



# Hyoid and tongue surface movements in speaking and eating

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## Abstract

The human hyoid moves continuously in feeding, facilitating movements of the tongue surface and the processing and transport of food. The hypothesis that similar hyoid movements support tongue movements in speech was tested in 10 normal young adults of both sexes, who were recorded with lateral-projection videofluorography when feeding on hard and soft foods and when reading the 'Grandfather Passage', which includes the major vowel-consonant combinations in English. Recordings were made with and without tongue-markers. Images were analysed with a digital frame grabber and computer. Each participant served as his/her own control. The hyoid moved continuously during speech and feeding. In speech, hyoid motions were irregular and not linked to jaw movement, as they were for feeding. The centroids and variances of the domains for all reference points were compared for speech and feeding; the centroid represents the average position of a structure and variance its amount of motion. Gape and hyoid centroids were significantly different for feeding and speech ( $P < 0.001$ ), but differences for gape averaged  $< 1$  mm while the difference for the hyoid centroid was  $> 7$  mm. There were no significant differences in gape attributable to sex. Consistent with the known differences in hyolaryngeal position there were significant differences in hyoid centroid ( $P = 0.031$ ) but not variance. In speech, tongue-markers had a smaller spatial domain ( $P = 0.001$ ) condensed within the larger feeding domain. The small shift in the gape centroid does not explain the larger forward shift of the hyoid during speech. These findings raise questions about the neuromotor control of hyoid position in the two behaviours and the biomechanics of the supralaryngeal vocal tract. © 2002 Elsevier Science Ltd. All rights reserved.

**Keywords:** Hyoid; Jaw; Tongue; Speech; Eating; Swallowing; Videofluorography

## 1. Introduction

Humans are unique in having an oropharyngeal complex that serves two fundamentally different functions, eating and speaking. The human supralaryngeal vocal tract consists of two partially separate tubes of variable dimensions (Fig. 1A): (1) an anterior, horizontal component stretching from the lips anteriorly to the posterior oropharyngeal wall, behind the soft palate (SVT<sub>h</sub>), and (2) a posterior vertical component (SVT<sub>v</sub>) from the nasopharynx (above the soft palate) to the vocal folds (Negus, 1949). Exhaled air can

move throughout these spaces as well as through the nasal cavity above the hard palate. In contrast, the movement and manipulation of food is normally restricted to the mouth, oropharynx and hypopharynx (Fig. 1A). The morphology of the tract changes with age: at birth the posterior segment is very short, with the tip of the epiglottis behind the soft palate, i.e. the 'intranarial larynx' (Negus, 1949). The hyolaryngeal complex descends in the neck during childhood, reaching its adult position relative to the cervical vertebrae (C2–C3) at about 2 years (Lieberman et al., 2001). Thereafter, further descent is associated with the overall growth of the pharynx and vertebral column, but with a further pubertal descent in males. Fitch and Giedd (1999) studied the age changes in the system using midsagittal sections from cranial magnetic resonance images of individuals ranging in age from 3 to 25 years. The results of that cross-sectional study and the more

*Abbreviation:* SVT, supralaryngeal vocal tract

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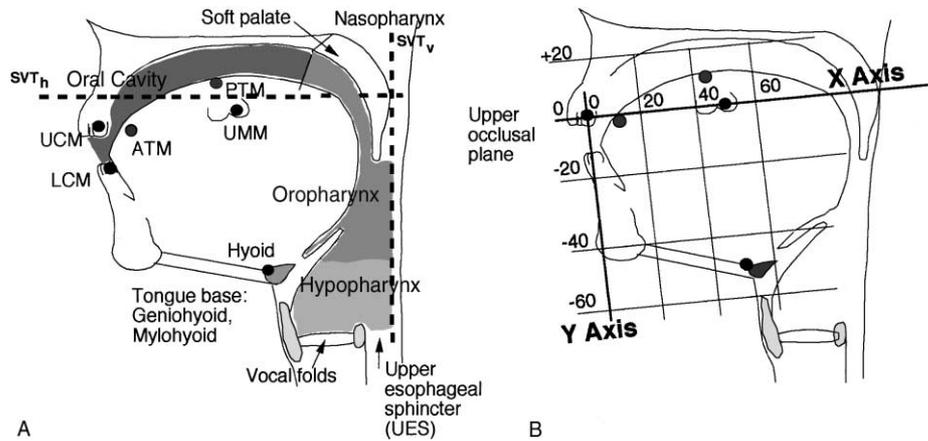


Fig. 1. Diagrammatic parasagittal sections through the human oropharyngeal complex. (A) The major anatomical features of the oropharyngeal complex discussed in the text are shown. The spaces used in feeding are shaded: food is normally processed in the oral cavity, triturated food (or a liquid bolus) passes into the oropharynx, and then through the hypopharynx into the oesophagus through the opened upper oesophageal sphincter. The volumes of the vertical and horizontal components of the supralaryngeal vocal tract are different. The horizontal component ( $SVT_h$ ) runs from the lips to the posterior pharyngeal wall, i.e. behind the soft palate, the vertical ( $SVT_v$ ) includes the nasopharynx. While food does not, normally, enter the nasopharynx, air passes anteriorly through the mouth in speech. The upper canine marker (UCM) and upper molar marker (UMM) are the reference points used to establish the upper occlusal reference plane. The lower canine marker (LCM) is used as the reference for jaw movement (gape) and the superoanterior corner of the hyoid shadow is the hyoid reference. Tongue-markers (ATM, anterior; PTM, posterior) are shown as circles. (B) Illustrates the coordinate 'grid' used to prepare the data and Figs. 3–7. The grid is zeroed at the UCM. Given the use of an upper occlusal plane, tongue-marker positions, when the tongue is in contact with the hard palate, occur above that plane (i.e. both  $X$  and  $Y$  are positive). In contrast, tongue- and hyoid-marker positions below that plane have positive  $X$  and negative  $Y$  values, unless the lower jaw is protruded such that the LCM moves anterior to the  $Y$ -axis. For clarity, Figs. 5–7 are shown as sections of this grid, rather than as plots using the entire field as in Fig. 3.

recent longitudinal study (Lieberman et al., 2001) based on the serial radiographs obtained for the Denver Growth Study show a consistent growth pattern for both sexes, followed by an additional pubertal descent of the hyoid in males.

The extent to which the tongue may have a different role in eating and speech is poorly understood. Changes in tongue surface shape, such as lengthening, shortening and rotation, are known to result from contraction of its intrinsic muscles (Napadow et al., 1999). However, changes in overall tongue position relative to the hard palate result from changes in hyoid position produced by differential activity in the hyoid and extrinsic tongue muscles (Palmer et al., 1997; Hiimae and Palmer, 1999). Normal tongue behaviour involves a shortening of the tongue base (Fig. 1A) in which the hyoid moves forward and lengthens the anteroposterior dimension of the oropharynx, unless compensated by contraction of, say, the pharyngeal sphincters. Conversely, lengthening of the tongue base with posterior movement of the hyoid can shorten the anteroposterior lumen of the pharynx. The same effect might also be produced by a posterior expansion of the pharyngeal surface of the tongue. The movements of the tongue in feeding, while not yet fully described, involve high-amplitude movements in all three planes (El Malik, 1955; Palmer et al., 1997) as well as patterns of intrinsic expansion and contraction (Hiimae et al., 1995). In sound production, the tongue surface changes shape to achieve tongue–palate contact (Perkell, 1969; Kent, 1972). Napadow

et al. (1999), using magnetic resonance imaging, report that the tongue assumes stereotypical configurations; they argue that these determine the overall shape of the vocal tract.

Phylo- and ontogenetically, the role of the mouth and pharynx in feeding precedes its use in complex vocalisation and speech (Hiimae and Crompton, 1985; Hiimae, 2000). In addition, feeding is a more essential activity than speech. It is reasonable, therefore, to postulate that in speech the oropharyngeal complex functions within physiological constraints dictated by the demands of feeding (Lieberman et al., 2001). MacNeilage (1998) has developed this concept into a theory. He posits that the fundamental difference between human speech and vocalisation in non-human vertebrates is a cycle of mandibular movement based on the 'open–close' movement of the jaws in perinatal behaviours such as suckling and babbling. MacNeilage equates a single open–close cycle of 'ingestive behaviour' with a 'frame' corresponding to a syllable, the opening and closing movements within that frame subserving the production of vowels and consonants, respectively. These phases of jaw movement are described as 'segments'. While not impossible, it is unlikely that a tongue musculature developed for, first, suckling and then the consumption of semisolid followed (temporally) by solid foods supports a range of surface profile changes unique to speech, with or without jaw movements. What makes MacNeilage's theory attractive is that it links known infantile behaviours, and behaviours found in extant adult

higher primates, with an hypothesis for the origin of speech. In particular, he argues that ingestion-related cyclicities of mandibular ‘oscillation’ (MacNeilage’s phrase), such as lip smacks, tongue smacks and tooth chattering, became the earliest ‘communication’ signals, leading to the ultimate evolution of modern human speech.

