EMG Activities of Two Heads of the Human Lateral Pterygoid Muscle in Relation to Mandibular Condyle Movement and Biting Force

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Hiraba, Katsunari, Kazuto Hibino, Kenji Hiranuma, and Takefumi Negoro. EMG activities of two heads of the human lateral pterygoid muscle in relation to mandibular condyle movement and biting force. J. Neurophysiol. 83: 2120–2137, 2000. Electromyographic (EMG) activities of the superior (SUP) and inferior heads (INF) of the lateral pterygoid muscle (LPT) were recorded in humans during voluntary stepwise changes in biting force and jaw position that were adopted to exclude the effects of acceleration and velocity of jaw movements on the muscle activity. The SUP behaved like a jaw-closing muscle and showed characteristic activity in relation to the biting force. It showed a considerable amount of background activity (5–32% of the maximum) even in the intercuspal position without teeth clenching and reached a nearly maximum activity at relatively lower biting-force levels than the jaw-closing muscles during increment of the biting force. Stretch reflexes were found in the SUP, the function of which could be to stabilize the condyle against the biting force that pulls the condyle posteriorly. This notion was verified by examining the biomechanics on the temporomandibular joint. The complex movements of the mandibular condyle in a sagittal plane were decomposed into displacement in the anteroposterior direction (Ac) and angle of rotation (RAC) around a kinesiological specific point on the condyle. In relation to Ac, each head of the LPT showed quite a similar behavior to each other in all types of jaw movements across all subjects. Working ranges of the muscle activities were almost constant (Ac <3 mm for the SUP and Ac >3 mm for the INF). The amount of EMG activity of the SUP changed in inverse proportion to Ac showing a hyperbola-like relation, whereas that of the INF changed rather linearly. The EMG amplitude of the SUP showed a quasilinear inverse relation with RAC in the hinge movement during which the condyle rotated with no movement in the anteroposterior direction. This finding suggests that the SUP controls the angular relationship between the articular disk and the condyle. On the other hand, the position of the disk in relation to the maxilla, not to the condyle, is controlled indirectly by the INF because the disk is attached to the condyle by tendinous ligaments.

INTRODUCTION

The grinding movement of the mandible is a most important movement in mastication and requires a bilaterally distinct pattern of action of the temporomandibular joint (TMJ). On the working side where the food is crushed between the upper and lower molars, stiffness of the TMJ is required. The mandibular condyle must be kept stable in the temporomandibular fossa against the biting force produced by the jaw closing muscles. In contrast, on the contralateral nonworking side, the condyle has to move widely and smoothly in the medioanterior direction. In addition, the coordinated movements of the condyle and the articular disk are necessary for smooth movements of the mandible.

In these movements of the TMJ, the lateral pterygoid muscle (LPT) plays a crucial role. The LPT has two heads, the superior (SUP) and inferior (INF) heads in man and monkey. The SUP originates from the infratemporal fossa and is inserted mainly into the articular disk of the TMJ, whereas the INF arises from the lateral surface of the lateral pterygoid plate and is inserted into the condylar neck of the mandible (Heylings et al. 1995; Honée 1972; Ress 1954; Schmolke 1994; Wilkinson 1989). On the basis of such anatomic arrangements of the two heads, it has long been believed that the SUP and INF are synchronously active only during jaw opening to displace anteriorly the disk and the condyle, respectively. However, the electromyographic (EMG) activities obtained by Kamiyama (1961) in man and McNamaara (1973) in the monkey disagree with this view. The SUP was active mainly during clenching of the teeth and the INF during jaw opening, suggesting nonsynchronous functioning of the two heads in the movements of the condyle and the disk.

A number of EMG studies on the LPT suggest that the SUP functions like a jaw-closing muscle, whereas the INF functions like a jaw-opening muscle (Gibbs et al. 1984; Lehr and Owens 1980; Luschei and Goodwin 1974; Mahan et al. 1983; Miller et al. 1982; Sessle and Gurza 1982; Widmalm et al. 1987; Wood et al. 1986). However, the EMG patterns of either head of the LPT reported in these studies are quite variable. Furthermore, none of them has analyzed the EMG in relation to the condylar movement.

Because of the deep location and small size of the LPT, it is difficult to place the electrodes correctly in the target head. Even with a careful stereotaxic technique, the electrode advanced toward the SUP or INF is misplaced easily in or very close to the head, which is not the target. It is not surprising that previously reported EMG patterns of each head are markedly different. Actually, McNamaara (1973) stated that the EMG patterns differed widely depending on the position of the electrodes in the LPT. In living humans, however, there is no reliable means for confirming electrode placement. Accordingly, it would be practicable to select the EMG data on the basis of the EMG pattern rather than the position in the LPT.
from which the EMG is recorded and then to analyze the
pattern-identified EMG activities in relation to the oral func-
tions, such as biting force and movements of the incisor and
condyle of the mandible.

The movement of the human mandibular condyle is rather
complex because rotational condylar movement is more or less
associated with displacement of the condyle. The trajectory of
condylar movement shows a wide variation depending on the
position of the reference point on the condyle. However, a
simple jaw-opening, -closing movement on the sagittal plane
can be decomposed into displacement and rotation by the use
of the “kinematic axis,” which connects a specific point on
the condyle on both sides (Kohno and Ishiwara 1971; Yatabe et al.
1995). It was reported that the trajectory of condylar movement
with reference to the kinematic axis showed a narrow belt-
shaped form, the width of which was 0.7 mm on the average.

The mandibular movement on the sagittal plane consists of a
rotation around the axis and the displacement of this axis. If the
rotational angle of the condyle is calculated with reference to
that specific point, it will be possible to reconstruct the jaw
movement two dimensionally in the sagittal plane on the basis
of two parameters: displacement of the condyle and “rotational
angle of the condyle” (RAc).

The purpose of the present study is to investigate the roles of
the SUP and INF in controlling the condylar movement and in
stabilization of the condyle against the biting force in humans.

For this purpose, coordination of the activities of the SUP with
those of the jaw-closing muscles, masseter and temporalis
muscles, was investigated during a controlled biting task, and
the activities of the two heads of the LPT were analyzed in
relation to the jaw-movement parameters, such as anterior
displacement of the condyle (Ac) and RAc during a stepwise
mode jaw-positioning task. We designed the jaw-positioning
task in a stepwise manner so that the effect of movement
velocity on the EMG activity was negligible. The functional
significance of the two heads of the LPT was ascertained by the
findings on the biomechanical properties of the TMJ investi-
gated in cadavers. In addition to the EMG data in voluntary
movements, stretch reflex responses of the two heads of the
LPT were compared with those of the jaw closing muscles.

A part of this study appeared in an abstract form (Hiraba et al.

METHODS

Subjects and sessions

The subjects were seven male volunteers aged 27–33 yr. All the
subjects had normal and complete dentition and no history of man-
dibular dysfunction. They gave informed consent to this study. The
experiments were conducted in accord with the Code of Ethics of the
World Medical Association (Declaration of Helsinki) for Human
Experiments.

