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# Coordinate spaces in speech planning

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Understanding coordination of the articulators in the oral cavity requires that the geometry of their motion be specified. To this end tongue and jaw movements were measured using the X-ray microbeam system. Paths (sequences of positions) of pellets attached to the tongue and mandible were examined during fast, normal and loud speech. The observed movements of the tongue were complex, exhibiting curved paths for CV transitions. The degree of curvature varied with the speaking volume. The paths exhibited by the jaw, on the other hand were straighter. When jaw motion was examined in a joint frame of reference (motion about the center of rotation of the condyle and translation of the axis of rotation along the articular eminence) it was found that the proportion of rotation and translation varied with different consonants. Finally, the influence of the jaw on the movement of the tongue surface was examined by projecting the tongue movements into a jaw coordinate space. This analysis revealed that part of the complexity of the tongue pellet paths was due to the jaw motion.

## 1. Introduction

Speech is both a linguistic activity and a complex motor skill. In both depictions, global behavioral patterns (segmental structure, vocal tract shape) are determined by the behavior of a large number of smaller elements (features, oral articulators). A fundamental question facing us is how these constituents are coordinated to achieve fluent speech. In motor control, one approach to this problem has been to ask in which coordinate space a movement is planned (e.g. Hollerbach & Atkeson, 1987). By coordinate space we mean the spatial reference frame that a motion is organized with respect to. For example, the motion around a simple hinge joint can be described in terms of the angular motion around the centre of rotation of the joint. Alternatively, the same movement could be described in terms of linear coordinates that are referenced to the external world. In this paper we will present alternative descriptions of tongue and jaw movements and discuss the implications of these representations in the context of experimental data.

Before doing this we must note that a prerequisite for understanding oral coordination is that good spatial descriptions of the movements be achieved. Much

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of the research on the motor control of orofacial movement, however, has been based on the one dimensional kinematics of individual tissue points. Interarticulator relative timing measures for a single spatial dimension (e.g. lip and jaw lowering) as well as estimates of movement amplitude, duration and maximum velocity for individual articulators measured in a single spatial dimension (e.g. lip protrusion) have been reported. The characteristics of motion in two or three spatial dimensions have received less attention (cf. Houde, 1968; Perkell, 1969; Kent & Moll, 1972*a*; Westbury, 1988; Edwards & Harris, 1990) even though these kinds of data provide a potentially rich source of information on the requirements of coordination and the strategies adopted by the nervous system to meet these requirements. In this paper we focus on the two-space (mid-sagittal plane) motion of the tongue and jaw and the resulting motion of the tongue–jaw system under different speaking conditions.

We will examine tongue and jaw kinematics in two alternative coordinative frames. However, it is first useful to consider the way in which alternative coordinate systems have been used to describe other motor systems. In the study of arm reaching, researchers have debated whether movements are best represented in joint angular (intrinsic) coordinates or in coordinates corresponding to the position of the hand in Cartesian space (extrinsic). For example, in the absence of obstacles and other constraints, the path of the hand in horizontal planar arm movements is characteristically straight when described in external Cartesian $(x, y)$ coordinates (Abend, Bizzi & Morraso, 1982). However, when the same movements are described in joint angular coordinates (where the angle at the shoulder is plotted against the angle at the elbow) the paths are sometimes straight but often curved, as illustrated in Fig. 1. Thus, in joint angular coordinates, a more complex pattern is observed. In the case of horizontal arm movements, straight line Cartesian endpoint paths have been interpreted as evidence of planning in endpoint coordinates.

Figure 1 shows a schematic representation of a simple two-degree-of-freedom arm. In this system the joint angles shoulder ($S$) and elbow ($E$) can be changed but the links are of fixed extent. A change to either or both of the joint angles will result in a change in the position of the limb endpoint $B_{x,y}$. Movements are shown in endpoint space $(x, y)$ coordinates and joint space $(E, S)$ coordinates. The figure illustrates the nonlinear mapping between these coordinate systems. Figure 1((a),(b)) illustrates a motion in which the path in joint coordinates (b) is a straight line. The corresponding path of the endpoint in Cartesian coordinates is curved (a). In contrast, Fig. 1((c),(d)) demonstrates a motion in which the path in endpoint coordinates (c) forms a straight line. This corresponds to a curved path in joint angular coordinates (d).

The problem facing us in the study of arm movements is how to account for the path (sequences of positions in space) and the trajectory (time history of successive positions) of the endpoint. In the vocal tract where the patterns of surface positions over time are responsible for distinctive sound generation we are faced with similar problems. What form do the paths and trajectories of the vocal tract surfaces take and what determines them? In the two degree-of-freedom model illustrated in Fig. 1, three kinematic factors combine to determine the endpoint behavior. The first is the relative timing of the movements of the two joints. In the extreme case, if joint $S$ moves its full extent before joint $E$ begins to move, an extremely curved endpoint path—reflecting the joint rotations—would be observed.

