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Evaluation of jaw and neck muscle activities while chewing using EMG-EMG transfer function and EMG-EMG coherence function analyses in healthy subjects

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HIGHLIGHTS

- Rhythmic chewing is evaluated by the EMG-EMG transfer and coherence functions.
- Power and time coordination are evaluated by the gain and the phase characteristics.
- Synchrony of muscle activities is evaluated by coherence.
- Phase of the non-chewing side neck muscle reflects bilateral/unilateral coordination.

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ABSTRACT

This study aims to quantitatively clarify the physiological features in rhythmically coordinated jaw and neck muscle EMG activities while chewing gum using EMG-EMG transfer function and EMG-EMG coherence function analyses in 20 healthy subjects. The chewing side masseter muscle EMG signal was used as the reference signal, while the other jaw (non-chewing side masseter muscle, bilateral anterior temporal muscles, and bilateral anterior digastric muscles) and neck muscle (bilateral sternocleidomastoid muscles) EMG signals were used as the examined signals in EMG-EMG transfer function and EMG-EMG coherence function analyses. Chewing-related jaw and neck muscle activities were aggregated in the first peak of the power spectrum in rhythmic chewing. The gain in the peak frequency represented the power relationships between jaw and neck muscle activities during rhythmic chewing. The phase in the peak frequency represented the temporal relationships between the jaw and neck muscle activities, while the non-chewing side neck muscle presented a broad range of distributions across jaw closing and opening phases. Coherence in the peak frequency represented the synergistic features in bilateral jaw closing muscles and chewing side neck muscle activities. The coherence and phase in non-chewing side neck muscle activities exhibited a significant negative correlation. From above, the bilateral coordination between the jaw and neck muscle activities is estimated while chewing when the non-chewing side neck muscle is synchronously activated with the jaw closing muscles, while the unilateral coordination is estimated when the non-chewing side neck muscle is irregularly activated in the jaw opening phase. Thus, the occurrence of bilateral or unilateral coordinated features in the jaw and neck muscle activities may correspond to the phase characteristics in the non-chewing side neck muscle activities during rhythmical chewing. Considering these novel findings in healthy subjects, EMG-EMG transfer function and EMG-EMG coherence function analyses may also be useful to diagnose the pathologically in-coordinated features in jaw and neck muscle activities in temporomandibular disorders and whiplash-associated disorders during critical chewing performance.

1. Introduction

The jaw and neck muscle activities are coordinated while chewing [1–4]. Kohno et al. [1] first observed that the sternocleidomastoid muscle is more active on the working side than on the non-working side while chewing. Other researchers have replicated co-activation of the chewing side masseter and sternocleidomastoid muscles [3,4]. Furthermore, the functional relationship between the masseter muscle and the sternocleidomastoid muscle has been elicited from the viewpoints of experimental muscle fatigue by jaw clenching [2] and the increased activity in the sternocleidomastoid muscle in response to the chewing load by hard food [3].

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Although these previous studies statistically evaluated the effect of the jaw motor task performance and its conditioning to neck muscle activities in the sternocleidomastoid muscle, the function coordination between the jaw and neck muscle activities in rhythmical chewing has yet to be reported. To evaluate the coordination of two muscle activities during rhythmical movements, the interrelationship of the two EMG signals must be quantitatively analyzed. For example, Nielsen et al. [5] reported that a stride-cycle frequency during gait can be represented as the first peak in the power spectrum of the frequency analysis of EMG signals. Focusing on this first peak in the power spectrum of EMG signals, we analyzed the coordinated features between jaw and neck muscle activities while chewing by means of transfer function and coherence function analyses, which are mathematical techniques to calculate the relationship of two signals in the frequency domain.

