HUMAN JAW MOTION CONTROL IN MASTICATION AND SPEECH

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ABSTRACT. Detailed kinematics are presented of two-dimensional jaw motion in mastication and speech. The relationship between jaw translation and jaw rotation is described and experimental records are compared with simulations based on the equilibrium point hypothesis (λ model). In general, in both speech and mastication, jaw rotation and jaw translation were found to start and end simultaneously and their coordination was typically characterized by straight line paths when rotation was plotted against translation. A number of manipulations are described which suggest that jaw rotation and jaw translation can be separately controlled. For example, when jaw movements in speech were examined, the slope of the relationship between rotation and translation varied with the consonant but did not depend on the vowel or speech rate. The kinematic details of jaw motion are well accounted for by the λ model. The model demonstrates that separate central commands can be defined associated with jaw translation, jaw rotation, and co-activation of muscles without motion. Central commands may be superimposed to produce combinations of rotation, translation and muscle coactivation. Empirical patterns can be captured by the model under the assumption of simple constant velocity shifts in equilibrium governed by central commands.

1. Introduction

In this paper, we examine the kinematics of two-dimensional human jaw movement in mastication and speech. We focus on the relationship between jaw translation and jaw rotation and present evidence that these can be independently controlled. A computer model of jaw movement based on the equilibrium point hypothesis (λ model) is briefly described. The model includes separate central control signals for jaw rotation, jaw translation and muscle co-contraction without motion (see Flanagan, Ostry & Feldman, in press, for details). The model shows that simple constant velocity shifts in the threshold lengths of all muscles simultaneously can account for jaw movements in both mastication and speech. The λ model has been previously applied to both human single-joint (Feldman, 1986) and two-joint arm movements (Feldman, Adamovich, Ostry & Flanagan, 1990; Flanagan et al., in press) as well as to human eye movements (Feldman, 1981). The planar jaw system is different than the planar arm system in that the two degrees of freedom are located at the same joint rather than at two different joints.

During jaw opening, the jaw rotates downward and translates forward; the opposite pattern is observed during closing. These motions in the sagittal plane are produced by three groups of muscles. Thus, jaw closers, such as masseter and medial pterygoid, act to both raise and

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retract the jaw; jaw openers, such as the anterior belly of the digastric, lower and retract the jaw; the lateral pterygoid produces jaw protrusion. The closers and openers both rotate and translate the jaw whereas the protruders tend to translate the jaw without rotation. Because of this mapping between muscle actions and kinematic degrees of freedom, all three muscle groups must be coordinated to produce rotation, translation or co-contraction without motion. With the model we have shown that it is possible to define central commands which produce pure rotation, pure translation and pure co-contraction independent of the jaw position.

We have recorded the kinematics of human jaw movements using the X-ray microbeam system (Abbs, Nadler & Fujimura, 1988; Westbury, in press). The microbeam is a low-dosage narrow beam X-ray which "tracks" the two-dimensional motions of multiple radiodense markers (typically 2-3 mm spherical gold pellets). The rotation of the condyle and the translation of its axis of rotation along the articular eminence are calculated from the motion of X-ray tracking pellets on the jaw.

2. Methods

Mid-sagittal recordings of tongue and jaw movement were obtained using the X-ray microbeam system. Tracking pellets were attached to the tongue and jaw using a dental cement. Additional pellets were used to correct for planar head motion and to locate the occlusal plane. The projected positions of mandibular and maxillary pellets located off the image plane were corrected using a simple geometric transformation (Westbury, in press). Microbeam mid-sagittal palate tracings were obtained for each subject.

Coordinate systems were defined in both cartesian oral cavity space and mandibular joint coordinates (see Munhall, Ostry & Flanagan, in press for a discussion of orofacial coordinate systems). In the oral cavity coordinate system one axis coincides with the occlusal plane and the other is perpendicular to the occlusal plane and passes through the origin at the tip of the maxillary incisors. In the joint space representation movements are defined in terms of rotation of the jaw about the mandibular condyle and translation of the condyle along the articular eminence.