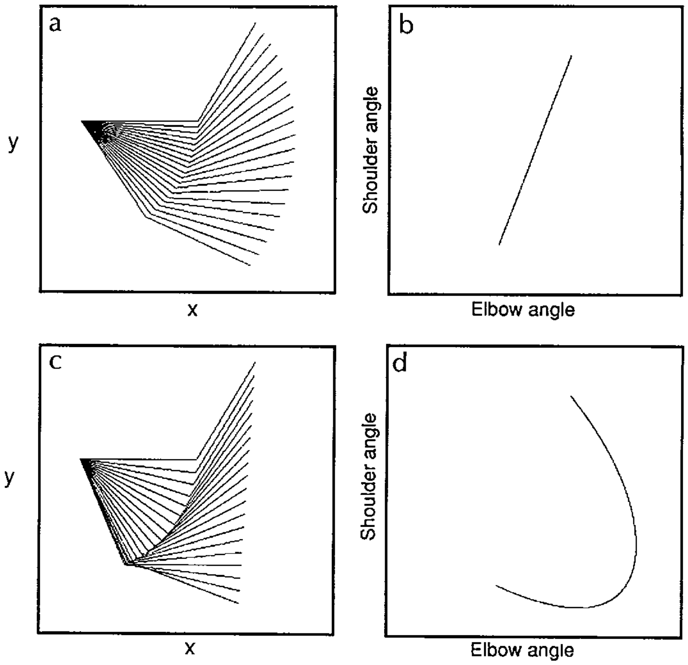

**Figure 1.** Schematic of a simple two joint system for arm movement. (a) Lowering motion of the limb in which there is motion at both joints and a curved endpoint path. (b) Corresponding joint space representation of the motion in (a). (c) Lowering motion of the limb in which there is motion at both joints and a straight endpoint path. (d) Corresponding joint space representation of the motion in (c).

The second factor that influences the endpoint path is the trajectory at the individual joints. For a given relative timing of the onsets and offsets of movement, the time course of the movement at the two joints will determine the resulting endpoint path and trajectory (Flanagan & Ostry, 1990). If for example, the two joints start and end their motion simultaneously the trajectories at the two joints must differ in form to yield a straight endpoint path. (See Munhall, Ostry & Parush, 1985, and Adams, 1990, for a discussion of trajectory shapes in speech and Hollerbach & Atkeson, 1987, for a discussion of a range of joint and endpoint control strategies.)

Finally, the path of the individual articulator's motion can in principle contribute to the endpoint path. In the example in Fig. 1, each joint has only a single degree of freedom and therefore can only influence the path by variation in the extent of rotation. In the speech cases we will be examining, however, the motion of the individual articulators is more complex. The tongue and jaw, for example, have multiple mechanical degrees of freedom.

Figure 2 presents a simple geometric model of the jaw with two degrees of freedom. The jaw is drawn as if composed of two segments with fixed extent which form a constant angle (i.e. the angle of the mandible). We have chosen to represent the position of the jaw in terms of rotation ($\alpha$) about the condyle (the centre of rotation) and translation ($\tau$) of the condyle along the articular eminence. Alternatively, the jaw's position can be described in terms of the Cartesian coordinates

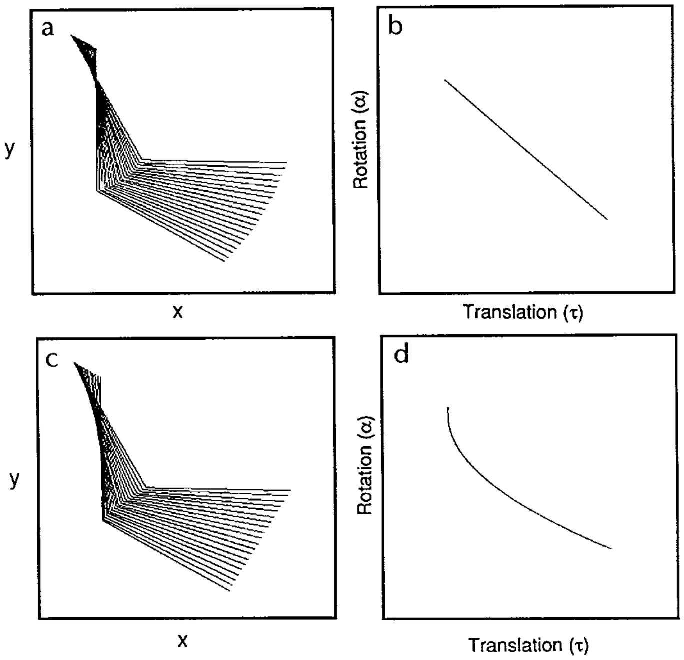

**Figure 2.** A model of the jaw with two degrees of freedom. (a) Lowering motion in which the jaw rotates about the condyle and condyle translates along the articular eminence. The path of the endpoint is curved. (b) Corresponding joint space representation—translation *vs.* rotation—of the motion (a). (c) Lowering motion in which the jaw rotates about the condyle and condyle translates along the articular eminence. The path of the endpoint is straight. (d) Corresponding joint space representation—translation *vs.* rotation—of the motion (c).