The present study consisted of two series of experiments carried
out on separate days. The main point of the first series was to
examine the coordination pattern of the SUP with the jaw-closing
masseter and temporalis muscles during biting tasks and to com-
pare the reflex responses of the two heads with those of these
jaw-closing muscles during stretching of the respective muscle.
The second series aimed at analyzing the relationship between the
condyle movement and the EMG activities of the two heads
recorded simultaneously, especially during three types of stepwise
changes in jaw position. In both experimental series, several kinds
of jaw movements and tasks were performed to reveal the basic
characteristics of the EMG activity of each head: movements of
jaw opening and closing, anteroposterior, lateral, clenching, and
chewing, and tasks of stepwise changes in jaw position and biting
force. These movements and tasks were performed in this order. In
some cases, hinge jaw-opening, -closing movements were added to the
habitual movements.

EMG recording

In the first series, bipolar surface electrodes (interpolar distance: 2.5
cm) were placed on the skin over the masseter and temporalis
muscles. The activities of these muscles were recorded simultaneously
with those of the SUP, and of the INF in a few cases, on the subject’s
habitual chewing side. In the second series, EMG recordings were
made from the unilateral SUP and INF.

To record a well-isolated EMG activity of each head of the LPT, the
proximal part of the LPT, 0.5–1.5 cm from the origin, was selected as
the recording site because at this region the cross-sectional area of the
SUP is maximum and the muscle bellies of the SUP and INF clearly
are separated by a septum of connective tissue (Widmalm et al. 1987).

To precisely insert the recording electrode into the SUP and INF

FIG. 1. Procedures for electrode insertion into the superior (SUP) and inferior (INF) heads of the lateral pterygoid muscle (LPT)
and monitoring the movements of incisor and condyle of the mandible. A: method for electrode insertion. For stereotaxic control
of electrode orientation a face-bow was applied to the head of the subject and a plastic plate equipped with a guideline of 20°
inclination was attached to the side beam of the face-bow at a right angle. Ear rod of the face-bow was the indicator for the coronal
and horizontal planes. B: locations of the dye verified in the SUP (c) and INF (m) of 12 cadavers as plotted on the standard
configuration of the LPT. C: jaw tracking equipment carrying 2 light-emitting diodes (LEDs) on the lower central incisor and the
mandibular condyle.
The subject sat in a dental chair with a headrest. To minimize artifacts in EMG recordings and dislocation of the electrodes by condylar movements, the subject was instructed to open the jaw maximally and then the electrode was inserted anterior to the mandibular condyle, which was maintained at the anterior-most position (Mahan et al. 1983). At the end of the first recording, the tip of the indicator bar of the face-bow was clamped at the insertion point on the skin as the landmark for insertion of the electrodes in subsequent recordings. The distance from the surface of the skin to the recording point of the SUP was 42–48 mm (46.5 on average) and 35–50 mm (46.0) for the INF.

### STEPWISE CHANGE IN JAW POSITION AND BITING FORCE

The vertical component of the position of the lower incisor was displayed on the oscilloscope in front of the subject. The most closed jaw position at which all posterior teeth contact with opposing molars by means of cusps and fossae is referred to as the intercuspal position (ICP). In the ICP, the mandible is fixed in the anteroposterior and lateral as well as vertical directions. From the ICP, the subject was asked to open the jaw by an amount corresponding to the distance between two horizontal grid lines of the oscilloscope and keep the position as steadily as possible for ~2 s by the aid of visual feedback of the jaw position. In the next step, the subject opened the jaw wider in the same manner. Thus the subjects changed the jaw position in a stepwise manner throughout the range between the intercuspal and the maximally open positions (stepwise jaw-movement task). The activities of the SUP were characterized by the presence of background activity in the ICP and its rapid change in inverse proportion to interincisal distance in a range of 10–15 mm. This range corresponded to a very narrow range, 3–5 mm of Ac. To examine the relation of the SUP EMG to the Ac in detail, the amount of stepwise change in jaw position must be small, especially near the ICP. Therefore at the jaw positions near the ICP, the incisor position was monitored on the oscilloscope with a high gain in which one step corresponded to an interincisal distance of ~1.0 mm. At nearly maximally open positions, interincisal distance was monitored with a low gain in which one step corresponded to a distance of ~5.0 mm. At the intermediate jaw positions, one step corresponded to an interincisal distance of ~2.0 mm.

In addition to the habitual stepwise jaw movements, two different modes of stepwise movements were performed in the second series. In the “intent-retrusive jaw-opening, -closing movement” (Int-Ret JM), the subject moved the jaw while paying attention so as to maintain the position of the condyle at the ICP as much as possible particularly in the early stage of jaw-opening and the late stage of jaw-closing movements. In the “intent-protrusive jaw-opening, -closing movement” (Int-Pro JM), the subjects moved the jaw while paying attention so as to protrude the condyle as much as possible in the same stages as in the Int-Ret JM.

The subject changed the biting force stepwise, as in the stepwise jaw-movement task, between 0 and ~50% of the maximum biting force under visual feedback from the oscilloscope on which the biting force was displayed linearly. Each step lasted ~2 s (stepwise biting task). The maximum biting force was measured in advance by the use of metal biting plates (see following text) without insertion of EMG recording electrodes.

### STRETCH REFLEXES

To stretch the LPT, pressure was applied to the menton with the thumb by an experimenter in the posterosuperior direction so that the mandible was passively moved posteriorly. In this test, the metal biting plates were not in place, and the subject was instructed to be relaxed and to take a rest position of the mandible. The stretch reflex-like response of the SUP that was elicited by tapping the menton was compared with the stretch reflexes simultaneously recorded in the masseter and temporalis muscles. The menton tapping was done with an electrically controlled mechanical stimulator. The duration and interval of stimulus were controlled: 5 ms in duration, 30 stimuli at 1-s intervals (Dia Medical System, DPS-250 SH). To monitor tapping force, a force transducer was attached at the tip of the mechanical stimulator. Magnitude of displacement of the stimulator probe was adjusted so that the tapping force was ~4.9 N (500g weight) in each trial.

### Monitoring jaw movements

In the first series, the movement of the incisor point was monitored three dimensionally by detecting the position of a small magnet (6 × 9 mm in length, 23 gauge) attached to the lower incisor tooth. The position of this magnet was monitored on the oscilloscope with a high gain in which one step corresponded to a distance of ~1.0 mm. At nearly maximally open positions, interincisal distance was monitored with a low gain in which one step corresponded to a distance of ~5.0 mm. At the intermediate jaw positions, one step corresponded to an interincisal distance of ~2.0 mm.

