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JAW MOTIONS IN SPEECH ARE CONTROLLED IN (AT LEAST) THREE DEGREES OF FREEDOM

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ABSTRACT

In vocal tract models, jaw motions are almost always characterized in terms of sagittal plane rotations about a fixed axis. However, in fact, jaw motion in speech consists of rotation in the midsagittal plane and horizontal and vertical translation. Small amplitude lateral rotations (yaw) are also observed. In this paper, we assess these jaw motion components in speech by examining their patterns of kinematic variation and we contrast these behaviours with the patterns observed in chewing. We also assess the relationship between sagittal plane jaw motions and lateral motions of the jaw. When jaw movements in speech were plotted to show sagittal plane rotation as a function of horizontal translation we observed straight line paths in which the component rotations and translations could vary independently. The vertical elevation of the jaw could also vary, independent of the actual motion path of the jaw. The occurrence of lateral jaw motions in mastication suggests this degree of freedom may be controlled as well.

I. INTRODUCTION

In this paper, we present Optotrak recordings of human jaw movement in speech and mastication. We describe jaw movements in terms of the three orientation angles and three positions which fully characterize the motion of the jaw. In this context, we explore how control signals are coordinated in systems such as the jaw in which muscles have multiple mechanical actions and contribute to motion in more than one degree of freedom. We suggest that control is not organized directly in terms of commands to individual muscles. Rather the nervous system may use a control space in which control variables are specified for each mechanical degree of freedom separately. A superposition of these basic commands produces motion in multiple degrees of freedom.

Consider the problem of the control of multi-muscle systems in the case of jaw movement. Jaw motions in the sagittal plane involve a combination of rotation and translation (see Figure 1). During opening, the jaw rotates downward (increasing pitch angle) and translates forward and downward along horizontal and vertical axes. The pattern is reversed during closing. Muscles such as masseter and temporalis act to raise and retract the jaw. The anterior belly of the digastric produces lowering and retraction. The lateral pterygoid produces protrusion and rotation. Since there is no one to one mapping between muscle actions and mechanical degrees of freedom central control signals must be coordinated to produce movements such as jaw rotation or translation, either alone or in combination.

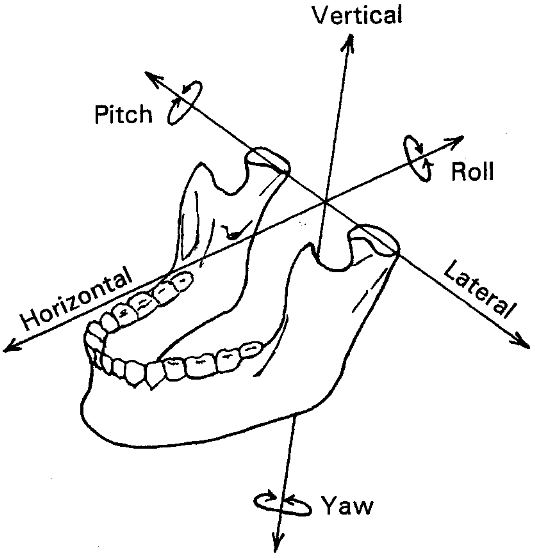

Figure 1. The coordinate system for three dimensional jaw motion.

We have previously presented empirical evidence, using X-ray microbeam data, consistent with the proposal that the nervous system organizes jaw movement in terms of an equilibrium horizontal position and an equilibrium sagittal plane orientation [1]. Two kinds of evidence were presented. We showed that the sagittal plane orientation and horizontal position of the jaw could vary separately. We also showed that when sagittal plane orientation is plotted as a function of horizontal jaw position, the movements are characterized by straight lines regardless of the initial orientation and position of the jaw. The evidence suggests that the system may specify sagittal plane jaw rotation and horizontal translation separately.

In the present paper, we extend this work to demonstrate that vertical jaw position may also be controlled separately and that jaw orientation about a vertical axis - yaw - may be controlled as well. An initial report of this study is presented in Bateson and Ostry [2].

II. METHODS

The study examines jaw motion in both speech and mastication. In the speech experiment, subjects produced repetitive *VCVCa* sequences composed of the consonants *s, sh, l, r, t, k, f, p* and the vowels, *a, o, i*. Loud, normal and fast speech rates were tested. In the mastication experiment, subjects chewed repetitively on the following foods: carrot, celery, octopus, peanut, sandwich, steak. Bolus size was manipulated. The movements were recorded at 200 Hz using Optotrak and the three orientation angles and three positions which characterize the motion of the jaw were computed. Two different light-weight acrylic and metal dental appliances were used during these tests. One appliance was attached unilaterally to the mandibular molars. Results with this appliance are shown in Figure 2. A second appliance was seated bilaterally, covering the buccal surface of the mandibular incisors. The data shown in Figures 3 through 5 were obtained with this appliance.

