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Changes in Load Both on Working and Balancing Side Temporomandibular Joint During Steady Unilateral Chewing in a Japanese Monkey

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To obtain a definite answer to a question when the maximum load on the temporomandibular joint (TMJ) occurres during each masticatory cycle, the load on the TMJ and EMG activities of bilateral masseter muscles in a Japanese monkey during mastication of some pieces of sweet potato were simultaneously measured. A micropressure sensor, which consisted of hydroxyapatite and lead zirconate titanate ceramics, was implanted on the antero-superior surface of the left condylar head of the monkey. The relationship between output potential of the sensor and EMG activities showed that the maximum load of each cycle occurred during the motionless period both of working and balancing side masseter EMGs. The mastication phase analysis showed that mean duration of Phase-2, which was the duration between the points from the initiation of inactive of the working side masseter EMG to the maximum load occurred, was 45.3 msec for the left side chewing and 55.3 msec for the right side chewing. It was also found that the duration of Phase-2 was almost constant irrespective of the period of each chewing cycle, and that the duration of Phase-2 for the left side chewing (working side TMJ) was less variable than those for right side chewing (balancing side TMJ). From these results it was concluded that the maximum load on the antero-superior surface of the condylar head of the monkey during steady unilateral chewing occurs at the end of occlusal phase, and the duration of Phase-2 is considered to be the contact duration of teeth in the occlusal phase.

Key words : Biomechanics, TMJ loading, EMG activity

INTRODUCTION

The symptoms of the temporomandibular disorders (TMD) such as mouth opening disordes, the noise of temporomandibular joint (TMJ), and the pain of the TMJ and masticatory muscles have been shown to be due to internal derangement of the TMJ accompanied by positional and morphological abnormalities of the articular disc, or osteoarthrosis of the TMJ accompanied by regressive changes such as degeneration of articular cartilage, disc perforation, and degeneration of hard tissue[1~3]. However, concerning the pathogenesis of TMD, the mechanism of its development remains unclear though abnormal loads on the TMJ are considered to be an important factor. To clarify the cause of TMD, the load on the TMJ during jaw movements should be measured.

There have been many studies on the load in TMJ during jaw movements. As the indirect method to estimate the load acting on the TMJ based on the bone strain data, for example, Hylander and Bays[4], Hylander[5] and Hylander, Johonson, and Crompton[6] measured bone strains with rosette strain gauges cemented at the condylar neck during mastication of food in *Macaca facicularis* and *Macaca mulatta*. They deduced the loads on the TMJ from bone strains and concluded that the TMJ was loaded with compressive forces during mastication and that the loads in the TMJ were greater on balancing side

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than on working side. They also concluded that the level of loading on the TMJ during clenching was the highest among levels of loading induced by various mandibular movements

Brehnan et al.[7] and Boyd et al.[8] directly measured the load on the TMJ using a thin piezoelectric foil in *Macaca arctoides* during chewing, incisal biting, and drinking and also during aggressive behaviors. However, the load values obtained in their study corresponded to the total load acting on the entire condylar head surface, ignoring the direction of the load, and therefore, its physical meaning is obscure. Furthermore, since the piezoelectric foil covered the entire condylar head, its surgical invasion may have some influence on jaw movements.

To minimize the influence of surgical invasion of sensor implantation, Inuzuka et al.[9~10] developed a micropressure sensor that consists of a piezoelectric lead zirconate titanate (PZT) and hydroxyapatite (HAP) ceramics. This micropressure sensor was implanted into the antero-superior area of the condylar head of Japanese monkeys, and the load acting on a microarea (3 mm in diameter) of the condylar head during mastication of some pieces of sweet potato was directly measured. The maximum pressure of 0.29 MPa was obtained in maximum mouth opening. Based on marks on the load data obtained by recording synchronized with the maximum mouth opening of each masticatory cycle, the maximum load during each mastication cycle occurred at the end of the mouth opening phase.