### Electromyograms (EMGs) of days 1 and 2 were recorded in the first experimental series in which EMG activity was recorded from either head of the lateral pterygoid muscle (LPT) and those of days 3–7 were done in the second series in which EMG activities of both heads were recorded simultaneously. SUP and INF, superior and inferior heads of the LPT; CL and OP, patterns in which strong activity appeared in only the closing phase or only the opening phase, respectively.
TABLE 2. Incidence of EMG patterns recorded from the SUP and INF

<table>
<thead>
<tr>
<th></th>
<th>CL</th>
<th>CL &gt; OP</th>
<th>OP &gt; CL</th>
<th>OP</th>
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<tbody>
<tr>
<td>SUP</td>
<td>29</td>
<td>17 (59%)</td>
<td>9 (31%)</td>
<td>3 (10%)</td>
</tr>
<tr>
<td>INF</td>
<td>18</td>
<td>4 (22%)</td>
<td>1 (6%)</td>
<td>2 (11%)</td>
</tr>
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</table>

EMG patterns classified on the basis of EMG activities of the SUP and INF during jaw-opening, -closing movements. The incidence of each EMG type depends significantly on the electrodes’ position in the LPT. Because frequencies of the some types in this table were <5, we arranged this table by gathering the CL and CL > OP types into one group and the OP and OP > CL types into another group. Probability was finally estimated in 2 × 2 contingency table by Fisher’s exact probability test. P < 0.01.

13 mm, 3-mm thick) attached to the labial surface of the lower central incisors. The sensors were mounted on an eyeglass frame (Myotronics, MKG system, K5).

In the second series, the movements of the central incisor and condyle of the mandible were recorded on the sagittal plane, with two semiconductor-position detectors responding to infrared ray from light-emitting diodes (LEDs). The position detectors were mounted on the subject’s head with a headgear (Tokyo-Shizaisha, Saphon Visiontronics, C-II). The minimum detection sensitivity was <0.01 mm, and a rectilinear relation between the position and the output of the detector was <2%. The LED carrier was fixed to the labial surface of the lower anterior teeth with cyanoacrylate (Fig. 1C). One LED was placed 3 cm anterior to the lower central incisor on the occlusal and mid-sagittal planes, and an additional LED was 4 cm lateral to the skin over the mandibular condyle. The position of the LED on the condyle was adjusted to minimize the difference in the forward and backward courses of the LED during tapping and opening-closing movements. The kinesiological reference point was determined ultimately by computer simulation of the mandibular movements as described in the following text.

At the end of each recording trial, a 20-mm-thick wooden stick was interposed between the upper and lower incisors. By means of interpolation and extrapolation of the output value from the jaw tracking system at 20 mm jaw opening, the “vertical displacement of the incisor” (Vi) at any jaw position was calculated as interincisal distance in millimeters. Because there is no serious disparity between the actual condylar position and LED position on the sagittal plane during simple jaw-opening, -closing movements, the displacement of the condyle was represented as that of the LED.

Measurements of biting force

In the stepwise biting task, two metal biting plates similar to those used in dental clinics for the intraoral gothic arch tracing (Bailey and Winkler 1979) were fixed on the maxillary and mandibular dentition with cyanoacrylate. The upper plate had a screw in the center of the plate, and only the tip of the screw made contact with the lower plate so that on biting the opposing teeth were apart by 2–3 mm interincisal distance. A strain gauge was attached to the upper plate. The output of the strain gauge amplifier was linear ±490 N (50 kg). To measure the biting force at a fixed jaw position that corresponded to the ICP, the position was determined previously by the gothic arch tracing method (Bailey and Winkler 1979). A dimple was drilled at this position on the lower plate. When biting, the subject was asked to fit the tip of the screw to the dimple.

Dissection of the temporomandibular joint and the LPT muscle in cadavers

In 12 cadavers, after removing the temporalis muscle and coronoid process, the lateral surface of the LPT was exposed. The condyle with...
the attaching disk, disk ligaments, and LPT was isolated from the glenoid and infratemporal fossae by dissecting the peripheral surrounding tissue of the superior joint space, the posterior bilaminar zone, and the origin of the LPT at the lateral pterygoid plate (Wilson 1989). The cut ends of the bellies of the SUP and INF were pulled manually, and the effects on the positions of the disk and condyle were examined visually.

Data analysis

The data were stored on six-channel FM tapes driven at 9.5 cm/s (flat frequency response: 0–1.25 kHz), and played back on an eight-channel thermal array recorder (Nippon Denki Sanei, 8 M24).

The data of rectified and low-pass filtered (7 Hz low-pass, 24 dB/oct) EMGs of tested muscles, jaw positions, and biting force were fed into a personal computer (NEC, PC-9801 VX) through an A/D converter (sampling at 100 Hz, 12-bit resolution). The mean values of the rectified EMG amplitude, the incisal and condylar positions, and the biting force were determined during the steady state at each step of the stepwise motor tasks. The mean amplitude of the EMG activity was expressed as a percentage of that recorded during maximal clenching of the teeth for the SUP, masster, and temporalis muscles and during maximal jaw opening for the INF. The raw EMG responses to taps of the menton were A/D converted (sampling at 10 kHz, 12-bit resolution) and averaged 30 times using the onset of tapping as the trigger.

ROTATIONAL ANGLE OF THE CONDYLE. The trajectories of the incisor and condyle on the sagittal plane were visualized as lines connecting the points representing the mean values of consecutive steps. The mandibular movement on the sagittal plane was computer-simulated by originally designed software simulating the movement of a right triangle, in which the incisor and condylar points were represented by its two apexes (Fig. 2). Using this computer simulation of the mandibular movements, fine adjustment of the position of the kinesiological reference point on the condyle was carried out by trial and error so that the trajectories of the condyle showed the narrowest belt-shaped configuration throughout stepwise opening-closing movements. By the use of this point as the kinesiological point, the RAc was calculated, and then the condyle movements were transformed into two-dimensional movements (compound condyle movements, CCM), by using the RAc and Ac as the two axes of coordinates.

FIG. 4. Synchronous EMG activities of the str-SUP of CL type with the masster and temporalis muscles during jaw-opening, -closing (A), chewing (B), and clenching (C) movements. Ai, anterior displacement of the lower incisor. PO, posterior direction. Several small strokes of intercuspal tapping movements were performed between the standard tasks and movements (in A and C) to determine the ICP (- - -) of the incisor points. MSS and TMP: masster and temporalis muscles, respectively. Abbreviations same as in Fig. 3.

FIG. 5. EMG activities of the str-INF as classified as OP type based on the activity during jaw-opening, -closing movements. A–C: jaw-opening, -closing, chewing, and stepwise jaw-opening, -closing movements. Smaller amplitude of EMG activities appeared in the closing phase of chewing (B). Several small strokes of intercuspal tapping movements were performed between the standard tasks and movements (in A) to determine the ICP (- - -) of the incisor points. In C, rectified and low-pass filtered EMG activities (¥) are shown below the raw EMG records. Abbreviations as in Fig. 3.
and low-pass filtered EMGs (A) are shown below each raw EMG in C during biting with decrementing force in lines are the data obtained during biting with incrementing force, thin lines were made two to eight times in each subject. The patterns were classified into four types on the same subject when the insertion of the electrodes was made on different days. The patterns were classified into four types on the basis of the EMG activities of the SUP and INF during jaw-opening, -closing movements. A pattern, in which strong activity appeared only in the opening phase, was classified as CL type. The closing phase is the period from the most-closed position to the most-opened position. In contrast, a pattern in which strong activity appeared only in the opening phase, with no activity in the closing phase was classified as OP type. The remaining intermediate types, in which EMG activities were found in both phases were classified as either CL>OP type or OP>CL type depending on the phase in which larger EMG activity was present.