Transfer function analysis evaluates the relative amplitude and delay of one signal against the other at each frequency [6–9], while the coherence function analysis evaluates the synchrony of two signals at each frequency [10–13]. Applying transfer function and coherence function analyses to two EMG signals, and evaluating the results at the first peak frequency allows the relative strength, time difference, and synchrony of two muscle activities during the chewing rhythm to be quantitatively evaluated in healthy subjects. This information can also be used to elucidate the power coordination and temporal coordination of jaw and neck muscle activities while chewing in temporomandibular disorder (TMD) and whiplash-associated disorder (WAD).

In this study, jaw closing and opening muscles and neck muscle related to chewing are evaluated via EMG-EMG transfer function and coherence function analyses. This is a novel study to define the physiological features in the coordination between jaw and neck muscle activities while chewing in healthy subjects.

2. Materials and methods

2.1. Subjects

Twenty male volunteers (mean age 24.3 years, range 20–32 years) participated in this study. The sample size was estimated by the program G*Power 3 (noncommercial program that can be downloaded from University of Dusseldorf, Germany) [14], which hypothesizes the parameters with a significance level of 0.05, a statistical power of 0.8, and an effect size of 0.25 (medium effect). Because the necessary sample size was 17, we planned to recruit a minimum of 20 participants to detect significant differences. Subjects were recruited among Nihon University Dentistry at Matsudo staff members and dental students. Subjects had complete dentitions and normal occlusions measured with pressure sensitive sheets (Dental Prescale 50H R type, Fuji Photo Film, Tokyo, Japan). All subjects were free from pain and dysfunctions in the oromandibular, maxillofacial, head, or neck and shoulder regions. The screening questionnaire and protocol of the hospital affiliated with Nihon University Dentistry at Matsudo were used to recruit and examine the subjects. Prior to the study, each subject provided informed consent according to the World Medical Association's Declaration of Helsinki. This study was approved by the Committee on Ethics of Nihon University School of Dentistry at Matsudo (No. EC-12-008).

2.2. Experimental procedures

The subjects were comfortably seated in an upright position without back support or a headrest. A piece of chewing gum (1 cm^3, 1 g, hardness; 9.3×10^3 Pa·s, tasteless gum, Lotte, Tokyo, Japan) was used as the test food. The subjects performed two chewing sessions, one on the right and the other on the left side, in random order. First, a bolus of chewing gum was placed in the mouth at rest. Then the subject was verbally instructed to chew at the beginning and the ending of chewing session on one side. The session was repeated on the other side. The recording time on each session was 80 s (this time was decided from the analysis time described later).

2.3. Recording of surface electromyography

EMG signals in the jaw and neck muscles were recorded using surface EMG electrodes. After cleaning the skin with ethanol, a pair of bipolar Ag/AgCl electrodes 7 mm in diameter was attached to the skin overlying the muscles. The electrodes were positioned bilaterally on the center of masseter (Mm, jaw closing muscle), anterior temporal (Ta, jaw closing muscle), anterior digastric (AD, jaw opening muscle) muscles, and on the insertion of sternocleidomastoid (SCM, neck extensor/protrusion/rotator muscle) muscle in parallel to the direction of muscle fibers with an inter-electrode distance in 20 mm. In addition, a ground electrode was attached to the left ear lobe. The EMG signals were amplified (Polygraph Bioelectric ampl 1253A, San-ei MED, Tokyo, Japan), with a high frequency cut-off filtered at 1 kHz and a time constant of 0.03 s. The amplified EMG signals were digitized with 16-bit resolution by an A/D converter (APA16-32/2(OB) F, CONTEC, Tokyo, Japan), and were downloaded onto a personal computer at a sampling rate of 1 kHz.

2.4. Analysis in the frequency domain

The recorded EMG signals were analyzed using a software package (Multi Scope EMG/Ver. 1.8.4, Medical Try System, Tokyo, Japan). Frequency analysis of the EMG signals was conducted using the method described by Halliday et al. [15] where the EMG signals were full wave rectified (Fig. 1A). Fast Fourier Transform (FFT) analysis [16] was used to calculate the power spectrum (i.e., the power of the voltage signal at each frequency) of the EMG signals from 0 to 500 Hz (Fig. 1B). Hereafter, the prefixes of ‘C’ and ‘NC’ denote the chewing side and non-chewing side muscles, respectively (e.g., chewing and non-chewing side Mm values are expressed as C-Mm and NC-Mm).