Unfortunately, there has been little integration of studies of the physiological mechanisms involved in both behaviours. Patterns of mandibular movement have been the traditional focus for studies of feeding. With the exception of the study by Palmer et al. (1992) of mastication and swallowing, electromyographic studies have focused on jaw movements, examining activity in the adductors, anterior digastric, geniohyoid and mylohyoid (see Miller, 1991). The exceptions are two studies (Moore et al., 1988; Smith and Denny, 1990) that examined activity in the adductors and the anterior belly of digastric with synchronous recording of jaw position during a variety of speech and non-speech tasks. Comparisons between the amplitudes of mandibular movements in feeding and speech showed that the amplitude of speech movements was very much smaller, with little deviation from the midline and a maximally closed position with a freeway space (Gibbs and Messerman, 1972). This finding is supported by Ostry et al. (1997), who used a sophisticated, computer-based, optoelectronic system to analyse mandibular movement with 6 d.f. Their study provides a valuable resource for data on jaw movement but did not address the larger issues of the integrated function of the orofacial complex because no soft tissue measures could be included.

While there is general agreement that the patterns of rhythmic jaw movements seen in feeding result from motoneurone outflows regulated from a central pattern generator in the hindbrain (Dellow and Lund, 1971), Moore et al. (1988) argue that speech production involves activation patterns in the mandibular muscles that are not related to the coordinated patterns produced by the central pattern generator. In contrast, MacNeilage (1998) argues strongly that if, as he proposes, the movement patterns of speech evolved from, or are based on, the cyclical movements of mastication, then there must be at least some commonality between the central pattern generator for feeding and the regulation of movements in speech.

In the late 1950s and 1960s, the potential of X-ray cinefluorography as a technique for studying the complex functional interrelationships of the soft tissues involved in human feeding and speech was enthusiastically recognised, leading to classic studies such as those of Ardran and Kemp (1955) on swallowing and Perkell (1969) on sound production. Perkell’s (1969) 35-mm lateral-projection cinefluorographic study of a single male shows in great detail the changes in the position of the hyoid and the shape of the tongue surface involved in the production of 13 ‘non-sense utterances’, each with an unstressed followed by a stressed syllable involving a combination of seven vowels and six consonants, as well as a very short sentence. Perkell also measured pharyngeal dimensions, the vertical dimen-

sion of the airway between tongue and hard palate, and lip movements, and focused on how each sound was produced. Although work continued in the early 1970s, interest in cinefluorographic studies in humans waned. The explanation for this may be as simple as restrictions on the use of cinefluorography and its successor, videofluorography, for research rather than purely diagnostic purposes, given its perceived health risk to participants coupled with the expensive and time-consuming analysis required. In the past decade, with major technical improvements, videofluorography has become the technique of choice. Magnetic resonance imaging, while providing greater detail of soft tissues than videofluorography (Fitch and Giedd, 1999; Napadow et al., 1999), is too slow to capture the changing relations between the tissues during the activities of eating and speaking.

The different foci, and so presentation, of studies of oropharyngeal mechanics during speech or food processing make it difficult to examine from published data the hypothesis that the movements used in speech fall within the range used in feeding. Comparisons of the fairly slow rhythmic jaw movements of chewing with the perception of fast tongue and lip movements in speech could easily lead to serious misinterpretations of the underlying activity unless both are examined using the same technique with appropriate controls. A comprehensive, continuing, videofluorographic study of the oropharyngeal complex in feeding (Palmer et al., 1997; Hiiemae and Palmer, 1999) created the opportunity to test a null hypothesis, that hyoid movement in speech would occur within the sagittal domain used in feeding, so that no distinct differences would be expected between the movements and sagittal domains for the hyoid and tongue in the two behaviours.

## 2. Materials and methods

The protocol (approved by the Human Subject Review Boards at Johns Hopkins University, Syracuse University and Good Samaritan Hospital) provided for videofluorography of normal human participants speaking and feeding on chicken spread, banana and ‘cookie’ (shortbread fingers; Walker Ltd., Aberlour-on-Spey, Scotland), with and without tongue and tooth markers. All participants met general and specific dental health requirements for inclusion in the study. The experimental protocol for videofluorography is described in detail in Palmer et al. (1992, 1997) and Hiiemae and Palmer (1999). As described in Palmer et al. (1997), anterior and posterior tongue-markers were glued to the gustatory epithelium of the tongue with a dental adhesive (Ketac Bond; Espe-Premier Sales Corp., Norristown, PA, USA).

### 2.1. Data acquisition

Participants were 10 healthy adults, ranging in age between 21 and 28 years, five of each sex, with one African-American, two Asian-Americans and one Latino (Cuban) male; the others were Caucasian. In addition to

consuming chicken spread, banana and the shortbread, each participant read the 'Grandfather Passage', chosen for the following reasons: (a) it includes almost all of the vowel–consonant combinations used in English (having been developed for use in the diagnosis of speech pathologies; see Darley et al., 1975)); and (b) it takes about 50 s to read aloud and could be used within the time constraints for videofluorographic exposure dictated by the approved protocol. The text is as follows:

You wish to know all about my Grandfather. Well, he is nearly 93 years old, yet he still thinks as swiftly as ever. He dresses himself in an old black frock coat, usually several buttons missing. A long beard clings to his chin, giving those who observe him a pronounced feeling of the utmost respect. When he speaks, his voice is just a bit cracked and quivers a bit. Twice a day he plays skilfully and with zest upon a small organ. Except in winter when the snow and ice prevent, he slowly takes a short walk in the open air each day. We have often urged him to walk more and smoke less, but he always answers 'banana oil'. Grandfather likes to be modern in his language.

Lateral-projection videofluorographic recordings (30 frames per second, 60 interlaced videofields) were made for each participant, first without, and then with, tongue-markers. In a single participant, only 'with marker' data were recorded. Note that the male group included three individuals with distinctively accented speech (all three had learned English as a second language, their original languages were one of the major Chinese languages, Hindi and Spanish).

The time constraints on videofluorographic recording (5 min for each individual, including the mandatory diagnostic swallows) required that recording be initiated as soon as the participant began to eat or speak. No attempt was made formally to establish a 'rest position' for the hyoid or tongue during data acquisition. However, given the preliminary results, all the videofluorographic tapes were re-examined and where even a few hundreds of a second of mandibular 'rest' (immobility) before the initiation of the required activity occurred, the hyoid and tongue-marker coordinates for all such videofields were considered to be 'pre-activity' positions. The availability of such records was uneven, but some data were available for all participants (5–2 records per individual). The duration of such 'resting periods' ranged from 2.0 to 0.3 s. The available hyoid records were then digitised using the methods described below. The participant was determined to be 'at rest' when no jaw movement occurred: this did not mean there was no hyoid movement; in most cases, the hyoid was moving within a very small 'domain'.

## 2.2. Data reduction and analysis

Videotapes were analysed as described in detail in Palmer et al. (1997) and Hiimae and Palmer (1999). The upper

occlusal plane (Fig. 1B) was used as the reference plane for this study, as it both reflects the working surfaces of the teeth and has a fixed anatomical relation to the hard palate, which the tongue contacts in both feeding and speech. In viewing the speech recordings in slow-motion and stop-frame modes, attention was paid to the possible occurrence of swallows ('dry' or saliva); this occurred in only three of the 16 records, and only once in each.

Cartesian coordinates for all the reference points shown in Fig. 1A were acquired for each videofield and entered into Excel spreadsheets (Microsoft, Redmond, WA, USA) for individual participants. The positions of the markers of particular interest (jaw, hyoid, tongue) were computed relative to the upper occlusal plane for each videofield in each record. These data allowed us to prepare time–position plots (Fig. 2) or *XY* 'domain' plots (Fig. 3). Fig. 1B illustrates the grid dimensions in millimetres, shown in Figs. 3 and 5–7. The *X* and *Y* reference planes intersect at the upper canine marker (Fig. 1B), so all plots are 'zeroed' at that marker. Fig. 3 shows examples of the domains, for all reference points (jaw, hyoid and tongue-markers), in (a) eating and (b) speaking in the same participant.

Given the interindividual variation in oropharyngeal anatomy (e.g. mouth dimensions, tooth size and neck length (C1–C5)), each participant was used as his/her own control. Data for individual participants were aggregated for all foods consumed. This pooling of data was founded in the rationale that each aggregate set of values would represent the normal range of jaw and hyoid sagittal movements in normal feeding and show the effect, if any, of using tongue-markers.

To facilitate quantitative domain analysis, all Cartesian coordinates or data pairs (*XY* data for each of the mandibular, hyoid and tongue reference points) were manipulated to identify their position in each videofield with reference to the upper occlusal plane (Fig. 1B) for each feeding sequence (banana, chicken spread, cookie). These data were then pooled to obtain the very large sample sizes for gapes *X* and *Y*; hyoids *X* and *Y* in feeding used in the analysis. The feeding data sets could then be compared with the same individual's data for speech (Tables 1 and 2; Fig. 4). The size of the data sets (Table 1) was surprisingly consistent across all participants when the 'no tongue-marker' or 'tongue-marker records' were compared, i.e. for feeding (no markers) the mean value of *N* for males was 3145 (S.D. 620.02), with a range of 2341–4010; with tongue-markers, the mean was 3106 (S.D. 692.67) and the range 2302–4002; for speech (no markers) mean *N* was 2480 (S.D. 352) and the range 2149–2979; whilst for speech with markers, mean *N* was 2519.8 (S.D. 228.19), range 2160–2763. When these values and those for the female participants (no markers: mean 2915 (S.D. 272.76), range 2529–3367; tongue-markers: mean 2743 (S.D. 737.06), range 1820–3619) were compared, no significant differences could be found: *P* ranged from 0.83 to 0.96 (Microsoft Excel 98; Student's *t*-test).