$(x, y)$ of the movement endpoint (i.e. the tip of the mandible). Note that in the arm model (Fig. 1) the two degrees of freedom are distributed to different joints whereas in the jaw model (Fig. 2) the two degrees of freedom are coupled at a single joint.

Figure 2((a),(b)) shows that straight line paths in joint space $(\tau, \alpha)$ correspond to endpoint paths which are only slightly curved. This might suggest that these two spaces are difficult to distinguish on the basis of straight line motion paths of the endpoint. However, as shown in Fig. 2((c),(d)) straight line endpoint paths correspond to markedly curved paths in joint space. This indicates that these two spaces can, in fact, be distinguished at the joint level. Interestingly, small changes in curvature in endpoint space can exact large changes in curvature in joint space. The reason for this is that translation has a relatively minor effect on the path of the mandibular incisor (in comparison to rotation) whereas the form of the path in joint space is greatly affected by both the vertical and horizontal motion of the endpoint.

We have used the X-ray microbeam system to record tongue and jaw movement data which we have treated in both oral cavity and joint coordinate systems. Our subjects produced simple speech utterances involving the vowels /æ/, /i/, /ɑ/ and /u/ in combination with velar and alveolar consonants /k/, /s/ and /t/. In order to force the articulators to function over different regions of the articulator space, the utterances were produced at preferred and fast speech rates and at normal and loud volume. A matching manipulation was carried out for mastication. Orofacial control in mastication should be of particular interest to speech researchers because the study of speech and mastication allows the separation of general coordinative constraints from specific constraints imposed by speech tasks. Both speech and mastication contain free motion and compliant or restricted motion phases involving external contact forces. We have shown elsewhere that the same nervous system control signals can produce both kinds of motion (Flanagan, Ostry & Feldman, 1990). In mastication, subjects chewed on rubber tubing which differed both in cross-sectional area and compliance. Further, rate of chewing was manipulated. The same subjects were tested in both the speech and mastication parts of the study. The advantage of the within subjects design is that the properties of the physical plant and the articulator geometry are held constant while the task requirements change. Only a small part of this data set is presented here.

## 2. Method

To date, two subjects have been tested. Both subjects were speakers of American English with no known speech or orofacial abnormalities. Subject A was an adult male; subject B was a female.

The X-ray microbeam system at the University of Wisconsin was used to record tongue and jaw kinematics in the mid-sagittal plane. Gold tracking pellets were placed on the tongue (tip, blade and dorsum) and jaw (between the mandibular incisors and on both the left and right mandibular molars) using a dental cement (Ketac). The distances between pellets and the mid-sagittal image plane, determined from dental impressions, were used to correct for projection errors that occur when recording the position of off-image plane pellets.

The $x$ and $y$ position data for each pellet were smoothed using a second order Butterworth filter with a cut-off frequency of 10 Hz. The motion of the tongue and jaw pellets was transformed into two-space Cartesian coordinates in an occlusal plane reference system, and the motion of the jaw pellets was also transformed into two-space joint coordinates. In the Cartesian representation, one axis coincides with the occlusal plane and the other runs perpendicular to the occlusal plane through the maxillary incisors. The occlusal plane was defined with respect to the molar bite surface and the maxillary incisor cusp. In the joint space representation, the rotation of the mandible and the translation of its axis of rotation along the articular eminence were considered. In order to compute jaw rotation and translation, the position of the mandibular condyle with respect to the positions of pellets on the jaw was determined by palpation. Jaw translation and rotation refer specifically to translation of the mandibular condyle and rotation of the jaw about the condyle.

Simulation studies, conducted in collaboration wth John Westbury of the X-ray Microbeam Facility, were carried out to assess the error associated with the reconstruction of the position of the mandibular condyle from the recorded positions of pellets on the jaw. We used both simulated microbeam data incorporating typical two-space noise distributions and the actual recording of the rotation in two-space of a plastic frame with three markers placed at known distances. With both the model data and the actual pellet rotations, the prediction algorithms were able to use two points plus a distance and angle to reconstruct the recorded (or simulated) location of the third without systematic bias.

In a final analysis the motions of the tongue pellets were projected onto a mandibular reference system in which one axis was defined by the mandibular molar bite surface and the other axis intersected at the mandibular molar incisor. The net effect of this transformation was to remove the jaw contribution from the overall tongue pellet motion (see also Mermelstein, Maeda & Fujimura, 1970; Kent & Moll, 1972*b*).