In speech trials, subjects produced cyclical consonant-vowel combinations at different rates and volumes. Consonants *t* and *k* and vowels *a* and *e* were used. Syllables involving the vowel *a* are associated with large amplitude jaw movements whereas syllables involving the vowel *e* are associated with smaller amplitude movements. In the mastication trials, the subjects chewed unilaterally on rubber tubing of varying compliance. Jaw tracking pellets were sampled at frequencies between 60 and 90 Hz and then low-passed filtered at 8 to 10 Hz. Mandible rotation and translation were computed from the motion of the tracking pellets on the jaw.

3. Jaw Motion Kinematics

In this section jaw movements will be considered in both oral cavity and joint based coordinate frames. Empirical data will be presented which suggest that jaw rotation and jaw translation can be controlled independently by the nervous system.

Figure 1 shows the motion paths of jaw pellets in oral cavity coordinates, projected onto the mid-sagittal plane. The paths for both mastication (solid line) and speech (dotted line) are presented for the full data set. The paths to the right of the figure are for movements of the

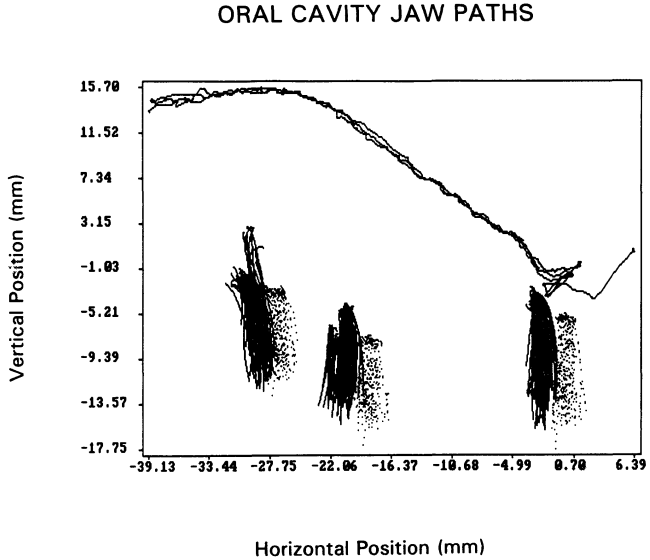

Figure 1. Oral cavity motion paths of jaw pellets during mastication (solid) and speech (dots). The palate tracing at the top of the panel is provided for reference. The positions of all pellets were projected onto the mid-sagittal plane and corrected for off-image plane distance.

mandibular incisors; the paths to the left are for movements of pellets attached to left and right side mandibular molars. A mid-sagittal palate trace is also shown. The amplitude of jaw movements can be seen to be greater in mastication than in speech. For this subject, the jaw appears to be more protruded in the production of speech sounds. However, the tendency for the jaw to be more protruded in mastication has been observed in other subjects.

The motion paths of the jaw were also examined in mandibular joint coordinates. Figure 2 shows the rotation of the jaw plotted as a function of horizontal jaw translation for cyclical jaw movements in both mastication (solid lines) and speech (dotted lines). It can be seen that straight line paths are obtained. This indicates that rotation and translation begin and end at the same time and that the ratio of their amplitudes is preserved over the movement.

Figure 2 also shows that the coordination between translation and rotation is not fixed. Moreover, different subjects reveal different patterns of coordination. In some subjects, we have observed that the slopes of rotation plotted against translation differ for mastication and speech. In other cases, the slopes are similar for speech and mastication but the two kinds of movements are produced in different parts of the workspace. Figure 2 shows a complex situation: the slopes and intercepts for mastication and speech can be seen to differ; the slopes and intercepts for speech alone also differ.

