Role of Impedance Control in Achieving Precision in Orofacial Movement

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Abstract

In the context of jaw movement in speech, we show that spatial precision in speech production is systematically associated with the regulation of impedance and in particular, with jaw stiffness. We estimated jaw stiffness and also variability during movement using a robotic device to apply brief force pulses to the jaw. We applied this technique to data from 31 subjects whose jaw movements were perturbed during simple speech utterances and matched non-speech movements. We observed systematic differences in stiffness over the course of jaw lowering and raising movements that were matched by measures of kinematic variability, which points to the idea that stiffness regulation is integral to the control of orofacial movement variability.

1 Introduction

What is the means by which the nervous system regulates variation in movement? One possibility is that precision is achieved by iteratively optimizing control signals on an ongoing basis using information from sensory feedback [10]. A related possibility is that the nervous system selects motor commands so as to restrict variation that affects final outcomes while allowing ample variation in variables that have little or no affect on final values [6]. There is also evidence from measures taken under stationary conditions [9, 3, 7, 8, 5] that movement variability is controlled through neural signals that modify the limb's resistance to displacement, a phenomenon known as impedance control [4]. However, it is unknown whether precision is regulated in a similar fashion during movement.

To address this question we have examined movement variability and impedance in speech production. To deal with the small movement amplitude and rapid time course of speech movements, it was necessary to develop two new techniques to estimate impedance. Using these techniques, we show here that impedance varies systematically over the course of movement and that variability in speech varies directly with differences in impedance. Moreover the patterns of both impedance change and kinematic variation that we observe are not restricted to speech movements but occur in a similar fashion in matched non-speech movements. The consistent linkage that is observed between impedance and movement variability suggests that impedance regulation is an integral component in the control of orofacial movement.

2 Methods

Thirty-one young adults participated in the experiments. Jaw stiffness was estimated using a small robotic device (Sensable Technologies, Phantom 1.0) that permits unrestricted movement of the jaw in three spatial dimensions and the recording of jaw position and subject-generated force (Fig. 1). The subject's jaw was connected to the robot by means of a custom-built dental appliance that was attached to a rotary connector at the end of the robot arm. A second appliance, attached to the maxillary teeth, was used for head stabilization during testing. Jaw position was measured using encoders in the robotic device. Subject-generated force was measured using an ATI Nano-17 force-torque sensor that was mounted at the distal end of the robot arm. Position and force were both recorded at 1 kHz and low-pass filtered at 30 Hz.

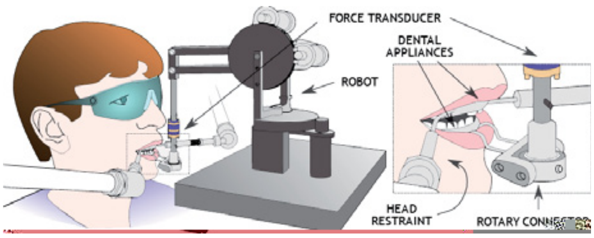


Figure 1: Experimental setup.

Stiffness estimates were obtained in a speech condition and a matched non-speech condition with the order of testing balanced over subjects. In the speech condition, subjects were instructed to repeat the utterance "see sassy" at a conversational rate and normal volume. In the non-speech condition, subjects were asked to produce individual jaw lowering and raising movements that were matched to the movement for /sas/ in the speech condition in terms of amplitude and duration. Both conditions began with a practice run of 30 repetitions. This was followed by three blocks of 180 repetitions each. During the experimental sequence, the robot delivered 50 ms, 1 N perturbations to the jaw, on average one trial in five, with perturbations acting in six equally spaced directions about a circle in the sagittal plane. The start time of the perturbation varied such that perturbations were distributed throughout the jaw lowering and raising movement associated with the sass portion of the utterance.

We developed a new procedure based on the application of brief force pulses to the jaw and a Fourier transform based interpolation technique that estimates the required reference trajectory, that is, the trajectory that would have been followed in the absence of load [2]. The Fourier transform based procedure was used to obtain estimates of the reference trajectory for each perturbed movement. The basic idea is that position and force data outside of the perturbation interval are used to predict the form the signal would have taken within the perturbed part, had there been no perturbation. To prevent noise from propagating into the predicted positions and forces, we use a low-pass filtered version of the signal in the unperturbed part of the movement to generate the interpolated signal within the perturbation interval. The restoring force vector, $\delta\mathbf{F}$, and the displacement vector, $\delta\mathbf{x}$, both measured at the mandibular incisors are determined by taking the difference within the perturbation interval between the actual signal and the computed reference trajectory.