Jaw movement kinematics were studied both in Cartesian occlusal plane coordinates and in a joint coordinate system (motion about the centre of rotation of the condyle and translation of the axis of rotation along the articular eminence). Tongue data were studied in occlusal plane coordinates and in mandibular joint coordinates.

## 3. Results

Figure 3 shows paths during the production of the /kɑ/ portion of the CVC /kɑk/ for tongue dorsum, tongue blade and mandibular incisor pellets. The ordinate plots vertical motion (i.e. perpendicular to the occlusal plane) while the abscissa represents the occlusal plane. The subject is facing toward the right. Note that the scales of the two axes are different so that the aspect ratio of the data is visually distorted. In each of the three sections of the figure, a number of repetitions produced by a single speaker are shown. The top trace in each panel is a rough palate trace performed after the experiment.

The three panels show paths for utterances spoken at a normal rate and volume (a), at a fast rate (b) and at a loud volume (c). Note first that the tongue pellet paths are curved in all conditions. The tongue first moves forward as it begins to lower from its highest position and then moves backward toward the pharyngeal wall in the latter half of the lowering movement. The data show a moderate trend for the path variance to increase as the tongue/jaw system lowers. This is most clear for the loud condition, where it can be seen that the spatial variance is far less in early portions of the tongue pellet paths.

In this subject's data the degree of curvature increases with loudness though not with changes in speaking rate. Normal and fast speech rates follow the same paths for the tongue dorsum pellet, and the movements differ only slightly in extent. Between normal and loud condition, by contrast, the vertical amplitude of the tongue dorsum movement varies more, although the anterior–posterior (a–p) position at maximum opening does not differ greatly. (This is consistent with acoustic data reported recently by Schulman, 1988; see also Lindblom, 1988.) Moreover, the paths moved in achieving these final positions are quite different for normal and loud utterances; the degree of curvature increases with loudness. The same basic findings are true for other vowels.

In Fig. 4 the lowering and raising motion for the vowel ɑ are shown for (a) normal volume and (b) loud volume. As has been shown previously by Houde (1968) and others, the production of CVC sequences produced by the tongue/jaw system can involve complex movement paths for tissue points. In these data, raising and lowering motions follow different paths, forming a sort of ellipse for the CVC. The direction of motion in all of our data is clockwise (lowering then raising). The

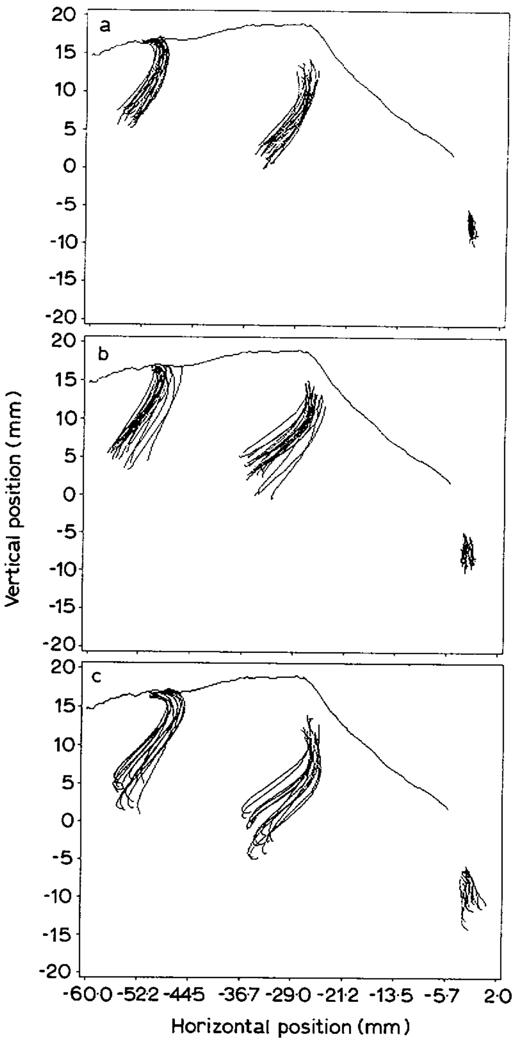

**Figure 3.** Paths of tongue dorsum, tongue blade and mandibular incisor pellets for /kɑ/ in (a) normal, (b) fast and (c) loud conditions produced by Subject A. In this and subsequent figures the speaker is facing right.

overall area of the ellipse traced by the movement path of each tongue pellet increases with speaking volume.

