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Control of Articulator Stiffness as a Means to Achieve the Precision Requirements of Speech

Douglas M. Shiller[†] **and David J. Ostry**[†,‡]
† McGill University, Montreal, Canada
‡ Haskins Laboratories, New Haven, U.S.A.
E-mail: shiller@psyc.queensu.ca, ostry@motion.psych.mcgill.ca

ABSTRACT

Studies of arm movement have suggested that the control of stiffness may be important for maintaining stability during interactions with the environment. Here we have examined the voluntary control of stiffness in the human jaw. The goal was to determine whether changes in jaw stiffness might be used to maintain jaw position in the face potentially destabilizing mechanical loads. A series of force pulses was applied to the jaw using a robotic device. The loads were designed to disrupt the ability of subjects to maintain a static jaw posture. In all cases, subjects increased the magnitude of jaw stiffness in order to maintain jaw position. A clear effect of the magnitude of the destabilizing load was observed — greater increases in stiffness were observed when larger forces were applied. Moreover, subjects were able to differentially modify stiffness in the direction of the destabilizing load in the case of loads in the vertical direction. The observed change in the relative magnitude of stiffness in different directions indicates some ability to control the pattern of stiffness of the jaw. The results indicate that jaw stiffness can be adjusted voluntarily, and thus may play a role in maintaining stability. Stiffness regulations may similarly provide a means to achieve the differential precision requirements of speech.

1. INTRODUCTION

The ability to maintain articulator position in the context of potentially unpredictable mechanical loads is of particular importance in the context of orofacial behaviors such as mastication and speech. In the case of mastication, the applied bite force has to appropriately match changes over time in the physical properties of the food bolus. In speech, loads arise as a consequence of coupled articulator motions and may have an effect on the ability to achieve the varying precision requirements of different speech sounds. Under such conditions, the nervous system may achieve stability by increasing, on the basis of muscle coactivation, the system's mechanical impedance — a term that globally characterizes the system's resistance to motion. In particular, an increase in the system's spring-like behavior or stiffness may provide a powerful mechanism for position control during interactions with the environment [1].

In the present study, we have investigated the control of stiffness in the human jaw. Jaw stiffness in the sagittal plane has been reported previously [2]. We have examined the control of jaw stiffness by applying destabilizing loads to the jaw using a robotic device. The purpose of the loads was to disrupt the ability of subjects to maintain a static posture.

We have tested the idea that stiffness may be scaled in magnitude in an adaptive fashion to counteract the effect of unpredictable loads. We have also examined the extent to which the spatial pattern of stiffness may be selectively modified so as to counteract external loads that act in different directions. The results support the idea that stiffness magnitude — and to a more limited extent the shape of the stiffness field — can be controlled in the jaw, and thus may play a role in regulating interactions with the environment in the orofacial system. Stiffness control may similarly serve as a means to achieve the differential precision requirements of different speech sounds.

2. MATERIALS AND METHODS

Jaw stiffness was measured using a computer-controlled robotic device that was capable of delivering forces and measuring positions in three dimensions (Figure 1). Resistive forces generated by the subject were measured using a force / torque sensor mounted on the tip of the robot. Jaw position and force were both sampled at 1000 Hz.

The initial phase of the experiment involved the estimation of jaw stiffness in the absence of any other manipulation (the no-load condition). Subjects were instructed to maintain a stable jaw position without any vocalization while a series of small ramp-and-hold force perturbations was applied. The maintained jaw position corresponded to the production of the mid-vowel /e/. The perturbations were delivered in 18 directions spaced equally about a sphere.

The subject was instructed to keep the jaw as close as possible to the target position on the basis of visual feedback of jaw position. Jaw perturbations were delivered only if the jaw was held stationary. Following the measurement of stiffness in the no-load condition, a series of trials were carried out using a task that was designed to elicit an increase in jaw stiffness. The task involved the rapid application of force pulses during which subjects were required to maintain a near-stationary jaw position, that is, to counteract the perturbing effects of the load. If,

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after two seconds of load application, the subject was able to maintain a stable jaw position for a period of 500 msec, a ramp-and-hold perturbation that permitted the measurement of jaw stiffness was delivered. The procedure for stiffness estimation was exactly the same as that used under no-load conditions.

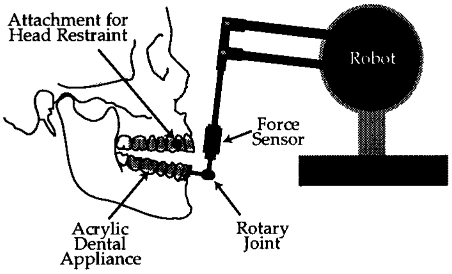

Figure 1 Schematic of the experimental setup.

In previous studies characterizing planar (2D) stiffness in the limb and jaw, the values of the 2 x 2 stiffness matrix have been represented graphically as an ellipse [3, 2]. The stiffness ellipse shows the predicted restoring force in each direction resulting from a displacement of unit amplitude (Figure 2A). The major axis of the ellipse defines the direction and magnitude of maximum stiffness, while the minor axis defines the direction and magnitude of least stiffness (Figure 2B). In the present study, the concept of the stiffness ellipse is extended to allow for the graphical depiction of a 3 x 3 stiffness matrix. The result is an ellipsoid that characterizes jaw stiffness in 3D (Figure 2C).