Fukushima et al.[11] measured the load on the TMJ in a monkey both on working and balancing side during mastication of some pieces of sweet potato using a similar pressure sensor and speculated that the maximum pressure was induced in the opening phase based on the ratio of the occlusal phase during the mastication period and the EMG activities of the masticatory muscles. However, the phase in which the maximum load occurs in each masticatory cycle remains unclear. To obtain a definite answer to a question when the maximum load occurs during each masticatory cycle, the relationship among jaw movements, the load on the TMJ and electromyographic (EMG) activities of masticatory muscles should be clarified.

In this study, the load on the TMJ and bilateral masseter EMG activities were simultaneously measured during unilateral steady chewing of pieces of sweet potato in a Japanese monkey, and their relationship was evaluated.

MATERIALS AND METHODS

A male Japanese monkey (estimated age : 8 years, weight : 12 kg) without tooth defects or physical abnormalities were used. During the experimental period, no marked changes in weight were observed.

The micropressure sensor used in the measurement of the load on the TMJ was the same type as that Inuzuka et al.[9,10] developed using a piezoelectric PZT disk. This sensor consisted of a piezoelectric PZT disk (PCM-88, Matsushita Electric Industrial Co., Ltd., 3 mm in diameter, 0.15 mm in thickness) in the central layer with electrodes (phosphor bronze, 20 micron in thickness) cemented on its both sides, and HAP disks (3 mm in diameter, 0.5 mm in thickness) covering the entire sensor. Due to polarization treatment in the thickness direction, the PZT disk responds only to the vertical component of the load acting on the HAP cover[12]. The load value obtained from the output of this sensor corresponds to the total load value acting on the HAP cover with a diameter of 3 mm. Assuming a uniform distribution of the load on the sensor, this load value can be converted into pressure. To waterproof the pressure sensor from tissue fluid and blood, the PZT disk and output terminals of the electrodes were sealed with epoxy resin (Barrier D, NMB, USA).

EMG activity was measured using paired, Teflon-insulated, fine wires electrodes, 0.42 mm in diameter with an inter-electrode distance at the insertion site of 10 mm, which was fixed with chemicaly activated resin (Ostron II, GC Dental Products Inc.) and an insertion depth of 10 mm, which was marked in the tip of the hypodermic needles[13,14]. These wires were inserted with the aid of 20-gauge hypodermic needles (0.9 × 38 mm, Terumo Co., Ltd) into the center of the superficial part of the masseter muscle (about 5 cm above the inferior margin of the mandible). A ground electrode was placed in the left femoral muscle.

A pressure sensor was implanted only into the left TMJ of the monkey. Anesthesia was induced by intramuscular injection of 10~20 mg/kg ketamine chloride (Ketalar 50, Sankyo Co., Ltd.), and general anesthesia was performed by in travenous injection of 25 mg/kg sodium pentobarbital (Nembutal, Abott). Under local anesthesia with lidocaine chloride (2% Xylocaine for dental use, Fujisawa Pharmaceutical Co., Ltd.) in the left TMJ, a preauricular incision was made in the anterior area of the tragus, and dissection was performed to the condylar head with caution not to injure soft tissue. In the operative field, the condylar head was confirmed, and the surface of the antero-superior area of the condylar head was exposed with adequate attention to the articular disk, and a minimum cavity that allows pressure sensor implantation (3～4 mm in diameter, 1.2～1.5 mm in depth) was formed. The cavity was filled with bone cement (Surgical Simplex, Pfizer Pharmaceutical Inc.), and a pressure sensor was cemented using a cyanoacrylate adhesive (Aron alpha A for body, Sankyo Co., Ltd.) For the prevention of postoperative infection, a synthetic penicillin (Pentcillin for intramuscular injection, Fujisawa Pharmaceutical Co., Ltd.) was intramuscularly injected at a dose of 150 mg/day for 1 week.

