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# Quantitative Analysis of Activity Patterns in the Muscles of Mastication and Deglutition

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## Abstract

Surface electromyograms (EMGs) were recorded from the masseter (Mass), one of the major muscles for chewing, and from the suprahyoid (SH) muscles, involved in swallowing. Activity patterns of these EMGs were analyzed with a  $T_p$  method that was developed specifically to quantify muscle activity patterns. To compare individual EMG bursts in a participant with different amplitudes and active durations, the bursts were cumulatively integrated to standardize the amplitudes and active durations. Each  $T_p$  value calculated by this method indicated a relative location of an EMG burst on a standardized time scale free from changes in the amplitudes and active durations. Both  $I_p$  and  $D_p$  values were derived from the  $T_p$  values and also applied to the burst. A  $T_{50}$  value indicated the standardized time for half of the final cumulatively integrated EMG burst. Five groups of application samples were introduced to demonstrate the usefulness of the  $T_p$  method in comparing activity patterns of the Mass and SH EMGs during chewing and swallowing, while participants were in different body positions and experiencing different tastes and textures of sample foods. Finally, limitations and perspectives of the  $T_p$  method are discussed.

**Keywords:** electromyogram, activity pattern, masseter, suprahyoid, quantification

## 1. Introduction

More than two decades ago, a simple but fundamental research question about evaluation of EMG data arose. Shouldn't two or more EMG bursts with similar amplitudes and duration of activity but visibly different activity patterns be expected to encode different functional meanings? At that time, however, such EMG bursts were generally regarded as the same from a quantitative aspect, namely, the activity patterns were ignored in the evaluation. I realized that the situation was mainly caused by the lack of a suitable and specific parameter for the evaluation, although some researchers used the term, activity patterns, differently or (maybe) inappropriately. This is the reason why I intended to newly develop a parameter for quantitative evaluation of activity patterns of EMGs, which is introduced in this chapter.

### 1.1 Neural basis of mastication and deglutition

Mastication is one of the movements essential for the survival of mammals, including humans, and the reciprocal activities of the jaw-closing and

jaw-opening muscles are among the prominent features of the movement. The Mass, innervated by motoneurons of the trigeminal nerve and one of the major jaw-closing muscles, works to crush and grind the food ingested into the mouth during natural mastication. The digastric muscle is composed of the anterior and posterior bellies that are innervated by motoneurons of the trigeminal and facial nerves, respectively. This muscle is one of the SH muscles that are part of the major jaw-opening muscles. Amplitudes and active durations of the jaw-closing and jaw-opening muscles change moment by moment both reflexively and voluntarily in accordance with physical and chemical conditions of the chewing food (bolus) in the mouth [1]. Mastication is performed not only by the jaw but also by the tongue and its related muscles as well. Basically, the jaw-closing muscles are coordinated with the tongue retractors during natural chewing, whereas the jaw-opening muscles are coordinated with the tongue protractors [1]. These and other tongue muscles—all but the palatoglossus—are innervated by the XII motoneurons [2].

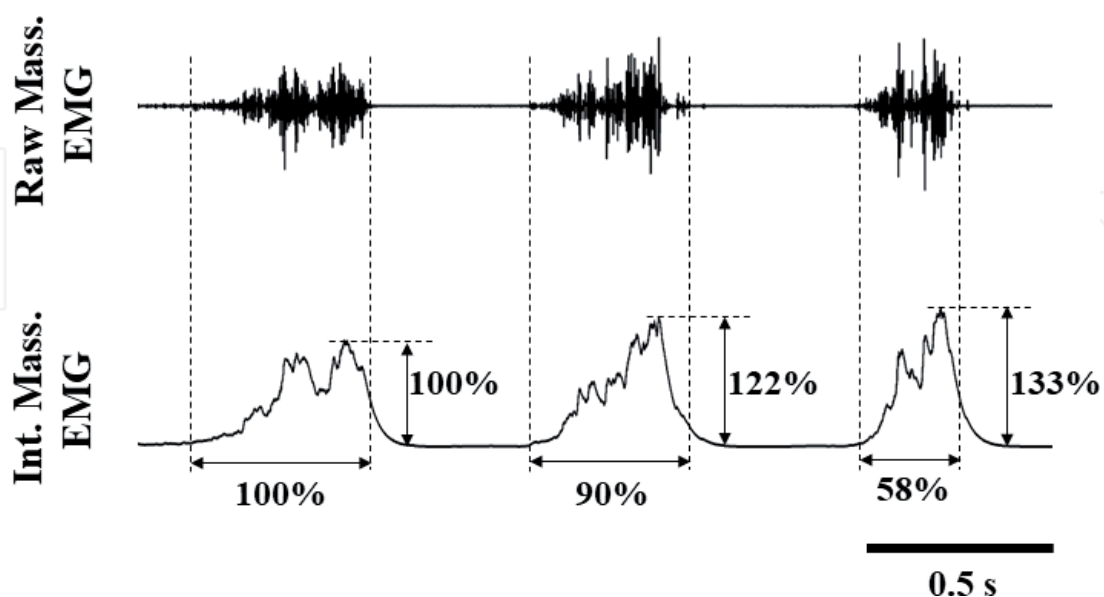
Deglutition followed by mastication is also one of the essential movements for survival. A previous study [3] revealed that healthy Japanese adults swallow, on average, 585 (range, 203 to 1008) times a day. Swallowing is a complicated and coordinated movement performed by approximately 22 muscles [4]. The SH muscles are innervated by three pairs of cranial nerves (V, VII, and XII) and are composed of eight muscles: digastric, geniohyoid, genioglossus, hyoglossus, mylohyoid, palatoglossus, styloglossus, and stylohyoid. Conventionally, the sequence of deglutition is classified as the oral, pharyngeal, and esophageal stages. The SH muscles are among the major components of the muscles especially related to the pharyngeal stage of deglutition. Pharyngeal swallowing is a highly automated or a kind of “stereotyped” movement [5]; therefore, once the movement begins, a series of muscle excitations should occur at a fixed order. However, swallowing is affected by subjective factors, such as age, and by objective factors, such as volume of foods [6].

The sensory systems in the oropharyngeal and laryngeal regions provide critical cues for reflexive and voluntary regulations of masticatory and deglutition movements. These regions have four groups of sensory receptors: mechanoreceptors, thermal (temperature) receptors, chemical receptors, and nociceptors [5]. All except nociceptors are involved in the processes discussed in this chapter. Each of these three sensory receptors has different transduction mechanisms, but once they are excited by sensory stimuli, identical action potentials are conveyed from these sensory receptors to the central nervous system through four pairs of cranial nerves: trigeminal (V), facial (VII), glossopharyngeal (IX), and vagus (X) nerves [5]. The chorda tympani nerve is a sensory (taste) branch of the facial nerve, and the superior laryngeal nerve is a sensory branch of the vagus nerve. Many previous studies have documented that the chemoreceptors in the oropharyngeal and laryngeal regions and the neurons in the central nervous system driven by the chemoreceptors often respond not only to taste but also to mechanical or thermal stimuli or both (i.e., multiple sensitivity of receptors and neurons). For example, an electrophysiological study in rats showed that 62.3% of 169 taste neurons in the nucleus of the solitary tract (the primary taste nucleus), which connected with the neurons in the parabrachial nucleus (the secondary taste nucleus), were excited by mechanical or thermal stimuli (or both) as well as by chemical (taste) stimuli applied to the oral region [7]. This multiple sensitivity is characteristic of the chorda tympani [8], parabrachial nucleus [9], thalamic [10], and cortical neurons [11].