In all of these data the tongue paths tend to be curved whereas the paths of the jaw movement are more straight. In Fig. 5 jaw lowering movements are shown in oral cavity coordinates for two subjects collected in a separate experiment. Figure 5(a) shows paths for /kæ/ and /sæ/ in loud speech, and Fig. 5(b) shows paths for a different subject for /kæ/ and /tæ/ at a normal rate and volume. As in all the figures, the subject is facing right. The movement of pellets on the mandibular incisor and one or two mandibular molar pellets are shown. The subject shown in Fig. 5(a) had a slightly backward motion during lowering while the subject shown in Fig. 5(b) tended to move the jaw more vertically. This path direction was unaffected

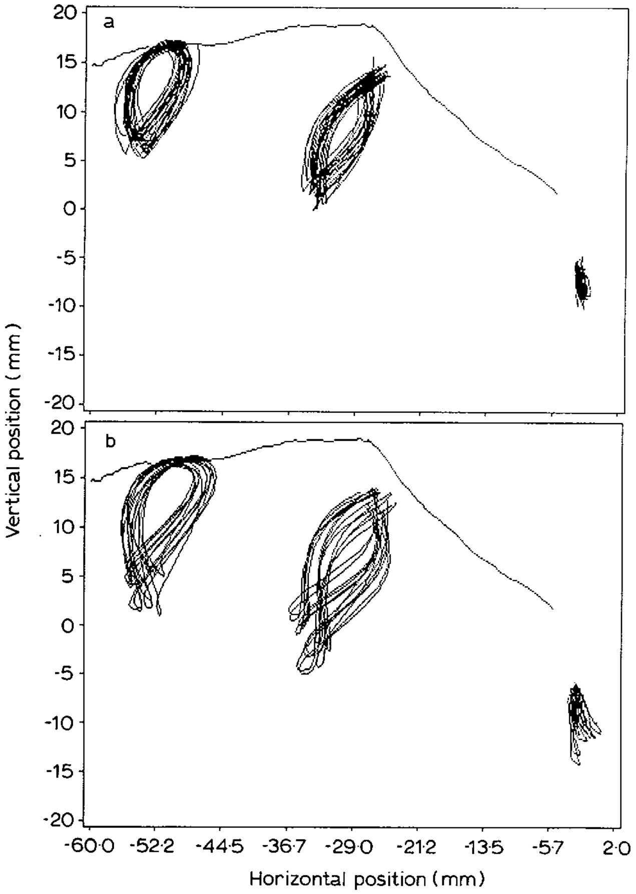

**Figure 4.** Paths of tongue dorsum, tongue blade and mandibular incisor pellets for /kɑk/ in (a) normal and (b) loud speaking conditions, produced by Subject A.

by rate or volume of speaking, although the slope of the paths tended to differ for different subjects.

These motions of the jaw are the result of movement at the temporomandibular joint. In Fig. 6 the rotation of the jaw is shown on the ordinate; horizontal translation is shown on the abscissa. The reference (zero) angle for jaw rotation is the angle of the jaw at occlusion. In Fig. 6(a) /sɑ/ and /kɑ/ are plotted when spoken at a fast rate. In Fig. 6(b) /sɑ/ and /kɑ/ spoken at a loud volume are shown and Fig. 6(c) shows /sæ/ and /kæ/ spoken in a loud volume. In general, across vowels, consonants and speaking conditions, relatively straight motion paths are observed in joint space. This indicates that jaw rotation and translation start and end simultaneously and have similarly shaped velocity profiles. Indeed, inspection of the data show that the velocity profiles of both rotation and translation are approximately bell-shaped. Straight line paths in joint coordinates are also observed in mastication. Thus, speech movements are characterized by straight motion paths of the jaw in both the joint level and endpoint level coordinate systems. (See comments on this pattern in the Introduction and Discussion.)

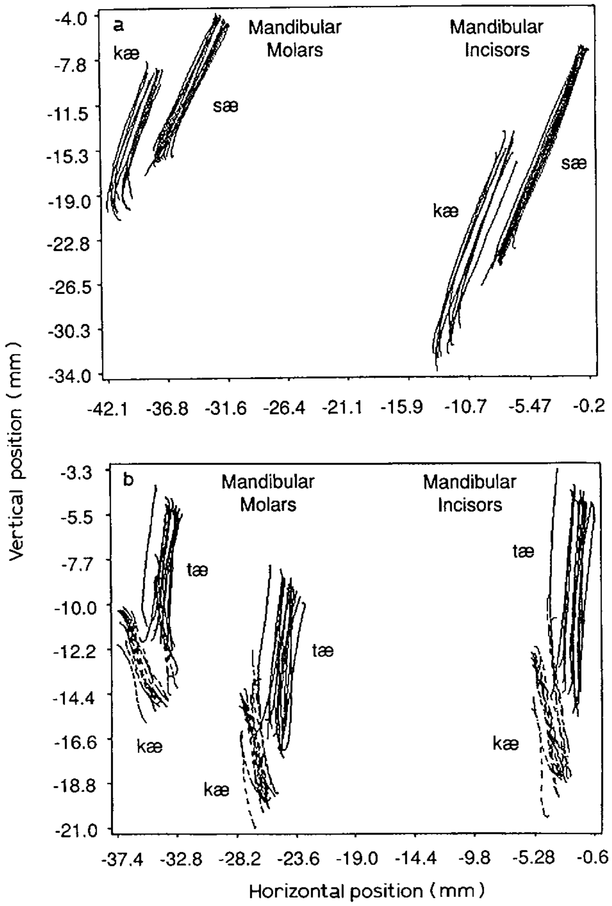

**Figure 5.** Paths of mandibular incisor and molar pellets for (a) /kæ/ *vs.* /sæ/ and (b) /kæ/ *vs.* /tæ/ for two different speakers.