A number of manipulations involving both mastication and speech suggest that jaw rotation and jaw translation can be separately controlled. When jaw movements in speech were examined, the slope of the relationship between rotation and translation, and thus the

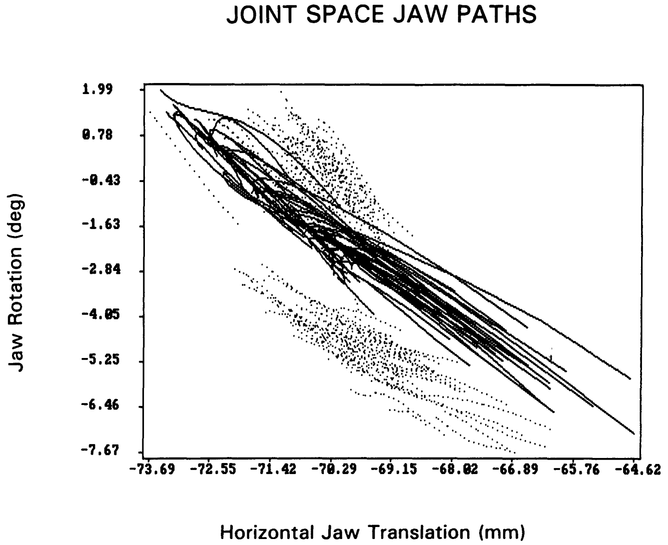

Figure 2. Joint space motion paths for jaw movements in mastication (solid) and speech (dotted). Jaw rotation is plotted as a function of horizontal jaw translation. (The horizontal axis is parallel to the occlusal plane).

coordination between these two degrees of freedom, varied with the consonant but did not depend on the vowel or speech rate. Figure 3 shows jaw motion paths in speech for the same subject as displayed in Figure 2. It can be seen that the slope of the relationship between jaw rotation and jaw translation was steeper for *t* than for *k*. In addition, movements for *k* are produced from a more protruded position.

A number of further manipulations are consistent with the view that jaw rotation and jaw translation can be separately controlled. When loud and fast speech were compared during cyclical repetition of the syllables *sa* and *ka* the slope of the relationship between rotation and translation was affected by the consonant but not by speech volume or rate (Figure 4). This indicates that the coordination between rotation and translation can be altered by the nervous system. Translation may also occur without affecting the balance of rotation and translation. Thus, in repetitions of *sa* the jaw translated forward for loud speech but the slope of path in joint coordinates in repetitions of *sa* was unaffected. The coordination between jaw rotation and translation also varied under different mastication conditions. For example, at fast chewing rates, jaw rotation was in some cases observed without any accompanying translation whereas at slower rates, both rotation and translation were observed.

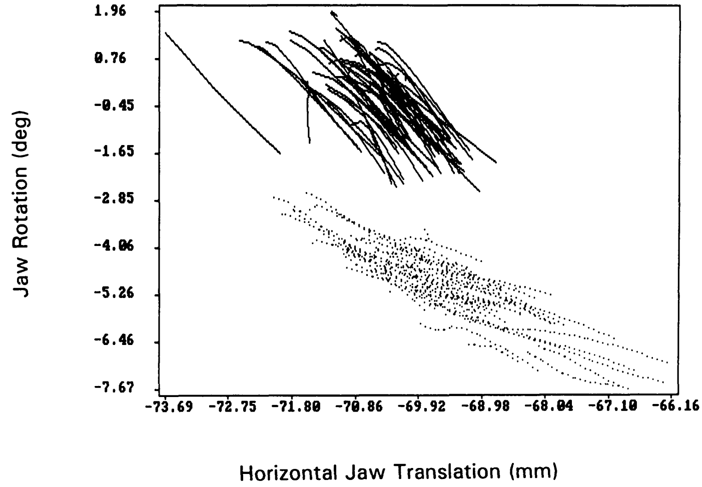

Figure 3. Joint space paths for cyclical speech movements. The solid lines are for the syllables *ta* and *te*; the dotted lines are for *ka* and *ke*.