## 1.2 Necessity of a new parameter for activity pattern

A chewing sequence is composed of a series of several bursts of masseteric activities, and each burst usually has a different amplitude and active duration. **Figure 1** depicts sample data of masseteric activity, which were recorded during the chewing of a pineapple-flavored gummy candy (GC) by a healthy young adult. The raw masseteric EMG is elicited by contraction of the Mass, and the height of the integrated EMG reflects firing rates of the muscle. The raw masseteric EMG bursts appear periodically during the jaw-closing phase and are silent during the jaw-opening phase, although the active duration of masseteric activity does not always exactly match with the jaw-closing phase [1]. The firing rates of the masseteric EMG in **Figure 1** gradually increased, reached a peak of approximately one every 0.3 s after the beginning of firing, and diminished rather rapidly; therefore, the individual raw masseteric EMG recordings looked like spindles. Moreover, the integrated masseteric EMG shows that the height of the peaks, as well as the length of active duration, differed among the three bursts: The peak height of the integrated EMG of the third burst is 33% larger than that of the first, whereas the active duration of the third burst was 42% shorter than the first.

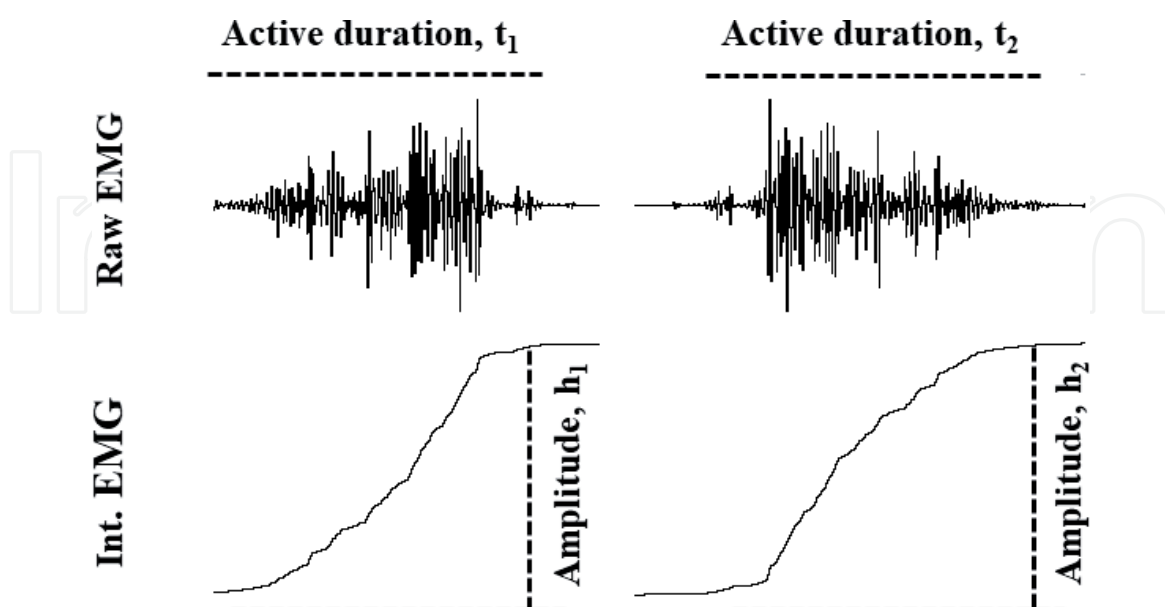
The term “pattern” is somewhat confusing because changes in amplitudes and active durations of muscle activity are often difficult to interpret. In the majority of previous studies, the term reflects a more comprehensive concept than in my study. For example, in a previous study [12], the authors recorded masseteric activity during the chewing of various foods. The behavior was classified into five subgroups with a cluster analysis technique, mainly by chewing time and muscle work rate. Masseteric EMGs of the same activity (analogous masseteric EMGs) with different amplitudes and active durations must have similar appearances or the same changes in percentages, but I believe that analogous bursts should be regarded as having the same pattern. In this [12] and other studies [13–15], the authors evaluated the patterns of masticatory muscle activity according to the amplitude and duration parameters or their derivatives



**Figure 1.** Sample data of raw and integrated Mass activity during chewing of a gummy candy. Three successive bursts in an electromyogram of the Mass, recorded during natural chewing of a pineapple-flavored gummy candy. Percentages in amplitudes and active durations of the second and third bursts are shown in reference to those of the first burst. Vertical dotted lines indicate the beginnings and ends of activity (bursts) of the electromyograms. Scales for the vertical axis are omitted for clarity. Raw Mass. EMG: raw masseteric electromyogram; Int. Mass. EMG: integrated masseteric electromyogram.

for the individual sequences. In contrast to these previous studies, my colleagues and I used specific parameters,  $T_{50}$  and  $D_{50}$  values (described later), to evaluate individual chewing bursts in standardized amplitude and duration scales. It is necessary to standardize both the amplitude and active duration to avoid such confusion and to compare their pure activity patterns. According to our method, analogous EMG bursts are judged to have the same activity patterns even if there are large differences in amplitudes, active durations, and derivatives among the EMG bursts.

**Figure 2** further clarifies the reason why a specific parameter is needed to analyze activity patterns. The masseteric EMG on the left side was recorded during chewing, and the EMG on the right side was digitally produced by reversing the time sequence of the EMG on the left side. Consequently, both heights and active durations of the EMGs should be completely identical because the original data were the same. However, this figure shows that the masseteric activity is weaker during the initial stage and stronger during the last stage on the left side than on the right side. In the other words, these EMGs show different activity patterns: The left one shows a firing pattern of increments, and the right one shows a firing pattern of decrements. According to the  $T_p$  method (see “Development and verification of a  $T_p$  method” section), these two firing patterns are quantified as clearly different values: For the incrementing firing pattern, the  $T_{50}$  value is 0.579, whereas for the decrementing pattern, the  $T_{50}$  value is 0.423. These results suggest that the strength of masseteric contraction depends on the stages (e.g., initial, middle, and last) of the chewing burst. Masseter contraction during natural chewing, not clenching, generates force to break down the food between the teeth. Therefore, chewing of different sample foods can alter firing sequences of the Mass. It is very difficult to appropriately interpret the sequences only by the changes in amplitudes and active durations of the Mass. This is why a specific parameter,  $T_p$  value, is needed to evaluate muscle activity patterns;  $T_p$  values can reveal differences in the activity patterns of individual bursts among various foods.



**Figure 2.**

Comparison of two EMGs with identical amplitude and active duration. The EMG on the left is the same as the second one in **Figure 1**, whereas the EMG on the right was produced mathematically on the basis of the left side. The left EMG has a pattern of increments, whereas the right EMG has a pattern of decrements. Horizontal dotted lines indicate the beginnings and the ends of activity (bursts) of the EMGs. Scales for the horizontal and vertical axes are omitted for clarity. Raw EMG: raw electromyogram; Int. EMG: integrated electromyogram.

