Modulation of jaw tapping force in response to unexpected changes in vertical jaw position

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Purpose: The purpose of the present study is to investigate the modulation of jaw tapping force to unexpected changes in the occlusal vertical dimension.
Materials and Methods: A device to change the vertical jaw position at tapping (VJPT) was applied to eight healthy subjects, and they were instructed to perform rhythmical jaw tapping movements. The VJPT was increased or reduced during repeated tapping, and tapping frequency (Hz), closing distance (mm), peak tapping force (N), and time to peak force (ms) were examined.
Results: The closing distance was smaller immediately after an increase than after a decrease in the VJPT. The peak tapping force was greater in the first trial than that in the second or third trial after an increase in the VJPT, but it was smaller in the first trial than in the second trial after a decrease in the VJPT. The time to peak force decreased in the second trial compared with the first trial after a decrease in the VJPT, but no difference was observed after an increase in the VJPT.
Conclusion: The results indicate that, when the vertical dimension is changed unexpectively, the jaw tapping force is likely to change markedly immediately without changing the maximum jaw gape. This modulation appears to be almost completed in first two to three trials after a change in VJPT, and a feedback and a feed-forward mechanisms are considered to be involved in it. **(Int Chin J Dent 2006; 6: 21-28.)**
Key Words: anticipation, force, jaw tapping movement, modulation, vertical jaw position.

Introduction

The food varies widely in volume and hardness, and the physical characteristics of food change during mastication. Moreover, the intra-oral environment during mastication is changed by various factors, e.g., the presence of a foreign substance in food, the use of a new denture and so on. The ability to appropriately modulate masticatory movements to these changes in the intra-oral environment is essential for maintaining the health of the chewing system. A steel ball or a thin plastic strip placed between the upper and lower teeth during cortically induced rhythmic jaw movements (CRJMs) in an anesthetized rabbit increases the masseteric electromyographic activity (EMG)[1-5] and the masticatory force.[3-5] This faciliatory masseteric muscle response (FMR) is hardness-dependent, and the relevant feedback and feed-forward mechanisms are considered to be involved in its modulation.[3,5]

In humans, also, it has been suggested that the masseteric EMG is increased by loading with an external force simulating food resistance, that this additional muscle activity (AMA) consists of the peripherally induced AMA and the anticipatory AMA, and that the former overcomes the resistance of food boluses different in hardness and volume while the latter modulates the closing movement by food contact.[6-11] Suenaga et al.[12] analyzed voluntary modulation of the tapping force during repetitive lower jaw tapping movement under visual biofeedback and showed that modulation becomes more dependent on feedback information as the target force is greater.

All these reports kinematically support that the jaw muscle force is modulated appropriately during mastication. If such modulation is a mechanism for the protection of the masticatory system from excessive mechanical stress generated by changes in the intra-oral environment, the modulation is expected to be completed as rapidly as possible in a manner dependent on the direction of the stress load (increase or decrease). However, details of this modulation largely remain unclear. Particularly, responses to a decrease in the occlusal height are scarcely known. The objective of this study was to analyze when and how the jaw-closing force is adjusted when the vertical dimension of tapping is changed unexpectedly during repetitive lower jaw tapping movement.

Materials and Methods

Examinees and experimental device

The examinees were eight healthy adults (two females and six males; 22 to 40 years old; average 26.6 years old) with natural normal dentition and without any subjective or objective stomatognathic functional abnormalities who participated in the study on the basis of informed consent. The study protocol was approved by the Nagasaki University Ethics Review Committee (No. 09, May 2001).

Fig. 1 shows an experimental device to change the vertical jaw position at tapping (VJPT). The device (Fig. 1a) equipped with a stepping motor (M1524-V-24-590, Arsape Co. Inc., La Chaux-de-Fonds, Switzerland) was attached to the upper metal frame, while a screw pin of about 5 mm in height was attached to the lower metal frame in such a manner that the tip of the pin would contact the disc surface perpendicularly in the center of the segment of the tapping disc located most anteriorly (Fig. 1b).

