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An Examination of the Degrees of Freedom of Human Jaw Motion in Speech and Mastication

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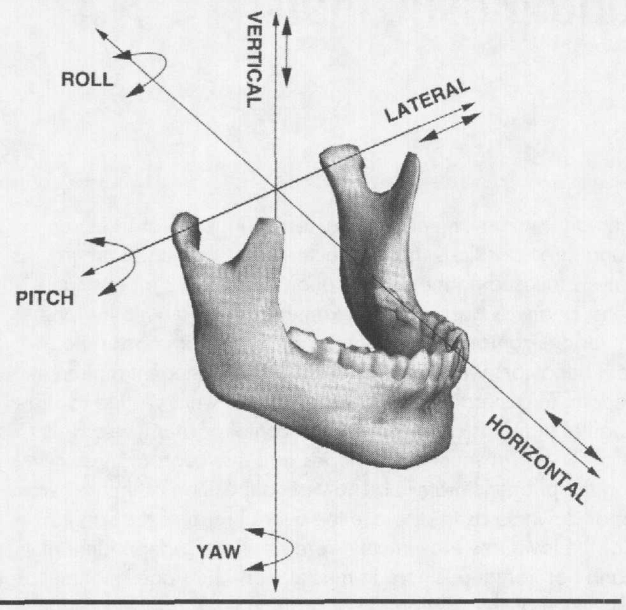
The kinematics of human jaw movements were assessed in terms of the three orientation angles and three positions that characterize the motion of the jaw as a rigid body. The analysis focused on the identification of the jaw's independent movement dimensions, and was based on an examination of jaw motion paths that were plotted in various combinations of linear and angular coordinate frames. Overall, both behaviors were characterized by independent motion in four degrees of freedom. In general, when jaw movements were plotted to show orientation in the sagittal plane as a function of horizontal position, relatively straight paths were observed. In speech, the slopes and intercepts of these paths varied depending on the phonetic material. The vertical position of the jaw was observed to shift up or down so as to displace the overall form of the sagittal plane motion path of the jaw. Yaw movements were small but independent of pitch, and vertical and horizontal position. In mastication, the slope and intercept of the relationship between pitch and horizontal position were affected by the type of food and its size. However, the range of variation was less than that observed in speech. When vertical jaw position was plotted as a function of horizontal position, the basic form of the path of the jaw was maintained but could be shifted vertically. In general, larger bolus diameters were associated with lower jaw positions throughout the movement. The timing of pitch and yaw motion differed. The most common pattern involved changes in pitch angle during jaw opening followed by a phase predominated by lateral motion (yaw). Thus, in both behaviors there was evidence of independent motion in pitch, yaw, horizontal position, and vertical position. This is consistent with the idea that motions in these degrees of freedom are independently controlled.

KEY WORDS: jaw, kinematics, speech, mastication

In this paper, we examine human jaw movements in speech and mastication in terms of the three orientation angles and three positions that fully characterize the motion of the jaw. Our aim is to provide both a comparative study of mastication and speech and to determine the independent dimensions of jaw motion control. By systematically manipulating the phonetic composition of the speech task and the characteristics of the bolus in mastication we will provide evidence of the independent control of jaw motion in four degrees of freedom in both speech and mastication—sagittal plane orientation (pitch), horizontal position, vertical position, and coronal plane orientation (yaw).

In both speech and mastication, jaw motion involves a combination of rotation and translation. During jaw opening, the jaw rotates downward and translates both forward and downward (see Figure 1). During

Figure 1. The coordinate frame for jaw motion. The horizontal axis is aligned with the occlusal plane. The lateral axis passes through the condyle centers at occlusion. The origin is at the intersection of this axis and the mid-sagittal plane. The three angular motions are defined as follows: pitch is rotation in the midsagittal plane about a lateral axis; roll is rotation in a frontal plane about a horizontal (protrusion/retraction) axis; yaw is rotation in a coronal plane about a vertical axis.



closing, the pattern is reversed. Significant lateral motions are observed, primarily in jaw closing movements during mastication. The mapping between jaw muscle actions and the mechanical degrees of freedom of jaw motion is complex. All muscles contribute essentially to both rotation and translation (Laboissière, Ostry, & Feldman, 1996; McDevitt, 1989, for review). Thus, in order to produce movements involving rotation or translation either alone or in combination, the control signals to jaw muscles must be coordinated.

We have previously presented empirical evidence on the organization of sagittal plane jaw motions in mastication and speech (Ostry & Munhall, 1994; Vatikiotis-Bateson & Ostry, 1995). We have shown that in speech, the sagittal plane orientation and the horizontal position of the jaw may vary independently (see Edwards & Harris, 1990; Westbury, 1988, for related findings). In mastication, no comparable independence of the constituent jaw motions has been reported.