For each participant, the data sets (aggregated *XY* values) were, given the high value of *N*, of similar size for

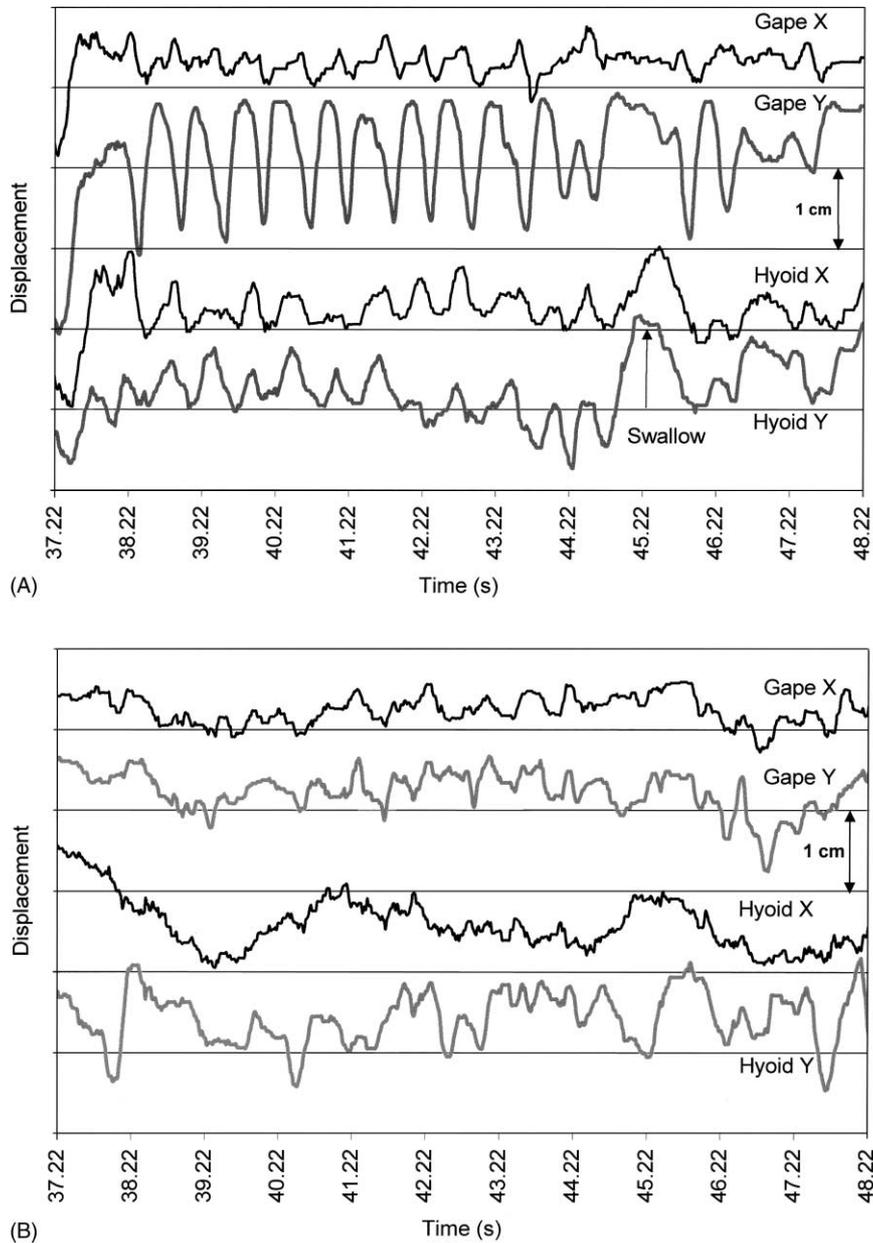


Fig. 2. Position–time plots for gape X (lower canine X), i.e. movement parallel to the upper occlusal plane, and gape Y (lower canine Y), i.e. movement perpendicular to the upper occlusal plane. The equivalent data for hyoid movement relative to the upper occlusal plane are shown. The upper plot (A) is a complete sequence of a male participant eating chicken spread. To facilitate temporal comparisons, the lower plot (B) shows part of the speech record for the same individual of the same duration as the feeding sequence. The 1:1 relation between jaw and hyoid cycles in feeding is clear and contrasts with the irregular (and lower amplitude) movements of the jaw in speech. Movement towards the top of the figure is either forwards (X-axis) or upwards (Y-axis). The upper plot was originally published in *Dysphagia* (Hiimeae and Palmer, 1999) and is published here with permission from Springer–Verlag.

statistical purposes. They were not, however, uniformly Gaussian. Fig. 4 shows the typical distribution of these data for a male and a female. Histograms were plotted for all participants using SYSTAT 6 (SPSS Inc., Chicago, IL, USA) and the patterns were consistent. Contour maps of the

XY-coordinate distribution for position of the hyoid bone are shown in Fig. 5 for eight participants. The centroids (mean X- and Y-coordinates) were calculated for each structure of interest (jaw, hyoid, tongue-markers) during speech and during feeding, with and without markers. Fig. 6 is a

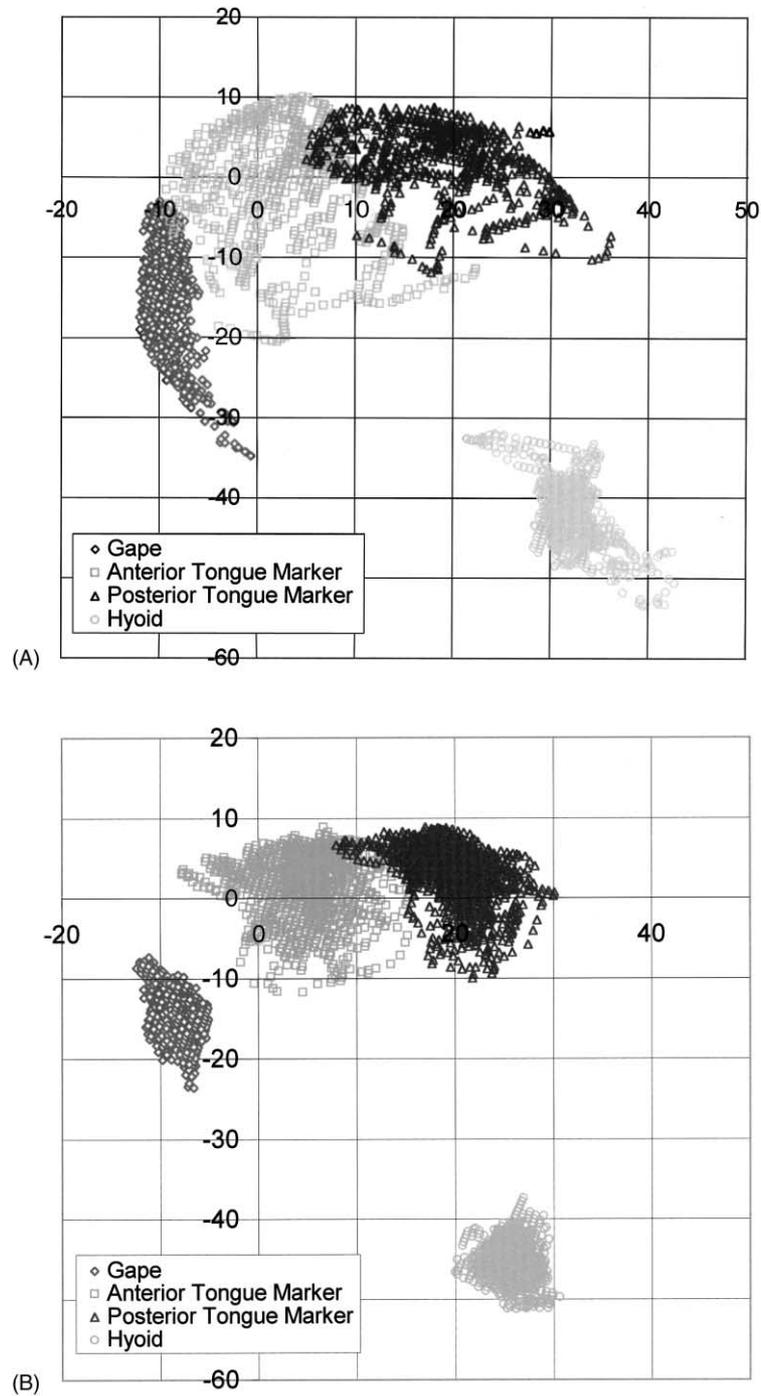


Fig. 3. Domain plots for a complete sequence on (A) cookie and (B) for the same participant reading the 'Grandfather Passage', illustrating the dynamic anatomical relations between the jaw, tongue and hyoid. Both tongue-markers contact the hard palate during eating, producing the curved upper profile of the marker domains (A). In contrast, the area of tongue-palate contact is very much smaller in speech. The much greater sagittal area in which the markers move during feeding reflects the extensive anteroposterior and superoinferior movements of the tongue (see text, and Hiimae and Palmer (1999)). Swallows occurred in both recordings.