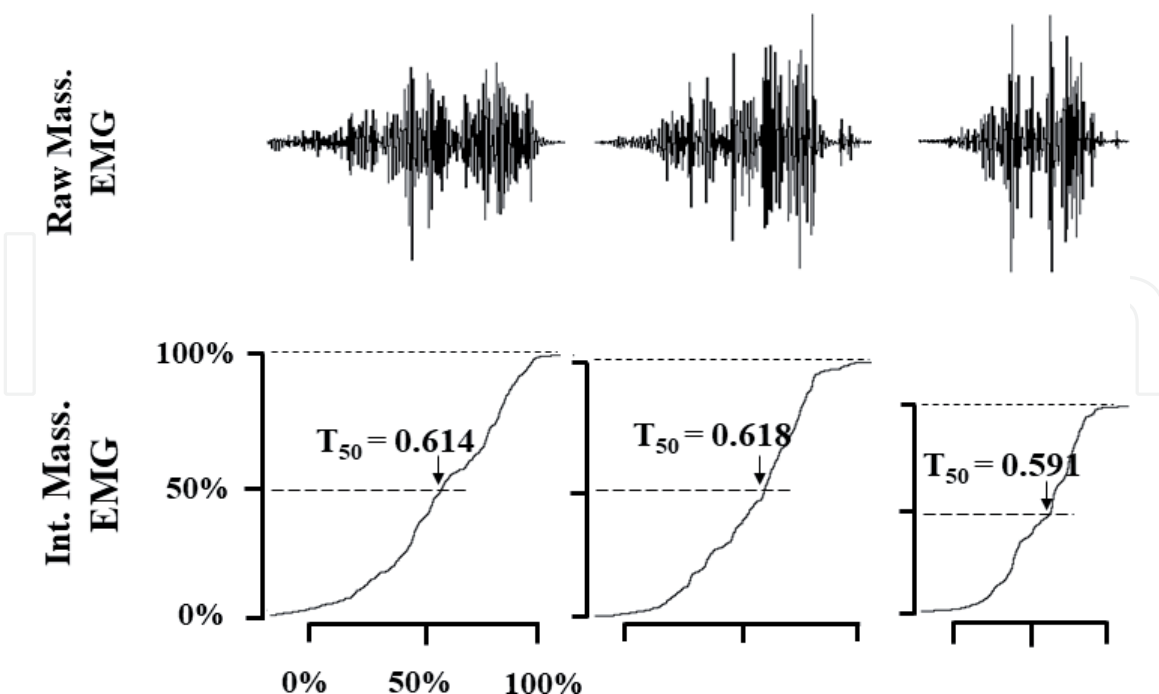


## 2. Development and verification of a $T_P$ method

### 2.1 Development of a $T_P$ method

The outlines of the standardization and calculation of  $T_P$  values are as follows (**Figure 3**): (1) Individual active durations of muscle bursts of an EMG were set to 1.0 to standardize the durations; (2) the EMGs were cumulatively integrated from the beginning to the end of the duration; (3) the final value of the cumulative integration was set at 100%; (4) the 100% value was divided into 4, 5, or 10 equal sections (i.e., each section contained 25%, 20%, or 10% of the final value, respectively); (5) the standardized durations corresponding to individual 25%, 20%, or 10% activity sections were determined; and (6) the intervals for the individual sections were successively named in the  $T_P$  format (from  $T_{25}$  to  $T_{100}$ , from  $T_{20}$  to  $T_{100}$ , or from  $T_{10}$  to  $T_{100}$ , respectively). The use of any  $T_P$  value basically depended on the precision of data analysis: A  $T_{10}$  series was more suitable for a more precise analysis of activity patterns than were the  $T_{20}$  and  $T_{25}$  series. According to this simple method, each  $T_P$  value indicated a relative location of the EMG on a standardized time scale that was free of changes in amplitudes and active durations; for example, a  $T_{50}$  value indicated the standardized time for half of the final cumulative integrated EMG, and the  $T_{100}$  value was, by definition, always 1.0.

The  $T_P$  method was applied to the data in **Figure 1**, and three  $T_P$  ( $T_{20}$ ,  $T_{50}$ , and  $T_{80}$ ) values were calculated for the data (**Figure 3**). In this example, a  $T_{50}$  value is used instead of  $T_{40}$  and  $T_{60}$  values just for the sake of convenience. If the Mass constantly fired during chewing through the active duration, then the three  $T_P$  values should be 0.200 (for  $T_{20}$ ), 0.500 (for  $T_{50}$ ), and 0.800 (for  $T_{80}$ ) according to the definition of the  $T_P$  method. In general, lower  $T_P$  values indicated stronger firing than the constant firing, although larger  $T_P$  values indicate weaker firing, as



**Figure 3.**

Calculation of  $T_P$  values from raw and cumulative Mass. EMG. The raw masseteric EMGs are identical to those in **Figure 1**. The three  $T_{20}$  values of those EMGs are 0.436 (for first burst), 0.382 (for second burst), and 0.369 (for third burst); the three  $T_{80}$  values are 0.827, 0.752 and 0.713, respectively. Each lower horizontal dashed line indicates 50%, and each horizontal dotted line indicates 100%, of the integrated masseteric EMGs. Real scales for the horizontal and vertical axes are omitted for clarity. Raw Mass. EMG: raw masseteric electromyogram; Int. Mass. EMG: integrated masseteric electromyogram.

described later [16]. Accordingly, the calculated three  $T_{50}$  values (0.614, 0.618, and 0.591) in **Figure 3** suggest that the activity pattern of the first burst is similar to that of the second one but not to that of the third one. However, some people may disagree with this suggestion of the  $T_{50}$  values. Contrary to the  $T_{50}$  values, the three  $T_{20}$  values calculated—0.436, 0.382, and 0.369—suggest that the activity pattern of the second burst is similar to that of the third one but not to that of the first one. Furthermore, the three  $T_{80}$  values calculated—0.827, 0.752, and 0.713—suggest that the activity patterns differ among the three bursts. Thus, sometimes at least three  $T_P$  values (e.g.,  $T_{20}$ ,  $T_{50}$ , and  $T_{80}$ ) may be needed in order to understand activity patterns appropriately.

## 2.2 Verification of the $T_P$ method

The  $T_P$  method was verified mathematically by a computer simulation, in which the inverse Gaussian distribution was used. In the computer simulation, three EMG models ( $pro_A$ ,  $pro_B$ , and  $pro_C$ ) were generated as prototypes for different activity patterns:  $pro_B$  was a symmetric burst model, and the other two were asymmetric ( $pro_A$  was a “left-handed” burst model and  $pro_C$  was a “right-handed” burst model; see **Figure 2** in [16]). The asymmetric models are similar to the two firing patterns shown in **Figure 2**. Physiologically,  $pro_A$ ,  $pro_B$ , and  $pro_C$  presumably corresponded to decrementing, spindle-shaped, and incrementing EMG bursts, respectively. In the EMG of the  $pro_A$  model, the peak activity was at approximately the center of its active duration, whereas the peak activities of the asymmetric models were at the early and late stages of their active durations. The locations of the peak points on the time scale are definitely different among the three models. This difference suggests three different activity patterns of EMGs: The peak of the integrated EMG is located at an earlier point (close to zero on the horizontal axis) in the model  $pro_B$  (see left column in **Figure 2** in [16]), whereas it is located at later point in the  $pro_C$  model (see right column in **Figure 2** in [16]). The locations of the peak points differ, but the peak amplitudes, as well as the active durations, were not different among the three models.