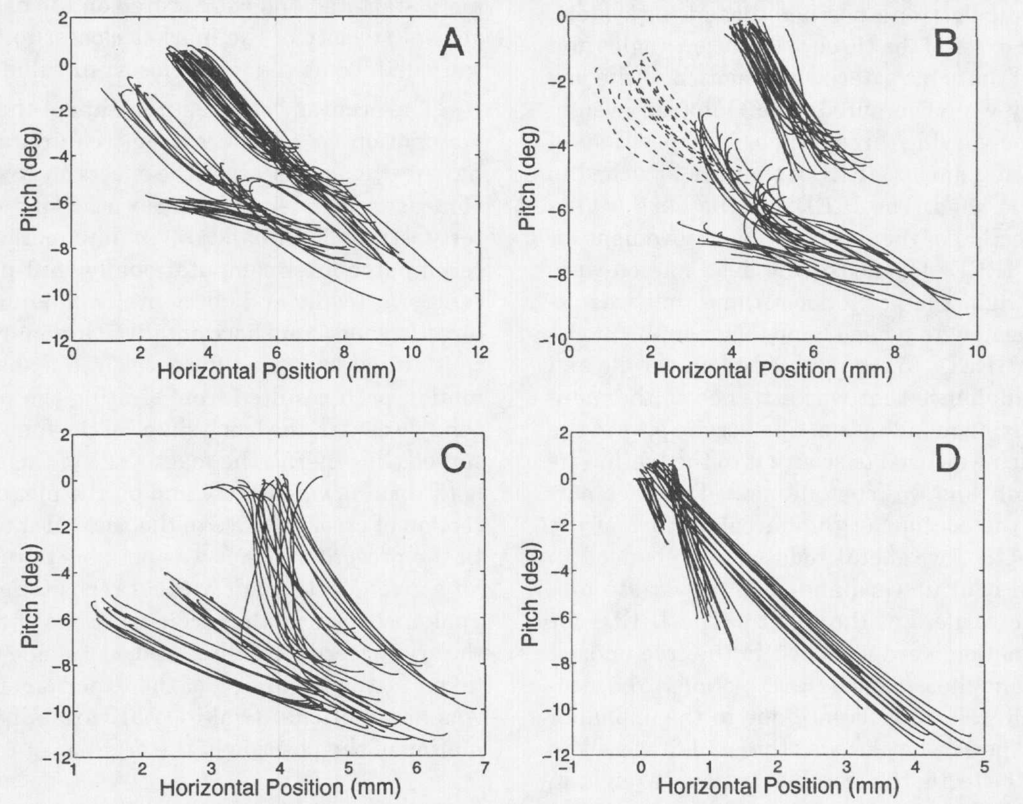
We have also explored how control signals to individual muscles might be coordinated in the context of a model of jaw and hyoid motion based on the lambda version of the equilibrium point hypothesis (Laboissière et al., 1996). We have shown that independent motion in each of the model's kinematic degrees of freedom may be produced using a linear combination of commands to individual muscles. In order to extend this work either to a three-dimensional model of jaw motion or to incorporate the motions of other articulators, as well as to yield, in the context of the model, testable hypotheses about the organization of control signals to muscles, all independently controlled motions of the jaw must be identified.

A number of differences in mastication and speech have been documented that are consistent with the idea that control signals to muscles may be coordinated differently in these two behaviors. Mastication is a stereotyped behavior. The possibility in a number of species including nonhuman primates of a subcortical central pattern generator (CPG) for mastication (see Luschei & Goldberg, 1981, for review) is consistent with the idea that the central control of mastication and speech is differently organized. The kinematics themselves differ. Jaw motions in speech are more or less confined to the sagittal plane. The amplitude of motion is typically less in speech than in mastication. Moreover, jaw movements are faster in speech (Bishop, Plesh, & McCall, 1987; Folkins, 1981; Gibbs & Messerman, 1972; Luschei & Goldberg, 1981; Ostry & Munhall, 1994). The patterns of muscle activity also differ in mastication and speech (Moore, Smith, & Ringel, 1988). Mastication is characterized by distinctly reciprocal patterns of activity in jaw closer and jaw opener muscles (masseter and temporal vs. anterior digastric)—a characteristic of CPG patterned output (Lund, 1991)—whereas speech movements tend to involve patterns of coactivation of closers and openers.

Our aim in the present paper is to determine the dimensions of the control of jaw motion by identifying the primary sources of independent variation in movements. We should clarify the usage of a number of terms that will be employed to describe jaw motions. The movement of the jaw as a rigid skeletal structure can be decomposed into six orthogonal dimensions or degrees of freedom. These six dimensions provide a complete mechanical description of jaw motion. The goal is to identify which of these dimensions are kinematically independent and hence presumably independently controlled.

We will report on the decomposition of jaw motion into its six component rotations and translations. In order to identify the jaw's independent motions, the data are assessed over the course of jaw opening and closing movements by plotting the motion paths in speech and mastication. By examining sets of paths recorded under different experimental conditions it is possible to identify movement dimensions that may vary independently. In the simplest case in which motion paths are linear (for example, Figure 2), the independence of the movement dimensions that define the paths may be determined by examining each path's slope and intercept. The kinematic variables that define the paths are independent if different treatment conditions are characterized by motion paths in which differences in the value of slope

Figure 2. Jaw motion paths showing pitch angle versus horizontal jaw position. Panels A and B give data for the same subject (EB) recorded in two sessions 18 months apart. The paths show loud volume speech for all combinations involving the vowel *i*. Panel C (subject EB) shows trials involving the consonant-vowel sequences *so*, *ro*, *lo*, and *to*. The paths involving pure rotation are for *to*. Panel D (subject MT) is for trials involving *sh*. The two sets of paths involving almost pure rotation are for *sho* in normal (shorter paths) and loud conditions. The remaining set of paths are for loud volume trials with *sha*.



and/or intercept are observed. Differences in slopes indicate that the relative magnitudes of movements in the two dimensions may vary with treatment condition. Differences in intercept indicate that the initial (or final value) in one movement dimension is independent of the corresponding value in the other dimension. Thus, the entire function may be shifted, either horizontally or vertically.

It should be noted that previous research on jaw motion in mastication and speech has focused on either rotation of the jaw in the mid-sagittal or frontal planes or upon the motion of individual tissue points. Since the position in space of individual points on the jaw can be achieved by infinite combinations of jaw orientation angles and positions, determination of the jaw's independent movement dimensions requires a full six-dimensional analysis of the motion of the jaw as a rigid body.

Methods

Jaw motion kinematics were recorded in both speech and mastication. In the speech condition, the utterances were composed of the vowels (*V*) *a*, *o*, *i* (as in large, sew, and see) and consonants (*C*) *s*, *sh*, *l*, *r*, *t*, *k*, *p*, *f*. Participants produced repetitive speech-like sequences of the form *VCVCa*, for example, *ososa*, *ikika* for 15–20 seconds. All combinations of the three vowels and eight consonants were tested in loud and normal volume conditions. Loud speech was included in order to obtain movement amplitudes throughout the full functional range of the jaw in speech. (In the loud volume condition participants were instructed to speak very loudly.) At least 10 utterances of each type were recorded. We have used nonspeech sequences rather than continuous speech for several reasons. These sequences enabled the examination of a relatively large corpus. They permitted systematic variation of the phonetic material and they enabled us to minimize changes to the contextual environment. The test sequences also enabled us to examine movements throughout the workspace of the jaw.