The rotation speed of the stepping motor was 60˚/15 ms, and the motor was programmed by personal computer (Vaio PCG-F14, Sony, Tokyo, Japan) to rotate clockwise and counter-clockwise in 60˚ steps with trigger pulse generated at 30% level of the average jaw gape. A tapping disc of 20 mm in diameter was attached to the tip of the motor axle. The surface of the disc was divided into six equal fan-shaped segments at a central angle of 60˚, and the thickness of the six segments was changed by 0.5 mm (Fig. 1c; H0, H0.5, H1.0, H1.5, H2.0, and H2.5 from the thinnest to the thickest). The VJPT could be changed by rotating this disc by $60˚\times\alpha$ ($\alpha=\pm1$-6). The upper metal frame and this disc were fixed in such a manner that the surface of the disc would be as parallel to the occlusal plane as possible and that the center of the fan-shaped segment located in the most anterior position would be at the intersection of the line between the centers of the occlusal surfaces of the maxillary first molar teeth and the median line (Fig. 1d).

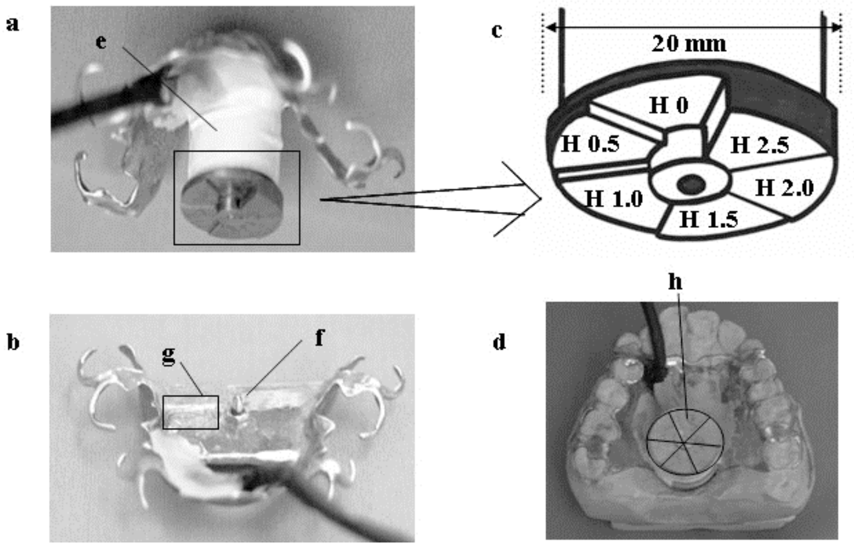


Fig. 1.
A device to change vertical jaw position at tapping (VJPT).
a, Upper metal frame with a device to change vertical jaw position at tapping;
b, Lower metal frame with screw pin;
c, Tapping disc;
d, Occlusal view of upper model with the upper metal frame;
e, Stepping motor;
f, Screw pin;
g, Strain gauge*; and
h, Segment to be tapped.

*KFG-02-C1-16, Kyowa Electronic Instruments Co., Inc., Tokyo, Japan.

Exercise task and experimental conditions

Before recording the data, upper and lower metal frames were applied to the subjects. A metronome was clicked at 1.0 Hz, and the subjects were instructed to repeat rhythmical light lower jaw tapping to these clicks and to continue tapping even if they felt vertical changes in the lower jaw position during the maneuver. The metronome was stopped during data recording. The subjects were in the upright sitting posture with no restriction of head movement.

In the experiment, a session consisting of tapping repeated 50 or more times was performed five times. Each session was divided into five sub-sections (SS; SS0-SS4) each consisting of seven to 13 tappings (Fig. 2; upper and middle rows). The VJPT was increased or reduced by the same distance by rotating the disc at each transition of SS, and this maneuver was repeated two times in each session (Fig. 2; lower row). The distance of change in the VJPT in a session was one of the five differences in the disc thickness (0.5, 1.0, 1.5, 2.0, and 2.5 mm), and it was selected in a random order. In addition, during each interval between the sessions, dummy tasks different in the number of tappings, number of sub-sections, and number of trials in one sub-section were performed, and a rest of at least 5 minutes was interposed between the sessions. Before the beginning of each session, the subjects were instructed to maintain the state with the mouth closed at VJPT H2.5 for less than 10 s and to perform repetitive lower jaw tapping with a starting signal.