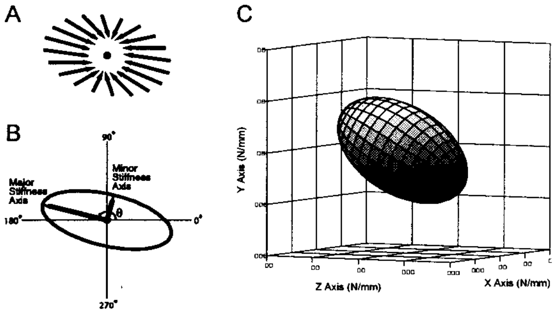

Figure 2 The graphical representation of the stiffness matrix. *A*, Restoring force vectors predicted from a 2 x 2 stiffness matrix on the basis of unit displacements in directions about a circle. *B*, The resulting 2D stiffness ellipse. *C*, The graphical depiction of a 3 x 3 stiffness matrix is an ellipsoid that characterizes jaw stiffness in 3D.

The magnitudes and directions of the applied force pulses were determined for each subject separately on the basis of the pattern of jaw stiffness measured in the no-load condition. In the absence of load, jaw stiffness in the mid-sagittal plane is anisotropic, with a major axis in the direction of jaw protrusion and retraction and a minor axis in the direction of jaw raising and lowering [2]. The directions of applied force were chosen to correspond to these two principle axes, in addition to the axis orthogonal to the sagittal plane. Specifically, force pulses were applied along the following the three axes: (1) the direction of maximum stiffness in the mid-sagittal plane (Axis 1 in Figure 3A, labeled the *horizontal* stiffness axis), (2) the direction of minimum stiffness in the mid-sagittal plane (Axis 2 in Figure 3A, the *vertical* stiffness axis), and (3) a lateral axis orthogonal to the mid-sagittal plane (Axis 3 in Figure 3A, the *lateral* stiffness axis). In other words, the directions of the force pulses corresponded to the axes that define the 3D stiffness ellipsoid. As shown in Figure 3, the major axis of this ellipsoid was tilted downward from the occlusal plane (by 27 degrees). Note that force pulses applied along a given axis were delivered in both the positive and negative directions along that axis, in a randomized sequence. For example, for the vertical stiffness axis, forces were applied in both the upward and downward directions.

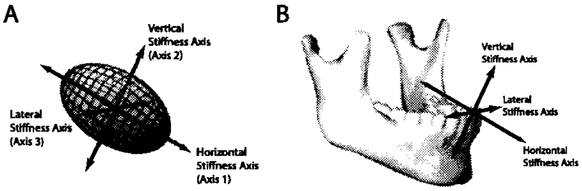

Figure 3 The directions of applied loads, corresponding to the axes that define the 3D stiffness ellipsoid. *A*, The three principle axes of the stiffness ellipsoid: (1) the direction of maximum stiffness in the mid-sagittal plane (*horizontal*), (2) the direction of minimum stiffness in the mid-sagittal plane (*vertical*), and (3) a lateral axis orthogonal to the mid-sagittal plane (*lateral*). *B*, The same three force directions shown relative to the mandible.

3. RESULTS

In the first phase of the experiment, 3D stiffness patterns were estimated for each subject in the no-load condition (Figure 3). In general, jaw stiffness patterns were not uniform. The magnitude of stiffness on the major axis of the stiffness ellipse (that is, on the horizontal or Z axis) was considerably greater than stiffness on the vertical or Y axis (jaw raising/lowering) and the lateral axis (X). In addition, stiffness along the vertical axis was greater than stiffness along the lateral axis.

In the second phase of the experiment, jaw stiffness was estimated following the application of force pulses to the jaw. Figure 4 illustrates the typical effect of applied force magnitude on the pattern of jaw stiffness for a single subject. In this case, the loads were applied in the lateral direction. In each panel, the inner ellipse (or ellipsoid) corresponds to stiffness under no-load conditions and the outer ellipse corresponds to a condition involving the application of force pulses that acted to destabilize jaw position. The top row (Panels A and B) shows jaw stiffness ellipses for the condition involving the lowest applied force level. The bottom row (Panels C and D) shows stiffness ellipses for the highest force level. For both magnitudes of applied load, an increase in jaw stiffness relative to the no-load condition can be seen. However the high force level shows a considerably greater increase in jaw stiffness compared with the low force level.