Table 1

Aggregated coordinate data for all foods (banana, chicken spread and cookie) and for reading the ‘Grandfather Passage’<sup>a</sup>

	Gape X		Gape Y		Hyoid X		Hyoid Y		ATM X		ATM Y		PTM X		PTM Y	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Average centroid for all participants																
Feeding	0.28	3.32	-11.90	2.08	42.64	5.39	-37.69	2.60	11.28	5.41	0.30	1.63	25.42	5.84	5.03	2.03
Speaking	-0.66	3.47	-11.23	1.94	35.68	5.91	-39.97	4.69	10.86	3.27	1.28	1.69	24.62	4.01	5.09	1.89
Female	-0.26	1.12	-11.49	1.93	38.21	5.90	-35.98	2.82	10.39	2.49	1.43	1.83	23.00	3.26	5.60	1.63
Male	-0.13	4.60	-11.62	2.13	40.02	7.21	-41.39	2.85	11.74	5.73	0.16	1.34	27.04	5.56	4.52	2.10
Markers	0.01	3.40	-11.33	2.23	39.37	6.69	-38.59	3.81								
No markers	-0.40	3.45	-11.82	1.77	38.94	6.68	-39.09	4.12								
Average variance for all participants																
Feeding	3.36	1.10	44.03	10.33	12.75	5.73	23.75	7.04	38.04	17.52	55.45	12.73	36.84	14.56	31.18	10.86
Speaking	1.36	0.61	5.40	2.17	3.48	1.28	6.92	2.84	13.30	6.20	13.80	3.42	11.04	5.42	12.82	4.51
Female	2.17	1.32	22.60	20.09	7.28	5.00	16.39	11.78	21.91	15.41	32.38	23.11	20.72	17.31	22.71	15.31
Male	2.53	1.37	26.62	21.96	8.86	7.21	14.39	8.38	29.44	20.40	36.86	24.34	27.16	16.99	21.28	9.49
Markers	2.27	1.28	24.33	21.15	7.18	5.99	14.83	9.79								
No markers	2.47	1.43	25.14	21.24	9.15	6.51	15.90	10.56								

<sup>a</sup> ATM, anterior tongue-marker; PTM, posterior tongue-marker. Data are segregated by sex (5 males and 5 females but without data for female no. 5 (no tongue-markers)); the much lower value for *N* for females eating (no tongue-markers) reflects the absence of those data. The number of data points for eating and speech in males (where *N* is 5, all individual records) clearly demonstrates the marginal effect of introducing tongue-markers in terms of time spent per activity (videofields per second). All linear measurements are in mm from origin (Fig. 1A and B).

Table 2  
DM, repeated-measures ANOVA: summary of results for the eight principal analyses<sup>a</sup>

Effect	Wilk's $\lambda$	F-statistic	d.f.	P
DMANOVA for gape centroid				
Sex	0.98	0.078	2.6	0.926
Behaviour (feeding/speech)	0.04	71.340	2.6	<0.001
Markers (present/absent)	0.51	2.910	2.6	0.131
DMANOVA for gape variance				
Sex	0.88	0.41	2.6	0.683
Behaviour (feeding/speech)	0.02	151.44	2.6	<0.001
Markers (present/absent)	0.89	0.39	2.6	0.693
DMANOVA for hyoid centroid				
Sex	0.31	6.58	2.6	0.031
Behaviour (feeding/speech)	0.01	220.46	2.6	<0.001
Markers (present/absent)	0.60	2.01	2.6	0.210
DMANOVA for hyoid variance				
Sex	0.73	1.09	2.6	0.500
Behaviour (feeding/speech)	0.10	25.93	2.6	0.001
Markers (present/absent)	0.34	5.73	2.6	0.040
DMANOVA for ATM centroid				
Sex	0.76	1.09	2.7	0.390
Behaviour (feeding/speech)	0.69	1.57	2.7	0.270
DMANOVA for ATM variance				
Sex	0.82	0.77	2.7	0.500
Behaviour (feeding/speech)	0.07	45.19	2.7	<0.001
DMANOVA for PTM centroid				
Sex	0.58	2.49	2.7	0.152
Behaviour (feeding/speech)	0.92	0.30	2.7	0.747
DMANOVA for PTM variance				
Sex	0.82	0.79	2.7	0.490
Behaviour (feeding/speech)	0.15	19.92	2.7	0.001

<sup>a</sup> ATM, anterior tongue-marker; PTM, posterior tongue-marker.

summary diagram incorporating the data for the nine participants for which data (no markers) were available. The variance was also calculated for each structure of interest during speech and feeding with and without markers. The variance is a reasonable measure of the 'spread' in the data, and reflects both the amplitude of movement and the size of the sagittal domain for a structure during a given behaviour.

Further statistical analysis was limited to a reduced data set consisting of the centroid and variance of each structure of interest in each participant performing each behaviour (speech and feeding) with and without markers (Table 2). Doubly multivariate (DM), repeated-measures ANOVA was used to test the effects of participants' sex, behaviour and tongue-markers on the centroids for the jaw, hyoid and each tongue-marker (data for participant no.5 were excluded from this ANOVA because no records without markers were available). This calculation enabled us to compare the location of the sagittal domains among the various conditions (Table 2). The X- and Y-coordinates of the centroid for a

given structure (for example, hyoids X and Y) were the dependent variables in each DM, repeated-measures ANOVA. The independent variables in each analysis were sex (male/female), behaviour (speaking/feeding) and presence of tongue-markers (present/absent). Of these, only sex was an interindividual variable; the others were intersubject variables. A similar set of DM, repeated-measures ANOVA was performed using the variances of the X- and Y-coordinates as dependent variables to compare the size of the sagittal domains.

To establish the mean 'pre-activity position' of the hyoid before either feeding or speaking, the mean, S.D. and variance of both the X- and Y-coordinates of the hyoid were established for that period using the values for each included videofield. As expected, given the criteria, both the S.D. and the variances were very small. The means were plotted on to domain plots for each participant and examined in relation to the domains of the feeding and speaking behaviours in that individual.