Fig. 2 shows an example of vertical (a) and horizontal (c) jaw position and vertical (b) and horizontal (d) force signals for a representative subject in a perturbed trial (shown in black) in the speech condition. The superimposed reference trajectories derived using a Fourier-based procedure are shown in green. Estimates of error are shown at the bottom of each panel. The speech condition is represented in blue and non-speech is in red (the scale of the position errors bars are multiplied by ten, for visualization purposes).

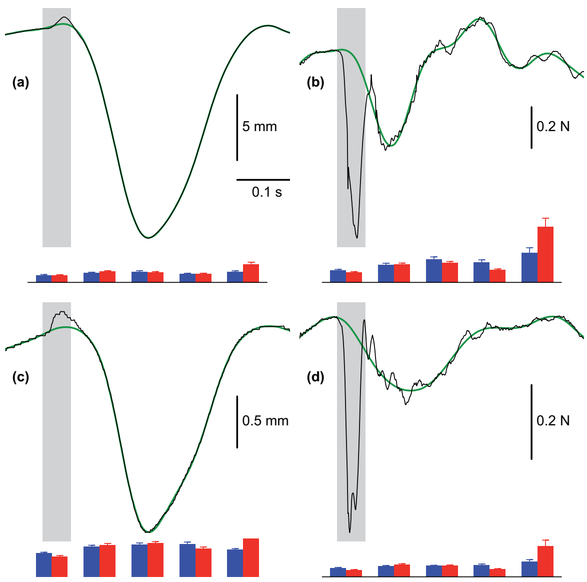


Figure 2: Reference trajectory estimation.

3 Results

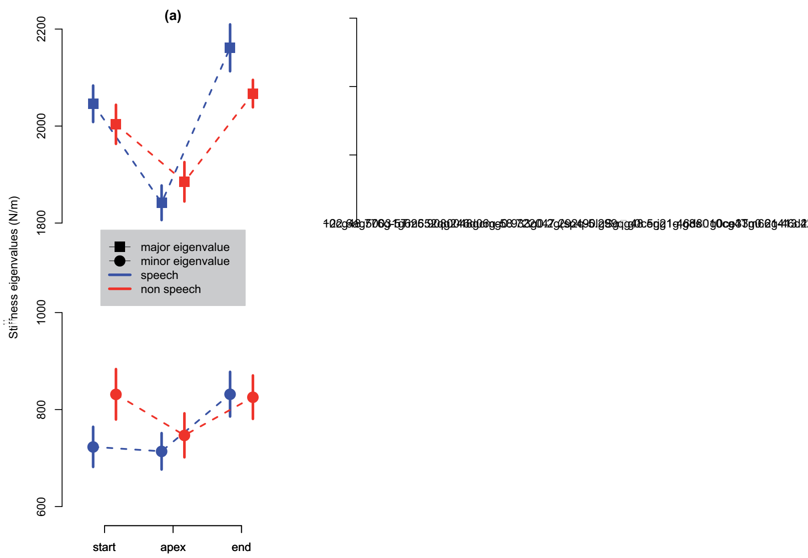
Jaw stiffness estimates were obtained for three intervals over the course of movement by partitioning the set of perturbations for a given subject and condition (speech/non-speech) into three bins of equal size based on their time of occurrence. On average, each bin contained data from approximately 40 perturbations.

With the dataset partitioned into bins, estimates of position change and force change due to the perturbations were used to compute three separate stiffness estimates for each subject in speech and non-speech conditions. An iterative procedure based on a moving average model that is reminiscent of the Expectation- Maximization (EM) algorithm [1] was used to obtain estimates of stiffness. Fig. 3A shows average magnitudes of stiffness for the major and minor axes of the jaw stiffness ellipse in each phase of movement. It can be seen that similar patterns are observed in speech and non-speech movements. In each case, for the direction of greatest stiffness (protrusion and retraction), stiffness is high in the early and late phases of movement and lower in the middle (by about 80 N/m on average). For the direction of least stiffness (raising and lowering) there is no phase dependent change in the observed magnitude of stiffness. Repeated-measures ANOVA confirmed that, in the direction of greatest stiffness, measured stiffness values differed over the course of movement ($p < 0.0001$), such that values for stiffness were less in middle of movement than at either the beginning ($p < 0.001$) or at the end ($p < 0.001$) as assessed by Bonferroni corrected comparisons.