From 1 week after operation, the monkey fixed in a monkey chair was fed some pieces of sweet potato (divided into 8 portions, 8～10g each), and the load on the TMJ and EMG activities during mastication were simultaneously measured. Feeding was initiated when the monkey had no food in the cheek pouch and was in a relaxed state confirmed by macroscopic observation. For data recordings and analysis, a multipurpose biological information analysis program (BIMUTAS-II, Kissei Comtec Co., Ltd.) was used. The output potential of the pressure sensor was amplified by a charge amplifier (CAM-001, TSK Inc.), modulated a FM carrier signal and transmitted from a transmitter (ZB-581Z, Nihon Koden Co., Ltd.) to a recevier (ZR-581G, Nihon Koden Co., Ltd.) ouside the animal. The FM signals received were demodulated and sampled by analogue-to-degital converter (ADJ-98, Canopus Co., Ltd.), and stored in hard disk in computer. EMG activity was also transmitted from the transmitter to the receiver and recorded without being amplified by the charge amplifier. All data were sampled at a sampling frequency of 2 kHz. EMG activities recorded were passed through a band-pass filter (50-1,000 Hz), rectified, and analyzed. When loads were calculated from the output potential of the pressure sensor, the output potential was integrated and converted to the load using a calibration curve. According to the method previously reported 9,10), the calibration of the pressure sensor was performed, and a calibration curve was obtained.

RESULTS

In this study, the output potential of the micropressure sensor and the EMG activities of bilateral masseter muscles during unilateral steady chewing of some pieces of sweet potato were simultaneously measured. Shown in Fig. 1 is a typical example of a relationship between the output potential of the pressure sensor and the patterns of EMG activities of bilateral masseter muscles showing stable masticatory rhythm during chewing on the left side. In this output potential of the sensor, the load reduction rate reaches a maximum at point A, and point B represents the initiation of an increase in the load. At point C load increse rate reaches a maximum and at point D an increase in the load changes to a decrease. At this point, the maximum load occurred, and the load reduction rate reaches a maximum again at point E. The output potential of the sensor from point A to point E constitutes one chewing cycle. For mastication phase analysis, three durations were measured from the output potential of the pressure sennsor : Phase-1, the duration from point A to point C, Phase-2, the duration from point C to point D, and Phase-3, the duration from Point D to point E.

The relationship between output potential of

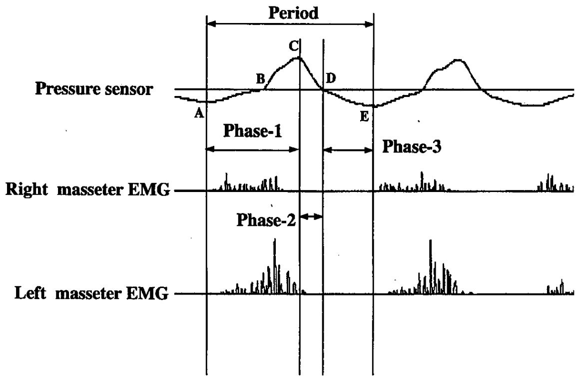

Fig. 1 A typical example of the output potential of the micropressure sensor and bilateral masseter EMGs in a masticatory sequence during left side chewing of a piece of sweet potato.

Table 1 Mastication phase analysis of the data obtained from the output potential of the micropressure sensor implanted on the left TMJ during unilateral steady chewing.

	Left side chewing (working side TMJ) (85 cycles)	Right side chewing (balancing side TMJ) (332 cycles)	p-value
Period (msec)	344.0 (92.5)	342.0 (63.7)	0.846
Phase-1 (msec)	198.2 (86.7)	187.9 (49.1)	0.291
Phase-2 (msec)	45.3 (4.3)	55.7 (8.3)	<0.0001 *
Phase-3 (msec)	100.5 (18.1)	97.4 (28.7)	0.219
Phase-1/Period	0.562 (0.071)	0.547 (0.061)	0.072
Phase-2/Period	0.137 (0.024)	0.168 (0.035)	<0.0001 *
Phase-3/Period	0.301 (0.057)	0.285 (0.062)	0.030 *

( ) S.D.

the sensor and EMG activities showed that the maximum load of each chewing cycle was occurred during the motionless period both of working and balancing side masseter EMGs. It was found that the initiation of EMG activity of masseter muscle on the working side nearly corresponded to point A for most chewing cycles during both left and righrt side chewing. It was also found that the point of the peak amplitude of working side EMG activity corresponded to the point B when the load began to increase.