In spite of their temporal correspondence, a number of manipulations in both speech and mastication suggest that jaw rotation and jaw translation can be separately controlled. At fast chewing rates rotation can be observed without jaw translation. In speech, similarly, the relationship between rotation and translation is not fixed but varies with the composition of the utterance, as illustrated in Fig. 6. In general, the slope of the relationship between translation and rotation depends on the consonant (less steep for /k/ *vs.* /s/ or /t/) but is similar for different vowels (/ɑ/ and /æ/) and for differences in speech rate and speaking volume. Fig. 6((a),(b)) shows that the slope does not differ in fast *vs.* loud speech; Fig. 6((b),(c)) shows that the slope differs with consonant but not vowel composition of the utterance.

Finally, the motion of the tongue pellet paths were projected into a Cartesian mandible coordinate space by homogeneous transformations (see Paul, 1981, for a discussion). The net effect of this coordinate transformation is to remove mathematically the jaw portion of the tongue/jaw system. Figure 7 (a),(c)) shows the tongue dorsum and blade pellets during the production of /kɑk/ spoken at a normal rate and volume. Figure 7((b),(d)) shows repetitions by the same speaker of

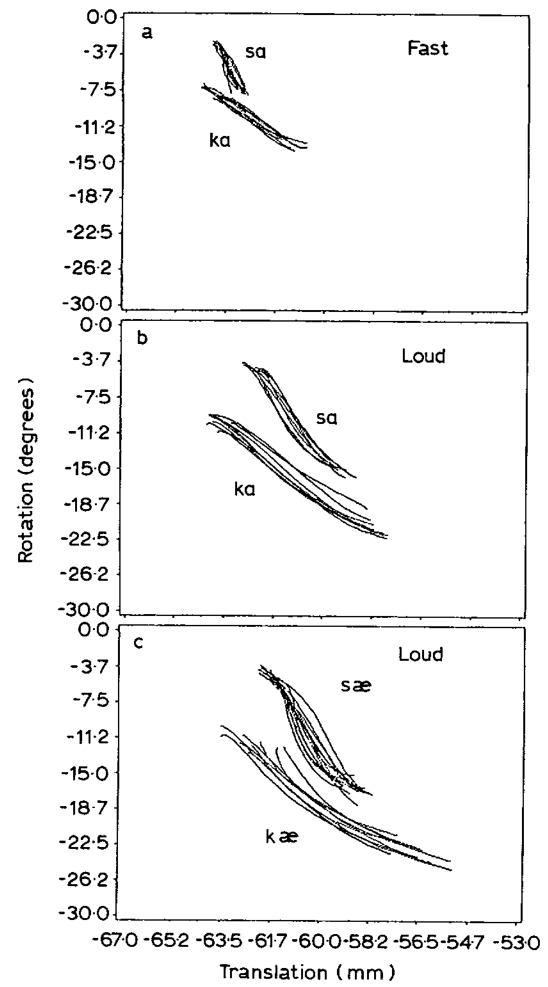

**Figure 6.** Paths of mandibular motion for /kɑ/ *vs.* /sɑ/ spoken at (a) a fast rate and (b) loud volume and (c) for /sæ/ *vs.* /kæ/ at a loud volume in a joint coordinate space produced by Subject B. The $y$ and $x$ axes show motion about the centre of rotation of the condyle and translation of the axis of rotation along the articular eminence respectively.

the same utterance at a loud volume. Figure 7((c),(d)) shows the paths of the tongue pellets with the jaw included; Fig. 7((a),(b)) shows the tongue paths after the jaw motion has been "removed" by the coordinate transformation. The origins of the various plots differ but they are all shown in the same scale. In the normal volume condition, the jaw movements are relatively small for this subject and their removal produces only a small reduction in vertical and horizontal motion in each tongue pellet. In the loud condition the removal of the jaw produces a great reduction in the complexity of the tongue pellet paths and also alters the proportionality of the vertical and horizontal movement components. The extra loops that are evident in the region of maximum opening in the paths for the loud condition appear to be the result of the relative timing of the jaw and tongue movements.