In the mastication experiment, participants chewed repetitively on the following foods: carrot, celery, octopus, peanuts, bread, steak. Bolus size was manipulated (normal vs. large). Participants were tested both under bilateral chewing conditions and during unilateral chewing on the participant's preferred side. Participants were instructed to chew repetitively at a normal rate. Between 10 and 15 chewing cycles were collected in each condition.

The jaw movements were recorded at 200 Hz using Optotrak, an optoelectronic position-measuring system, and the time courses of the three orientation angles and three positions that characterize the motion of the jaw as a rigid body were computed. The Optotrak system records the time-varying three-dimensional positions of infra-red emitting diodes (IREDs) that are attached to the jaw and the head. The IREDs on the head (6) enabled the correction of the data for head movement kinematics. The IREDs for measuring head motion were mounted on a lightweight bamboo frame that was attached to the head with a head band (Nagashima model 1861). The jaw IREDs (5) were glued to an acrylic and metal dental appliance that was attached to the mandibular teeth using an adhesive. The acrylic part of the appliance, which was used to secure it to the teeth, was seated bilaterally and was custom-molded for each participant to fit the contour of the buccal surface of the mandibular teeth. Two metal rods were embedded in the acrylic and bent upward and then forward to protrude from the corners of the mouth. The IREDs for tracking jaw motion were attached to the free ends of the metal rods and thus enabled IRED motions to be measured with Optotrak. Interference due to the appliance was minimal. The acrylic part was thin and fit closely to the contour of the teeth; the metallic portion was light in weight yet rigid. Participants reported little discomfort and there was minimal audible distortion of speech due to its use. (No formal acoustical comparison was conducted of speech with and without the appliance.)

In total, we have examined 3 vowels × 8 consonants × 2 loudness levels in speech, and 6 varieties of food × 2 bolus sizes × unilateral and bilateral chewing in mastication trials. Five individuals were tested (EB was tested only on speech and NC was tested only on mastication). Participants were adult male speakers of English. None reported a history of facial trauma or surgery, hearing loss, or neurological deficits.

The three-dimensional raw data for each IRED were low-pass filtered at 12 Hz using a second-order Butterworth filter. The cutoff frequency was first selected on the basis of Fourier analysis of the original data streams and then by direct comparison of raw and filtered records. The signal power at the cutoff frequency was 40 dB or more below the peak power. The jaw orientation angles and positions were derived using vendor-supplied software based on a quaternion method (Horn, 1987). The coordinate system of the reconstructed movements is shown in Figure 1. The origin is specified with respect to the position of the condyle center at occlusion. The coordinates of this point were obtained by palpation to locate the condyle center and by measurement of the horizontal and vertical distances from the condyle center to a known reference location (the upper margin of the central mandibular incisor at the midline). Movement start and end were scored on the basis of the tangential velocity of the marker closest to the teeth and were defined as the point closest in value to 0 cm/s.

The accuracy of measurements of the origin of the jaw motion coordinate system requires comment. We have previously assessed the effects on jaw motion paths of measurement error in the location of the condyle center (Ostry & Munhall, 1994). Jaw motion paths were recomputed after computationally shifting the condyle center vertically and horizontally (7.5 mm in a vertical direction and 5 mm horizontally). Our analyses indicated that although some differences in the shape of the jaw motion path resulted from shifting the position of the condyle center, the basic shape of the functions was preserved. In general, the magnitude of the error depends both upon jaw geometry and on the magnitude and direction of error relative to the actual center of rotation. In the present study, it was possible to record all trials for a given participant without repositioning the dental appliance. Hence, the reconstructions of the location of the origin were typically based on a single measurement taken at the beginning of the experiment. Thus, there was no additional trial-to-trial variability due to estimation of the position of the origin.

Results

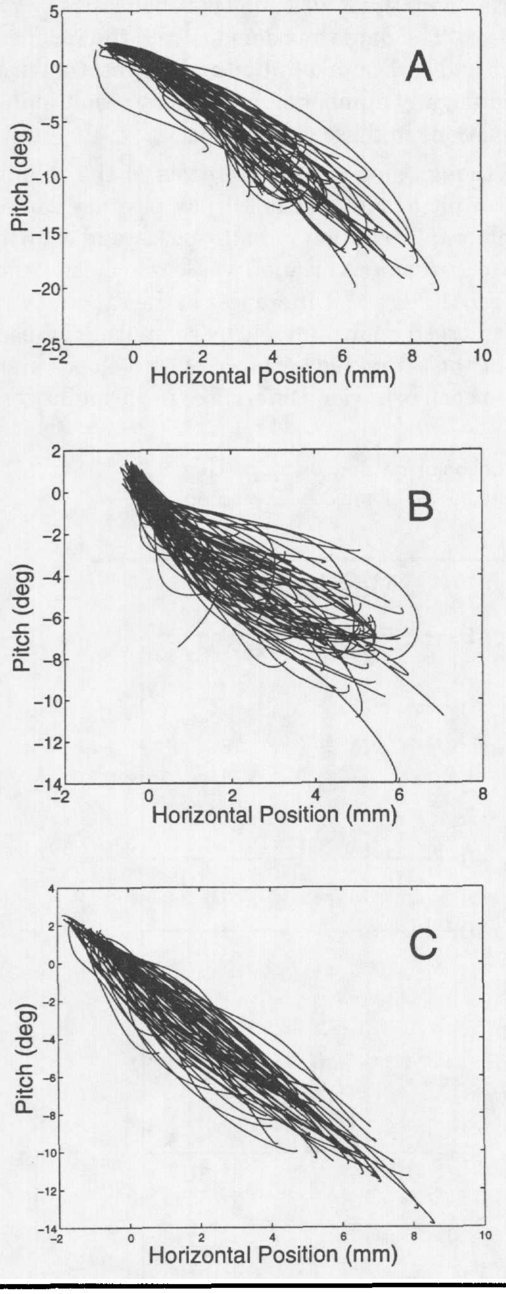
Jaw motion paths in mastication and speech were examined in various combinations of linear and angular coordinate frames. The aim was to identify the independent motions of the jaw. Note that the figures provide selected examples to illustrate the main findings. The statistical results of all analyses are reported on a per subject basis.