Measurements and statistical analyses

The tapping force was recorded using a strain gauge (KFR-02-C1-16, Kyowa Electronic Instruments Co. Inc., Tokyo, Japan)[12] (Fig. 1g), and the lower jaw movements were recorded using a mandibular kinesiograph (MKG) (K6, Myotronics-Noromed, Inc., Tukwila, WA, USA). To prevent the examinees from anticipating changes in the VJPT according to slight rotation sounds or vibration caused by the motor, the disc was rotated in all trials (Fig. 3). After the end of each session, each subject was asked whether he/she perceived changes in the VJPT during the session.

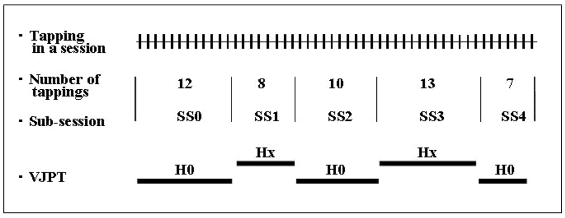


Fig. 2. Road map of an experimental session.
Hx, Height of VJPT;
X, 0.5, 1.0, 1.5, 2.0, and 2.5 mm.

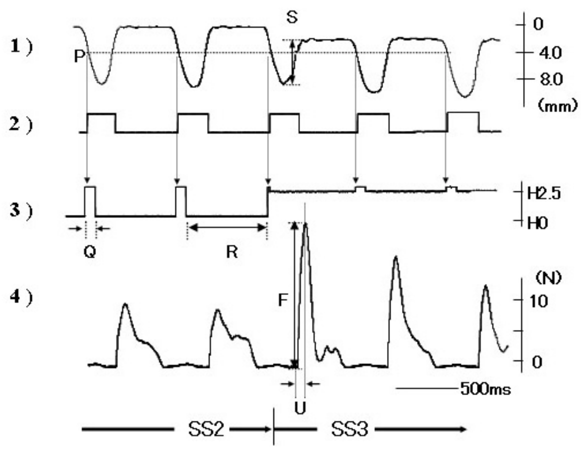


Fig. 3. An example of a raw record, data recorded before and after the height change was 2.5 mm (right).
1) Jaw movement; 2) Trigger pulse; 3) Thickness of tapping disc (rotary motion of tapping disc); and 4) Tapping force.
P, Threshold level of the trigger pulse; Q, Rotary motion period of the tapping table; R, Halt period of the tapping table; S, Closing distance (mm); F, Peak tapping force (N); and U, Time to peak force (ms).

The tapping frequency, closing distance (Fig. 3; S), peak tapping force (Fig. 3; F), and the time from the contact of the screw pin with the disc to the peak tapping force (time to peak force) (Fig. 3; U) were measured using a waveform analysis software (AcqKowledge, Biopac System Co. Inc., Tokyo, Japan). The data were analyzed statistically by four-way analysis of variance (ANOVA) with the main factors of examinees, VJPTs, SSs, and tapping numbers (TNs). When ANOVA showed a significant difference ($p<0.05$), the Fisher's least significant difference method was used for multiple comparisons.