Table 1 shows an example of variation of the EMG pattern of the SUP and INF observed in the same subject. In some subjects, all three types of SUP EMG activities, except for the OP type, could be recorded on different days. Among the types of the SUP, no OP type was found in any subject, and the majority was the CL type (59%, Table 2). Among the types of the INF, the majority was the OP type (61%, Table 2). The SUP of the CL type could be recorded at least once in each subject and the INF of the OP type in six of seven subjects. Occurrence of CL>OP and OP>CL types, regardless of SUP and INF, was not restricted to specific subjects. Such deviation of incidence of each EMG type depends significantly on the position of the electrodes in the LPT (Probability was finally estimated by Fisher’s exact probability test: \( P < 0.01 \)). In the following description, we use, instead of “SUP” and “INF”, the terms “stereotaxic SUP” (str-SUP) and “stereotaxic INF” (str-INF). This is because although we believe that we often have recorded genuine activity patterns of the SUP and INF, in some cases the records seemed to be a mixture of the activities of the two heads.

First we will present the typical features of the CL type of the str-SUP and the OP type of the str-INF. Then the EMG activities of the other types of the str-SUP and str-INF will be shown.

Figure 3 shows examples of simultaneously recorded EMGs of the str-SUP of the CL type and str-INF of the OP type. The str-SUP had a tonic background activity at the rest position of the mandible as well as in the ICP. This background activity disappeared during jaw-opening (Fig. 3A), anterior (Fig. 3C), and contralateral movements (Fig. 3D), whereas the activity increased or persisted during jaw-closing (Fig. 3A), posterior (Fig. 3C), and ipsilateral movements (Fig. 3D). In contrast, the str-INF showed no activity at all in the ICP but was strongly active during jaw-opening (Fig. 3A), anterior (Fig. 3C), and contralateral movements (Fig. 3D). It showed no activity during jaw-closing (Fig. 3A), posterior (Fig. 3C), and ipsilateral movements (Fig. 3D). During chewing of gum, the two heads of the LPT showed, regardless of the chewing side, a common pattern of variation of the EMG activities of the str-SUP and str-INF during habitual (left) and intent-retrusive (right) jaw-opening, -closing movements. Small tapping movements of several strokes were performed between the standard tasks to determine the ICP of the incisor and condyle points. ••• level of the ICP, ◆ and ▲ offset and onset points of the str-SUP, respectively.
complete reciprocal and monophasic burst activity. The str-SUP was active only in the jaw closing phase, and the str-INF in the jaw opening phase (Fig. 3B). Thus the str-SUP of the CL type and str-INF of the OP type are active clearly in a reciprocal manner during various kinds of movements as well as during chewing.

Figure 4 shows EMG activities of the str-SUP of the CL type recorded simultaneously with the masseter and temporalis muscles during jaw-opening, -closing movements, chewing, and clenching of the teeth. In these movements, the str-SUP was always active synchronously with those of the jaw closing muscles.

Figure 5 shows an example of EMG activities of the str-INF classified as the OP type (Fig. 5A), but its EMG activity was present not only in the opening phase but also in the closing phase during chewing (Fig. 5B) as if it was the OP > CL type. This means that the jaw-opening, -closing movement alone is not suitable to test whether the str-INF EMG record is contaminated by the EMG activity of high-threshold motor units in the str-SUP that are to be active only during chewing and clenching in which a greater activity of the str-SUP is required. Therefore we tested whether the str-INFs of the OP type show activities in the closing phase of chewing or not. As the result, smaller amplitude EMGs were found in the closing phase of chewing in 5 of 11 str-INF EMGs of the OP type that were classified based on the activity during jaw-opening, -closing movements.

If not specifically mentioned, the OP type of str-INF referred to in the following paragraphs showed negligible EMG activity in the closing phase of chewing.

Relationships of the EMG amplitude of the str-SUP to the biting force and interincisal distance

During the stepwise increment of biting force, the EMG activity of the str-SUP increased rapidly to reach a quasplateau earlier than that of the masseter muscle in which the rate of increase in EMG activity to the increase in biting force was low at lower biting force levels and became progressively higher at higher biting force levels (Fig. 6, A and B). The results obtained from four subjects in 10 recording sessions are shown collectively in Fig. 6, C and D. The str-SUP was clearly different from the masseter and temporalis muscles in that it showed a substantial background activity in the ICP ($V_i = 0$, 5–32% of the maximum; Fig. 6C). Because the metal biting plates caused jaw opening by 2–3 mm, the EMG amplitude at biting force $= 0$ was usually lower than that in the ICP without clenching.

When the subject started to open the jaw, the background activity of the str-SUP in the ICP diminished rapidly and disappeared at $\sim 5$ mm $V_i$ (offset point, i.e., the jaw position at which the EMG activity disappears; Fig. 7, left, △). In the jaw-closing phase, however, the EMG activity reappeared at 20 mm $V_i$ (onset point, i.e., the jaw position at which the EMG activity reappears; Fig. 7, left, △). In the Int-Ret JM (Fig. 7, right), which was performed with a slower velocity, the disparity of these two points was smaller. The onset and offset points of the str-INF were, regardless of the type of movement, very close to the offset and onset points of the str-SUP, respectively.

To exclude the effect of velocity of jaw movements on the onset and offset points, muscle activities of the two heads were examined in stepwise jaw movements. Figure 8 shows three types of stepwise jaw movements and EMG activities recorded in the same subject. Because the magnitude of each step in $V_i$ was controlled by visual feedback of the output of the jaw tracking system, the trajectories of $V_i$ of the opening and closing phases were symmetric. In contrast, those of $A_c$ were widely different among the stepwise movements.

In the stepwise habitual movement (Fig. 8, left), the wide disparity of the offset and onset points of the str-SUP still remained. However, in the stepwise Int-Ret JM (Fig. 8, middle), there was no appreciable difference between these points. They were roughly equal at $\sim 20$ mm $V_i$. In this stepwise Int-Ret JM, both the opening and closing movements within 20 mm $V_i$ were pure rotation because of no measurable change in $A_c$ (shown by 2 segments of a horizontal line in the middle of the panel). During this rotational movement of the mandible, the mean amplitude of the str-SUP was nearly inversely proportional to $V_i$. On the other hand, in the Int-Pro JM (Fig. 8, right), the offset point of the str-SUP shifted to 3 mm $V_i$. Although the presence of a small motor unit of the str-SUP activated at 10 mm in the closing phase made the onset point
of the str-SUP at 10 mm Vi, it was apparent that the major part of the working period of the str-SUP was restricted in a narrower range of Vi than the other types of movements.