To secure an adequate frequency resolution for the chewing cycle and confidence value in the coherence function analysis, an analysis time of 61.5 s was selected for the following reasons:

1) The frequency resolution in the FFT analysis depends on the number of samples analyzed. To acquire a smaller frequency resolution, more samples are necessary, requiring a longer recording time.
2) The confidence level (*CL*) in the coherence function analysis, which ensures that the coherence reaches a statistically significant level, depends on the average number of analysis segments. *CL* with a probability of 95% ($\alpha = 0.05$) is determined using the following equation

$$CL = 1 - 0.05^{1/(L-1)} \tag{1}$$

where *L* is the number of segments used in the coherence analysis [15]. If the coherence exceeds *CL*, it is statistically significant. To acquire a lower *CL* value, more segments are necessary, which also requires a longer recording time.

3) Therefore, to acquire a sufficient frequency resolution and *CL* while minimizing the recording time, the number of samples in a segment was set to $2^{12} = 4096$ (4.096 s) and the number of segments *L* was set at 15, resulting in a 0.24 Hz frequency resolution, 0.19 *CL*, and 61.5 s analysis time (4.096 s × 15 segments).

In the transfer function analysis, the relationships between the input signal to the transfer function and the output signal from the transfer function were evaluated by considering the relative strength and time lag of the output signal versus the input signal. The relative strength was calculated as the gain value in the transfer function analysis,