Sagittal Plane Motion Paths

Pitch and Horizontal Position

Characteristic jaw motion paths in speech and mastication are shown in Figures 2 and 3, respectively. The figures show jaw motion paths in which the vertical axis is the jaw orientation in the sagittal plane and the horizontal axis is the horizontal jaw position. The paths give jaw position/orientation combinations over the course of individual movements. The paths are shown for opening movements in speech and for jaw closing movements in mastication. We show different movements in speech and mastication in order to display, in each case, the

Figure 3. Jaw motion in mastication. Jaw orientation in the sagittal plane as a function of horizontal position. The figure shows bilateral chewing movements and all six types of food used in this study. The paths are given only for normal bolus size but the pattern observed with large diameter boluses is the same. Panel A is DO, B is AL, and C is MT.



most significant phase. However, for both of these behaviors, paths in the sagittal plane are similar for jaw opening and closing.

Consistent with earlier results (Ostry & Munhall, 1994; Vatikiotis-Bateson & Ostry, 1995), the figures show that when pitch is plotted as a function of horizontal jaw position, relatively straight paths are obtained regardless of the initial position or orientation of the jaw. In speech, the linear trend accounted for an average of 0.96, 0.97, 0.99, and 0.95 of the variance for DO, EB, MT, and AL, respectively. In chewing, the average proportion of variance accounted for by the linear trend was 0.97, 0.99, 0.98, and 0.92 for DO, MT, AL, and NC. The maximum standard error for these estimates was 0.014.

In speech, the slope of these paths and their initial orientation angle and horizontal position may vary, suggesting that jaw orientation in the sagittal plane and horizontal jaw position may be controlled independently (see statistical analyses below). The paths for mastication are in general more variable and show less of the systematic variation between conditions that characterizes motion paths in speech. Note that all participants show these same basic relationships.

Figure 2 gives examples of jaw motion in speech that are consistent with the notion that sagittal plane orientation and horizontal position are controlled independently. The upper two panels (A and B) show jaw motion paths during repetitive utterances of *iCiCa* sequences produced at a loud volume. The vertical axis gives the sagittal plane jaw orientation angle and the horizontal axis gives the horizontal jaw position. The paths for jaw opening movements are shown. Panels A and B were recorded about 18 months apart using the same speaker and the same speech material but different appliances (the B panel is from the second session). Although differences are apparent in the two sets of paths, it can be seen that the patterns are basically stable over this 18-month period and over different appliances. In both cases the sagittal plane jaw motion paths form essentially straight lines. Instances of jaw translation alone are observed. It is also seen that the initial jaw position in the workspace may be rotated downward or translated forward without affecting the slope of the jaw motion path in this coordinate space. Moreover, the curvature observed in some conditions indicates that the jaw is not constrained to produce only straight line sagittal plane motions.

Panels C and D of Figure 2 give other examples of the independence of pitch and horizontal position in speech, shown in the same coordinate system as the panels above. Both panels show instances of jaw rotation alone. In D, rotation movements are observed to occur from two different initial jaw positions. In C, almost pure rotation is observed from a position about 4 mm forward of the origin. Panel C also shows that in different phonetic contexts the balance of rotation and translation may change. Hence, movements are also observed in which the slope of the relationship between sagittal plane orientation and horizontal jaw position varies. Note as well that while slopes and intercepts may

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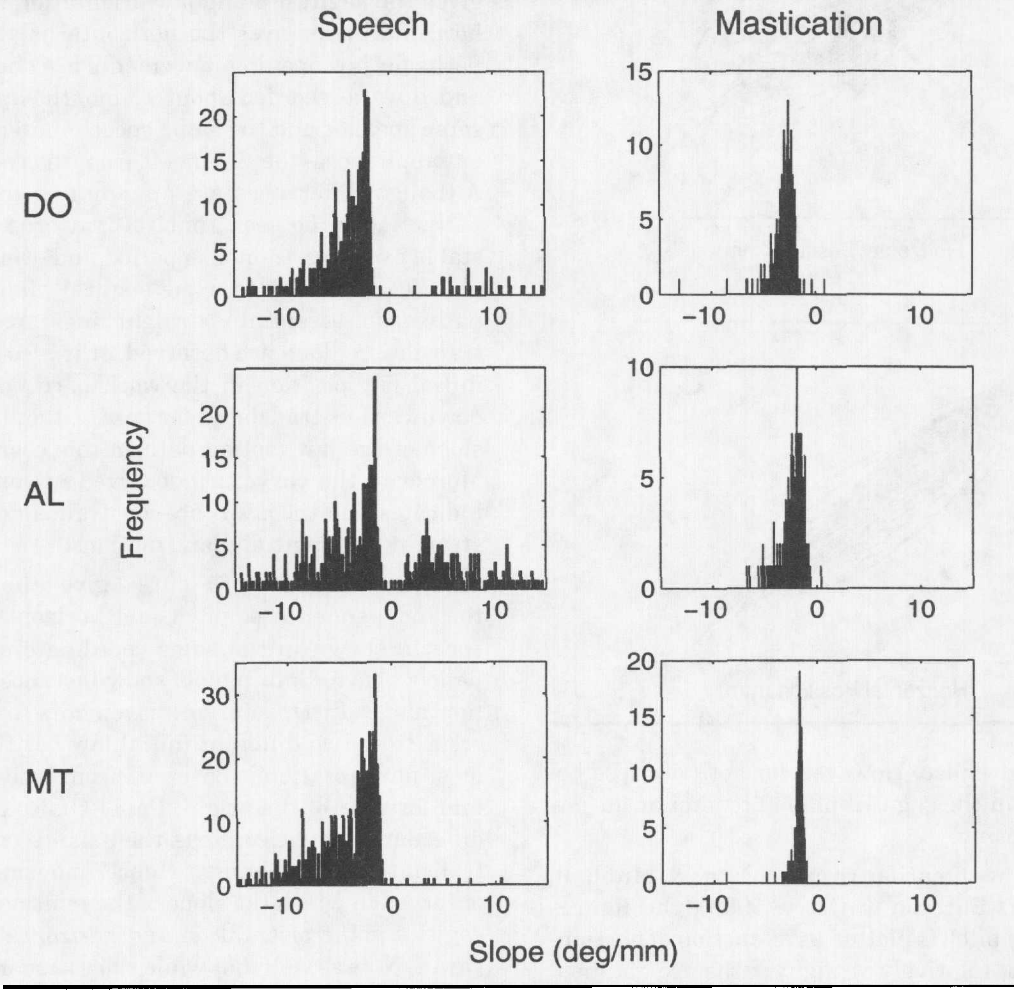
vary for different phonetic distinctions, the paths for particular consonant-vowel sequences are highly consistent.