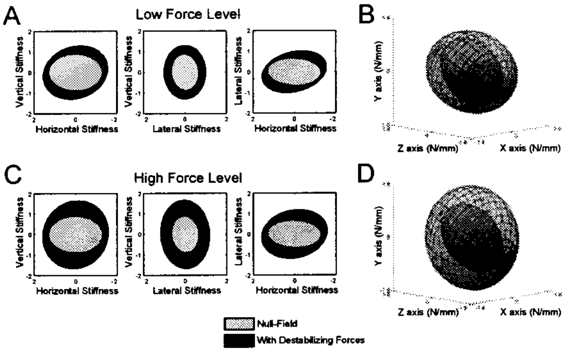

Figure 4 Effect of force magnitude on the jaw stiffness. Planar stiffness ellipses (shown to the *left*) are represented in terms of the three principle axes of the stiffness ellipsoid. A depiction of the same data as a set of 3D stiffness ellipsoids in head-centered coordinates is shown to the *right*. The top panels (*A* and *C*) show the change in stiffness between no-load conditions (*inner* ellipses) and the condition involving the lowest level of applied force (*outer* ellipses). The bottom panels (*C* and *D*) show the change in stiffness between the no-load condition and the highest force level. The higher force level is associated with a greater increase in jaw stiffness.

The effect of the applied force magnitude on jaw stiffness across subjects can be seen in Figure 5. In general, greater forces were associated with greater increases in jaw stiffness. This effect was observed for stiffness measured along the vertical and lateral axes (shown as green and blue lines), but not the horizontal axis (red line).

Repeated measures ANOVA was used to examine the effects of applied force magnitude on jaw stiffness using both the proportional and absolute measures of change in stiffness shown in Figure 5. For both measures, there was a significant effect of applied force level on vertical and lateral jaw stiffness ($p < 0.01$), but not for stiffness along the horizontal axis.

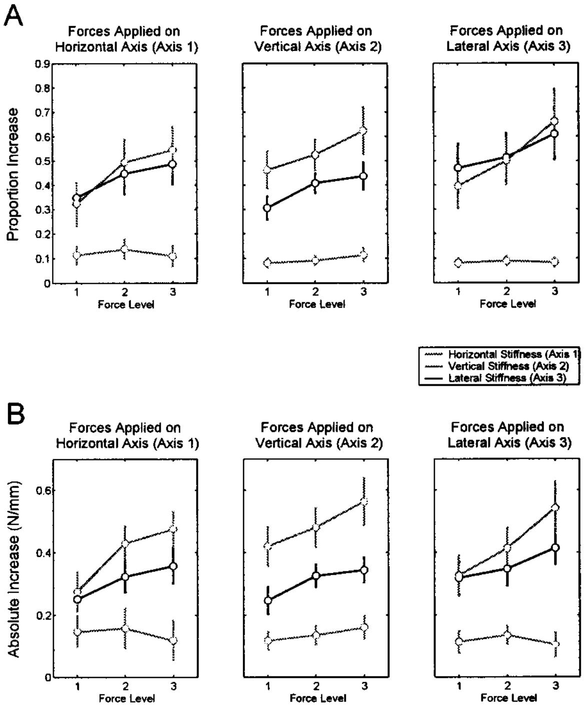

Figure 5 Mean values of stiffness change in all nine experimental conditions. Error bars indicate ± 1 standard error.

While there was a clear effect of force magnitude on the patterns of jaw stiffness, a more limited effect of the direction of force application on stiffness was observed. When forces were applied in the vertical direction (Figure 5, middle panels), the greatest increase in stiffness was observed in that direction (that is, along the vertical axis of the stiffness ellipsoid, shown in green). When forces were applied in the horizontal or lateral direction (left and right panels), the vertical and lateral axes showed a similar degree of stiffness increase. In all cases, stiffness along the horizontal axis (red line) showed no effect of the direction of force application, remaining at approximately 10% (or 0.14 N) under all conditions.

These effects were assessed using Tukey tests of pair-wise differences between means. When forces were applied along the vertical axis, the vertical stiffness increase was found to be reliably greater than the increase in the lateral direction, in terms of both proportions ($p < 0.05$) and absolute stiffness change ($p < 0.01$). When forces were applied in the other two directions (horizontal and lateral), no reliable differences between vertical and lateral stiffness change were observed ($p > 0.05$). For all three directions of force application, the change in jaw stiffness along the horizontal axis was significantly less than stiffness change on the other two axes, both in terms of proportional and absolute measures ($p < 0.01$ for all comparisons).

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4. CONCLUSIONS

We have explored the voluntary control of stiffness in the human jaw. Subjects increased the magnitude of jaw stiffness to counteract the effects of destabilizing external loads. The degree to which stiffness was increased to maintain jaw position was found to depend on the magnitude of the applied forces, such that greater force magnitudes were associated with greater increases in jaw stiffness. In addition the manner in which jaw stiffness was adjusted was found to be dependent on the direction of the destabilizing load. Specifically, when loads were applied along a vertical axis, jaw stiffness was found to increase to a greater degree in the direction of load application.

These results support the idea that the magnitude and, in a more limited manner, spatial characteristics of jaw stiffness can be controlled. In studies of arm motion, the control of endpoint stiffness has been shown to play a role in counteracting the effects of unstable interactions with the environment. The present results suggest that the modulation of stiffness may also play a role in the case of orofacial movements. The possibility that the differential precision requirements of different speech sounds are achieved through centrally specified changes to articulator impedance may be a direct extension of the present findings.

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