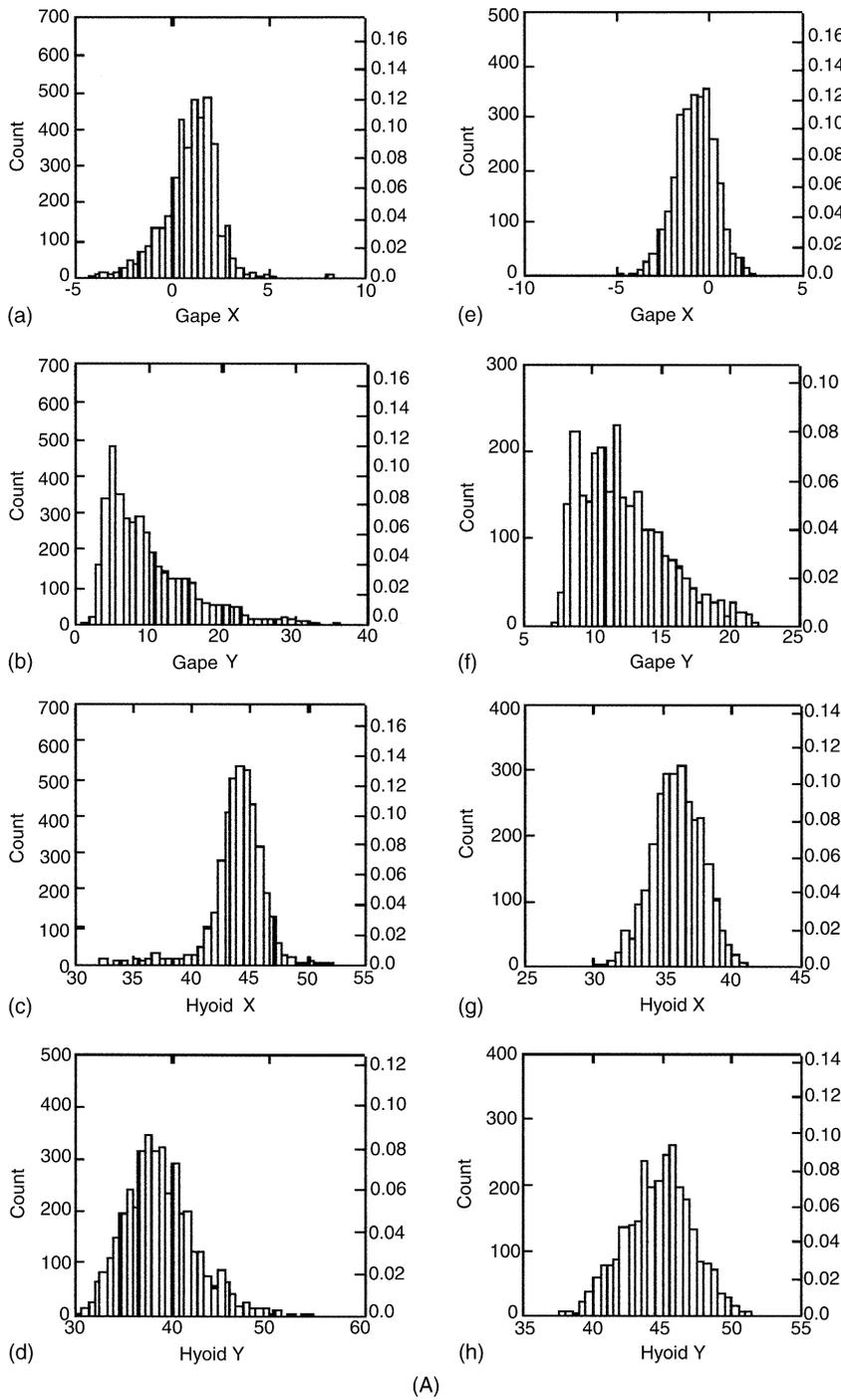


Fig. 4. Histograms showing the distribution of the data points for gapes X and Y; hyoids X and Y in a male (A) and a female participant (B). The skewed distribution for gape Y in eating reflects the wider gapes associated with the early part of the feeding sequence. Similarly, the smaller skew for gape Y in speaking shows that the jaws were generally separated by about 8–15 mm but occasionally by as much as 20 mm. Plots prepared using SYSTAT 6. (A) Male: plots a–d, eating; e–h, speaking. (B) Female: plots a–d, eating; e–h, speaking.

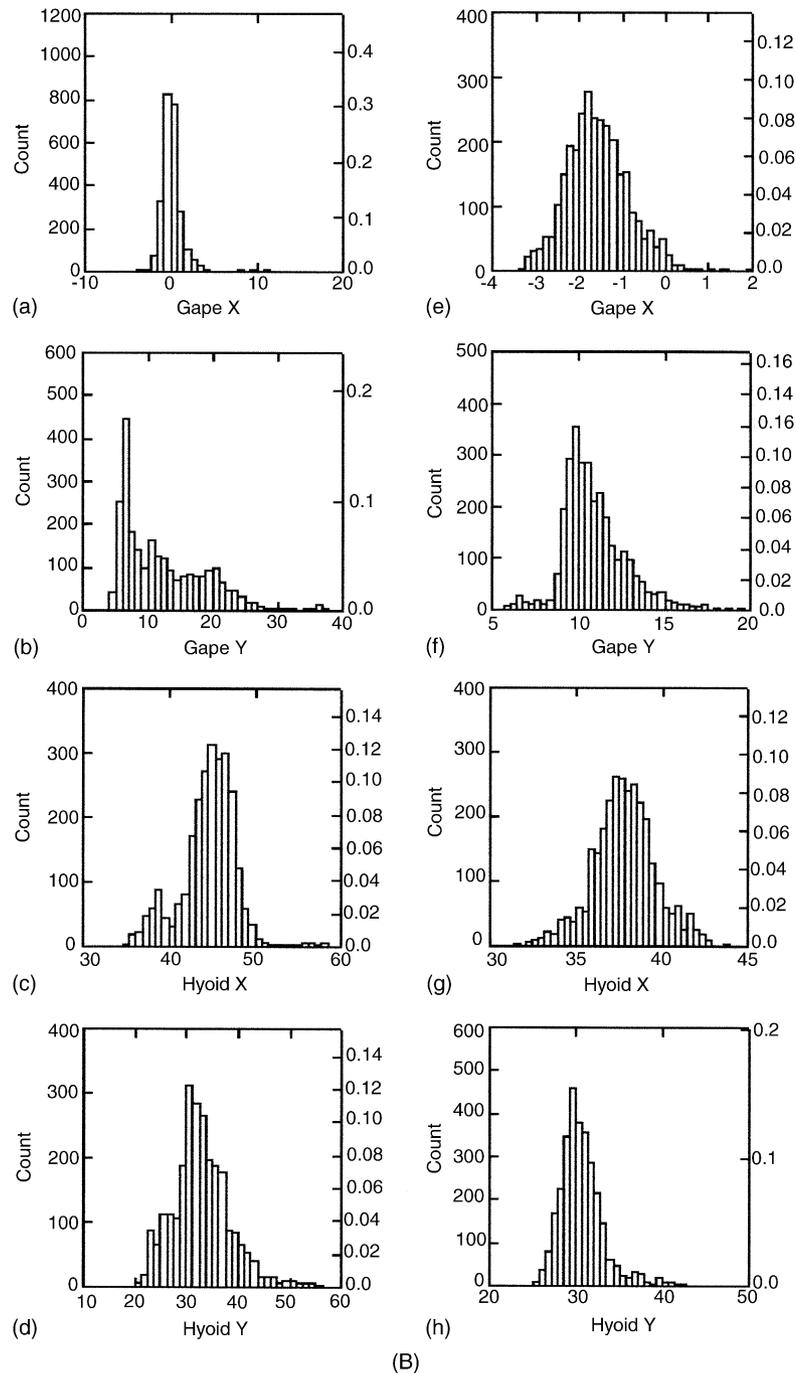


Fig. 4. (Continued).

### 3. Results

Although some results based on data obtained in this study on feeding behaviour and the mechanisms involved have already been published (Hiimae and Palmer, 1999), the goal here was to compare the sagittal domains

occupied by the hyoid and tongue-markers during normal feeding behaviour and continuous speech (Figs. 3 and 5–7). The sagittal domain represents the area in two dimensions (in this case anteroposterior and superoinferior) in which the jaw, hyoid or tongue reference-point coordinates appeared in the records (Hiimae et al., 1978). A sagittal domain plot

shows only the area within which the given reference point has moved in the 'time window' examined. Changes in the domain occupied by a specific reference point within or between behaviours would be highly suggestive of a change in the sensorimotor mechanism producing that behaviour.

### 3.1. Jaw movements

Time–position plots for the lower jaw and hyoid relative to the upper occlusal plane are shown in Fig. 2 for a complete feeding sequence lasting 10 s (chicken spread) and for a 10 s section of the continuous speech record for the same participant. Similar patterns were found in all participants. While there were subtle changes in the jaw movement profile within the feeding sequence associated with the reduction

and transport of the ingested food, anteroposterior (gape  $X$ ) and superoinferior (gape  $Y$ ) jaw movements were rhythmic, with the amplitude of the superoinferior much the greater. In contrast, jaw movements in speech appeared somewhat arrhythmic and of lower amplitude (Fig. 4). Table 1 gives the mean, S.D. and variance for gapes  $X$  and  $Y$ ; hyoids  $X$  and  $Y$  for all participants by sex for eating and speech.

The centroid of jaw position is a measure for the mean position of the jaw during a given activity (Table 1; Fig. 5). On average, this centroid was 0.68 mm lower and 0.93 mm further backward during feeding than during speech ( $F = 71.4$ ,  $P < 0.001$ ). The jaw centroid was not significantly affected by the participant's sex ( $F = 0.08$ ,  $P = 0.93$ ) or by the presence of tongue-markers ( $F = 2.9$ ,  $P = 0.13$ ; Table 2). There was, however, a small but significant