Table 1 shows the results of mastication phase analysis of the data obtained from the output potential of the micropressure sensor implanted on the antero-superior surface of the left condylar head during unilateral steady chewing. The analysis showed that mean duration of Phase-2, which was the duration between the points from the initiation of inactive of the working side masseter EMG to the maximum load occurred, was 45.3 msec for the left side chewing (wroking side TMJ) and 55.3 msec for the right side chewing (balancing side TMJ), and that the duration of Phase-2 on the working side TMJ was less variable than those on the balancing side TMJ. Form the statistical analysis, it was found that the duration of Phase-2 , the ratio of Phase 2/Period and the ratio of Phase-3/period were smaller on the left side chewing than on the right side chewing with statistically significant. The other statistics were not significantly different between on the working and balancing side TMJ.

Shown in Fig. 2 is the relationship between duration of Phase-1 and period of each chewing cycle during both left and right sides steady chewing. It was found that the relationship between the duration of Phase-1 and period of each chewing cycle was linear irrespective of the side of chewing. Shown in Fig. 3 is the relationship between Phase-2 duration and period of each cycle during left side chewing. Fig. 4 shows the relationship between Phase-2 duration and period of each cycle during right side chewing. During steady chewing, it was also found that the duration of Phase-2 was almost constant irrespective of the period of each chewing cycle and the side of chewing, and that the durations of Phase-2 for the left side chewing (working side TMJ) was less variable than those for right side chewing (balancing side TMJ).

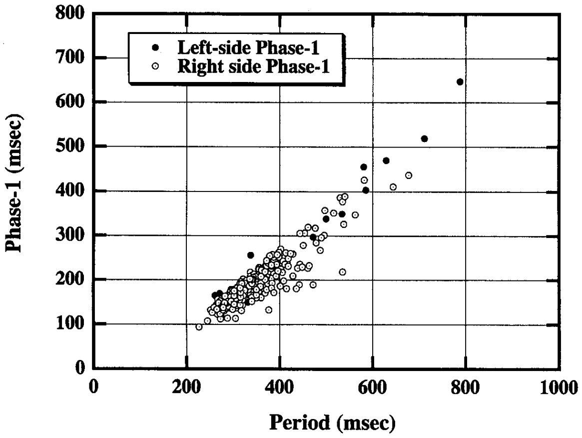

Fig. 2 Relationship between duration of Phase-1 and period of each masticatory cycle during both left and right side steady chewing.

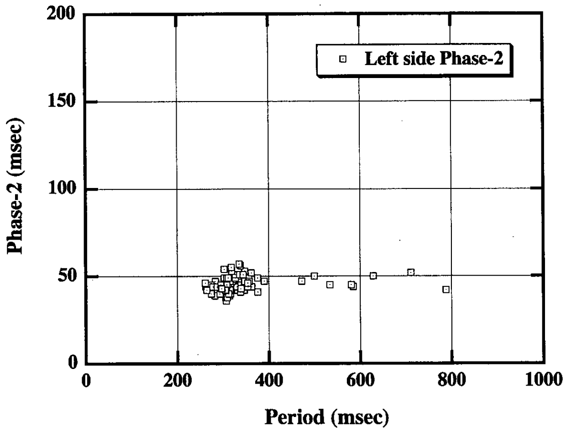

Fig. 3 Relationship between Phase-2 duration and period of each masticatory cycle during left side chewing.