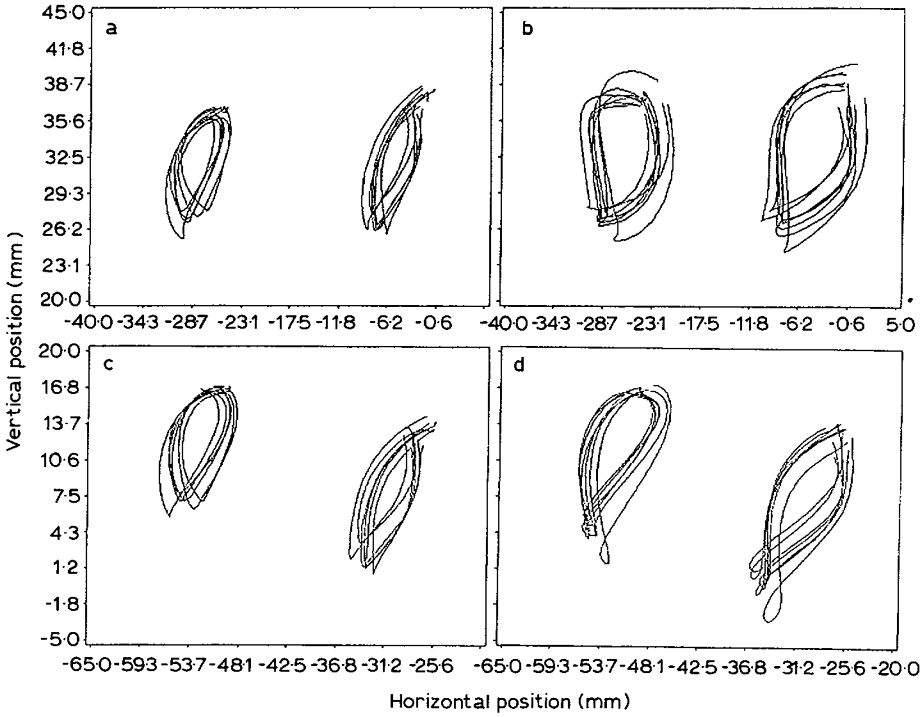

**Figure 7.** Paths of tongue dorsum and tongue blade pellets for /kak/ in ((a),(c)) normal and ((b),(d)) loud speech produced by Subject A with the jaw motion ((c),(d)) and with the jaw motion mathematically removed ((a),(b)).

## 4. Discussion

The examination of tongue movement plus jaw motion reveals complex curved pellet paths in Cartesian coordinates. The form of these paths can be largely accounted for on the basis of tongue movement alone since the paths of the tongue pellets are not greatly affected by the subtraction of jaw motion from tongue motion. The jaw motion alone when considered in Cartesian coordinates revealed less curved paths than were observed for the tongue. Additional analyses showed that the translation and rotation components of the mandible could be independently specified.

The tongue pellet paths presented in this paper are similar to those reported previously (e.g. Houde, 1968; Kent & Moll, 1972*a*). The origin of the shape of these paths, however, is not clear. In part, the paths are determined by the superposition of jaw and tongue movements. This is most clear in the difference between loud and normal speech shown in Fig. 7. In the loud condition the phasing of tongue and jaw movements is different from that in the normal condition. This results in complex paths for the tongue surface in the region of peak opening.

As can be seen in Fig. 7, the tongue movement itself is still elliptical even with no jaw contribution. Perkell (1969) speculated that at least two possible factors could contribute to this tongue pattern. First, coarticulation with different preceding and following segments may alter the tongue's movements. For example, Öhman (1966) has shown that place of articulation for velar consonants is shifted by different surrounding vowels. However, this seems an unlikely explanation for the present data since the consonants were always surrounded by the same vowels in each utterance. A second factor discussed by Perkell (1969) is that constant production with the tongue body (such as is involved in the production of /k/) may be controlled more efficiently by having the tongue move continuously rather than discretely when alternating between a vowel and a consonant position. Continuous movement can be accomplished by producing an elliptical movement path rather than straight back-and-forth movements. In this way, closures are produced by a sliding contact against the palate. Our data, however, suggest that the tongue's path is not a smooth ellipse throughout the entire CVC sequence. Rather, abrupt changes in direction occur in the tongue paths in both the opening and closing phases of movement (see Fig. 7). These "transition points" warrant further exploration, particularly in the context of other oral movements such as those involved with mastication.

Kent & Moll (1972*a*) have discussed the possibility that the forward motion of the tongue during opening may be due to the force of the air pressure behind the constriction. On the other hand, Coker (1976) has suggested that perhaps the direction of the tongue motion was an active adjustment to create the appropriate acoustic conditions for some phonetic contrasts. In particular, he suggested that the elliptical tongue motion in Houde's (1968) data for /VgVgV/ sequences may have allowed voicing for the /g/ to be maintained during closure. The tongue moving forward during closure would expand the back cavity and thus reduce the rate of build-up of pressure that would cause devoicing. The presence of this elliptical pattern in the present data for /k/ sequences suggests that Coker's (1976) account is at least not the sole explanation for the observed paths. The origin of the path shapes is not clear, but the form of the movement may still be perceptually important. Coker (1976) noted that if the paths were not reproduced in articulatory synthesis, /g/ was easily confused with /d/ in many contexts.