## 3. Application samples of the $T_P$ method and its derivatives

In this subsection, several application samples of the  $T_P$  method and its derivatives are introduced. **Table 1** summarizes the major findings that are presented.

### 3.1 Effects of food taste on suprahyoid activity patterns during swallowing

#### 3.1.1 Five basic taste qualities

Ten healthy young volunteers (five males and five females) were recruited as participants for the experiment. Each participant was recorded a SH surface EMG during swallowing of sample foods. A starch-based thickening agent, Mousse-up (MU, Nisshin Science, Yokohama, Japan), developed especially for dysphagic patients, was used as a basic material for the sample food. In this study, MU was dissolved in distilled water with taste substances for the five basic qualities (sweet, salty, sour, bitter, and umami); the tasteless sample food was prepared by dissolving MU in distilled water only. The used five taste substances and their concentrations were as follows: 0.5 M of sucrose (SUC) for sweet tastes, 0.5 M of sodium chloride (NaCl) for salty tastes, 0.1 M of hydrochloric acid (HCl) for sour tastes, 0.0001 M of quinine hydrochloride (QHCl) for bitter tastes, and 0.02 M of

Target	Parameter	Food factors			Human factors	
		Taste (chemical stimuli)		Texture and shape (physical stimuli)	Aging	Body position
		Five basic taste qualities	Umami			
Suprahyoid (SH) activity pattern during swallowing	$T_p$ value	Sourness and bitterness in sample foods affected (see 3.1.1)	Higher concentrations of umami substances weakly affected (see 3.1.2)	Textural properties of sample foods partly affected (see 3.2.2)	—	Body position did not affect but did affect tongue activity pattern (see 3.3)
	$In_p$ value	—	Higher concentrations of umami substances weakly affected (see 3.1.2)	—	Aged group differed from young and middle-aged groups (see 3.2.1)	—
Masseteric (Mass) activity pattern during chewing	$T_p$ value	Sweetness in sample foods affected (see 3.4)	—	Advance of chewing sequences affected (see 3.5.1 and 3.5.2)	—	—

Numbers in parentheses indicate subsection numbers of '3. Application samples of the  $T_p$  methods and its derivatives.  $In_p$  values are calculated by subtracting the preceding  $T_{p-10}$  values (in 10 equally divided sections) from  $T_p$  (see the text for details).

**Table 1.**  
 Summary of the major findings in this chapter.

monosodium glutamate (MSG) for umami tastes. Each participant was seated on a chair comfortably; approximately 8 g of one of the six sample foods (five with tastes and one without taste) at room temperature was placed randomly on the tongue (approximately 25°C), and participants were instructed to swallow the sample in one gulp. Each trial was followed by a rinse of the mouth with a sufficient amount of tap water. Occurrence of swallowing was monitored with a concomitant record of laryngeal movement. Two sessions were repeated for each participant, and the two sessions were separated by at least 1 week.

The six averages of calculated  $T_{50}$  values ranged from  $0.498 \pm 0.047$  (mean  $\pm$  standard deviation; for a sour sample food) to  $0.572 \pm 0.070$  (for a tasteless sample food) in the first session and from  $0.540 \pm 0.082$  (for a bitter sample food) to  $0.571 \pm 0.073$  (for a sweet sample food) in the second session. The average  $T_{50}$  value for the sour sample food was close to 0.500, which was expected for half of the final cumulatively integrated SH EMG on the standardized time scale. In contrast, the average  $T_{50}$  value in the tasteless sample food clearly exceeded 0.500. The average  $T_{50}$  values imply that the SH muscles produced a spindle-shaped (or symmetric) firing pattern with the sour food and an incrementing firing pattern to the tasteless one (see "Necessity of a new parameter for



activity pattern” section, especially **Figure 1**, and see **Figure 2** in [16]). In addition to the  $T_{50}$  values, the subjective difficulty during swallowing was examined with a psychometric method used in a previous study [17]. The examination revealed that the sour and bitter sample foods increased the subjective difficulty of swallowing. The SH activity patterns evoked by the sour and bitter samples are congruent with the previous finding of subjective difficulty associated with swallowing of those foods [17].

Gustatory signals from foods were reported in humans and rats to provoke somatic responses in the trigeminal [18–20], facial [21], and hypoglossal nerves [22–25]. Receptors of four pairs of gustatory nerves can be responsible for gustation in the oral cavity, pharynx, and possibly larynx: the chorda tympani, glossopharyngeal, superior laryngeal nerves (see “Neural basis of mastication and deglutition” section), and, on the soft palate, the superficial petrosal nerve. In this study, the ingested foods probably stimulated the mucosae of the areas innervated by these cranial nerves during swallowing; consequently, gustatory signals arising from all of these nerves were likely to be involved in the findings. Gustatory signals from the glossopharyngeal and superior laryngeal nerve affect swallowing, especially the threshold for elicitation of swallowing [26–28]. Although animal experiments have revealed peripheral and central sensory mechanisms of the glossopharyngeal and superior laryngeal nerves (e.g., [29–32]), no studies have established whether gustatory signals from the two nerves contribute to sensory evaluation. In a previous study, the effect of taste and palatability of solutions in two (moderate and high) concentrations on peak lingual swallowing pressures was examined in 10 healthy adult participants [33]. Moderate SUC, high NaCl, and high citric acid levels elicited higher peak lingual swallowing pressures than did water, whereas palatability did not. The previous results and the findings of this study may extend the knowledge about the effects of taste on swallowing movement.

### 3.1.2 Umami substances

Eight healthy young volunteers (three males and five females) were recruited as participants for this study. Sample foods consisted of MU dissolved in a mixture of MSG and IMP (disodium inosine-5'-monophosphate), in MSG alone, and in IMP alone. The procedures were identical to those in the first study (see “Five basic taste qualities” section for details). Analysis of  $T_p$  values revealed no synergistic effects on SH EMG activity patterns during pharyngeal swallowing of umami foods. The SH activity patterns were consistent with those in the sensory evaluation of the subjective difficulty of swallowing, which was examined in the same participants. The consistency between SH EMG activity patterns and sensory evaluations of swallowing implies that both methods of data analyses did not discriminate between unitary umami foods (MU dissolved in MSG only or IMP only) and binary umami foods (MU dissolved in both MSG and IMP) or between non-umami foods (MU dissolved in SUC and in NaCl) and tasteless (MU dissolved in distilled water) foods. In view of the findings of a previous study [34], I can conclude that the  $T_p$  method differentiates SH EMG activity patterns measured during pharyngeal swallowing of sour and bitter foods from those measured during swallowing of a tasteless food, although the method does not differentiate the activity patterns involved with sweet, salty, and umami foods (in both unitary and binary mixing solutions).