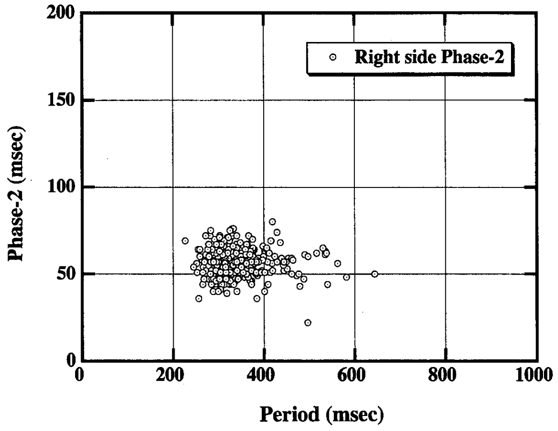

Fig. 4 Relationship between Phase-2 duration and period of each masticatory cycle during right side chewing.

DISCUSSION

Recent studies on the loading in TMJ by Hylander et al.[4~6], Boyd et al.[7,8], and Inuzuka et al.[9,10] have shown that the load acts on the TMJ during jaw movements. Hylander et al.[4~6] reported that the load on the TMJ during clenching is the maximum among loads induced by various jaw movements. Boyd et al.[7,8] reported that the maximum load on the TMJ occurs in a state close to the maximum mouth opening when monkeys screamed. Inuzuka et al.[9,10] described that the maximum load occurs at the end of mouth opening phase based on the location of marks recorded on load data synchronously with the maximum mouth opening of each masticatory cycle. Fukushima et al.[11] indicated that the maximum pressure in the TMJ was induced in the opening phase based on the ratio of the occlusal phase during the mastication period and the EMG activities of the masticatory muscles. In this study, to clarify the time of the occurrence of the maximum load during each chewing cycle, the output potntial of the micro-pressure sensor was measured simultaneously with bilateral masseter EMG activities, and their relationship was evaluated in detail.

As shown in Fig. 1, it was found that for most chewing cycles the initiation of EMG activity of masseter muscle on the working side nearly corresponded to point A when the load reduction rate reaches a maximum. Since masseter EMG activity is generally observed from the early stage of the mouth closing phase in human and monkeys[6,15], point A is considered to be the initiation point of the mouth closing phase. It was also found that the point of the peak amplitude of EMG activity on working side masseter corresponded to point B when the load began to increase. This point of the peak EMG activity is regarded as the point when the contact between food and the teeth occurs, and food begins to be fractured[6,15]. Therfore, point B is considered to be the initiation point of the occlusal phase. The termination point of the EMG activity on the working side masseter corresponded to point C indicating the maximum load increase rate. At point D indicating the occurrence of the maximum load, both side of masseter muscles EMG activities were inactive. Since in general masseter EMG activity terminates during the occlusal phase[6,15], the occlusal phase is considered to terminated at point D indicating the maximum load in each chewing cycle.

The mastication phase analysis showed that mean duration of Phase-2, which was the duration between the points from the initiation of inactive of the working side masseter EMG to the maximum load occurred, was 45.3 msec for the left side chewing (wroking side TMJ) and 55.3 msec for the right side chewing (balancing side TMJ), and that the duration of Phase-2 was almost constant irrespective of the period of each chewing cycle. It was also found that the duration of Phase-2 on the working side TMJ was less variable than those on the balancing side TMJ.

Luschei and Goodwin[16] simultaneously measured the EMG activities of jaw closing muscles and jaw movement during unilateral steady chewing in monkeys. They reported that during steady chewing, when the mandible reach its maximum position the jaw stops moving for 75-100 msec, and then abruptly moves rapidly downward. They also showed that the cessation of EMG activitys of jaw closing muscles occurs approximately 100msec before the start of the mouth opening phase. To a question why the jaw remains up in occlusion for significant period of time without EMG activity in the closing muscles, they speculated that the jaw is fold in occlusion by force from the jaw closing muscles, which continues after the cessation of EMG activity, and all muscles requied some time to relax after cessation of EMG activity.

Gibbs et al.[17] simultaneously measured the EMG activity of left masseter muscle and vertical motion of jaw in human during unilateral chewing. They found that for all subjects, a motionless period of EMG activity was recorded at the maximum intercuspal position for most chewing strokes and that the duration at jaw closure with no activity of the masseter muscle was 122.8 msec on the working side and 143.0 msec on the balancing side. They also found that the duration at jaw closure with no activity of the masseter muscle on the working side was less variable than those on the balancing side with statisticaly significant. These findings are in agreement with our results, though our data measeured in a monkey and there is a difference between the duration of jaw stopping and the duration of Phase-2 measured in this study. Therfore, the occlusal phase appears to terminate at point D.