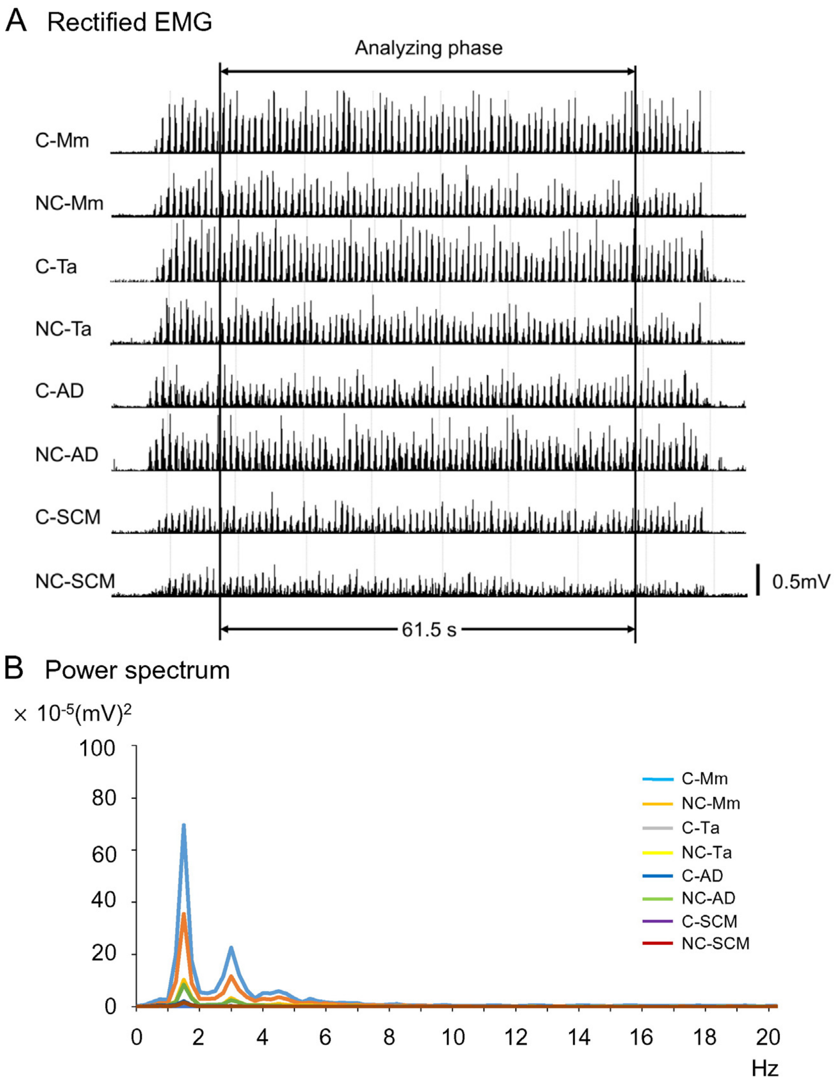

Fig. 1. EMG activities and power spectrum obtained by FFT. (A) Rectified EMG signals of the jaw and neck muscles while chewing gum for 80 s in a representative subject. Area between the vertical lines indicates the analyzing phase (61.5 s). Full wave rectification of the EMG signals is used in this study. (B) Power spectrum of the jaw and neck muscle EMG signals obtained by FFT from 0 to 20 Hz. Power spectra of the rectified EMG for all muscles are characterized from the first peak frequency.

which reflects the change in the variability of the output signal in response to the changes in the input signal [6,7,9]. The time lag was given as the phase value, which represents the temporal relationship in the phase [6,8,9]. For example, if the phase at a certain frequency is 180 degrees, the frequency components of the two signals are completely inverted. Based on the concept of a transfer function, the neural activity of the central pattern generator in the brainstem should be used as the input signal, but measuring the activity in the brainstem is difficult in human experiments. Because the agonist muscle (C-Mm) plays an agonist role and may also undergo a profound effect from the central pattern generation in the brainstem, C-Mm was used as the reference signal (i.e., the input signal of the transfer function) and all other muscles, which were synergist (NC-Mm and C-/NC-Ta), the antagonist (C-/NC-AD), and neck (C-/NC-SCM) muscles were used as the examined signals (i.e., the output signal of the transfer function).

The transfer function $H(f)$ between the input and output signals was calculated using the cross-spectral technique [17]. $Sxx(f)$ represents the auto-correlation function of the input signal, while $Sxy(f)$ denotes the cross-correlation function between the input and output signals.

$$H(f) = \frac{S_{xy}(f)}{Sxx(f)} \tag{2}$$

The gain $|H(f)|$ and phase $\Phi(f)$ were calculated as

$$|H\ (f)| = \frac{\left[H_R\ (f)^2 + H_I\ (f)^2\right]}{Sxx(f)} \tag{3}$$

$$\varnothing(f) = tan^{-1}\left[\frac{H_I\ (f)}{H_R\ (f)}\right] \tag{4}$$

where $H_R(f)$ and $H_I(f)$ are the real and imaginary part of $H(f)$, respectively.

The coherence $Coh^2(f)$, which indicates the synchrony between two signals and ranges from 0 to 1 [6], was obtained as shown below. $Sxx(f)$ and $Syy(f)$ represent the auto-correlation functions of the input and output signals, respectively.

$$Coh^2\ (f) = \frac{|Sxy\ (f)|^2}{[Sxx\ (f)Syy\ (f)]} \tag{5}$$

If two signals have complete synchrony at a given frequency, the coherence value is one, but as the synchrony deteriorates the values becomes closer to 0.

2.5. Analysis items

Because the first peak is evident in the power spectrum and represents the chewing rhythm, the gain, phase, and coherence were analyzed in the first peak frequency of the power spectrum. Fig. 2A–D show the power spectra of C-Ta, C-AD, and C-SCM and the corresponding muscle gain, phase, and coherence of a representative subject. The correlations between the phase, gain, and coherence were examined to further estimate the intermuscular relationships.