The independence of pitch and horizontal jaw position was demonstrated quantitatively by computing slope and intercept estimates for each participant on a trial-by-trial basis. Statistical differences among slopes and intercepts were assessed by ANOVA—as a function of vowel, consonant, and volume in speech, and bolus material, bolus size, and unilateral versus bilateral chewing. The analyses revealed highly individual patterns of differences in slope and intercept values. In speech, a number of factors were found to influence the relationship between pitch angle and horizontal jaw position. For different individuals, slopes were found to differ as a function of consonant ($p < .01$, for 3 subjects), vowel ($p < .01$, for 3 subjects), and volume ($p < .01$, for 2 subjects). Intercept estimates in speech differed for consonant ($p < .01$, for all 4 subjects), vowel ($p < .01$, for 2 subjects), and volume ($p < .01$, for 3 subjects). In mastication, the slopes and intercepts were also affected by a variety of different factors in different individuals. Slopes differed with bilateral versus unilateral chewing ($p < .01$, for 1 subject), bolus material ($p < .01$, for 3 subjects), and bolus size ($p < .01$, for 2 subjects). Intercept estimates in mastication differed for bilateral versus unilateral chewing ($p < .01$, for 2 subjects), bolus material ($p < .01$, for all 4 subjects), bolus size ($p < .01$, for 1 subject). The data thus demonstrate the independence of pitch and horizontal position and suggest that in a given individual, any number of factors may result in independent motions in these dimensions.

Although slopes and intercepts of the relationship between pitch and horizontal jaw position varied with experimental condition in both speech and chewing, the range of systematic variation was less in mastication than in speech (Figure 4). Differences in the range of variation were assessed quantitatively by computing for each participant the estimated variance of both slopes and intercepts in each behavior. Differences in variability between

Figure 4. Distribution of estimated slopes of pitch angle versus horizontal jaw position in speech and chewing. The range of variation of slope estimates in speech is greater for all subjects. Comparable patterns are obtained for estimated intercepts.



speech and mastication were tested with the F statistic. For all participants, the variability of both slope and intercept estimates was found to be significantly greater in speech than in mastication ($p < .01$, in all cases). Note that the figure includes data for all conditions for the 3 individuals tested in both speech and mastication.

Vertical and Horizontal Position

Vertical and horizontal jaw position were also found to be independent. The general pattern is given in Figure 5, where vertical jaw position is shown on the ordinate and horizontal position is on the abscissa. The basic shape of the paths is similar to that of the articular eminence of the upper skull. Although the eminence provides a hard tissue boundary to jaw position, in both speech and mastication conditions, parallel paths are observed that differ primarily in terms of the vertical position of the jaw. In speech, the upper set of paths is for normal volume movements and the lower set is for loud speech. In mastication, the three sets of paths are for different food types and different bolus diameters (see figure caption). The shift in vertical position, in the absence of other changes to the sagittal plane motion path of the jaw, suggests that the vertical and horizontal position are independent.

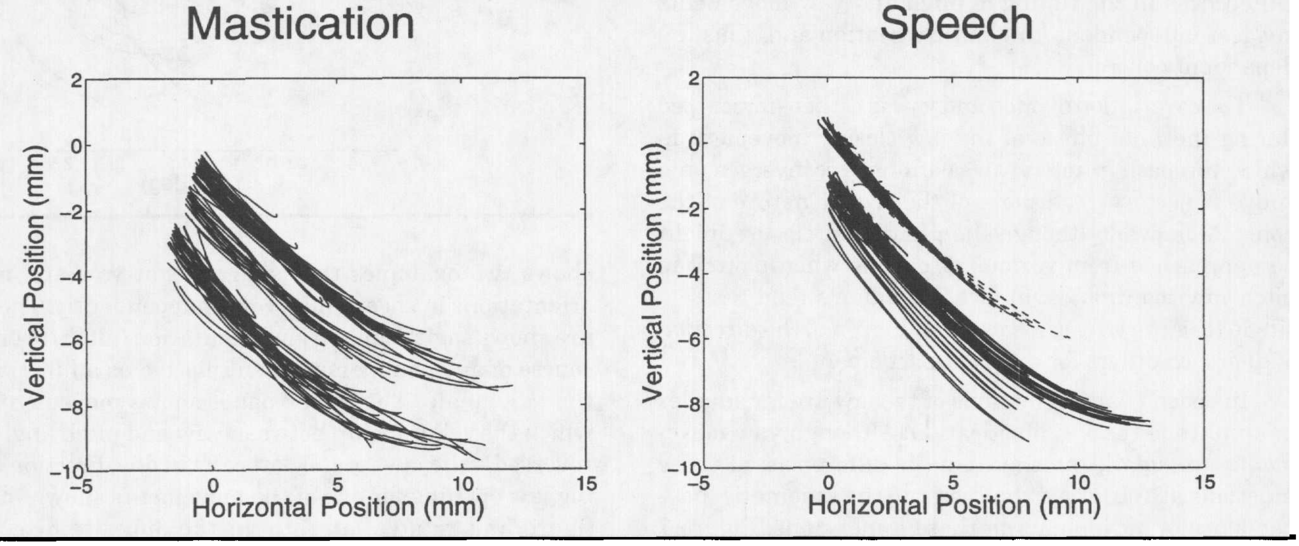
We tested the possibility that the basic form of the jaw motion path in the sagittal plane was preserved but could shift spatially in a vertical direction by fitting a second order polynomial of the form $y = ax^2 + bx + c$ to the relationship between vertical and horizontal jaw position. The fit was carried out on a trial-by-trial basis for each participant with y representing vertical jaw position and x representing horizontal jaw position. The parameters a and b correspond to the form and slope of the polynomial, and c represents the intercept. Changes to the vertical position of the function are indicated by changes in the value of c.