Regardless of the type of movement, the onset and offset points of the str-INF changed in parallel with the corresponding points of the str-SUP. The activity of the str-INF increased in parallel with the amount of Ac. For example, in the stepwise Int-Pro JM (Fig. 8, right), both the offset point of the str-SUP and onset point of the str-INF in the opening phase shifted to 3 mm Vi so that the working period of the str-SUP became shorter and that of the str-INF longer. The activity of the str-INF showed a very similar profile with the trajectories of the Ac.
These findings strongly suggest that the disparity of the onset and offset points of the str-SUP and str-INF that typically was found in the habitual movements are attributable to the difference in the mandibular movements performed in opening and closing phases. In addition, it appears that muscle activity of the str-SUP may be primarily correlated with rotation of the condyle and that of the str-INF may be correlated with Ac.

Correlation coefficients of the EMG activities of the str-SUP and str-INF to jaw-movement parameters

To estimate the correlation between the EMG activities of the two heads and the jaw-movement parameters, the “mean amplitude of the EMG activities of the str-SUP (EMG\textsubscript{SUP}) and str-INF (EMG\textsubscript{INF})” in each step during stepwise movements was plotted against the Vi, Ac, and RAc. Figure 9 shows examples during the stepwise habitual movement. There are significant correlations between the EMG activities of the two heads and the jaw movement parameters. The EMG\textsubscript{INF} is positively and the EMG\textsubscript{SUP} is negatively correlated with all three parameters (Table 3).

Correlation coefficients also were estimated during Int-Ret JM. In this type of movement, there was a tendency that correlation coefficients of the EMG\textsubscript{SUP} with Ac were weaker than in the stepwise habitual movement, and in some cases

<table>
<thead>
<tr>
<th></th>
<th>INF</th>
<th>SUP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vi</td>
<td>Ac</td>
</tr>
<tr>
<td>Range</td>
<td>0.99–0.89</td>
<td>0.99–0.67</td>
</tr>
<tr>
<td>Mean</td>
<td>0.95 ± 0.03</td>
<td>0.92 ± 0.08</td>
</tr>
</tbody>
</table>

Pearson’s correlation coefficients were estimated for opening and closing phases separately. Values are means ± SD. There were 16 samples. All of them, except for three cases of anterior displacement of the condyle (Ac) for the SUP, are statistically significant; \( P < 0.001 \). EMG\textsubscript{INF} and EMG\textsubscript{SUP}, mean amplitude of the EMG activities of the str-INF and str-SUP, respectively. RAc, rotational angle of the condyle; Vi, vertical displacement of the lower central incisor.

FIG. 10. Incisal and condylar movements and the mean EMG amplitude during 3 types of stepwise jaw movement in 1 subject. Left, middle, and right: stepwise habitual, intent-retrusive, and intent-protrusive jaw-opening, -closing movements, respectively. Trajectories of the incisor (INC) and condyle (CND) movements on the sagittal plane were plotted using ICP as the 0 point of the coordinate (dashed and dotted lines). Mean EMG amplitude was plotted against both Vi (bottom) and Ac (top) for the str-SUP (solid lines) and str-INF (dotted lines). Thin and thick lines represent jaw opening and closing phases, respectively.  and , offset and onset points of the str-SUP. Shaded area in the EMG/Ac relations (top) indicate the working range of the str-SUP (Ac <3 mm). Two or 3 traces were superimposed. Mean EMG amplitude was expressed as a percentage of the maximum. Vi and Ac are shown in millimeters. Subject is the same as shown in Fig. 8.
they were nonsignificant. Even in these cases, however, EMG_{SUP} still exhibited a significant correlation to the RAc as well as Vi. In every case, regardless of jaw-movement type, Vi strongly correlated with RAc with correlation coefficients $\geq 0.98$. These findings indicate that the significant high correlation between the EMGs and Vi is attributable to this inherent correlation of Vi with RAc and that EMG_{SUP} correlates primarily with RAc.

Relationships of EMG activities of the str-SUP and str-INF to movements of the incisor and condyle

To study the relationships of the EMG activities of the two heads of the LPT to the movements of the incisor and condyle, the trajectories of the incisor and condylar points were imposed on the sagittal view of the mandible (Fig. 10, middle). In association with their sagittal movements, EMG_{SUP} and EMG_{INF} were plotted against the Vi and Ac, individually. With respect to Vi, EMG_{SUP} and EMG_{INF} were plotted by taking the Vi as the downward-ordinate and EMG as the abscissa (Fig. 10, bottom); with respect to Ac, EMG_{SUP} and EMG_{INF} were plotted by taking the Ac as the leftward-ordinate and EMG as the ordinate (Fig. 10, top).

Figure 10 illustrates an example obtained from a subject. The movements of the incisor point were clearly different among the three types of stepwise movements. In addition, the onset and offset points of the EMG activities of both heads and the curves of the EMG_{SUP} and EMG_{INF}/Vi relations were widely different depending on the types of movement. Although there seemed no appreciable difference in the trajectories of the incisors movements between opening and closing phases of stepwise habitual movements (bottom, dashed and dotted lines, INC), it was found that there was a marked difference in the curves of the EMG_{SUP}/Vi relations between opening and closing phases as well as a wide disparity between the onset and offset points of the SUP.

In spite of wide difference in the movements of the incisor point among the three types of stepwise movements, the trajectories of the condylar point were virtually the same (Fig. 10, middle, dashed and dotted lines, CND). The relationships between the muscle activities of the two heads and Ac also showed no marked difference among the three types of jaw movements. EMG_{SUP} plotted against Ac showed a hyperbola-like relation, and EMG_{INF} was more or less linear. The working range of the str-SUP was between 0 and 3 mm Ac (shaded area) and that of the str-INF $\geq 3$ mm Ac (Fig. 10).

Rotation and displacement of the condyle

The reconstructed compound condylar movement (CCM) revealed a clear difference in the mandibular movement between the closing and opening phases in the range $< 3$ mm Ac, i.e., the working range of the str-SUP (Fig. 11, shaded vertical area). In the final closing phase of the stepwise habitual movement (Fig. 11, top), there was no change in Ac (thick lines), indicating that the mandible only rotates in this phase. In contrast, in the initial stage of the opening phase, Ac changed in parallel with RAc (thin lines), indicating that both displacement and rotation of the mandible take place. In the stepwise Int-Ret JM (Fig. 11, middle), the movements in the initial stage of jaw opening and final stage of jaw closing (RAc $< 8^\circ$) were rotation only because there was almost no change in Ac. In the stepwise Int-Pro JM (Fig. 11, bottom), the CCMs in the initial stage of opening and the final stage of closing were accompanied by displacement (shaded vertical area in CCM). As already shown in Fig. 10, it is to be noted that whatever types of jaw movement were performed, the working ranges of the two heads were almost constant (Ac $< 3$ mm for the str-SUP and Ac $> 3$ mm for the str-INF). It could be concluded that the str-SUP and str-INF work with a considerable steady relation to the Ac.