Analysis of tongue motions in speech and other oral activities is needed to determine why these paths take these shapes. Perhaps the observed tongue paths arise as a result of the biomechanical organization of the oral cavity. That is, the tongue paths may reflect factors such as muscle lines of action which are not specific to speech. If this is the case, similar patterns of motion will be observed in nonspeech tongue lowering movements and in speech lowering movements.

The motion of the jaw showed less complex kinematic patterns. The rotation and translation components of jaw movement showed very similar behavior across conditions with one exception: the proportion of jaw rotation and translation in a movement varied with consonant. In particular, jaw movements for /k/ involve a greater amount of translation and a lower condyle position than those for /s/ and /t/. (Perkell, 1969, also noted that the jaw motion for /k/ is different from that for other consonants, presumably to allow for the distinct tongue movement patterns required for /k/.) In spite of this consonant-dependent difference, all conditions showed straight line movement patterns when rotation *vs.* translation of the condyle were plotted. As was suggested in the introduction, the overall linearity of jaw motion in both joint and Cartesian frames of reference results from the relatively small effect that translation has on the path of the mandibular incisor in a linear coordinate space. This pattern of data is consistent with the planning and control of jaw motion in joint level coordinate space.

Evidence for the independent control of jaw rotation and translation served as a basis for specifying the central commands structure in a recently developed model of jaw motion based on the equilibrium point hypothesis (Flanagan *et al.*, 1990). The model includes three muscles: "opener", "closer" and "protruder" corresponding to the anterior digastric, masseter and lateral pterygoid. Although the terms "opener" and "closer" refer to the principle action of these muscles, it is important to note that both opener and closer muscles produce jaw retraction in addition to rotation. In contrast, the modeled protruder muscle did not produce rotation. As a consequence of the dual role of "closers" and "openers", all muscles must be controlled in concert in order to produce rotation, translation, or a combination of the two.

What kind of planning is necessary to control a multi-articulate system such as the oral motor system and in what coordinate space does this planning occur? In controlling even simple systems such as the ones shown in Figs 1 and 2, the nervous system is faced with a range of potential coordinate spaces in which the movements may be planned, and a set of sensorimotor transformations between these frames of reference to bring about coordinated movement (Saltzman, 1979). At the physiological level, control may be manifested in the muscle length at which the motoneuron recruitment begins (threshold length) (Feldman, Adamovich, Ostry & Flanagan, in press). Changes in the threshold length bring about changes in muscle activation and muscle length. At the joint level, planning may be in terms of joint angles, or in more complex joints such as the jaw, in terms of joint angles and centers of rotation. Finally, in endpoint control the movements are presumably described in some external reference system. For example, in reaching, the hand may be controlled with respect to the Cartesian coordinates of external space.

The present data suggest some preliminary answers to this coordinate space question. It is clear that there are many advantages to specifying goals in vocal tract space (Saltzman & Munhall, 1989). Primary among these is the relationship of the vocal tract shape to the acoustics. However, at least four factors should encourage us to seek alternative solutions to this problem. The first is the computational complexity of solving inverse problems in systems with complex dynamics. When movements are planned in a global reference frame (such as the vocal tract), movements of the components (the tongue and jaw) must be derived by mapping the endpoint behavior into articulator or joint spaces using inverse-dynamics equations or their equivalent. The second factor which can be seen in the present data is that the observed paths in the vocal tract are complex, particularly in extreme speaking styles such as speaking loudly. This suggests the possibility that planning at the vocal tract level is a good deal cruder than we have imagined. Paths may be defined with broad tolerances and the final form of the movements of the vocal tract surfaces will reflect many influences. Perkell & Nelson (1985) have recently demonstrated direction specific differences in pellet position variability. Spatial variation of the tongue during vowel production was less in a direction that was acoustically more important for the vowel. This suggests that some kinds of spatial variation of the vocal tract surfaces are not as important as others and perhaps this influences articulatory planning. Third, there is recent evidence in speech and in limb movement that successive movements in a sequence can be partially superimposed on one another (Flash & Henis, in press; Munhall & Löfqvist, in press). The net effect of this blending is to alter the observed movement paths. This superposition effect again implies that vocal tract planning may involve broad tolerances. Finally, the jaw data presented in this paper are consistent with the conclusion that joint space planning is involved in speech production. This is evidenced by the straight line paths of the jaw motion in joint coordinates. (This, of course, does not mean that other orofacial motions must be similarly planned.)

In closing, we emphasize that work on motor control should focus on the control mechanism quite independent of the particular coordinate system in which motions are planned or described. The Flanagan *et al.* (1990) model is important not only because it accounts for the data in the present study but because it does so with a control approach that is physiologically accurate and because the same overall mechanism can be implemented in different coordinate systems. The nervous system must only plan the rate and direction of the shift in the equilibrium point in either endpoint coordinates or joint coordinates.

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