In addition, the power ratio was calculated using the cumulative power from 0 to 500 Hz in the power spectrum, where the powers of the examined muscles (NC-Mm, C-/NC-Ta, C-/NC-AD and C-/NC-SCM) were divided by the power of the reference muscle (C-Mm). The power ratio was used to evaluate the reliability of the gain value.

2.6. Statistical analyses

Because none of the data obtained for the gain, phase, and coherence in the first peak frequency passed the Kolmogorov-Smirnov test for a normal distribution, the data were statistically examined using Friedman's repeated measured analysis of variance on rank to compare the examined muscles, whereas Dunn's method was used for multiple comparisons as a post-hoc test. Pearson's correlation coefficient was used to estimate the relationships among data for the gain, phase, coherence, and power ratio. Statistical analyses were performed using SigmaStat (3.11 Systat Software, Inc, CA, USA), and the results were considered significant when the value for comparison was <5%.

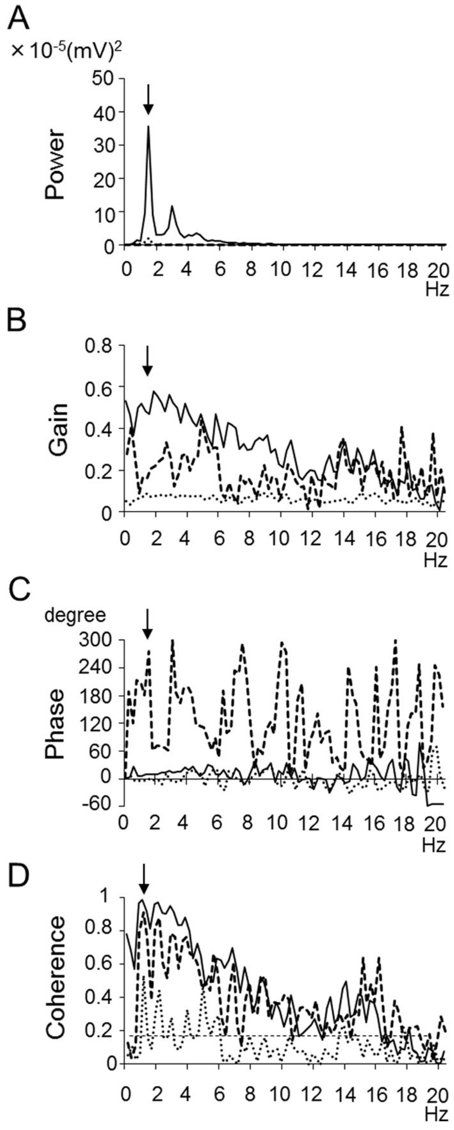

Fig. 2. Representative EMG activities, gain, phase, and coherence in the jaw and neck muscles. C-Ta, C-AD, and C-SCM are shown in a representative subject. (A) Power. (B) Gain. (C) Phase. (D) Coherence. Arrows indicate the first peak frequency. Horizontal line in D denotes the 95% confidence level (0.19) for the coherence spectrum.

3. Results

3.1. First peak frequency of the jaw and neck muscle activities during rhythmic chewing

The peak frequencies of all muscles were evaluated while chewing gum on the left and right side. Each subject exclusively shows a first peak frequency throughout all jaw closing, jaw opening, and neck muscle EMG signals during rhythmic chewing. For right side chewing, seven, eleven, and two subjects exhibited a first frequency of 0.98 Hz, 1.22, and 0.46 Hz, respectively. The average and standard deviation (SD) of the peak frequency is 1.21 ± 0.17 Hz. Fig. 3 shows the results of chewing gum on the right side. The results for left side are similar (1.16 ± 0.16 Hz). The gain, phase, and coherence values obtained for each individual first peak frequency are analyzed below.