Recently, Gallo et al.[18] and Fushima et al.[19] measured the jaw movements using the optoelectronic jaw-tracker and the condyle-fossa distance during unilateral mastication by mean of reconstruction of MRI. This method yields non-invasive, dynamic, and quantitative insight into the relationship between the articulating surfaces of TMJ. They found that the minimum condyle-fossa distance ranged between 0.7 and 2.2 mm during the jaw-opening-closing cycle, and the value of the minimum distance reaches the a minimum at the end of mouth closing phase. They also found that during unilateral mastication the grobal minimum condyle-fossa distance was significantly smller during closing phase than opening phase, and was significantly smaller on balancing side than on working side. Their findings supported our speculation that the maiximum load acting on the antero-superior surfece of TMJ in each chewing cycle occurs at the end of occlusal phase.

Evaluation of the relationship between changes in the load on the TMJ and EMG activity of bilateral masseter muscles measured suggests the following. The load on the antero-superior surface of the condylar head begins to increase in the early stage of the occlusal phase, reaches the maximum at the end of occlusal phase, but decreases at the initiation of the mouth opening phase. However, in this study, condylar head movements were not directly measured, but mandibular movements were estimated based on EMG acticity of masseter muscles, and the load on the TMJ simultaneously measured with this activity was analyzed. In the future, simultaneously measurement of the 3 items, i.e., jaw movements, EMG activity of masticatory muscles, and the load on the TMJ during mastication, will be necessary.

CONCLUSIONS

To obtain a definite answer to a question when the maximum load on the TMJ occurres during each masticatory cycle, the load on the TMJ and EMG activities of bilateral masseter muscles in a Japanese monkey during mastication of some pieces of sweet potato were simultaneously measured.

The mastication phase analysis showed that mean duration of Phase-2, which was the duration between the points from the initiation of inactive of the working side masseter EMG to the maximum load occurred, was 45.3 msec for the left side chewing and 55.3 msec for the right side chewing. It was also found that the duration of Phase-2 was almost constant irrespective of the period of each chewing cycle, and that the durations of Phase-2 for the left side chewing was less variable than those for right side chewing. From these results it was concluded that the maximum load on the antero-superior surface of the condylar head of the monkey during steady unilateral chewing occurs at the end of occlusal phase, and the duration of Phase-2 is considered to be the contact duration of teeth in the occlusal phase.

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日本サルの安定した片側咀嚼中における作業側および非作業側顎関節部荷重の変化

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キーワード：生体力学，顎関節部荷重，筋活動

各咀嚼サイクルにおいて顎関節部荷重がいつ最大値を示すかという問いに対して明確な解答を得るために，さつまいもを咀嚼運動中の一匹の日本サルの顎関節部荷重と両側咬筋筋電図を同時測定した．ハイドロキシアパタイトとチタン酸ジルコン酸鉛セラミックスから構成される微小圧力センサーをサルの左側下顎頭前上方部にインプラントした．圧力センサー出力と筋電図との関係から，各咀嚼サイクルにおける最大荷重は，両側咬筋筋電図において筋活動休止期で発生した．咀嚼相解析の結果，Phase-2，すなわち作業側咬筋筋活動が休止し始める点から最大荷重が発生する点までの期間，の平均値は左側咀嚼では45.3msec，右側咀嚼では55.3msecであった．また，このPhase-2の期間は咀嚼周期にかかわらずほぼ一定であり，左側咀嚼(作業側顎関節)の方が右側咀嚼(非作業側顎関節)の場合よりも変動が小さいことが分かった．これらの結果から，サルの安定した片側咀嚼運動では，下顎頭前上方部に作用する最大荷重は咬合相の終末に発生し，さらにこの期間は咬合相において歯が咬合接触する期間と考えられる．

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