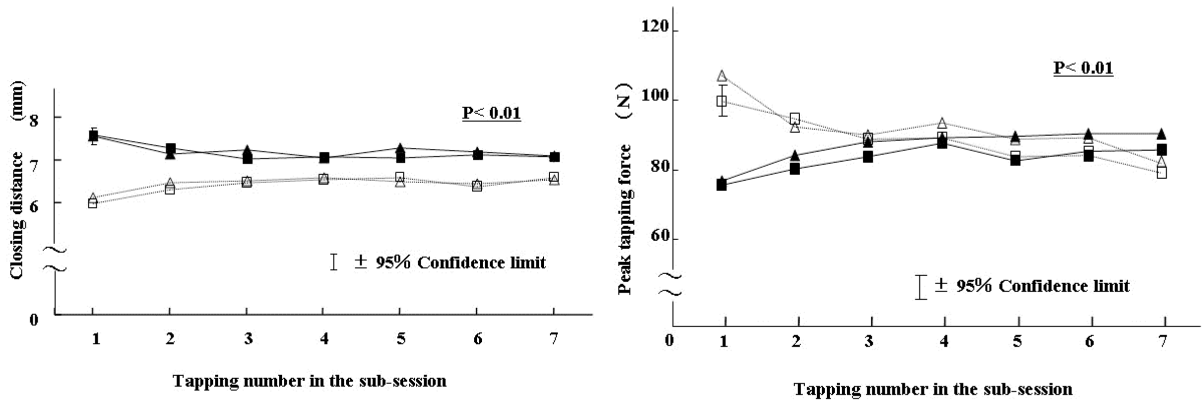
Results

Changes in the VJPT and tapping frequency

The VJPT at the contact of the screw pin with segment H0 of the tapping disc was a mean of 5.06±1.15 mm higher (maximum 6.5 mm, minimum 4.0 mm) than the occlusal vertical dimension in the intercuspal position. During the tapping maneuver, no trial did the tip of the screw pin miss the target segment of the disc. When the VJPT was changed by 0.5 mm (H0.5), the change was not recognized by five of the eight subjects. Two of them also did not recognize a change in the VJPT of 1 mm (H1.0). All subjects answered that they recognized changes in the VJPT when they were 1.5 mm or greater. The tapping frequency did not differ within the examinees, VJPTs, SSs, and TNs ($p>0.05$), and its mean was 1.09±0.13 Hz.

Closing distance

The factors that significantly affected the closing distance were the main factor SSs ($p<0.01$) and interaction between SSs and TNs ($p<0.0001$) other than components related to the examinees. Fig. 4 shows the effect of this interaction. The mean closing distance in the sub-sessions with an increase in the VJPT (SS1 and SS3) was 6.43±0.17 mm, which was significantly smaller than 7.22±0.18 mm in the sub-sessions with a decrease in the VJPT (SS2 and SS4). The closing distance increased gradually up to a trial number of three in the sub-sessions with an increase in the VJPT (SS1 and SS3) but gradually decreased in the sub-sessions with a decrease in the VJPT (SS2 and SS4) ($p<0.0001$). These fluctuations according to the number of trials become to be less after the third trial in all sub-sessions, and the closing distance was stabilized.



Figs. 4 and 5. Effect of interaction SSs vs. TNs on the closing distance (left) and peak tapping force (right). Open squares, sub-session 1 (SS1); Solid squares, sub-session 2 (SS2); Open triangles, sub-session 3 (SS3); and Solid triangle, sub-session 4 (SS4).

Peak tapping force

The factors that significantly affected the peak tapping force were the two main factors (SSs and TNs) and their interaction (SSs vs. TNs) ($p<0.01$) other than the components related to the examinees. Fig. 5 shows the effect of this interaction. The mean and SD of the peak tapping force calculated from the data shown in Fig. 5 were 87.65±6.61 N. The peak tapping forces of the first trials in the sub-sessions with an increase in the VJPT (99.93 N in SS1 and 106.95 N in SS3) were significantly greater than those of the second and third trials (88.71 N and 90.04 N). In the sub-sessions with a decrease in the VJPT (SS2 and SS4), the peak tapping forces of the first trials (75.47 N and 76.88 N) were smaller than those of the second trials (80.23 N and 83.97 N) (p<0.001). After the third trial, the peak tapping force changed slightly with the tapping number in all sub-sessions, but little difference was observed among the sub-sessions.