III. RESULTS

In this section, we present jaw motion paths in various combinations of linear and angular coordinate frames. Consistent with earlier results, we show that when sagittal plane orientation angle (pitch) is plotted as a function of horizontal jaw position straight line paths are obtained regardless of the initial position or orientation of the jaw. The slope of these paths and their initial orientation angle and horizontal position may vary suggesting that the nervous system can control jaw rotation (the sequence of jaw orientation angles) and jaw rotation (the sequence of jaw positions) independently. We also show that when jaw vertical position is plotted as a function of jaw horizontal position, the vertical and horizontal positions may be independent.

Figure 2 shows jaw motion paths during repetitive utterances of *iCiCa* sequences produced at a loud speech volume. The vertical axis gives the sagittal plane jaw orientation angle. The horizontal axis gives the horizontal jaw position. Figure 3 shows motion paths recorded about eight months later for the same subject and same speech material. The two sessions used different dental appliances to record jaw motions (see Methods). Although, differences are apparent between the two sets of paths, it can be see that, in both cases, the sagittal plane jaw motion paths form essentially straight lines. Instances of pure jaw translation (Figure 2) and pure jaw rotation (Figure 3) are observed. Moreover, the curvature observed in some conditions indicates that the jaw is not biomechanically constrained to produce only straight line sagittal plane motions.

Figure 4 shows jaw vertical position as a function of horizontal jaw position during a series of *aCaCa* utterances produced at loud and normal speech volumes. Vertical jaw position is shown on the ordinate; horizontal position is on the abscissa. The general shape of the paths is seen to be similar to that of the articular eminence of the upper skull. The eminence provides a hard tissue boundary to jaw position. However, the separate paths for loud and normal volume speech show that the jaw may be translated vertically downward without otherwise affecting the path of the condyle centre. 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 both sets of paths 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 either vertical or horizontal change in jaw position.

Figure 5 shows that the yaw angle - the jaw orientation about a vertical axis - may also be specified in the control of speech motions. The figure shows sagittal plane jaw orientation (pitch) over the course of a movement plotted as a function of the yaw angle. The curved paths are for jaw movements during mastication. The straight line paths are for jaw movements in speech. In mastication, the yaw angle and the sagittal plane jaw orientation both change over the course of the movement. In speech, the system maintains a single yaw angle throughout the movement while changing the sagittal plane orientation. The ability to change the mapping between the yaw and pitch angles of the jaw suggests that the yaw angle may be controlled independently.

IV. DISCUSSION

Three dimensional jaw motion paths were assessed in speech and mastication. The goal was to determine the degrees of freedom of jaw motion in speech and to provide evidence for the view that the control of jaw motion might be organized in terms of these biomechanical variables. In effect, we explored the idea that, in spite of the multiple mechanical actions of jaw muscles, control signals to the jaw are coordinated to produce motion in the system's degrees of freedom, both alone and in combination.

In the case of the jaw, we have presented evidence that (1) sagittal plane jaw orientation, (2) vertical jaw position, (3) horizontal jaw position and possibly (4) jaw orientation about a vertical axis are each controlled in producing speech movements. Note that, variations in both vertical and horizontal jaw position are large, in the range of 1 cm or more for horizontal translation. This is comparable to the linear extent of jaw opening due to downward rotation, measured at the mandibular incisors.

The control of lateral jaw motion in speech deserves particular attention. One possibility and the one favoured by the authors is that if the yaw angle is to remain constant in speech, the equilibrium yaw angle must of necessity be specified. An alternative, and somewhat more complicated possibility is that lateral jaw motion may be controlled in the case of chewing movements but not controlled in the

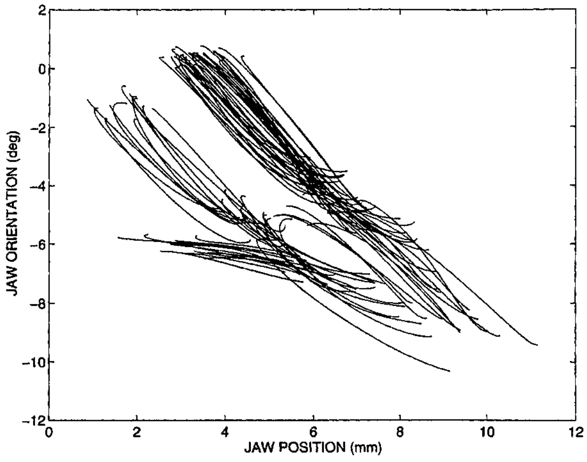

Figure 2. Sagittal plane jaw orientation plotted as a function of horizontal jaw position.