**FIG. 11.** Compound condylar movements and the mean EMG amplitude during 3 types of stepwise jaw movement in 1 subject. CCM, compound condylar movement. Top, middle, and bottom: stepwise habitual, intent-retrusive and intent-protrusive movements, respectively. Right: the mean EMG amplitude was plotted against RAc for the str-SUP (solid lines) and str-INF (dotted lines). Thin and thick lines represent jaw-opening and -closing phases, respectively. Long vertical shaded belt in the middle indicates the working range of the str-SUP as determined on the Ac axis. Shaded belts on the vertical plane (right) illustrated in an oblique way in the EMG/RAc relations show the variable working ranges of the str-SUP depending on the type of jaw movement. Mean EMG amplitude is shown as a percentage of the maximum. Subject is the same as shown in Figs. 8. and 10. Abbreviations as in Fig. 10.
Individual difference in usage of the str-SUP and str-INF

The jaw movements and EMG activities recorded from three subjects were compared in the jaw-closing (Fig. 12) and opening (Fig. 13) phases of the stepwise habitual movement. In general, interindividual differences in the relationships between the EMG amplitude and the jaw-movement parameters, especially Vi and RAc, were larger in the closing phase than in the opening phase. In addition, the positions of the onset and offset of the EMGs in the jaw-closing phase were markedly different among the subjects (Fig. 12).

Interindividual differences in the CCM performed in the working range of the str-SUP, <5 mm Ac (Fig. 12, shaded area), were also larger in the closing phase than in the opening phase. In subject 1, the late stage of jaw closing was displacement dominant and the final stage was rotation. In subject 2, rotation was followed by final displacement. In subject 3, the final stage consisted of both rotation and displacement. In spite of such wide difference in the CCM, the relations of the str-SUPs to Ac were basically similar, showing a hyperbola-like relation. In addition, the difference in the working range of the str-SUPs was not so large as could explain the wide interindividual difference in the relationship between the EMG amplitude and the jaw-movement parameters. On the other hand, during jaw opening there was no obvious difference in the CCM within the working range of the str-SUP, i.e., Ac <2 mm (Fig. 13, shaded area).

These findings indicate that a wide interindividual difference, such as a different position of the onset and offset points and a resultant different slope of the EMG/Vi and RAc relation lines, is mainly due to the difference in the CCM within the working range of each head but not due to the difference in nature of the LPT itself among the subjects. Consequently, these interindividual differences can be explained by three factors: the period in which the rotational jaw movement occurs, whether this period is within the working range of the str-SUP or without, and whether this period is without of the working range of the str-INF or within.

EMG activities of the other types of str-SUP and str-INF OP>CL TYPE OF STR-SUP. In the EMGs of the str-SUP in Fig. 14, two or more unitary activities of different amplitude appeared at jaw positions with large Vi. The activities of those units changed in parallel with the Ac and also with the EMG amplitude of the str-INF (Fig. 14C). In addition, bursts of EMG of the str-SUP occurred in the opening phase of chewing (Fig. 14E). However, both the unitary discharges of the str-SUP and the activity of the str-INF disappeared at the level close to ICP during hinge movement (Fig. 14, B and D). The hinge movement was performed with an effort to open the jaw with

![Diagram of jaw movement patterns and EMG activities](image)

**FIG. 12.** Relationships between jaw-movement patterns and the mean EMG amplitude during closing. Shaded belt on the horizontal plane shows the largest value of the working range of the str-SUP obtained in subject 3 (Ac <5.0 mm). Vertical shaded plane in CCM shows the period corresponding to the working range of the str-SUP as determined on the Ac axes. Three traces were superimposed for each subject. Vi and RAc are expressed as a percentage of the maximum of each subject. Amount of Ac is shown in millimeters. Correlation coefficients between the EMG and the parameters of jaw movements are summarized in Table 4 with respect to each subject. Abbreviations as in Fig. 10.
minimal anteroposterior displacement of the condyle. On the other hand, the background activity of low amplitude near the ICP, which is characteristic of the str-SUP of the CL type, still persisted.

In the str-INF, an activity of low or moderate amplitude appeared during hinge movement (Fig. 14, B and D) and the closing phase of chewing (Fig. 14E). The amplitude was higher during the opening phase of chewing. The EMG patterns of the str-SUP and str-INF were very similar to each other, especially during chewing: lower amplitude in the closing phase and higher amplitude in the opening phase. The EMG amplitude of the str-INF increased in parallel with the development of biting force (Fig. 14F). This EMG record of the str-INF is the same as shown in the Fig. 5.

**CL>OP TYPE OF STR-SUP.** The tonic background activity of the str-SUP in the ICP persisted during jaw opening (Fig. 15A) as well as the opening phase of chewing (Fig. 15C). During hinge movement, however, the activity of the str-SUP disappeared completely at a relatively small jaw opening (Fig. 15B). The pattern of EMG of the str-INF of this case was basically typical of the OP type.

**OP>CL, CL>OP, AND CL TYPES OF STR-INF.** EMG activities of the three types of the str-INFs, OP>CL, CL>OP, and CL types, were basically similar to those of the corresponding types of the str-SUPs, OP>CL, CL>OP, and CL types, respectively.

**TABLE 4. Correlation coefficients between EMGs and the jaw movements parameters of the three subjects during stepwise habitual movement as shown in Figs. 12 and 13**

<table>
<thead>
<tr>
<th>Subject</th>
<th>OP</th>
<th>CL</th>
<th>OP</th>
<th>CL</th>
<th>OP</th>
<th>CL</th>
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<tbody>
<tr>
<td>INF</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.98</td>
<td>0.99</td>
<td>0.97</td>
<td>0.98</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
<td>2</td>
<td>0.88</td>
<td>0.91</td>
<td>0.65</td>
<td>0.85</td>
<td>0.87</td>
<td>0.88</td>
</tr>
<tr>
<td>3</td>
<td>0.95</td>
<td>0.99</td>
<td>0.90</td>
<td>0.99</td>
<td>0.94</td>
<td>0.99</td>
</tr>
<tr>
<td>SUP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-0.87</td>
<td>-0.97</td>
<td>-0.87</td>
<td>-0.74</td>
<td>-0.85</td>
<td>-0.97</td>
</tr>
<tr>
<td>2</td>
<td>-0.94</td>
<td>-0.86</td>
<td>-0.90</td>
<td>-0.93</td>
<td>-0.95</td>
<td>-0.64</td>
</tr>
<tr>
<td>3</td>
<td>-0.91</td>
<td>-0.76</td>
<td>-0.77</td>
<td>-0.75</td>
<td>-0.91</td>
<td>-0.73</td>
</tr>
</tbody>
</table>

All of the correlation coefficients (Pearson’s) are statistically significant; \( P < 0.001 \).
extremely different among the three types of str-SUP, whereas the relations of the EMG amplitude to the biting force and the interincisal distance in the range of 0 –10 mm Vi were basically similar. The properties that were commonly observed among three types of str-SUP were the background activity in the ICP, earlier development of almost-maximum EMG activity than either MSS or TMP muscles, and inverse relationship between the EMG and Vi in the range of 0 –10 mm Vi. These properties are typical for the str-SUP of the CL type. These results obtained from the intermediate types of EMG strongly suggest that EMG activities of these types, OP CL and CL OP types, can be explained reasonably as a mixture of the two distinct reciprocal EMG activities that are characteristics for the str-SUP of the CL type and for the str-INF of the OP type and that they are not the third and fourth groups.