We assessed the relationship between jaw stiffness and kinematic variability by computing, for each subject, composite measures of stiffness and variability. For stiffness, we calculated the stiffness for each of the three phases of movement in both the major and minor axes. The calculation was done for each subject separately and was repeated to have values for both speech and for non-speech movements.

We computed an analogous measure for kinematic variability, again on a per subject basis and also for each movement phase separately. The pattern of kinematic variability was fit with a one standard deviation confidence ellipse that was derived using principal components analysis (see Fig. 4). The orientation and magnitude of the major axis of the ellipse corresponds to the direction and magnitude of maximum kinematic variability. The minor axis shows the direction and magnitude of minimum kinematic variability. A global measure of kinematic variability, analogous to the area of the ellipse, was obtained by computing the square root of the product of the magnitude of the major and minor axes of kinematic variability.

Fig. 4 shows the relationship between jaw stiffness and kinematic variability where each point



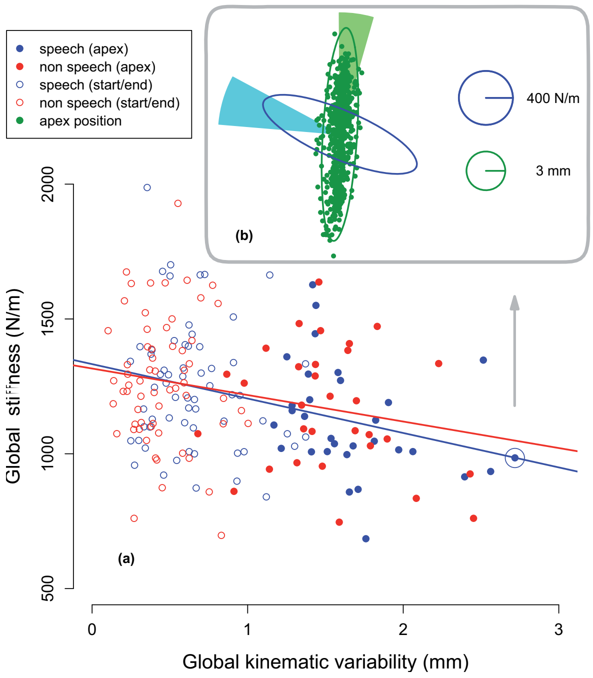


Figure 4: Kinematic variability in jaw movement is inversely related to stiffness.

dependent on the ability to adequately estimate the reference trajectory and importantly on the assumption that the subject does not voluntarily intervene over the course of the perturbation. Voluntary intervention is unlikely, at least during the perturbation interval. The perturbations are delivered at random points over the course of a movement and only on a subset of trials. Moreover, the perturbations are exceedingly small both in amplitude (approximately 1 mm) and duration (50 ms from start to end). Voluntary response can presumably be ruled out under these conditions.

4 Discussion

In the present study, we find that impedance is modulated over the course of movement and that the pattern of stiffness change is comparable for speech and matched non-speech movements. The modulation observed over the course of movement is basically similar to the pattern of stiffness modulation under stationary conditions where stiffness is greater at more elevated positions of the jaw and less for lower positions [9]. However, in comparison to measures taken when the jaw is stationary, stiffness during movement is higher by about a factor of two, particularly in the direction of jaw protrusion-retraction. We have seen that jaw stiffness is inversely related to kinematic variability and that stiffness is high in directions where variability is low and visa versa. Previous demonstrations of the relationship between either stiffness or muscle cocontraction and variability have been obtained at movement end [9, 3, 5] and may thus have been influenced by the unique stability requirements that arise at the end of movements. The results of the present study suggest that stiffness and variability are more globally linked and hence that stiffness regulation is a basic part of normal movement control.

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