width, [s]A being considerably narrower in most subjects ($p < 0.05$)(Fig. 7). A common pattern was that [s]A reached a stable phase with only one free electrode in the narrowest part of the groove, whereas [s]B had two. This pattern, however, varied between sessions and individuals.

Most of the speakers had a wider minimal groove constriction in both [s] sounds in session II than in sessions III and IV. Thus, the width differed significantly between sessions II and III ($p < 0.05$) and also between sessions II and IV ($p < 0.05$). The difference was commoner in [s]A than in [s]B ($p < 0.05$).

Considerable interindividual variation was found in

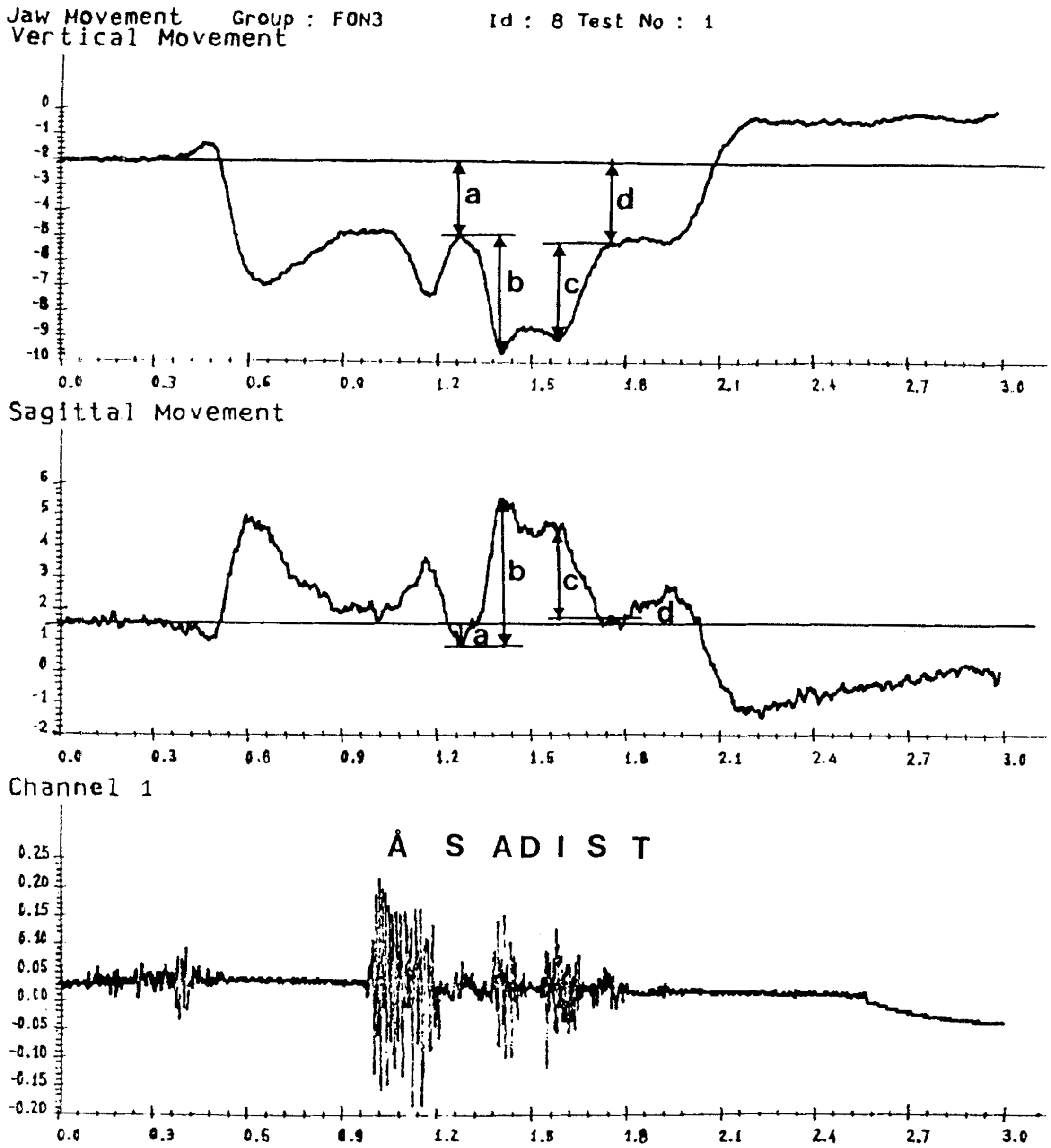

Fig. 5. An example of mandibular movements when uttering 'å sadist' and the measurements. a = distance from base-line to jaw position in the first [s]; b = distance from jaw position in the first [s] to jaw position in the [a]; c = distance from jaw position in the second [s] to jaw position in the [I]; d = distance from base-line to jaw position in the second [s].

various EPG aspects of [s] production, such as general groove width, length, and position. The position varied in both the sagittal and lateral dimension (Table 1).