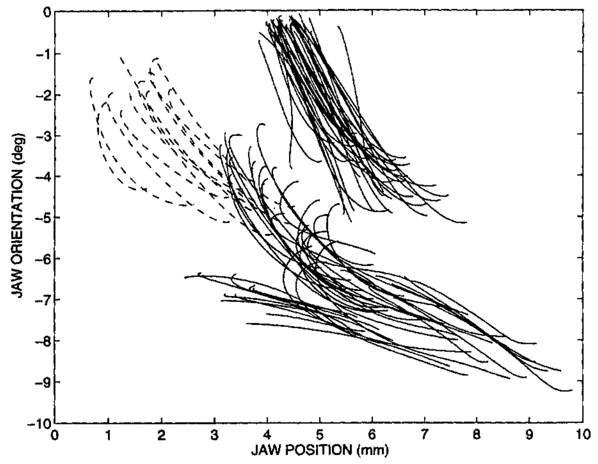

Figure 3. Sagittal plane jaw orientation plotted as a function of horizontal jaw position. Same subject and speech utterances as in Figure 2.

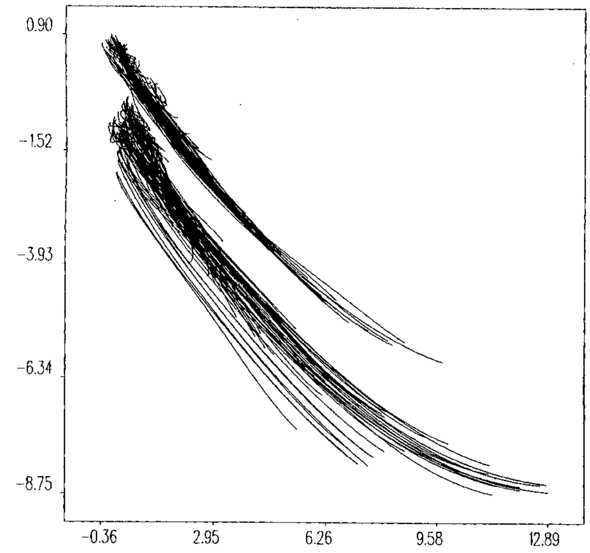

Figure 4. Vertical jaw position (ordinate) as a function of horizontal jaw position during loud volume (lower curves) and normal volume (upper curves) speech.

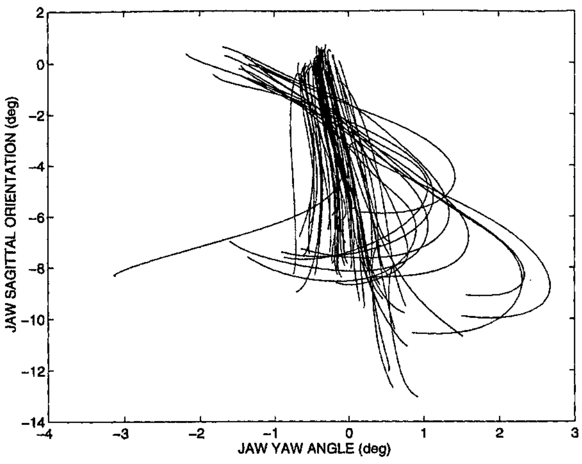

Figure 5. Sagittal plane jaw orientation angle (ordinate) as a function of yaw angle (abscissa) during mastication (curved lines) and speech (straight lines).

case of speech. Let us examine this in more detail.

Consider, for example, a jaw control system with four degrees of freedom (including yaw angle) which produces jaw motions in chewing through the use of well over a dozen muscles. We have demonstrated here and elsewhere [1] [2] that control to the jaw is organized in terms of the jaw's mechanical degrees of freedom. Jaw motions may be produced alone or in combination in these degrees of freedom. In order to define control signals which correspond to the system's mechanical degrees of freedom, the nervous system must establish specific mappings between changes in individual degrees of freedom, for example, in sagittal plane jaw orientation, and changes in the corresponding muscle-level control variables. Different mappings of this sort are needed to produce movement in each degree of freedom. Now, if jaw control in speech were to be based on only three degrees of freedom, excluding the control of the yaw angle, then new mappings between changes at the level of degrees of freedom and changes at the level of the muscle's controlled variables would have to be established for each degree of freedom. Indeed even sagittal plane jaw rotation which occurs in both mastication and speech would have to be controlled differently in the two behaviours, as would the other two degrees of freedom which are common to both. This alternative requires, in effect, that the entire control of neural signals to the jaw would have to be computed differently for speech and other jaw movements. There is at present no empirical basis to decide between these two alternatives.

V. REFERENCES

[1] Ostry, D.J. and Munhall, K.G. (1994) Control of jaw orientation and position in mastication and speech. *Journal of Neurophysiology*, *71*, 1528-1545.

[2] Bateson, E.V. and Ostry, D.J. (in press) An analysis of the dimensionality of jaw movement in speech. *Journal of Phonetics*.