Both  $T_p$  and  $In_p$  values were calculated to analyze activity patterns of the SH EMGs during pharyngeal swallowing of samples with MU dissolved in unitary (either MSG or IMP) and binary (both MSG and IMP) umami substances at low and high concentrations as well as sweet and salty sample foods. A newly developed parameter, the  $In_p$  value, was calculated by subtracting the preceding  $T_{p-10}$  values (in 10 equally divided sections) from  $T_p$  to improve precision in detecting

differences. SH EMG activity patterns measured during pharyngeal swallowing differed between the low- and high-concentration umami samples, both unitary (IMP alone) and binary (both MSG and IMP) mixtures. According to the definition of the  $T_p$  method, smaller  $T_p$  values on a standardized time scale imply early cumulative SH activity corresponding to the percentile points. Six deciles of  $T_p$  values for low-concentration umami sample foods (four  $T_p$  values from  $T_{50}$  to  $T_{80}$  in IMP sample foods and  $T_{10}$  and  $T_{30}$  in binary umami sample foods) were significantly smaller than those for higher concentration foods, which suggests that increased solvent concentrations affected activity patterns of the SH EMG during pharyngeal swallowing of the sample foods. Analysis of  $T_p$  and  $In_p$  values showed that SH activity patterns differed slightly between low and higher concentrations of unitary and binary umami sample foods (see **Figure 3** in [35]) but those SH activity patterns measured during swallowing of umami sample foods did not differ from those measured during swallowing of sweet, salty, or tasteless sample foods.

Synergism is an important concept that is widely recognized in the psychology and physiology of taste and one of the characteristic functional features of umami substances. In synergism, mixing two or more different tastes greatly enhances the umami taste. Such combinations include MSG, IMP, and disodium 5'-guanylate [36, 37]. Gustatory signals evoked by ingested umami substances can modify not only feeding behaviors [38–40] but also visceral functions [41, 42]. This study is probably the first report to document changes in muscle activity patterns elicited by increasing concentrations of umami substances in foods. Although researchers previously reported changes in activity patterns of masticatory muscles during chewing sequences [18, 43, 44], they examined conventional parameters, such as the number of chewing cycles, amplitudes, and durations of muscle activity to estimate activity patterns. Therefore, in these previous studies, activity patterns were evaluated indirectly by measurement of changes in conventional parameters; in contrast, my colleagues and I directly examined activity patterns of the SH during pharyngeal swallowing by using the  $T_p$  method. In this study, I analyzed increments of  $T_p$  values (i.e.,  $In_p$  values) first, and some significant differences were found in umami sample foods. Significant differences in both  $In_p$  values and  $T_p$  values were detected only between low-concentration and high-concentration umami foods. This result suggests differential influences of umami taste in foods on activity patterns of the SH muscles during pharyngeal swallowing.

### 3.2 Effects of food texture on suprahyoid activity patterns during swallowing

#### 3.2.1 Aging of participants

A total of 15 participants of both sexes were included in three participant groups: young adult (20 to 30 years old), middle-aged (40 to 50 years old), and elderly (60 to 70 years old). In each participant in the three groups, SH surface EMGs were recorded during swallowing of ordinary agar (OA) and gelatin samples that had textural properties. Both  $T_p$  and  $In_p$  values were calculated from the SH EMGs during swallowing. Statistical examination showed no significant differences in the average  $T_p$  values among the three groups. In contrast,  $In_p$  values—derived from  $T_p$  values—in the elderly group differed in part from those of the other two groups for gelatin. This result suggests that (1) the overall activity pattern of the SH muscles is basically preserved in elderly people, but slight, partial changes occur with age, and (2) the  $T_p$  method ( $In_p$  values) is useful in detecting the differences, although the differences with age were slight and partial. It is necessary to carefully analyze the characteristics of chewing and

swallowing functions of elderly people to respond to the demand for production of special foods adjusted to the needs of some elderly persons in an aging society. In this study, SH activity patterns in three groups of differing ages were compared to evaluate whether aging affects activity patterns of muscles related to swallowing.

The analysis of data with  $In_p$  values demonstrated a difference in SH activity patterns among the three groups during pharyngeal swallowing of gelatin. Rank correlation analyses revealed that the sequence of average  $In_p$  values in the elderly group differed from the sequences in the young adult and middle-aged groups for gelatin but not for OA. These results suggest that the difference in  $In_p$  values among the three groups (see **Figure 3** in [45]) is due to interactions between the properties of gelatin and the ages of participants. As an earlier report showed [46], textural properties of gelatin and OA clearly differ, and the properties of gelatin may cause the difference observed in  $In_p$  values. Because  $T_p$  and  $In_p$  values are by nature not influenced by either amplitude or duration of EMG bursts [34, 35, 47], the differences in peak amplitude and active duration of the SH EMG had no bearing on the difference found in  $In_p$  values. The freedom from the amplitude and active duration should be an advantage of the  $T_p$  method, and it allows the comparison of activity patterns in EMGs recorded in different trials and participants.

### 3.2.2 Food texture properties

Five healthy young volunteers (two males and three females) were recruited as participants for this study. Three sample foods with MU in low concentrations (3.0%; 3.0MU), medium concentrations (6.0%; 6.0MU), and high concentrations (9.0%; 9.0MU) at room temperature (approximately 25°C) were used. Before these food samples were given to participants, three textural properties (hardness, adhesiveness, and cohesiveness) were measured by a texturometer. One of the sample foods was selected randomly and delivered to each participant. EMG electrodes were attached to the participant for SH activity, and the participant was seated on a chair and instructed to accept the sample food. Three  $T_p$  values ( $T_{20}$ ,  $T_{50}$ , and  $T_{80}$ ) were calculated and analyzed in this study. The average  $T_{50}$  value for 6.0MU was significantly larger than that for 3.0MU but not that for 9.0MU, whereas there was no difference in average  $T_{20}$  and  $T_{80}$  values between the three sample foods. The averages of SH durations and cumulative SH activity and the ratios between these two parameters were measured as well. The average SH duration for 9.0MU was longer than that for 3.0MU, but there were no significant differences in the cumulative SH EMG activity or in the ratios of the used sample foods.

The hardness, adhesiveness, and cohesiveness values of the used three MU sample foods on average increased as the concentration of MU increased (see **Figure 2** in [48]). The hardness of 6.0MU and 9.0MU was much larger than that of 3.0MU (about 350% and 450%, respectively). Similar large differences between 3.0MU and the other two were shown in the adhesiveness and cohesiveness as well, and statistical examinations demonstrated significant differences in these three textural parameters among the three samples of MU. Previous studies documented that increasing the hardness, viscosity, and volume of sample foods prolongs the durations of oral and pharyngeal swallowing (e.g., [49, 50]). Similarly, a videofluoroscopic study also documented that swallowing high-density barium, in comparison with low-density barium, prolongs the oral and pharyngeal transit times in healthy participants [49]. Moreover, an electromyographic and manometric study demonstrated that the average duration of the SH activity during the swallowing of high-density agar fluid was longer than that of low-density agar [34, 35, 47]. Consequently, I can conclude that increasing the



textural properties of the sample foods is responsible for prolonging the duration of pharyngeal swallowing.