Palate contacts in [a] and [I] were small compared with [s]. The common pattern in [a] was contact in the back part—three or four electrodes—of the outer rows, with the six middle rows free; in [I] it was contact in the four outermost rows, with the four middle rows free (Fig. 7). There were no systematic changes between sessions. However, there were individual differences; especially, five subjects had a very narrow opening in [I], consisting of two completely free middle rows. Furthermore, seven subjects had cases of [a] contacts in five or more of the outer row of electrodes. Only one subject had cases of no [a] contact at all.

Mandibular movement data

The general jaw movement pattern in 'å sadist' was fairly similar for all subjects (Fig. 5). The vowels [a]

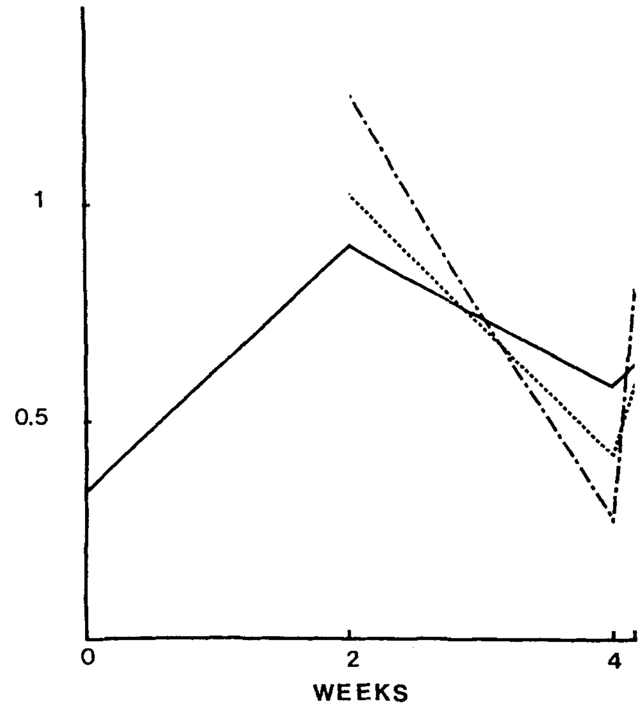

Fig. 6. Perceptual analysis of [s] both with the phrase 'å sadist' and the short text. Vertical axis = mean perceptual values. 0 = perfect; 1 = acceptable; 2 = slightly distorted; 3 = definitively distorted. Horizontal axis = time.

and [I] correspond to dips, and the consonants [s]A, [d], and [st] to peaks. The conspicuous depth of the [a] dip was fairly constant, whereas the depth of the [I] valley varied more. The [d] peak amplitude also varied considerably. Unlike this, both [s]A and [s]B showed a high mandibular position.

The shape of sagittal mandibular curves was similar to the vertical ones, showing oscillations in which vowels and consonants were usually antipodes (Fig. 5). However, their sagittal amplitude values were considerably lower in all sound segments except the [s] sounds ($p < 0.05$).

Measurements were made of absolute vertical and sagittal amplitude values in [s]A and [s]B and also of the vertical and sagittal amplitude differences between both [s]A and [a] and [I] and [s]B.

No significant vertical or sagittal jaw level difference between [s]A and [s]B was found.

The average vertical jaw movement amplitudes were smaller in session II than in session I ($p < 0.05$) and sessions III and IV ($p < 0.05$). However, the absolute jaw amplitude values in [s]A and [s]B did not differ significantly in the various sessions. These jaw movement values did not differ in either session III or session IV compared with session I. In addition to these differences in movement amplitude between sessions, some differences in curve shape were found. Thus two subjects