Differences among estimates of a, b, and c were assessed by ANOVA as a function of the phonetic composition of the speech material and the bolus characteristics in mastication. In both speech and mastication, all participants (excluding one tested in the speech condition) showed significant differences in c, the intercept of the polynomial, as a function of phonetic context or bolus characteristics ($p < .01$ in all cases). For 2 of the 3 individuals who showed significant differences in c, loud speech was associated with significantly lower vertical jaw positions ($p < .01$). In mastication, 3 out of 4 participants had lower jaw positions for larger boluses ($p < .01$). In addition, 2 participants in speech and 2 in chewing showed small but reliable differences in one or both of form parameters a and b ($p < .01$).

Thus, the jaw may be translated downward without affecting the shape of the path of the condyle center. This is consistent with the idea that jaw vertical position may be specified independently of the horizontal position of the jaw. Note in addition that in the upper left portion of the paths for speech movements in Figure 5 a number of short line segments may be seen. These are for movements in which both vertical and horizontal translation are essentially negligible. Thus, pure jaw rotation may occur without changes in either vertical or horizontal jaw position.

The independence of pitch and vertical position was also tested. Slope and intercept estimates were computed for each participant on a trial-by-trial basis and

Figure 5. Vertical jaw position against horizontal jaw position. Individual jaw motion paths for a single subject (MT). Mastication trials are for carrot, octopus, and celery (upper set of curves, all normal bolus size), bread (middle set of curves, normal bolus size), and celery and steak (bottom curves, large bolus size). The speech trials are for normal volume speech (upper set of curves) and loud speech (lower curves).



statistical differences were assessed by ANOVA. In both speech and mastication, all participants showed significant differences in slopes and intercepts as a function of bolus properties and phonetic material ($p < .01$). Thus, pitch and vertical jaw position may vary independently in both chewing and speech.

Lateral Jaw Motion Components

Pitch and Yaw

In mastication, the magnitudes of pitch amplitude and yaw amplitude are generally correlated (Figure 6). Movements involving greater pitch angles also tend to have greater amounts of yaw. However, pitch and yaw motions appear to be controlled independently. Chewing typically involves a jaw opening phase that entails primarily changes to the pitch angle (dashed lines), followed by a phase of lateral motion involving primarily changes to the yaw angle (solid lines), and finally a jaw closing phase in which pitch and yaw are linked (solid lines). The ability to produce motions separately in these two degrees of freedom is consistent with the idea of their separate control. (We have also observed a temporal decoupling of yaw and both vertical and horizontal jaw position that is similar to that observed for pitch and yaw.)

Differences in the timing of pitch and yaw in mastication were assessed by calculating on a trial-by-trial basis the time difference between the maximum pitch angle and maximum yaw angle. Systematic differences in pitch and yaw timing were observed for all experimental participants ($p < .05$). For 3 individuals, the timing varied with the type of food—pitch and yaw were more out of phase for steak than for the other foods that were tested. For the remaining participant, the timing of pitch and yaw differed as a function of bolus size. Jaw movements for larger boluses were more out of phase. Differences in the timing of pitch and yaw movements suggest independent kinematic variation and, thus, independent control.

The covariation of pitch and yaw is rather stereotyped during the final phase of the jaw closing movement in which the path in pitch/yaw coordinates converges on a single trajectory, regardless of the size or nature of the bolus. Moreover, although the position at closure might be approached from various directions when plotted in pitch/yaw coordinates, in fact, individuals tend to use a single trajectory. As can be seen in Figure 6, the direction of approach differs for different participants.

In speech, lateral motions of the jaw are far smaller in amplitude than in mastication. Although yaw movements are small, some systematic differences in these functions are observed that point to the kinematic independence of movements in these dimensions. Figure 7 shows two examples that suggest that yaw and pitch orientations in speech may vary independently. The figure shows sagittal plane jaw orientation (pitch) over the course of an opening movement plotted as a function of the yaw angle. The upper panel shows movements in which the relationship between yaw and pitch angles is reversed—the jaw rotates laterally in one direction during jaw opening for one of the movements shown in the figure and rotates laterally in the opposite direction

Figure 6. Pitch versus yaw angle in mastication. The figure shows bilateral chewing, normal bolus size—octopus, celery, steak, and peanuts. Panel A is DO, B is AL, and C is MT. Opening (dashed lines) and closing movements (solid lines) are shown.