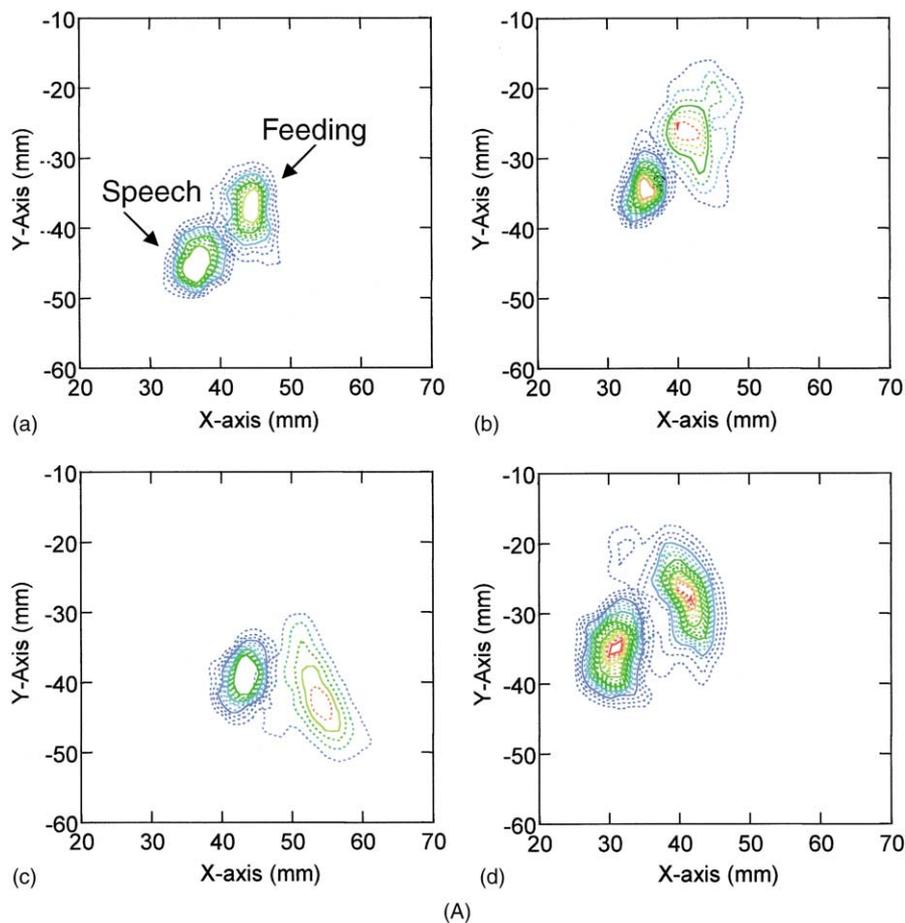


Fig. 5. Contour plots of hyoid position for (A) four male and (B) four female participants. Each plot shows all the coordinate data for a different individual and includes all the videofields for feeding (chicken spread, banana and cookie), i.e. about 3000  $X$ - and  $Y$ -coordinate pairs, and for the 'Grandfather Passage', about 2600  $X$ - and  $Y$ -coordinate pairs. The plots show the bivariate density of hyoid position collapsed into a 2D display using the density contour-plot functions of SYSTAT 9. The rings are essentially density isobars showing where the data points are most concentrated. The bivariate non-parametric kernel density is estimated using the Epanechnikov kernel. These plots demonstrate the separation between the sagittal domains for eating and for speaking. The extension of the feeding domain towards the upper left of the plot seen in some represents hyoid position in swallowing (see Fig. 7).

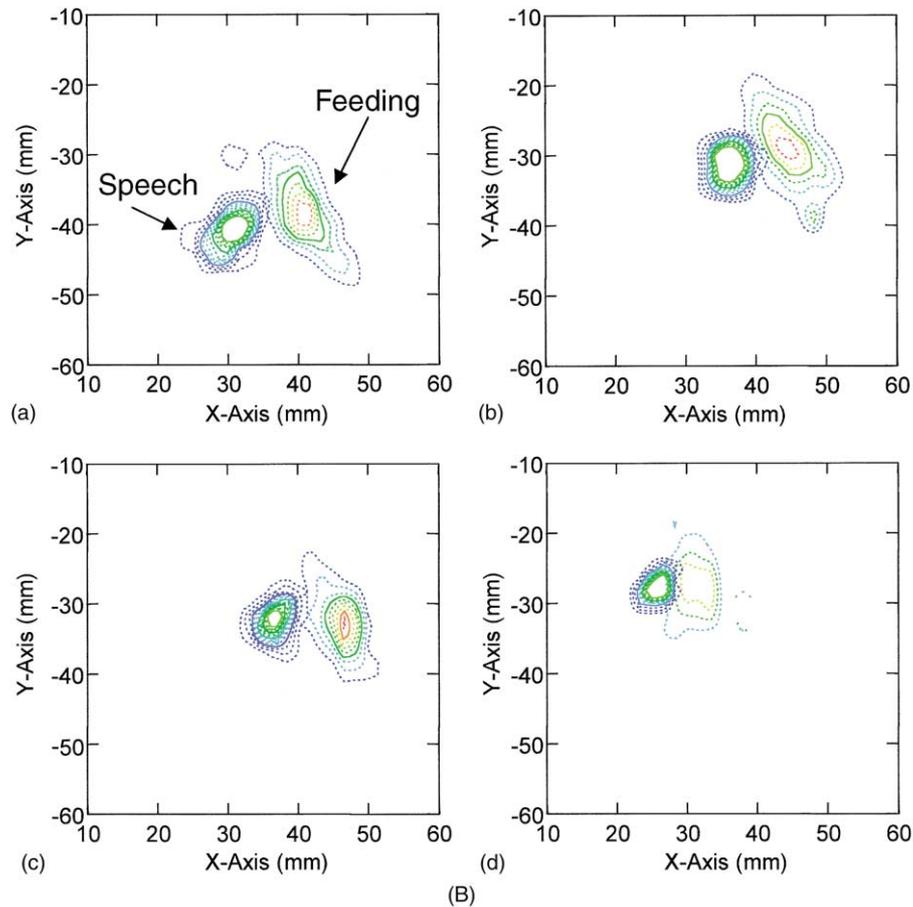


Fig. 5. (Continued).

interaction between behaviour (speech/feeding) and sex ( $F = 24.82$ ,  $P = 0.001$ ).

The variance of jaw movement is a measure of the size of the sagittal domain. This variance was much greater during feeding than during speech (gape  $X = 3.4$  and  $1.4$  mm, gape  $Y = 44.0$  and  $5.4$  mm, respectively;  $F = 220.46$ ,  $P < 0.001$ ). Sex had no significant effect on the variance ( $F = 0.41$ ,  $P = 0.68$ ); neither did the presence of tongue-markers ( $F = 0.39$ ,  $P = 0.69$ ).

These results show that the average position of the jaw differed by less than 1 mm between speech and feeding when very large data sets, representing complete sequences (feeding from stage I transport to terminal swallow) on foods of differing consistencies, were compared with a long speech passage. However, the sagittal domains for the lower canine marker (its movement being a measure of gape) were substantially larger for feeding, especially in the  $Y$ -axis. Figs. 3 and 5 explain this finding. During food processing and stage II transport, there was a general tendency for gape to diminish, reflected by the high marker density in the lower gape range in Fig. 3A, in which the sagittal domain was very similar to that for speech (Figs. 3B, 5).

### 3.2. Hyoid movements

Hyoid movements were correlated with each regular cycle of mandibular movement in feeding (Palmer et al., 1997). With the exception of the first cycle (stage I transport; see Hiimae and Palmer, 1999), there was a 1:1 relation between hyoid maxima and minima, whether in the  $X$ - or  $Y$ -axis, and the jaw movement cycle, such that inferior and posterior movement of the hyoid occurred during jaw opening and early jaw closing. In swallows, the amplitude of hyoid movement changed but the same 1:1 relation was maintained. In distinct contrast, the position–time plot for the mandible in speech had no clear cyclical pattern, although there were distinct, low-amplitude, opening and closing movements (Fig. 2B). The hyoid was in continuous but irregular motion; the amplitude of its vertical movement sometimes exceeded that of the jaws.

#### 3.2.1. Comparison of hyoid domains in feeding and in speech

Fig. 3 shows the sagittal domains for all markers in a single feeding sequence, in this case on cookie (A) and for

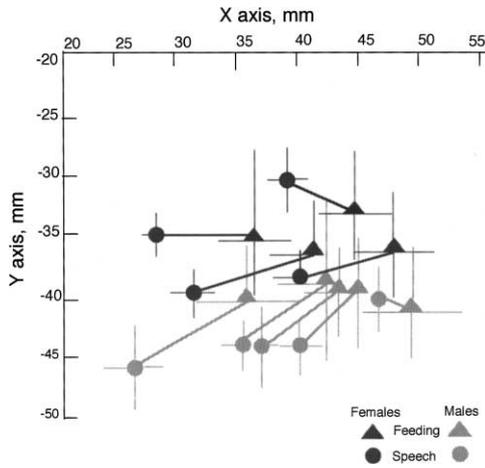


Fig. 6. The centroids (with S.D.) in the X- and Y-axes for the hyoid bone in nine participants (no tongue-markers), for feeding and speech, plotted on the XY grid used for all analyses and illustrated in Fig. 1(B). The larger S.D. for the Y-coordinate, especially in feeding, is expected, given the greater range of vertical movement in that activity. The length of the Euclidean distance between the means shows the distinct separation of ‘speech’ and ‘feeding’ hyoid domains.

the ‘Grandfather Passage’ (B). The figure illustrates the dynamic anatomical relations between the jaw, tongue and hyoid. Sagittal domain (XY) plots for hyoid-marker movement relative to the upper occlusal plane were made for each participant during feeding and speech (Fig. 5). The area within which the hyoid moved during feeding sequences was larger than that used for speech, with a substantial anteroposterior and superoinferior spread (Fig. 5). This spread reflected the superior and anterior drift of the hyoid as the feeding sequence progressed. The loosely distributed points at the lower right of the hyoid domain in Fig. 3 show hyoid position in stage I transport, when the hyoid was at its lowest and most posterior position, and when the lumen of the hypopharynx was often almost obliterated (Hiimeae and Palmer, 1999). As the feeding sequence progressed, the hyoid moved upward and forward, spending much of the sequence (processing) in a limited area; this is best illustrated by the central section of the hyoid domain in Fig. 3A. As the sequence proceeded to completion, with stage II transport and swallow (see Hiimeae and Palmer, 1999), the hyoid domain reached its most forward and upward position, again clearly shown in Fig. 3A. The domain used in reading the ‘Grandfather Passage’ was more constrained