### 3.3 Effects of body position on suprahyoid activity patterns during swallowing

Nine healthy young volunteers (six males and three females) participated in this study, and surface EMGs were recorded from the anterior tongue and SH muscles of each participant. Three sample foods with different concentrations (2.0MU, 5.7MU, and 9.1MU) of MU at the room temperature (approximately 25°C) were used. Each participant was positioned randomly for swallowing at one of the four angles: horizontal supine (0 degrees), 30 degrees inclined, 60 degrees inclined, and upright (90 degrees). The food sample was selected randomly among from the foods with three MU concentrations. Analysis of  $T_{50}$  values showed that the average  $T_{50}$  value of the activity patterns in the anterior tongue in the horizontal supine position was significantly higher than that in the upright position, but there were no significant differences in anterior tongue  $T_{50}$  values between the foods with the three concentrations. In contrast, analysis of SH  $T_{50}$  values showed that the average  $T_{50}$  value for 9.1MU was significantly higher than that of 2.0MU, but there were no significant differences in SH  $T_{50}$  values between the four body positions. The results indicated that anterior tongue activity pattern was altered from a decrementing firing pattern to an incrementing pattern by the shift from the upright position to the horizontal supine position, whereas SH activity pattern was altered from a decrementing firing pattern to an incrementing pattern by the shift from the low-concentration food to a high-concentration one.

According to the findings in this study, activity patterns of the anterior tongue and SH muscles are affected by both body positions and food properties. **Figure 4** demonstrates SH activities during swallowing of two concentrations, 2.0MU and 9.1MU, at four body positions, horizontal supine (0 degrees), 30 degrees inclined, 60 degrees inclined, and upright (90 degrees), in a healthy young male participant. Visual observation of this figure suggests that activity patterns seem similar among the four body positions but different between the two sample foods. Actually, four  $T_{50}$  values calculated for the 2.0MU are 0.414 (for 0 degrees), 0.450 (for 30 degrees), 0.522 (60 degrees), and 0.462 (90 degrees), whereas those for the 9.1MU are 0.625 (for 0 degrees), 0.509 (for 30 degrees), 0.622 (60 degrees), and 0.618 (90 degrees). The averaged  $T_{50}$  value for the 2.0MU (0.508) tended to be smaller than that for the 9.1MU (0.607). Because in general a smaller  $T_p$  value means relatively shorter time for the half of the integrated EMG and corresponds to a more active burst, the SH muscles demonstrated more activity in the first half of swallowing of the 2.0MU than that of the 9.1MU. Thus the  $T_{50}$  values calculated indicate that the two concentrations of the sample food affect activity patterns of the SH muscles during swallowing, but body positions do not. Precise analysis of the effects of body positions and thickener's concentrations is discussed later, but swallowing movement is not constant among body positions. Besides, activity patterns of the tongue were analyzed in the article described next because it is widely accepted that the tongue, as well as the SH muscles, plays an important role in swallowing (e.g., [5]).

According to the nature of the  $T_p$  values [16], the obtained results physiologically implied that the anterior tongue EMG during swallowing expressed a decrementing firing pattern in the upright position (with smaller  $T_{50}$  values) and an incrementing firing pattern in the horizontal supine position (with larger  $T_{50}$  values). Previous papers [51–53] documented that the four body positions affected neither durational nor amplitude parameters of the anterior tongue EMG during swallowing; the body positions modified only the activity patterns of the anterior tongue. The tongue contains skeletal muscles without attachment to the bone,

intrinsic muscles (longitudinal, transverse, and vertical muscle groups), other muscles attached to at least one bone, and extrinsic muscles (genioglossus, hyoglossus, and styloglossus) [54]. The electrodes were attached to the surface of the anterior tongue in this study [55], and so the EMG recording might have originated from the intrinsic muscles of the tongue, but it is very difficult to determine the origin precisely by the use of surface electrodes.

### 3.4 Effects of food taste on masseteric activity patterns during chewing

Ten healthy young volunteers (seven males and three females) were recruited as participants in this study. A surface EMG was recorded from the SH of each participant, and three  $T_p$  ( $T_{25}$ ,  $T_{50}$ , and  $T_{75}$ ) values were calculated from the EMG data (200  $T_p$  values for each GC). Four fruit GCs (apple-, grape-, orange-, and pear-flavored) were used as sample foods. Four textural properties (hardness, adhesiveness, cohesiveness, and gumminess) and chemical components (sugars and organic acids) of the GCs were analyzed. The hierarchical cluster analysis was applied to the three  $T_p$  values collected with each GC. The standardized Euclidean distance and the Ward linkage method were used for cluster amalgamation. Two predominant sugars, SUC and maltose, and four organic acids (citric, malic, phosphoric, and tartaric acids) were detected by the chemical analysis. In the cluster analysis, the  $T_{25}$  and  $T_{75}$  values were classified into four subclusters, and the  $T_{50}$  values were classified into three subclusters. In two  $T_{75}$  subclusters, the combined amounts of the two predominant sugars (SUC and maltose) differed significantly, but neither the four detected organic acids nor the textural properties differed. These findings indicate that SUC and maltose in GCs can affect masseteric activity patterns during chewing, particularly in the later stages, but their organic acids and textural properties do not have such an effect.

The authors of this study used a hierarchical cluster analysis method, followed by an ANOVA, to evaluate the textural properties and chemical components of individual sample foods corresponding to the clustered data for the three  $T_p$  values. The reason for the use of the analyses was that the same sample food item (1) could not be consumed by the participants, (2) could not be used for the textural measurements, and (3) could not be used for chemical analyses. Therefore, it was necessary to collect the textural properties and chemical components of each sample food separately, calculate their averages individually, and examine the correlations between  $T_p$  values and these food properties. In the hierarchical cluster analysis with the standardized Euclidean distance and Ward linkage methods,  $T_p$  values were fragmented according to their similarity and then grouped into three and four subclusters when the amalgamation level was established at 12% of the greatest distance in each dendrogram of  $T_{25}$ ,  $T_{50}$ , and  $T_{75}$  values. ANOVA could be used to compare the subclusters in terms of their textural properties and chemical compositions because each  $T_p$  value in the subclusters was associated with the specific textural properties and chemical compositions of each sample food.

In previous physiological studies in humans [18, 19, 38, 56, 57] and rats [20], investigators analyzed masseteric activity during chewing of various foods, as well as ingestion of liquids, with different tastes and textures. Activity patterns were evaluated indirectly by visual observation or with the use of parameters such as the number of chews, chewing time, and mean voltage of the masseteric activity. In none of these studies did the investigators use specific parameters for the evaluations. The use of specific parameters, such as  $T_p$  values, is essential for the precise evaluation of muscle activity patterns. In this study, the average  $T_{75}$  value measured during the chewing of the orange-flavored GC ( $0.725 \pm 0.008$ ) was lower than that measured during the chewing of the apple-flavored GC ( $0.767 \pm 0.008$ ).



As mentioned in other application samples, these  $T_{75}$  values imply that chewing the orange-flavored GC evoked a decrementing firing pattern in the Mass, which is characterized by smaller  $T_p$  values, and chewing the apple-flavored GC evoked an incrementing firing pattern, although the difference in the firing patterns is just “relative,” especially in such a small difference in  $T_p$  values (0.725 versus 0.767).