Table 1. General [s] groove characteristics for each subject

Subject no.	Lateral groove position: central (C), right (R), left (L)	Groove parallel (P) or oblique (O) in relation to sagittal plane	Groove symmetric (S) or asymmetric (A)	Sagittal groove position in relation to electrode row (row 1 in front)	Groove length (no. of electrode rows included in narrow constriction)	Groove width (no. of free electrodes)	Groove width in [s]A compared with [s]B	Groove width in session II compared with session III
1	L	O	A	3–4	2	2	Equal	II > III
2	C	P	S	3	1	2	[s]A < [s]B	II > III
3	L	O	A	1–3	3	3	[s]A > [s]B	Equal
4	C	P	S	2	1	1	[s]A < [s]B	II > III
5	C	P	S	2–3	2	1	[s]A < [s]B	II > III
6	L	P	A	2	1	2	[s]A < [s]B	II > III
7	C	P	S	2	1	1	[s]A < [s]B	II > III
8	C	O	A	1	1	1	[s]A < [s]B	II > III
9	C	O	A	2	1	2	Equal	Equal
10	C	P	S	1	1	1	Equal	II > III
11	C	O	A	2–3	2	2	[s]A < [s]B	Equal

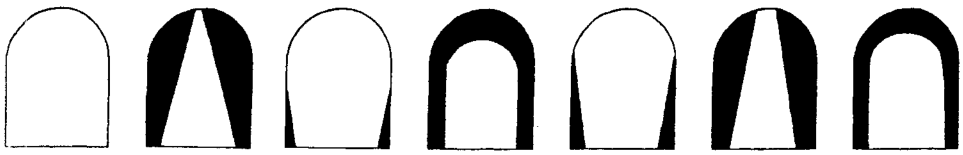

Fig. 7. Schematic electropalatographic (EPG) diagrams for the sounds in 'å sadist'.

had a vertical dip in [o] in session II but a peak otherwise.

The general appearance of the mandibular movements were oscillating, with practically no jerks or excursions. However, the phenomena described in the above paragraph are exceptions to the rule and found in just a few individuals.

Discussion

The EPG method proved to be appropriate for a detailed analysis of some highly important aspects of normal [s] production—namely the width, length, and position of the front tongue groove in the incisive region. These dimensions could be observed and measured both statistically and dynamically.

However, there are aspects that cannot be studied by this method, such as the groove depth and transverse shape or which part of the tongue is used. Other important aspects are also outside its scope, like the incisive dental position in relation to the frontal groove opening and the dimensions of the anterior cavity (12).

Consequently, an exhaustive analysis of vocal tract shape in [s] production has to combine EPG with other methods, like ultrasonic analysis, different X-ray mappings, optoelectronic articulatory movement tracking, and acoustic anlaysis. The possibilities and limitations of these and other methods have been discussed elsewhere (9, 13).

The optoelectronic method has been used earlier for analysis of masticatory movements (10) and more recently for speech examinations (17). An important matter to consider is the placement of the diode on the chin point. The tissue of the chin is movable in relation to the bony part of the mandible owing to activity of the mentalis muscle. In mastication this has proved to be a minor problem with an error of ± 0.5 mm (18). In speech, however, the error is evidently much greater in labial sounds, like [p b m f v] and [u o], but less in others. This error was of minor significance in this study, since the test phrase had no labial sound other than the rounded initial vowel [o].

In most cases a turning point occurred in the mandibular curve within a sound segment, a peak in a consonant and a dip in a vowel for the vertical dimension, representing maximally high and low momentary jaw positions. This is in line with the findings of other authors (17). Whenever this was the case, the amplitude of this point was measured. Sometimes no turning point occurred within a segment but rather a derivative turning point, appearing as a sloping shelf in the curve (Fig. 5). In this case the amplitude in the moment corresponding to the turning point of differentiated curve was measured. When none of these conditions occurred, the average amplitude of the whole sound segment was measured. This last case differs theoretically from the others, which all manifest a change in the muscular command pattern. In both [s]A and [s]B such mandibular patterns with no direct or derivative turning point were found, totally in about 30% of all cases.

The EPG study showed that the groove of [s]A was significantly narrower than that of [s]B ($p < 0.05$). This finding—a variable articulation— has to our knowledge not been reported previously. Earlier studies of [s] production have given the general picture of constancy, in contrast to several other sounds, such as in studies of the front tongue shape and position as seen in profile in the mid-sagittal plane (15, 19, 20). There may be two reasons for this contrast. First, previous studies have not investigated the groove width or other dimensional aspects, which may vary more than others. Secondly, and perhaps more important, [s] has earlier generally been studied in strong (stressed) position, with various vowel contexts only (21). In the present investigation, however, strength conditions were varied; [s]A appeared initially in an unstressed syllable, and [s]B was finally followed by [t] in a stressed syllable. Our material does not systematically separate vowel and strength position, so the relative importance of each factor cannot be settled here.