4. λ Model

The kinematics of jaw movement in mastication and speech are well accounted for by the λ model. Briefly, the λ model suggests that voluntary movements are a consequence of shifts in the equilibrium state of the system. The equilibrium state is determined by the interaction of central neural control signals, segmental reflex mechanisms, muscle properties and load. Central commands control this process by setting, in different combinations, the motoneuron recruitment threshold lengths of multiple jaw muscles (see Flanagan, Ostry & Feldman, in press, for a detailed treatment of the jaw model).

The λ model for the jaw combines three representative muscles (closer, opener, protruder) with central commands, reflex mechanisms and muscle properties including force-length relationships. The origins, insertions, and force generating capabilities of the muscles in the model have been selected to approximate as best possible those of the actual muscles which they represent. Equations of motion for the jaw model were derived by representing the jaw as a moving pendulum which is free to rotate about a suspension point which itself can translate diagonally along the articular eminence. The slope of the eminence was determined from empirical data.

The model posits separate central commands which independently control jaw translation and jaw rotation, and in addition, produce co-activation of muscles without motion. Each of these commands affects the recruitment threshold lengths (λs) of all three muscles. Central commands may be superimposed to produce combinations of rotation, translation and co-activation. Empirical patterns can be captured by the model under the assumption of simple constant velocity shifts in equilibrium associated with simultaneous changes in the threshold lengths of the three modelled muscles.

Figure 4 shows actual and simulated speech movements. In panel B actual jaw rotation and translation are shown during the cyclical repetition of *sa* at a loud speech volume. The simulated movements are shown in panel C. Jaw opening which is indicated by a decreasing value of α can be seen to be associated with forward translation (increasing τ). The individual changes to muscle λs which produce this pattern are shown in panel D. Simple constant velocity changes in muscle λs can be seen to produce smooth changes in the patterns of rotation and translation. Note that the rate and duration of λ shifts differ for the simulated jaw opening and closing movements in speech. In the speech simulations, λ shifts were determined by a combination of rotation and translation commands. The co-contraction command, and hence the level of muscle co-activation, was held constant.