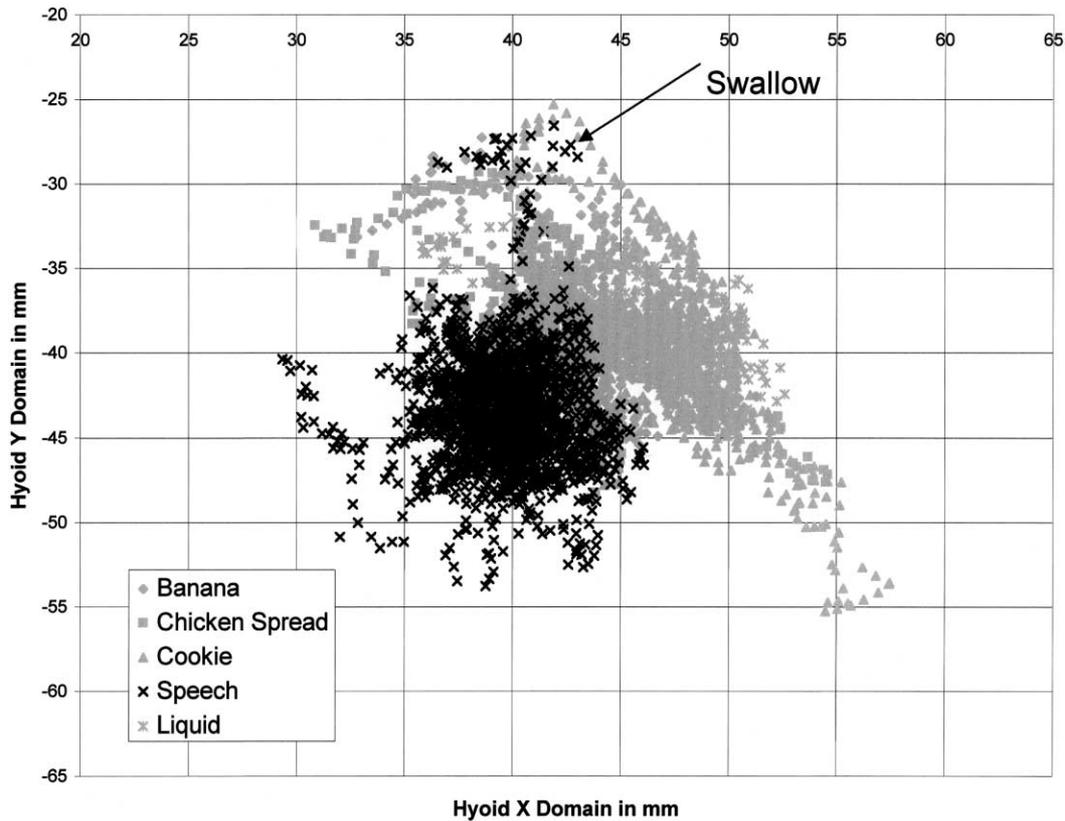


Fig. 7. Overlaid domain plots for feeding and speech, where the individual participant swallowed saliva during his/her reading of the passage. The rapid transition from the ‘speech domain’ to the ‘feeding domain’ for the swallow is clearly shown.

(Figs. 3B, 5), occupying an almost circular area anterior to that used in feeding and measuring a little over a 1.0 cm in both axes (Fig. 5). In all cases, in both sexes, the 2D 'space' in which the hyoid moved in feeding appeared very different from that used in speech, with very little overlap between the two domains. Contour plots for hyoid position during speech and feeding for four males and four females are shown in Fig. 5.

The Euclidean distances between the hyoid centroids during speech and feeding are shown in Fig. 6. On average, the hyoid centroid was 6.96 mm further backward and 2.28 mm higher during feeding than speech; this difference was statistically significant ( $F = 220.46$ ,  $P < 0.001$ ). The centroid of the hyoid bone was, on average, 1.82 mm further forward and 5.4 mm higher in females than in males ( $F = 6.58$ ,  $P = 0.031$ ). Univariate  $F$ -tests showed a significant effect of sex on the vertical ( $F = 12.96$ ,  $P = 0.009$ ), but not horizontal ( $F = 0.18$ ,  $P = 0.69$ ), position of the hyoid centroid. This finding was expected, given the greater descent of the larynx in the male (Lieberman et al., 2001) and the correlation between body size and vocal tract length (Fitch and Giedd, 1999). The presence of tongue-markers had no significant effect on the centroid of the hyoid position during speech or feeding ( $F = 2.01$ ,  $P = 0.21$ ). There was a small but significant interaction between sex and behaviour ( $F = 7.95$ ,  $P = 0.02$ ), but no significant interactions involving the presence of markers.

The variance of the hyoid position was significantly larger for feeding than for speech (hyoid  $X = 12.8$  and  $3.5$  mm, hyoid  $Y = 23.8$  and  $7.0$  mm for feeding and speech, respectively;  $F = 25.93$ ,  $P = 0.001$ ). This finding indicates that the sagittal domain was significantly larger for feeding than for speech. The hyoid variance was not affected significantly by sex ( $F = 1.09$ ,  $P = 0.4$ ). The presence of markers had a small but statistically significant effect on hyoid variance. The variance was slightly higher with markers (hyoid  $X = 7.2$  and  $9.2$  mm, hyoid  $Y = 14.8$  and  $15.9$  mm with and without markers, respectively,  $F = 5.7$ ,  $P = 0.04$ ).

### 3.2.2. The position of the hyoid before feeding and speech

The hyoid was not completely stationary in the moments before the initiation of either eating or speaking. The amplitude of this 'pre-activity' hyoid movement varied considerably between records for a single individual and between individuals. However, without exception, the range of movement was small, usually less than 5 mm in either the  $X$ - or  $Y$ -direction. It is noteworthy that the values obtained for the hyoid position when the lower jaw was 'stationary' did not generally fall within a narrowly defined area, i.e. were not identical or even very similar, record-to-record, for any individual participant. In all but two cases (different individuals, one record for each), the 'pre-activity' domain was within the larger domain used for feeding and usually towards its anterior edge. The two exceptions occurred in recordings of the 'Grandfather Passage'. In these cases, the mean 'pre-activity' position of the hyoid was within the

area used for speech, suggesting that those individuals had 'pre-positioned' the hyoid in anticipation of beginning to read.

### 3.3. Comparison of tongue-marker position in feeding and speech

The  $XY$  data for tongue-marker position in feeding and speech were also examined. No obvious disturbances in speech production could be detected on audio review of the tapes. Both the anterior and posterior tongue-marker domains overlapped (compare Fig. 3A and B). The centroid of the anterior tongue-marker did not differ significantly between feeding and speech ( $F = 0.17$ ,  $P = 0.69$ ), nor did that of the posterior marker ( $F = 0.30$ ,  $P = 0.75$ ). Neither were they significantly affected by the participant's sex ( $F = 1.09$ ,  $P = 0.39$  for the anterior marker;  $F = 2.49$ ,  $P = 0.15$  for the posterior). There was no significant interaction between behaviour and sex.

The variance of the position of the anterior tongue-marker was significantly larger for feeding than for speech ( $X = 38.0$  and  $13.3$  mm;  $Y = 55.5$  and  $13.8$  mm for feeding and speech, respectively;  $F = 45.19$ ,  $P < 0.001$ ). The variance of the position of the posterior tongue-marker was also significantly larger for feeding than for speech ( $X = 36.8$  and  $11.0$  mm;  $Y = 31.2$  and  $12.8$  mm for feeding and speech, respectively;  $F = 19.92$ ,  $P = 0.001$ ). Although the centroids for feeding and speech did not differ significantly, the sagittal domains of the anterior and posterior tongue-markers (as represented by the variance of marker position) were each significantly larger during feeding than speech.

### 3.4. Swallowing in feeding and speech

In three records, the participant swallowed saliva while reading the 'Grandfather Passage'. Before the swallow, the hyoid first moved rapidly superiorly and posteriorly. In the actual swallow, it moved anteriorly and then posteriorly and downwards as it returned to its pre-swallow position. These movements occurred within the domain used for swallows during feeding (Fig. 7). As soon as the swallow was completed, the hyoid returned to its 'speech domain'.

## 4. Discussion

The hyoid was never completely stationary, moving within a small area even when no visible jaw movement occurred. Hyoid movements were linked to those of the jaws in feeding, such that its most superior and anterior position in each jaw movement cycle occurred in jaw opening, and its most inferior position at about maximum gape. No such linkage was found in speech. In contrast to the ellipsoid domains used by the hyoid in feeding, angled posteroinferiorly to anterosuperiorly (Fig. 5), the domain for speech

was almost circular and, importantly, spatially highly differentiated from that used in feeding. Yet, when a swallow, even if only of saliva, occurred while the participant was speaking, the hyoid movements in that swallow occurred in the same domain space as those recorded for swallows during feeding.