Another finding was that the width of the groove was significantly wider in session II than in sessions III and IV. This might be anticipated, since speaking immediately after receiving an intraoral palate, without an adaptation period, must be difficult. This concerns particularly [s], for which the requirements for sensorimotor coordination are significant (22). The time required to adapt to the palate is individual, owing to factors such as motor ability, age, and motivation. This is similar to a prosthetic rehabilitation with a denture and an issue to consider in related speech problems. A time interval of 2 weeks between sessions II and III was chosen mainly because of earlier reported data on the adaptation period (23). Certainly, several persons will adapt faster—some of our subjects had a divergingly wide [s] groove only in the first phrase production in session II. In the following phrases, uttered some minutes later, the EPG pattern was quite like the one in sessions III and IV.

The position of the groove varied among the subjects (Table 1). Five of them had a symmetric groove in mid-position, but six had an asymmetric one with only left distribution. Six cases were oblique. In one case the groove was curved. An obvious stability was found for all subjects. This aspect of [s] production has been described earlier with similar result (24).

In general, no systematic differences in EPG patterns for the whole phrase could be seen between sessions. This implies that the frontal part of the tongue was successful in articulating most sounds in a constant manner despite the palate situation. This result is in line with the ability to adapt to speech production immediately in a new situation and has its application in prosthetic treatment (25, 26). However, the difference in the groove width between sessions II and III is an exception to this rule. A reasonable explanation might be the very strong accuracy prerequisites in [s] in comparison with most other sounds (22).

Generally, the mandible movements in vertical and sagittal dimensions were analog, the vertical movement being greater. However, in most cases of [s] pronounced by 10 subjects the sagittal movement deviated in this aspect, being clearly greater forwards. The reason for this is probably a special production condition: in [s] and other sibilants the front teeth play an important role as an obstacle that splits the air jet from the groove, resulting in a special, sibilant sound source, supposed to contribute significantly to its sharp and strong quality and strength (29). It is reasonable to suppose that the diverging forward sagittal jaw movement component has a connection with this special condition.

Some data from X-ray films on [s] of a single Swedish speaker also showed a noticeable forward sagittal jaw movement in [s] and other sibilants (20, 30). This has been interpreted as a result of this person's large overjet (30). According to our data, most speakers seem to have a special forward sagittal movement in [s]. Therefore, a reasonable hypothesis is that speakers with great overjet move their mandible more than others in the sagittal plane for [s] and similar sounds.

Both [s]A and [s]B had a high average mandibular position. This has been found also in other studies (20). There was no difference in position between [s]A and [s]B. Unlike most other sounds, a low jaw position cannot be compensated for by the tongue in [s]. This is generally ascribed to the need to create a tooth sound source in addition to the groove source and also the need to produce a small anterior resonance cavity (12, 20). Not only the front cavity length but also its other dimensions are important for a proper [s] (12). A larger cavity will produce a darker quality similar to [ʃ]. However, during [s] production in our material, the mandible moved continuously, and sometimes the movement was large—up to 5 mm but often 2 to 3 mm—in both [s]A and [s]B. In [s]A the mandibular curve usually fell from a maximum near the start, whereas in [s]B the jaw maximum came late in [s] or in [t], and the start of [s] had a lower jaw position. This means that the interplay between tongue and jaw must vary to a great extent, the tongue muscles working more to create the obstacle in the start in [s]B, in which the jaw is lower.

In all sessions [s] had a fairly constant absolute jaw amplitude. Moreover, in sessions I, III, and IV the amplitudes of movements between [s] and a neighboring vowel were similar. This probably means that the general jaw amplitude during the whole phrase in relation to the hard palate was not changed in sessions III and IV, despite the presence of the EPG palate, which was about 1 mm thick. Obviously, if there was adaptation to the new situation, the tongue was active. Tongue, and not jaw, adaptation was doubtlessly the case during the [s] segments in all sessions with the EPG palate.

The strong tendency to smaller jaw movements in session II than in the other sessions is an indication of the anticipated difficulty for the subjects to speak with a foreign object—the EPG palate—in the mouth for the first time. In session I no palate was worn, and in the later sessions an adaptation had occurred. Although the oral space was diminished in session II, the jaw was moving closer to the hard palate. The opposite would have been less surprising. Reasonably, this articulatory aberration contributed to the deteriorated perceived speech quality at this session. The need for further studies of [s] with simultaneous study also of tongue movements is obvious.

It is well known that oral rehabilitation with a prosthetic reconstruction may interfere with speech (3, 4). This is related to factors such as formation of the air jet, tongue tip position, and the front teeth (3, 5, 11, 16, 20, 24). Especially the [s] sound may deteriorate (4). However, the mechanisms of the speech interference are not fully clarified.

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