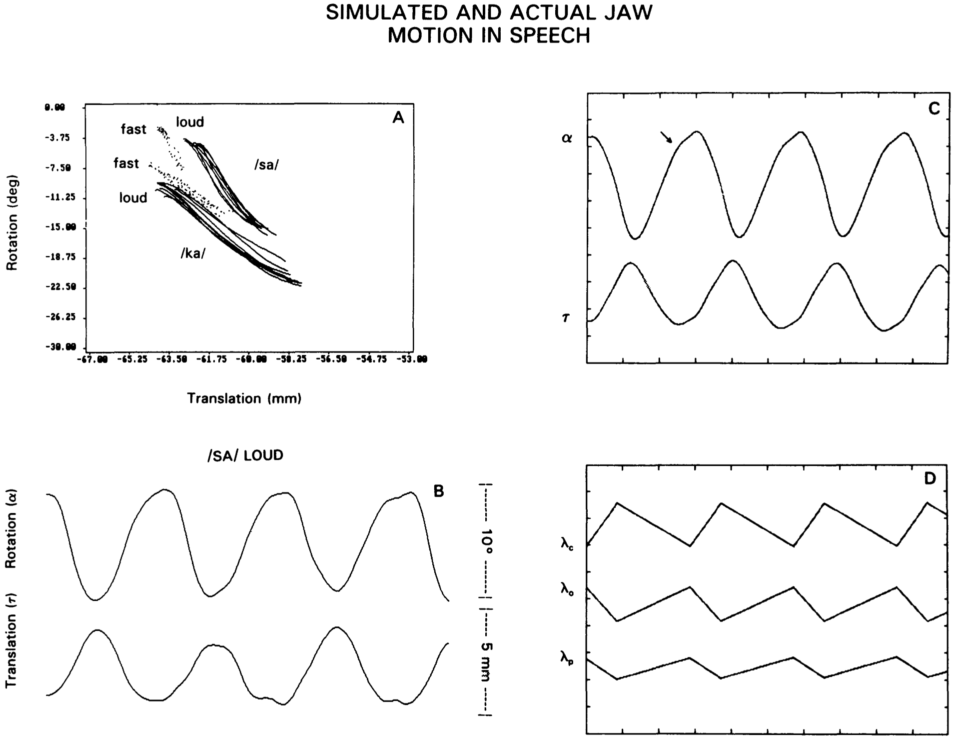

Figure 4. Actual and simulated jaw motion in speech. Panel A shows jaw motion paths during cyclical repetitions of *sa* and *ka* produced at both a fast speech rate and a loud volume. Actual patterns of jaw rotation (α) and translation (τ) are shown in panel B. The patterns are well accommodated by simulations (C) based on constant velocity shifts in the equilibrium angles of closer, opener and protruder muscles (D). (From Flanagan, Ostry & Feldman, in press.)

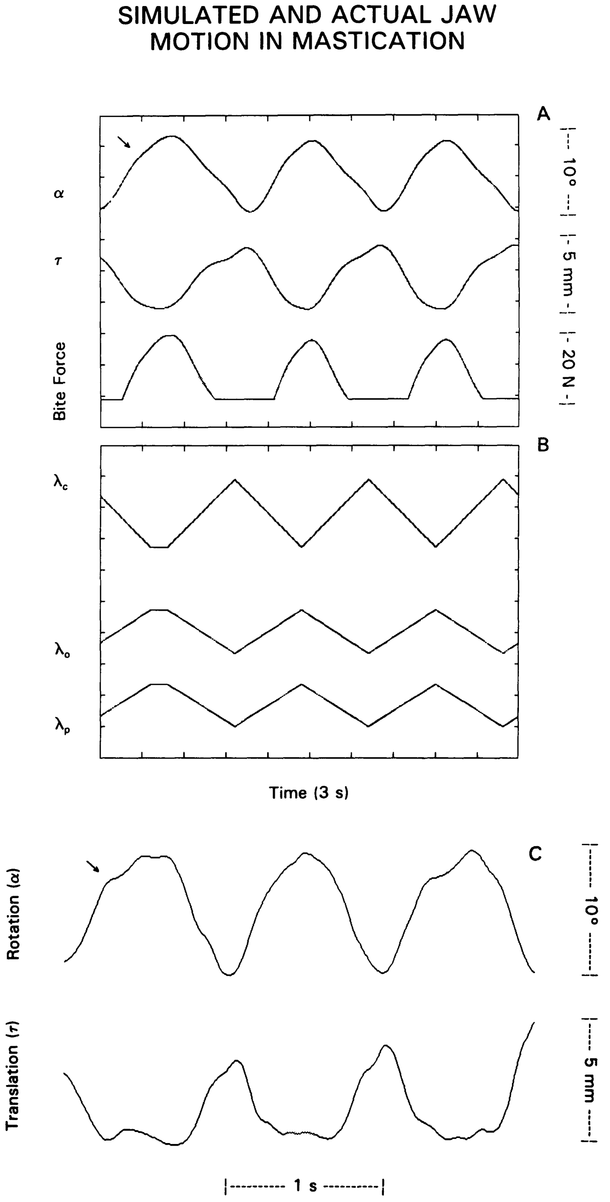

Figure 5. Actual and simulated jaw motion in mastication. Panel A shows simulated rotation (α), translation (τ) and predicted bite force during bolus contact. The equilibrium shifts controlling this movement are shown in panel B. An actual record of jaw rotation and translation during mastication is shown in panel C. (From Flanagan, Ostry & Feldman, in press.)