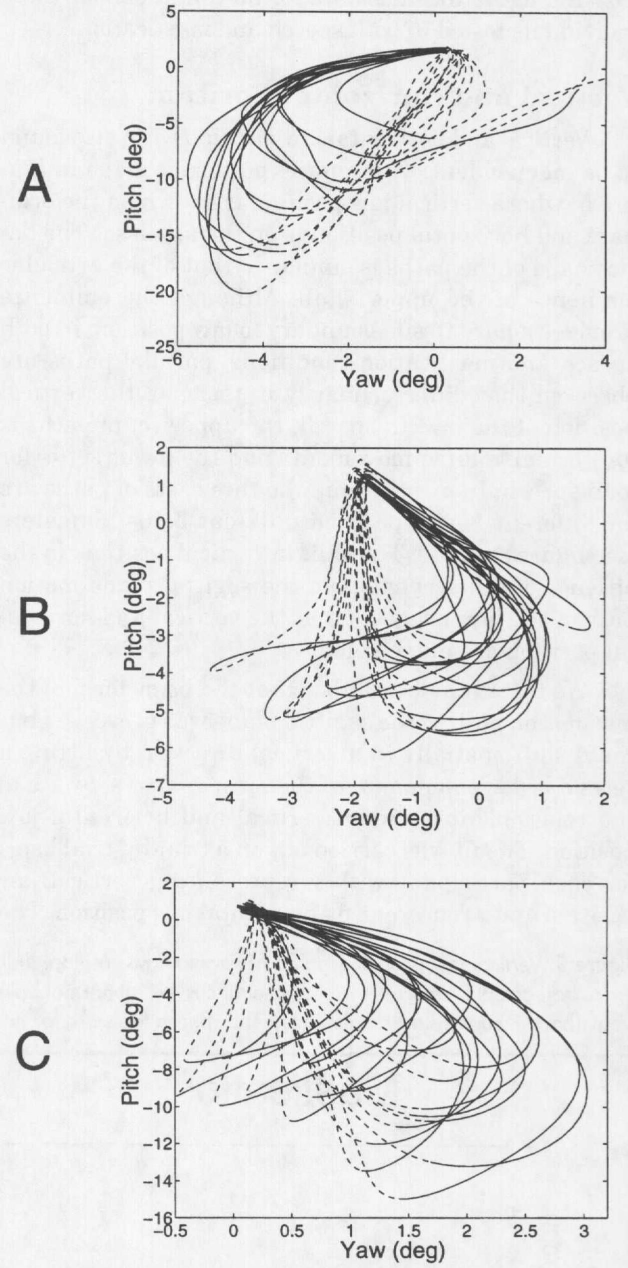
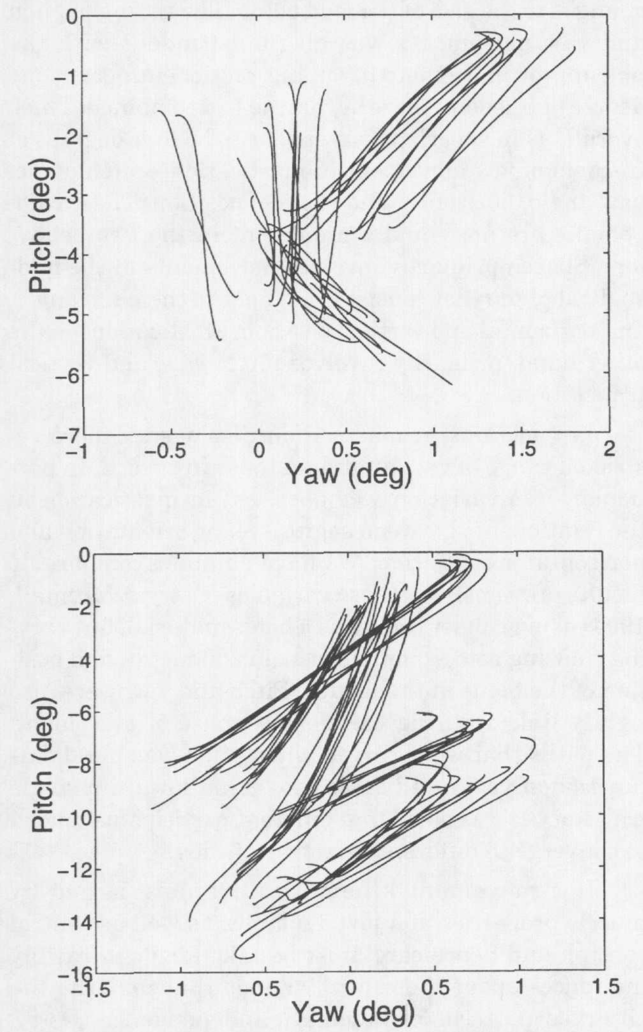


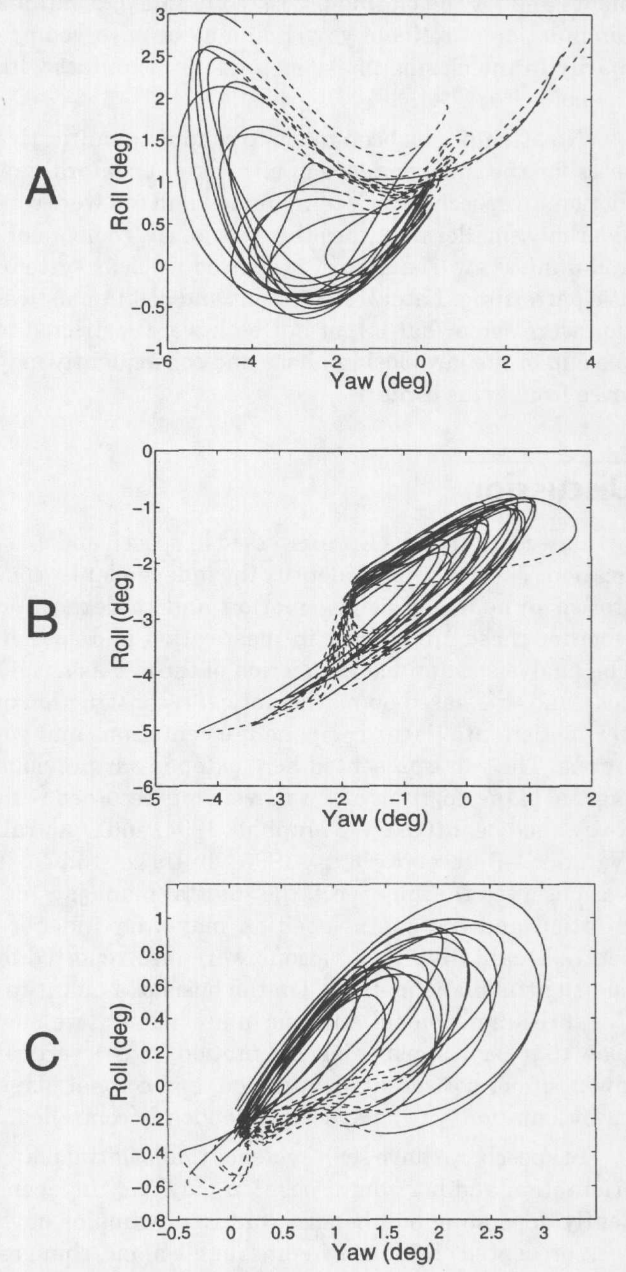
Figure 7. Jaw pitch angle plotted against yaw angle (subject EB). Upper panel is for trials involving loud volume *fi* (vertical paths), loud volume *si* (longer oblique paths), normal volume *ri* (short oblique paths). The lower panel gives data for trials involving *a*. The parallel sets of paths are for *sha* normal volume (top), *la* normal volume (middle), and *la* loud volume (bottom). The two remaining sets of paths are for sequences involving *ta* produced at a normal volume (shorter paths) and loud volume (longer paths).



during the opening phase for another. Changes to pitch angle without yaw are also observed. The lower panel shows that the slope of the relationship between yaw and pitch may vary and, as indicated by the three parallel sets of paths, the same yaw movements can be made from different initial pitch angles.