Time to peak force

The factors that significantly affected the time to peak force were the two main factors (SS and TN) and their interaction (SSs vs. TNs) other than the components related to the examinees (p<0.01) similarly to the peak tapping force (Fig. 6). In the sub-sessions with a decrease in the VJPT (SS2 and SS4), the times to peak in the second trials (137 ms and 157 ms) were significantly smaller than those in the first trials (176 ms and 211 ms) (p<0.001). However, in the sub-sessions with an increase in the VJPT (SS1 and SS3), no significant difference was observed between the first trial and the second or later trials, but the time to peak force of the seventh trial of SS3 (152 ms) was significantly longer than the value of the sixth (123 ms) or an earlier trial (p<0.0001). No effect of an increase or decrease in the VJPT was observed in the time to peak force in the seventh trial.

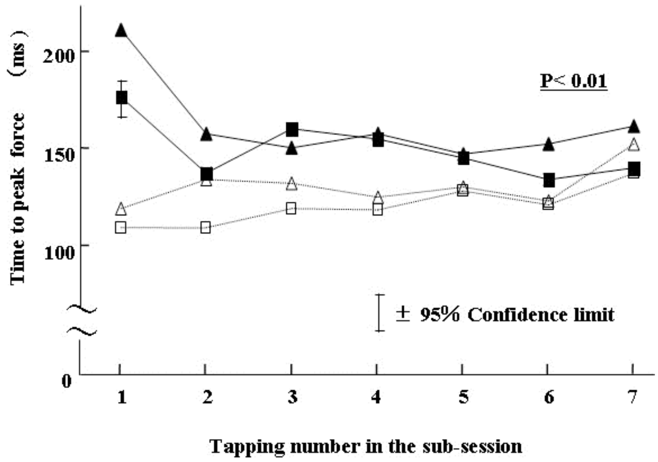


Fig. 6.
Effect of interaction SSs vs. TNs on the time to peak force.
Open squares, sub-session 1 (SS1);
Solid squares, sub-session 2 (SS2);
Open triangles, sub-session 3 (SS3); and
Solid triangle, sub-session 4 (SS4).

Discussion

Experimental design and execution of the tasks

The positional deviation of the tapping point is reported to be minimum when the tapping frequency is 1.0 Hz.[13] In this experiment, the subjects were instructed to perform light tapping at a frequency of about 1.0 Hz. The subjects actually performed tapping at a frequency of 1.09±0.13 Hz, and all tapping points converged on the intended segments of the disc. Human periodontal receptors can recognize the presence of a bite substance with a thickness of 20 μm,[14,15] and the discrimination threshold of thickness in biting a metal wire 5 mm in diameter in persons with natural normal dentition is reported to be 0.2 mm.[16] Also, the periodontal ligaments, temporomandibular mechanoreceptors, and muscle spindles of the jaw-closing muscles are considered to be involved in the position sense of the lower jaw.[17] In this study, when the change in the VJPT was 0.5 mm (H0.5), five of the eight subjects failed to recognize the change. These results indicate a decrease in the thickness discrimination ability in biting, and this decrease is considered to have been related to the lower jaw position in the application of the device, which was about 5 mm higher than the intercuspal position, a sensory decline or confusion of the periodontal ligaments due to splints, and differences in the motor task.

Changes in the closing distance

The mean distance of open-close jaw movement during tapping directed by acoustic signals at fixed 1.3 Hz cycles which was the mean frequency of arbitrary lower jaw tapping and that during random interval tapping were reported to be 8.1 mm and 5.5 mm, respectively.[18] The closing distance observed in this study fell in this range (mean; 6.83±0.44 mm). The maximum jaw-opening distance during chewing is considered to be related to the physical characteristics of food.[19-22] Therefore, without anticipation of the timing of changes in the VJPT, the closing distance naturally decreases immediately after heightening the VJPT (Fig. 4; SS1 and SS3) and increases immediately after lowing the VJPT (Fig. 4; SS2 and SS4). Also, the open-close jaw movement during repeated lower jaw tapping is reported to be nearly fixed.[18] To maintain this constancy under the condition of our experiment, the subjects must recognize the distance and direction of the change in the VJPT in the first trial after the change in the disc thickness and adjust the opening distance in the subsequent trials, i.e. decrease it after an increase in the thickness and increase it after a decrease in the thickness. From this point of view, the changes in the closing distance dependent on the direction of the change in the VJPT in the second and subsequent trials after the change are appropriate and interesting.