Stretch reflex

When the mandible was pressed on the menton posteriorly by the experimenter, the condyle usually was displaced passively 1–2 mm in posterosuperior direction. Such passively induced movement of the condyle results in longitudinal stretching of the SUP muscle fibers. Figure 17 shows a stretch reflex-like response elicited in the str-SUP classified as CL type. Such sustained posterior pressing of the jaw evoked vigorous reflex EMG response in the str-SUP.
MANDIBULAR CONDYLE MOVEMENT AND EMGs OF THE LPT

FIG. 15. EMG activities of the str-SUP of CL>OP type and str-INF of the OP type during habitual (A), hinge (B) jaw-opening, -closing, and chewing (C) movements. Several small strokes of intercuspal tapping movements were performed between the standard tasks and movements (in A and B) to determine the ICP (- - -) of the incisor points. Abbreviations as in Fig. 3.

Mechanical tap stimulation of the menton evoked reflex responses in the str-SUP after a latency of 7.7 ± 1.1 ms (mean ± SD, n = 4). The latency of the masseter and temporalis muscles evoked in the same manner was 8.0 ± 1.4 and 7.6 ± 0.7 ms, respectively. Figure 18 shows the responses of the str-SUP of the CL type. The averaged reflex responses were of highest amplitude in the ICP (Fig. 18), became smaller at the moderate jaw opening (Fig. 18, B and C), and disappeared at the maximally open position (Fig. 18D).

No response was found in the str-INF of OP type in response to either sustained passive jaw retrusion or tap stimulation of the menton.

Biomechanics of the temporomandibular joint

The condylar head is capped with the articular capsule and disk. The disk has two thick parts (anterior and posterior bands) and a thinner part (intermediate band) lying between them, like a saddle. These bands converge to the medial and lateral poles of the condyle and make ligamental attachment. Although the SUP and INF heads are closer to each other and finally fused at the region near the condylar neck, the SUP muscle fibers are inserted into mainly the anterior band of the disk and the INF is inserted into the condylar neck (Fig. 19E) (Heylings et al. 1995; Honée 1972; Ress 1954; Schmolke 1994; Wilkinson 1989). The mechanical effect of the contraction of each head on the positional relationship of the disk to the condyle was quite different (Fig. 19). Because the articular disk was rigidly attached to the condyle (Fig. 19, E and F), forward pulling of the muscle belly of the SUP could not produce any more anterior displacement of the disk, which was at mandibular rest position, but resulted in fixing the disk onto the condyle (Fig. 19C). When the pulled SUP muscle belly was released, the disk could roll back around the axis across the mediolateral poles of the condyle (Fig. 19). It should be noted that forward pulling of the INF muscle belly had no appreciable effect on this backward rotational movement of the disk (Fig. 19, B and D).

DISCUSSION

Although we elaborated the technique for placement of electrodes precisely in each head of the LPT, the EMG patterns of each head of the LPT were not always reproducible even in the same subject when examined repeatedly on different days. These EMG activities have been classified into four types based on their EMG pattern during jaw-opening, -closing movements. We carefully examined EMG activities of all types in relation to jaw movements and biting force. The results indicate that there must be functionally reciprocal components in the LPT. One is a jaw-closing component, and the other is a jaw-opening component. Such functionally reciprocal activities typically were found in the CL type and OP type, respectively. The CL type was recorded from the topographical SUP region with high incidence (59%) and the OP type from the INF region (61%). Accordingly we assume that the CL type is representative of the SUP muscle activity and the OP type is that of the INF muscle activity. In addition, we also have shown that EMG activities of other types, OP>CL and CL>OP types, can reasonably be explained by a mixture of the two different reciprocal EMG activities that are characteristics for the SUP of the CL type and for the INF of the OP type. It is not likely that the individual difference is responsible for the OP>CL and CL>OP types because occurrence of these types of EMG activity was not restricted to specific subjects. The fact that these various EMG patterns were found even in the same subject also supports this notion. Circumstantial evidence strongly suggests that OP>CL and CL>OP types were recorded by the electrodes inappropriately positioned in the LPT. Consequently it is conceivable that EMG variation depends critically on the position of the electrodes in the LPT, as originally claimed by McNamara (1973), rather than on the anatomic complex, multipinnate muscle structure of the LPT.

Miller et al. (1982) reported in the monkey that the INF was active during jaw opening in the range 8–10 mm Vi, whereas the SUP was active during jaw closing in the range 15 mm Vi. They did not monitor jaw movements, and the EMG recording...
was made under the condition in which the movement velocity could affect the onset point of the LPT. In a number of previous studies on the EMG of the LPT, neither the position of the condyle nor biting force was controlled sufficiently. Particularly was the condyle position ignored. The present study has analyzed the EMG activities of the two heads of the LPT in relation to the mandibular and condylar movements by using stepwise changes in the jaw position to exclude the influences of velocity of jaw movements. The reconstruction of the complex condylar movement in the form of CCM has enabled us to analyze which factor of the displacement or rotation of the condyle is related primarily to the EMG activity.

Mechanisms for stabilizing the TMJ against biting force

We found that the str-SUP is always coactive with the jaw-closing muscles during almost every kind of jaw movement and task. However, the str-SUP is clearly different from the closing muscles with respect to the biting force and unique in the presence of substantial background activity as much as 30% of the maximum in the ICP without teeth clenching. This background activity persisted until interincisal distance extended beyond 10 mm. Although the presence of background activity of the SUP was reported by Juniper (1981) in man, Sessle and Gurza (1982) in monkeys, and Kawamura et al. (1968) in cats, its functional significance has remained to be clarified.

Grant (1973) has calculated the mechanical moment of the SUP. In his study, jaw movements were expressed as a series of successive rotations of the mandible on the axis of which position changed continuously. The position of the instantaneous axis of rotation was not always limited in the condyle but shifted into the ramus of the mandible (Chen 1998; Grant 1973; Koolstra and van Eijden 1997). Grant (1973) reported that the human SUP has a mechanical moment in the closing direction with respect to the instantaneous axis at rest position. As confirmed in the dissected TMJ of cadavers in the present study, the contraction of the SUP fixes the disk to the condyle via the medial and lateral ligamental attachments and works to pull these structures as a whole. Development of activity of the str-SUP in parallel with the biting force level suggests that the str-SUP stabilizes the condyle in the temporomandibular fossa with its tonic background activity during the ICP. The str-SUP develops a nearly maximum activity at relatively low biting-force levels. As a result, the condyle is pressed strongly against the posterior slope of the articular eminence and can resist the force pulling the condyle posteriorly, which is generated by the jaw-closing muscles, particularly by the temporalis muscle. This notion is strongly supported by Osborn (1995), who examined the lateral pterygoid muscle activities at the maximum biting force by means of computer simulation. To set the preparatory stage of the TMJ against the biting force, it is reasonable that the str-SUP reaches its maximum activity earlier than other closing muscles.