The relationship between yaw and each of pitch, horizontal position, and vertical position in speech was examined quantitatively by computing slope and intercept for each participant on a per-trial basis. Tests for differences among slopes and intercepts were carried out using ANOVA. In each case, all 4 participants showed significant differences in slope and intercept

Figure 8. Roll angle versus yaw angle from the same trials as Figure 6. Opening movements are shown with dashed lines and closing movements with solid lines.



as a function of phonetic context ($p < .01$ in all cases). Thus, in speech, yaw can vary independently of pitch, and horizontal and vertical position.

Roll and Yaw

In mastication, it is typical for the jaw to both yaw and roll, particularly during the jaw-closing phase. In speech, both movements are quite small in amplitude. Figure 8 gives some examples of the relationship between yaw and roll motions in mastication. The most common pattern we have seen, which is shown for 2 of the 3 individuals in these figures, is for the jaw opening phase (dashed lines) to involve primarily yaw movements and for the closing phase (solid lines) to entail a combination of roll and yaw. Roll may be observed primarily in the closing phase as a result of contact with the bolus.

No attempt has been made to conduct quantitative tests for the independence of either roll or lateral jaw motion. In speech, both lateral motion and roll were considerably smaller than the other movement components and unlike yaw (see Figure 7) showed no clear systematic patterning. Lateral movement and roll in mastication were somewhat larger but both were restricted to the end of the jaw-closing phase and consequently may arise from bolus contact.

Discussion

Jaw motion paths were assessed in speech and mastication. The goal was to identify the independently controlled dimensions of jaw motion and to determine whether these are similar in mastication and speech. The analysis examined the motion of the jaw as a rigid body and was based on mathematical reconstruction of jaw motion into its six component orientations and positions. The work presented here extends our previous sagittal plane analyses of jaw movements recorded with X-ray microbeam (Ostry & Munhall, 1994) and Optotrak (Vatikiotis-Bateson & Ostry, 1995). In those studies, it was observed that in speech the sagittal plane jaw orientation and horizontal position may vary independently. Qualitative observations were also reported of non-sagittal plane motions. On the basis of a quantitative three-dimensional analysis of jaw motion, we now show that sagittal plane jaw orientation (pitch), vertical jaw position, horizontal jaw position, and coronal plane jaw orientation (yaw) may be independently controlled.

In speech, we have seen evidence that sagittal plane orientation and horizontal position may vary independently depending on phonetic context. Examples have been presented of changes in pitch angle alone, changes in horizontal position alone, and paths involving various combinations (Figure 2). The position of the jaw may also shift vertically, without affecting the overall shape of its motion path in the sagittal plane (Figure 5). The magnitude of yaw motions in speech was small, yet systematic. In plots of pitch and yaw both slopes and intercepts could vary with phonetic context (Figure 7). Thus, for the phonetic conditions examined in this study, it appears that four of the six degrees of freedom that characterize jaw motion—pitch angle, yaw angle, horizontal position, and vertical position—are independent and are presumably independently controlled during speech.

Jaw movements in mastication were also characterized by independent motion in four degrees of freedom. The slopes and intercepts relating pitch to horizontal position were more restricted in their range than that observed in speech but nevertheless differed statistically with factors such as bolus material and size. Jaw vertical and horizontal position were observed to vary independently, particularly as a consequence of changes to the size of the food bolus. The timing of pitch and yaw movements was also independent with the phasing of movement involving motion in either one degree of freedom, the other, or the two combined. Thus, overall, as in speech, there appear to be four degrees of freedom of jaw movement in mastication—pitch angle, yaw angle, horizontal and vertical position. These components are not equally prominent in the two behaviors. Speech primarily involves movements in the midsagittal plane that consist of changes to the pitch angle, and horizontal and vertical position. Mastication, on the other hand, primarily involves pitch, yaw, and vertical translation.

Jaw motions in mastication displayed a more restricted range of variation than those in speech. In particular, less variation was observed in mastication in the relationship between sagittal plane orientation and horizontal jaw position. We have obtained comparable results previously for these variables (Ostry & Munhall, 1994) using rubber tubing as a bolus material, but varying chewing rate, compliance, bolus diameter, and position of the bolus in the mouth. Pitch and yaw were also tightly linked during the closing phase of movement. The paths that we observed when pitch was plotted as function of yaw in all cases converged toward a single trajectory. It was noted that different participants tended to converge to different final trajectories.

Jaw movement kinematics are determined by muscle properties and jaw dynamics as well as central control, and hence care must be taken before drawing inferences about the control signals that underlie the observed patterns of kinematic independence (Ostry, Gribble, & Gracco, 1996). For example, the independence of pitch, vertical position, horizontal position, and yaw is observed in the context of a particular coordinate frame. The total number of degrees of freedom is not dependent upon this coordinate system—any rotation and translation of the coordinate space should yield the same number of degrees of freedom. Hence, our findings are consistent with the idea that the underlying control is of dimension four.

A number of unresolved issues and sources of experimental error require consideration. As is typically observed, the speech kinematics were characterized by differences in individual behavior. Participants did not all show the same patterns of kinematic variation. Our simulation studies using a model of jaw and hyoid motion (Laboissière et al., 1996) suggest that some of the kinematic variation may arise from individual differences in the physical characteristics of the vocal tract. Until differences due to vocal tract morphology are adequately accounted for, it will be difficult to assess the extent to which variations such as observed here arise from linguistic factors, speaking style, or biomechanics.

In summary, we have compared jaw motions in mastication and speech. The movements have been shown to vary independently in four degrees of freedom overall, suggesting that the underlying control of both mastication and speech is of dimension four. In speech, jaw motions primarily involve the control of pitch angle, horizontal position, and vertical position. In mastication, yaw, pitch, and vertical position appear to constitute the dimensions of control.

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