Modulation of the tapping force

The peak tapping force and time to peak force are variables that represent phenomena after the contact of the screw pin with the tapping disc in closing of the mouth and can be adjusted in the first trial after a change in the VJPT. When the thickness of the tapping disc was increased during repeated tapping (SS1 and SS3), the tapping force increased in the first trial after the change but decreased thereafter with increases in the trial number (Fig. 5). In contrast, when the thickness of the tapping disc was reduced (SS2 and SS4), the tapping force in the first trial after the change was smaller than that after an increase in the thickness (SS1 and SS3), and increased with the trial number to the third trial. The peak tapping forces were less-fluctuated in the third and subsequent trials after both an increase and a decrease in the disc thickness, and no clear difference was observed between the trials after an increase and those after a decrease (Fig. 5).

When resistance-simulating food is applied to the human lower jaw during rhythmical open-close movements, additional muscle activity (AMA) consisting of sensory-induced responses and anticipatory-induced responses is known to be induced in the jaw-closing muscle activities immediately after the load application.[6-11] Also, Abbink et al.[10] reported that sensory-induced responses disappeared immediately after removal of the load and that anticipatory-induced responses disappeared in the second and subsequent trials after removal. While they evaluated electromyographic activities (EMG) of jaw-closing muscles instead of the biting force, their observation that the tapping force was adjusted to a fixed level within two to three trials after a change in the VJPT was in agreement with our findings. In our study, motor modulations reported by Abbink et al., i.e., shifts of sensory-induced responses and anticipatory-induced responses, are considered to have occurred within the first second and third trials. This interpretation is basically in agreement with the opinion that the masticatory and the motor system copes with disturbances loaded during repetitive tasks using preprogrammed movements[3,5,8,9,23] based on a peripheral feedback mechanism and a feed-forward mechanism.

The closing movement during repeated lower jaw tapping decelerates about 10 ms before the tooth contact.[18] This suggests that the contact between the tapping disc and the screw pin occurs during deceleration of the closing movement when the VJPT is set at a low level (SS2 and SS4 in this study). In this case, the tapping force in the first trial is expected to be smaller than the target value of each examinee, as it was in SS2 and SS4 (Fig. 5). If a examinee faithfully performing the task recognizes that the tapping force is smaller than the target value, the examinee would subsequently modulate it in the same action (the first trial) by making it closer to the target value.[3,5] Moreover, the information obtained during the trial would be used for smooth and faithful execution of the following trials.[24,25]

If this is the case, the time to peak force is considered to be prolonged in such a situation. In fact, the mean time to peak force in the third to seventh trials after a change in the VJPT was about 130 ms, but that in the first trial was prolonged by about 50-90 ms to 180 ms in SS2 and 220 ms in SS4 (Fig. 6). The time to peak force during repetitive lower jaw tapping under visual biofeedback (voluntary modulation) is reported to be 110-160 ms,[26] thus modulation of the tapping force within the time to peak force observed in this study (180-220 ms) appears to be sufficiently possible. The tapping force was relatively stable in the third and subsequent trials, and little effect of an increase or a decrease in the VJPT was observed, indicating appropriate and rapid modulation of the masticatory system.

In conclusions, we found that, when the vertical jaw position is changed during repetitive lower jaw tapping, the tapping force is adjusted in a direction-dependent manner and that modulation of the tapping force is completed within two to three trials after the change. This direction-dependedness of the modulation of the tapping force and its completion in early trials are considered to be necessary for faithful execution of the task and protection of masticatory motor system.

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