### 3.5 Effects of food texture on masseteric activity patterns during chewing

#### 3.5.1 Food texture properties

Eight healthy young volunteers (all males) were recruited as participants in this study. A surface EMG was recorded from the Mass of each participant, and nine  $T_p$  values (from  $T_{10}$  to  $T_{90}$ ) were calculated from the EMG data. The two agars, OA and Ina-agar (IA), each at two concentrations, were used as sample foods: 0.5% OA (0.5OA), 1.5% OA (1.5OA), 2.5% IA (2.5IA), and 4.0% IA (4.0IA). The four sample foods differed partly in four textural properties: hardness, fracturability (defined as the force of the significant break in the curve on the first compression [bite]), adhesiveness, and cohesiveness. For example, the highest average hardness,  $4.05 \pm 0.08 (\times 10^4 \text{ Pa})$ , and the highest average adhesiveness,  $65.3 \pm 7.2 (\text{J/m}^3)$ , were observed in the 1.5OA, whereas the lowest average values,  $0.94 \pm 0.04 (\times 10^4 \text{ Pa})$  and  $2.9 \pm 1.1 (\text{J/m}^3)$ , were observed in 2.5IA. One of the four sample foods, selected randomly, was delivered to each participant. In addition to the  $T_p$  values, other four parameters (mastication time, number of chewing, cumulative masseteric activity, and amplitude rate) were analyzed. The average  $T_{50}$  values in the first cycles, for example, showed the lowest value for 2.5IA ( $0.515 \pm 0.021$ ) and highest value for 1.5OA ( $0.535 \pm 0.025$ ). Statistical analysis with Wilcoxon's test revealed significant differences in  $T_p$  values between the first and last cycles with 1.5OA (four of the nine  $T_p$  deciles) and with 2.5IA (five). The average  $T_p$  values of the first cycle tended to be larger, but not significantly so, than those of the last cycle (see **Figure 3** in [47]).

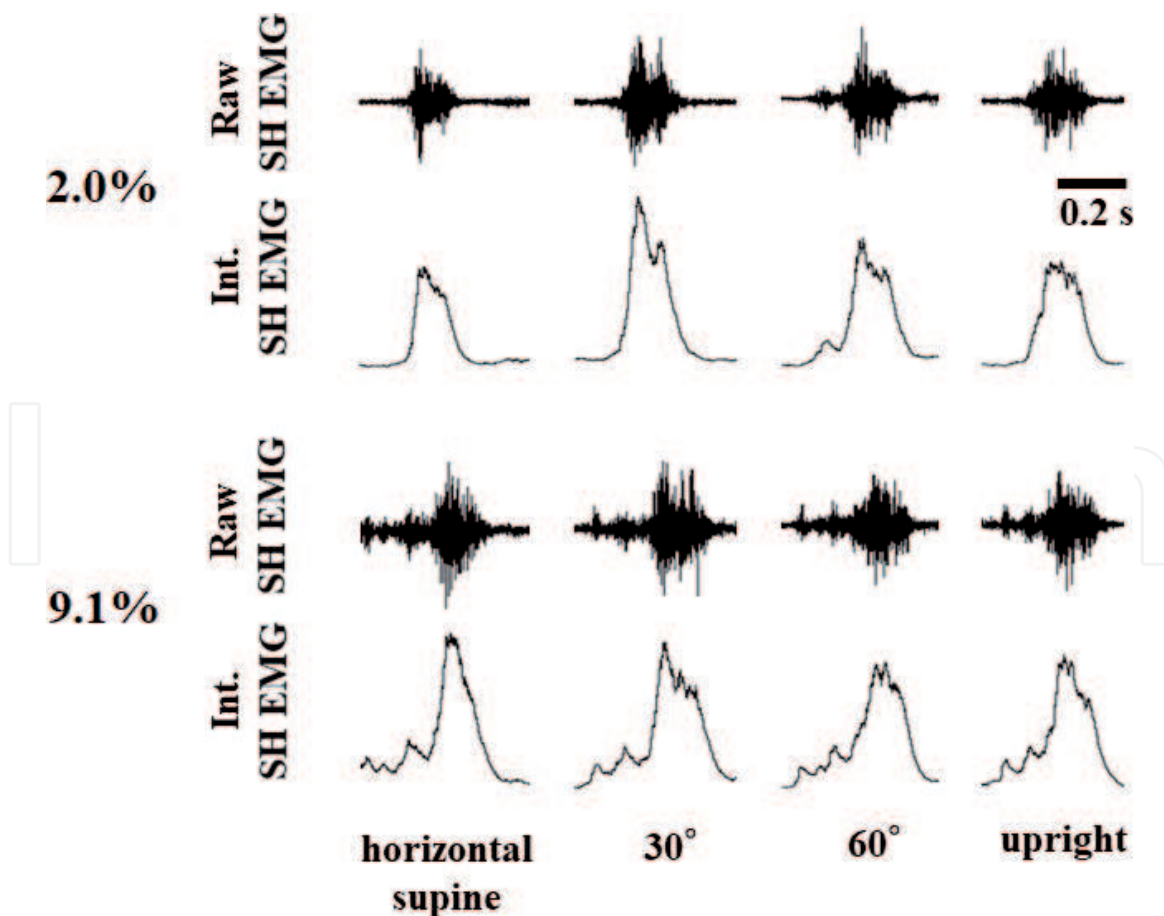
One of the major findings of this study was the significant differences in  $T_p$  values detected between the first and last cycles. The finding suggests that sequential changes in masseteric activity patterns occur at the beginning and end of chewing. In previous studies, researchers reported changes in activity patterns of masticatory muscles during chewing sequences by measuring conventional parameters, such as the number of chewing cycles, and amplitude and duration of muscle activity (e.g., [18, 43, 44]). This study, in which the  $T_p$  method was used, added new information about sequential changes in activity patterns of the Mass. The result indicates that the masseteric activity observed in chewing 2.5IA reached the half of the final cumulative masseteric activity slightly earlier than it did with the other three agars. However, the average  $T_p$  values between the used four agars were not significantly different between the first chewing cycles or between last chewing cycles. The result suggests that hardness and other textural properties measured before chewing do not affect the masseteric activity patterns, at least in the first and last cycles of the chewing sequences.

#### 3.5.2 Food shapes and textures

Ten healthy young volunteers (seven males and three females) were recruited as participants in this study. A surface EMG was recorded from the Mass of each participant, and three  $T_p$  values ( $T_{25}$ ,  $T_{50}$ , and  $T_{75}$ ) were calculated from the EMG data. Six foods (cheese, GC, marshmallow, prune, rice cracker, and sponge cake) were used as samples. These sample foods differed partly in three shape dimensions

(length, width, and height) and in four textural properties (hardness, fracturability, adhesiveness, and cohesiveness). One of the six sample foods, selected randomly, was delivered to each participant. In addition to the three  $T_p$  values, other three parameters (number of chewing, sequence length of chewing, and active duration of masseteric activity) were analyzed. The major results by linear model analysis in relation to textural properties of the sample foods showed that (1) the  $T_{25}$ ,  $T_{50}$ , and  $T_{75}$  values were increased by 0.015, 0.020, and 0.021 points, respectively, by a 100-kPa increase in the hardness; (2) the  $T_{25}$  and  $T_{50}$  values were decreased by 0.061 and 0.070 points, respectively, by a 100-kPa increase in the fracturability; and (3) the number of chewing cycles was reduced by 8.8 cycles by a 100-kPa increase in the fracturability and 6.6 cycles by a 5.0-kJ/m<sup>3</sup> increase in the adhesiveness. These findings suggest that the combination of several parameters can enhance discriminability between foods owing to differential sensitivity to food properties.