The primary hypothesis of this study was that the range of movement of the hyoid bone during speech falls within that of feeding; this was investigated by comparing the centroid and variance of the hyoid position during speech and feeding. The null hypothesis was that these would not differ between the two behaviours. This hypothesis is rejected for the hyoid (Figs. 5 and 6). Even though lateral-projection videofluorographic records provide 2D images of 3D events, the data reported here provide clear evidence of a dichotomy in hyoid movement patterns between feeding and speech. To produce the complex sounds of the 'Grandfather Passage', the hyoid adopted a movement domain anterior to its domain during the processing stage of feeding and below that used in pre-swallow cycles and actual swallows. That domain was distinctly and highly significantly different between males and females with respect to hyoid *Y*-values, which reflect the length of SVT<sub>v</sub>.

Before discussing the implications of these results, we will address three technical points.

First: To what extent are the results affected by the absence of data on movement in the coronal plane?

While no quantified data are available for humans, data for non-primate mammals (e.g. Anapol, 1988) suggest that there is very little mediolateral hyoid movement in feeding. Our unpublished studies of feeding using posteroanterior-projection videofluorography suggest that hyoid position is stable mediolaterally in normal humans. The data included in Perkell (1969) and Kent (1972) also suggest that there is little mediolateral movement during speech. We, therefore, argue that the data presented here are an accurate reflection of hyoid position during both tasks. The same assumption does not hold true for the tongue-markers. The larger tongue-marker domains seen in Fig. 3A certainly reflect their extensive movement in feeding, while data in Fig. 3B illustrate a constrained sagittal domain in speech. Work in progress shows extensive and complex mediolateral as well as anteroposterior and rotational movement of tongue-markers during feeding. Such a difference in movement pattern is masked by the statistical comparison of the two data sets (Tables 1 and 2). However, we had not expected the statistical similarity in the centroids of jaw movement (gapes *X* and *Y*) in eating and speaking. While there is no question that jaw movements have a greater range of amplitudes during feeding (as reflected by their greater variances), the differences in centroid were much smaller than those seen in the hyoid, suggesting that the jaw position during speech and feeding is nearly the same (Table 2). On the other hand, the variance in jaw position during feeding was much larger than during speech, indicating a larger range of jaw movements. This finding

may be explained by the following mechanism: although the average position of the jaw during speech is slightly more open than it is during feeding, the range of its motion during speech is smaller. Gibbs and Messerman (1972) assert that the amplitude of jaw movement in speech is much smaller than in feeding. Our findings reveal that this assertion is only partly correct, as the average amount of jaw opening during speech was actually greater than during feeding.

Also significant is the smaller domain (as shown by the lower variance) used by the tongue-markers in speech, and their limited palatal contact (Fig. 3B). This difference indicates a more tightly controlled pattern of movement during speech, with limited rotation of the tongue about its longitudinal axis, possibly driven by the need for precise reproduction of speech sounds.

Clearly, the anterior position of the hyoid domain for continuous speech reflects an increase in the anteroposterior dimension of the hypopharynx as compared with its dimension in feeding (Fig. 1A). However, the data can provide no evidence about whether this anteroposterior 'expansion' of the SVT<sub>v</sub> airspace is accompanied by any change in the mediolateral width of the pharynx. Movement of the lateral walls of the pharynx is difficult to record or measure accurately. If, as well may be the case, current acoustic models of the SVT<sub>v</sub> were, in fact, developed with the hyoid in the 'speaking position' we identify, then this result will have no effect on those models. However, when hyoid position in feeding is compared with speaking, its range of position in speaking is very limited. The unexpected finding was that the dimensions of the oro- and hypopharynx change dramatically during eating and in a systematic pattern associated with progression through the masticatory sequence (Palmer et al., 1997; Hiimeae and Palmer, 1999).

Second: To what extent, if any, did the presence of tongue-markers on the gustatory epithelium affect behaviour?

We analysed all data: gapes *X* and *Y*; hyoids *X* and *Y*, as well as the position of anterior and posterior tongue-markers. For statistical purposes, we recognise the subtle differences in the reported patterns of hyoid movement when the data sets for 'no markers' and 'markers' (eating and speaking) are compared. We do not consider those small differences to have any functional significance, given the reported intraindividual variation in the behaviour of the oropharyngeal complex (Hiimeae and Palmer, 1999).

Third: Did 10 participants, five of each sex, form a sufficiently representative sample?

Having more participants is always useful, but there is no evidence to suggest that additional participants will significantly change the results. The differences in hyoid *Y* domain in speech between males and females confirm the results of other careful anatomical studies (Fitch and Giedd, 1999; Lieberman et al., 2001). Those differences are a function of the pubertal growth spurt in males, which leads to a downward (relative to the hard palate) 'migration' of the hyoid

and so the whole laryngeal complex. We, therefore, believe that the dramatic and consistent shift in hyoid domain between feeding and speech is not an artefact of sampling bias.

#### 4.1. The physiological implications

In evaluating these results, it is essential to recognise what they do, and importantly, do not, show. First, the data do represent the position, relative to the upper occlusal plane, of the hyoid (or tongue-marker) during the ingestion, processing and swallowing of three foods of different consistencies, and during about 50 s of continuous speech. The tongue surface or hyoid might adopt and/or move through positions not recorded here. The tonguing of the trumpeter, the soprano hitting a high C, or the protrusion of the tongue by a child making emotive gestures might all lead to 'extreme' positions of the landmarks we used as references. But the impossibility of recording all possible variations/behaviours in a study of this type does not invalidate the results: it makes sense to analyse the normal range of movements during habitual tasks.

The results show a basic change in the 'operating position' of the hyoid relative to the upper teeth between feeding and speech. Clearly, the small difference in jaw position between feeding and speech does not, in and of itself, explain the large difference in average position (centroid) of the hyoid bone. To generate such a different movement domain there could be a relative shift in the operating length of the anterior and posterior suprahyoid muscles, such that the anterior group, especially geniohyoid are overall, functionally 'shorter' and the posterior 'longer' in speech than in feeding. The infrahyoid musculature would not be equivalently affected, as the vertical displacement of the hyoid in speech is within the range used in feeding. Further (albeit difficult and invasive) studies are needed to examine the electrical activity and mechanics of these muscles during both behaviours.

We are particularly intrigued by the observation (Fig. 7) that when participants needed to swallow saliva while reading, the hyoid moved very rapidly into the 'swallow position', the swallow was executed and then the hyoid returned equally rapidly to the speech domain. Swallowing is also considered to be regulated by a central pattern generator in the hindbrain (see Jean, 1990). Our finding suggests that not only are swallows patterned, but also that once conditions for a swallow are initiated, that behaviour overrides all others until completed.

The data, as represented by Fig. 2, indicate, as Moore et al. (1988) argue, that activation patterns in the mandibular muscles in speech are not related to the rhythmic patterns of chewing. At a gross level that assertion may be correct: the rhythmic, cyclical movements of both mandible and hyoid seen in Fig. 2A, and in all other feeding records, are nowhere found in the speech records. This does not mean to say that the movements producing vowel–consonant combinations are without pattern. On the contrary, those patterns may be 'learned' during early childhood development

(Lieberman, 1991). Our results do show, in young adults, a pattern of open–close movements of the mandible during the reading of the 'Grandfather Passage'. The asymmetry of those movements could well reflect the differences in the vowel–consonant combinations in the passage. Beyond that, the data support the intriguing hypothesis advanced by MacNeilage (1998), that speech depends on a mandibular oscillation and that this pattern could well have had its evolutionary precursor in the 'ingestive cyclicities' associated with chewing and sucking. The fact that the hyoid has to move forward if the tongue is to be protruded might explain the origin of the separate hyoid domain of speech. However, very careful examination of our data and additional experiments is needed to determine how the patterns recorded in this study and those modelled by MacNeilage might be related.

#### 4.2. The evolutionary implications: phylogeny and ontogeny

Speech is a uniquely human attribute. We do not have any direct evidence about when the combination of biomechanical (sound production) and neuronal mechanisms, whether in parallel or phased, resulted in the evolutionary transition between the highly nuanced 'vocal signals' in non-human primates and the rapid, complex, information transmission and retrieval system that is modern quantal speech (Cartmill, 1998; Lieberman and McCarthy, 1999; Fitch, 2000a). This study does not, ipso facto, address that question.

The hyoid is in continuous motion in all mammals so far examined (Hiimae and Crompton, 1985; Hiimae, 2000). There is also evidence that vocalisation in some non-primate species with intranarial larynges can involve changes in hyoid position to expand the oropharynx and depress the larynx (Fitch, 2000b). Further research to study the evolution of the unique configuration of the vocal tract and pharynx in humans is necessary, and needed, to integrate data on the functions and constraints imposed by feeding and speech as well as respiration. Moreover, the constraints imposed by feeding are more limiting than those imposed by speech: a human infant must be able both to breathe and suckle before it can be weaned and eat solid foods. The development of quantal speech follows. Our data demonstrate that the sagittal movements of the tongue surface in speech occur within the domains used in feeding. It, therefore, seems reasonable to hypothesise that the tongue and hyoid patterns for speech developed/evolved as distinctively patterned variants within the neuromotor framework required for feeding.

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