Actual and simulated patterns in mastication are shown in Figure 5. The upper panel gives simulated patterns of jaw rotation and translation and the predicted bite force developed during cyclical chewing movements. The corresponding changes to muscle λs necessary to produce this movement are shown in the centre panel. As in speech movements, constant velocity changes in muscle λs are sufficient to produce the smooth patterns observed in the data. Actual jaw rotation and translation during chewing are shown in the lower panel. Note, the similarity between the simulated and actual jaw rotation patterns at the point of contact with the bolus (shown as an arrow in the figure). In the mastication simulations, λ shifts were obtained by a combination of all three commands. The co-contraction command, and thus the level of muscle co-activation, was increased during jaw closing. This increases the stiffness of the system in preparation for contact with the bolus.

5. Discussion

We have presented planar jaw kinematics in both cartesian oral cavity coordinates and mandibular joint coordinates. When jaw motions were examined in the joint coordinate frame, manipulations involving both mastication and speech suggested that jaw rotation and jaw translation can be separately controlled.

Since the jaw is a rigid body, in principle, six degrees of freedom are required to describe its position. However, in both our experimental and modelling work, we have assumed that jaw movement is planar and in addition that the condyle translates linearly (along the articular eminence). Consequently, only two degrees of freedom are necessary to describe the jaw's position: rotation of the jaw about the mandibular condyle and linear translation of the condyle (i.e., the centre of rotation) along the articular eminence.

We have shown that separate central commands can be defined for each of the kinematic degrees of freedom that are modelled. There are separate commands for rotation and translation as well as for co-contraction without motion. Through simulations with the model it was possible to demonstrate that these commands are independent of jaw position. That is, for each command, the same set of shifts in muscle threshold lengths produce the same result (i.e. pure rotation, pure translation or co-contraction without motion) regardless of jaw position. This is a surprising finding since the moment arms and forces of the opener and closer muscles change in different ways with jaw location. Nevertheless, biomechanical factors appear to be balanced such that central commands are invariant across differences in jaw position.

The λ model assumes that movement occurs when the actual joint angle differs from the equilibrium joint angle. In general, the discrepancy may be signalled by changes in the afferent activity of spindle primary and secondary receptors. Jaw closing muscles in humans contain large numbers of muscle spindles. However, there are few muscle spindles in the jaw openers. The feedback which is used to achieve the equilibrium angle may arise from sources other than muscle spindle feedback. Mechanoreceptors associated with the temporomandibular joint may provide this information. However, sensory feedback is not strictly required to achieve the equilibrium position. According to the λ model the equilibrium state is determined by a combination of central commands and afferent feedback. Thus, central commands alone may enable the nervous system to specify desired positions without the use of afferent information.

6. References

Abbs, J.H., Nadler, R.D. & Fujimura, O. X-ray microbeams track the shape of speech, SOMA, 29-34, 1988.

Feldman, A.G. Composition of central programs subserving horizontal eye movement in man. Biol.Cybern., 42: 107-116, 1980.

Feldman, A.G. Once more for the equilibrium-point hypothesis (λ model) for motor control. J.Motor Behav. 18: 17-54, 1986.

Feldman, A.G., Adamovich, S.V., Ostry, D.J. & Flanagan, J.R. The origins of electromyograms - explanations based on the equilibrium point hypothesis. In J. Winters and S. Woo (Eds.), *Multiple muscle systems: Biomechanics and movement organization*. London: Springer-Verlag, 1990.

Flanagan, J.R., Ostry, D.J. & Feldman, A.G. Control of human jaw and multi-joint arm movements. In G. Hammond (Ed.), *Cerebral control of speech and limb movements*. London: Springer-Verlag, in press.

Munhall, K.G., Ostry, D.J. & Flanagan, J.R. Coordinate spaces in speech planning. J.Phonetics, in press.

Westbury, J.R. Head position during X-ray microbeam experiments: Its significance and measurement. J.Acoust.Soc.Am., in press.