The  $T_p$  method was used to evaluate the masseteric activity patterns during the chewing of the six sample foods with different textural properties. Cheese differed from GC, marshmallow, rice cracker, and sponge cake in all three  $T_p$  values ( $T_{25}$ ,  $T_{50}$ , and  $T_{75}$ ; see **Figure 4** in [58]). The differences between  $T_p$  values raise a question: How can these results best be interpreted? One possible interpretation may be that there was relatively more activity during the early period of the masseteric EMG during the chewing of cheese than there was during the chewing of GC. The difference resulted in different cumulative masseteric EMG curves: The masseteric EMG curve for cheese exceeded the line that indicated theoretically tonic activity of the EMG throughout



**Figure 4.**

*Comparison of SH EMG among four body positions and between two concentrations of sample foods. The SH EMG and integrated SH EMG were recorded during swallowing of two sample foods with low (2.0%) and high (9.1%) concentrations of a thickening agent in four body positions: horizontal supine, 30 degrees inclined, 60 degrees inclined, and upright. Scales for the horizontal and vertical axes are omitted for clarity. Raw SH EMG: raw suprahyoid electromyogram; Int. SH EMG: integrated suprahyoid electromyogram.*

its active duration, whereas the masseteric EMG curve for GC fell below this line. The interpretation suggests that the masseteric EMG of cheese shows a decremting firing pattern, which is characterized by smaller  $T_p$  values, during the first chewing cycle in comparison with the masseteric EMGs of the GC, marshmallow, rice cracker, and sponge cake. However, it should be noted that there are no absolute criteria that allow an investigator to discriminate between incrementing and decremting firing patterns of EMG activity. In other words, it is not possible to say that an EMG activity pattern is a decremting one if the  $T_{25}$  value exceeds 0.300 points.

The regression coefficients estimated in the linear model analysis for the three  $T_p$  values were not particularly large with regard to the hardness of the sample food used. These regression coefficients were all statistically significant, but the result suggests that hardness only weakly contributes to the masseteric activity patterns evaluated by  $T_p$  values. Ten deciles (e.g.,  $T_{10}$  and  $T_{20}$  values) were used in previous studies [34, 35, 53, 59], and the use of 10 deciles may provide more information about EMG activity patterns than quartiles ( $T_{25}$ ,  $T_{50}$ ,  $T_{75}$  values). However, my colleagues and I found that it was often difficult to interpret the 10 decile results in this study. According to our experience of using both  $T_p$  values in the previous and current studies,  $T_{50}$  values can be compared with each other. The  $T_{50}$  values differed slightly from those in the previous studies [34, 35, 53, 59], but statistical testing was not performed to determine the significance of these differences. It is difficult to know whether these differences reflect the difference in the muscles used (SH versus Mass) or the difference in functions examined (swallowing versus chewing). Suitability of using  $T_{50}$  values or other  $T_p$  values may be dependent on the functions.

#### **4. Advantages, limitations, and perspectives of the $T_p$ method**

The  $T_p$  method can have at least three advantages. The first advantage is that the calculation from numerical data is simple and the digitization to numeral data from the original records is now common in most laboratories. The calculation itself is surely simple, but my colleagues and I needed to develop a special software for the calculation on a personal computer because of the huge amounts of data. Indeed, my colleagues and I had to handle 100,000 rows of a data sheet for numerical EMG data of only 10 s in the calculation of a  $T_p$  value. The second advantage is the ease of comparison of EMG data with largely different amplitudes because of the nature of the  $T_p$  method (see “Development and verification of a  $T_p$  method” section): that is, the relative time corresponding to the final cumulated SH EMG is important, although the absolute amplitudes are not. The third advantage is the independence of analysis from active durations of the EMG in the  $T_p$  method, as in the second advantage.

The validity of the  $T_p$  method was examined mathematically and theoretically by a computer simulation (see “Development and verification of a  $T_p$  method” section) but was not experimentally. This is the first and major limitation of the  $T_p$  method. It seems to be effective for the verification experimentally by kinesiological analysis of chewing and swallowing movements with concomitant recording of muscle activities. The analysis can provide useful information about functional meanings of differences in  $T_p$  values among recorded EMG bursts. The second limitation is based on the nature of the  $T_p$  method:  $T_p$  values are calculated from a cumulative EMG, and so the calculated values are not independent in each burst. It is meaningless to compare two or more  $T_p$  values (e.g.,  $T_{20}$  and  $T_{40}$  values) of an EMG burst. However, the problem seems not to be serious, inasmuch as such a comparison rarely occurs and the same  $T_p$  values (e.g.,  $T_{50}$  and  $T'_{50}$ ) in different EMG bursts are usually compared for quantitative evaluation of two or more activity patterns of the EMG.



The  $T_P$  method is just a tool for analyzing muscle activity patterns and can provide quantitative information for the patterns but not any direct cues for the central nervous system mechanism responsible for the patterns. Thus it is necessary to conduct experiments in which data of both central and peripheral nervous system muscle activities are recorded. Concomitant analysis of these activities can be used to explore the central nervous mechanism, and the  $T_P$  method should be useful for analysis of peripheral muscle activity. As shown previously (see “Application samples of the  $T_P$  method”), the  $T_P$  method is useful for evaluating activity patterns of EMGs quantitatively. The method is applicable to various EMG bursts with different amplitudes and active durations observed during mastication and deglutition. This chapter focused on these two functions only, but the  $T_P$  method must be also applicable to muscle activities of other movements, such as respiration and locomotion, because these movements have neural mechanisms similar or common to those of mastication and deglutition (e.g., [60–62]).

As summarized in **Table 1**, in this chapter I showed application samples that were related to chewing and swallowing functions in healthy participants. However, the  $T_P$  method should be applicable to other cyclic functions, such as breathing, walking, and swimming. Besides, the  $T_P$  method should also be applicable to wider research fields and clinical sites, especially as one of the diagnostic tools for patients with motor diseases. For example, disorders in the motor system may command abnormal signals to the target muscle(s), and activity patterns of the EMG may reflect the abnormal command signals.

## **5. Conclusions**

Activity patterns of the Mass EMG during chewing and the SH EMG during swallowing were analyzed with a  $T_P$  method. The  $T_P$  method compared activity patterns of individual EMG bursts with different amplitudes and active durations on standardized time scales free from changes in the amplitudes and active durations. Five groups of application samples were introduced to compare the activity patterns of these EMGs during chewing and swallowing at different body positions of participants as well as by different tastes and textures of sample foods.

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## **Conflict of interest**

The author reports no conflicts of interest. The author alone is responsible for the contents and writing of this book chapter.

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