In combination with such voluntary muscle activity of the str-SUP, the stretch reflex-like response can contribute to maintaining the condyle in the normal position against the
force that pulls the condyle posterior during biting and chewing. This is also the case during lateral jaw movements in which the str-SUP and temporalis muscles ipsilateral to the movement direction and the contralateral str-INF and masseter muscles all act as synergists for horizontal rotation of the mandible. The vector of these muscular contraction forces, particularly of the contralateral str-INF and ipsilateral temporalis muscles, functions to displace the ipsilateral condyle laterally and posteriorly. However, during horizontal rotation of the mandible, the str-SUP is so strongly active that the ipsilateral condyle cannot move and stays in the temporomandibular fossa to serve as the axis of horizontal rotation of the mandible (Fig. 20A). It is most likely that the stretch reflex-like response of the str-SUP functions to automatically stabilize the ipsilateral condyle in the temporomandibular fossa during lateral jaw movements, chewing, and biting. Thus the str-SUP and temporalis muscles can be regarded as antagonists in spite of their synchronous activation during various kinds of jaw movements.

Functions of the str-SUP and str-INF in controlling the condylar movement

It was found that there is a considerable constancy in terms of the range of jaw position when the str-SUP and str-INF are active. The working range of the str-SUP was between 0 and 3–5 mm Ac, and for the str-INF, Ac²–5 mm. The str-SUP was related inversely with Ac taking a course like a hyperbolic curve, whereas...
the str-INF correlated with Ac rather linearly. However, the type of jaw movement occurring in that Ac range was widely different among subjects and movement phases even in the same subject. In the subjects whose final stage of closing movement was performed mainly by rotation, the onset point of the str-SUP and the offset point of the str-INF on Vi axis were distant from ICP. In the subjects with a displacement-dominant type of closing, these two points were close to ICP.

The condylar movement requires coordination with that of the articular disk. As revealed by examining the biomechanical aspects of the SUP, INF, and articular disk in the present study, the movement of the articular disk involves rotation on the axis across the mediolateral poles of the condyle. When the jaw opens, the disk rotates backward around the condyle. Such positional change of the disk relative to the condyle is enabled by relaxation of the str-SUP that is tonically active to fasten the disk onto the condyle in the ICP. Although it is difficult to describe quantitatively the relative positional changes of the disk and the condyle, the movements of both the disk and condyle are rotation only, but in the opposite direction in the hinge movements during Int-Ret JM. During this rotation, the str-SUP changes its activity linearly and in inverse proportion to RaC. This suggests that the str-SUP does not work to change Ac but acts to regulate the angular relationship between the condyle and disk within its working range between 0 and 3–5 mm Ac. During Int-Pro JM, however, displacement of the condyle occurs in addition to its rotation. Although the positional change of the disk associated with displacement of the condyle could not be directly measured in this study, it is likely that displacement of the condyle is a principal factor causing the nonlinearity of the EMG_{SUP}/RaC relation. It can reasonably be concluded that functional significance of the str-SUP for the condylar movement is to control the relative positional relationship between the disk and condyle, whereas the position of the disk in relation to the maxilla, not to the condyle, is controlled indirectly by the str-INF because the disk is attached to the condyle by tendinous ligaments (Ress 1954; Schmolke 1994; Wilkinson 1989).

Consequently, the functions of the two heads of the LPT in controlling the movements of the condyle and disk can be summarized as follows. For the jaw to open, the str-SUP has to be relaxed enabling the disk to rotate backward around the condyle. After rotation of the disk, the condyle can rotate around the mediolateral axis (Fig. 20Bb). In this situation activation of the str-INF can move the condyle anteriorly (Fig. 20Bc). At the maximal open position, the str-SUP is completely relaxed and the str-INF is maximally active so that both the condyle and disk are located in the anterior-most position in relation to the maxilla. In this moment, however, the disk is located in the posterior-most position in relation to the condyle (Fig. 20Bd). During jaw-closing movements, the str-INF decreases its activity to allow the condyle to return into the temporomandibular fossa, whereas the str-SUP becomes active to change the position of the disk relative to the condyle.

**Stretch reflex**

The tap stimulation of the menton has evoked stretch reflex-like responses in the str-SUP but not in the str-INF. The latency was comparable to that of the monosynaptic stretch reflex response of the masseter and temporalis muscles (Goldberg 1971). The inverse relationship between the interincisal distance and the amplitude of the reflex responses evoked in the str-SUP, masseter, and temporalis muscles suggests that these muscles belong to the same group, i.e., jaw-closing muscles. Stretch reflex-like responses of the LPT have been observed in cats (Kawamura et al. 1968) and humans (Widmalm et al. 1987). In the present experiment, the amplitude of the EMG of the str-SUP increased in parallel with the posterior and upward displacement of the condyle and disk during passive and tonic jaw retrusions (Fig. 17). The condylar movement in these directions results in stretching the LPT muscle fibers longitudinally. The presence of muscle spindles in the LPT, though without specifying the head of the LPT, was shown anatomically in humans (Gill 1971; Honée 1966; Rakhaway et al. 1971) and monkeys (Karlsen 1969). Kubota and Masegi (1977) reported topographical details of the location of the spindle in the human LPT. They reported that muscle spindles were present in the SUP as well as INF. There is also electrophysiological evidence that the trigeminal mesencephalic neurons innervating the muscle spindles in the LPT make monosynaptic excitatory synaptic linkage with the LPT motoneurons in the guinea pig (Nozaki et al. 1984, 1985). Accordingly, the stretch reflex-like responses elicited in the human str-SUP in the present study are probably the monosynaptic reflexes triggered by muscle spindles in the LPT.

**Anterior dislocation of the articular disk in TMJ disorders**

In many cases of TMJ disorders, the condyle is shifted to the posterior-most position in the temporomandibular fossa, and
the posterior band of the disk is dislocated to the front of the condyle due to elongation of the ligaments of the articular capsule connecting the disk to the condyle (Wilkinson 1989). It seems impossible that the disk moves anteriorly independently of the condyle because the disk is attached rigidly to the medial and lateral poles of the condyle by tendinous ligaments (Ress 1954; Schmolke 1994). Therefore the force that continuously pulls the disk anteriorly must be the major cause of the elongation of those ligaments in the patients with TMJ disorders.

The force responsible for the abnormally anterior displacement of the disk is generated most probably by the str-SUP because it has a rigid mechanical connection with the disk and can contract by stretch reflex. Posterior displacement of the condyle from the normal position in the temporomandibular fossa would create in front of the condyle a space into which the posterior band of the disk slips. At the same time the stretch reflex of the str-SUP evoked by posterior displacement of the condyle will increase the tension of the muscle and facilitate further anterior displacement of the disk.

A therapeutic appliance, which often is called an “occlusal splint,” is used for patients with TMJ disorders. This type of appliance inevitably increases interincisal distance. The subtype of “occlusal splint” that forces the mandible in the position anterior to the habitual position has usually better clinical effects. On the basis of the characteristics of the str-SUP, it is obvious that the increase in Vi and anterior positioning of the condyle results in decreasing the str-SUP muscle activity.

It is most likely that the probable direct cause of anterior dislocation of the disk in TMJ disorders is an abnormal hyperactivity of the str-SUP produced by posterior dislocation of the condyle.

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