3.2. Gain and the relationship between the gain and the power ratio of the jaw and neck muscles

We evaluated the gain of the examined muscles [jaw closing (NC-Mm and C-/NC-Ta), jaw opening (C-/NC-AD), and neck (C-/NC-SCM)] while chewing gum on exclusively the left or right side. The gains were significantly different among the muscles (Friedman test, $p < 0.05$). For right side chewing, the gain of the jaw closing muscle (NC-Mm and C-/NC-Ta) is significantly higher than those of the C-/NC-AD and C-/NC-SCM muscles (Dunn's Method, $p < 0.05$) (Fig. 4). The gains for left side chewing are similar to those of the right side.

The relationship between the gain and the power ratio was examined. There is a significant positive correlation between the gain and the power ratio in jaw closing muscles (NC-Mm and C-/NC-Ta), C-/NC-AD, and C-SCM (Pearson's correlation coefficients range between 0.40 and 0.84, $p < 0.05$), whereas no significant correlation is observed in NC-SCM.

3.3. Phases of the jaw and neck muscles

The phases of the examined muscles were evaluated while chewing gum exclusively on the left or right side. The phases were significantly different among the muscles (Friedman test, $p < 0.001$). For right side

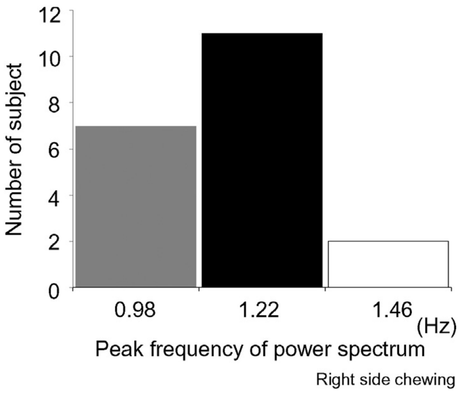

Fig. 3. Number of subjects and the first peak frequency in the power spectrum of the jaw and neck muscle activities while chewing gum on the right side. Number of subjects showing the first peak frequency at each frequency is indicated. All subjects show an exclusive peak frequency throughout all jaw and neck muscle activities.

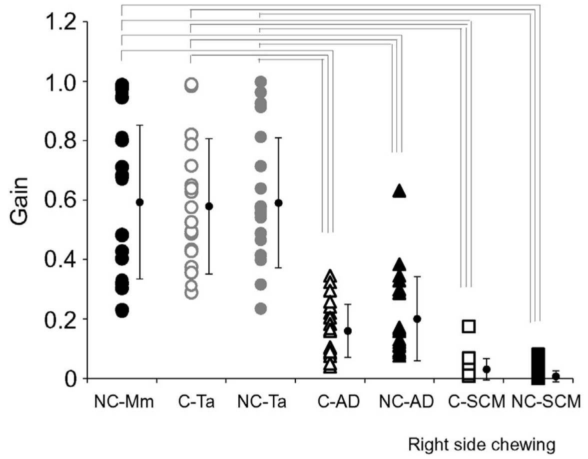

Fig. 4. Gain in the first peak frequency of the jaw and neck muscle activities for individual subjects. Dots and error bars represent the mean values and standard deviation, respectively. Inter-muscle lines show significant differences (Friedman test and Dunn's Method, $p < 0.05$) between the jaw and neck muscles. Gain for the jaw closing muscles is significantly greater than that for the jaw opening and neck muscle activities.

chewing, the phases of jaw closing (NC-Mm and C-/NC-Ta) and C-SCM muscles are synchronized. Additionally, the phases of jaw closing muscles (NC-Mm and C-/NC-Ta) show significant anti-phase activity to C-/NC-AD (Dunn's Method, $p < 0.05$). Furthermore, the phase of SCM shows a significant anti-phase activity to AD (Dunn's Method, $p < 0.05$). The phase of NC-SCM is broadly distributed from the jaw closing phase to the opening phase. Fig. 5 shows the results for chewing gum on the right side. The phases of the jaw closing and jaw opening muscles and neck muscle on the left side are similar to those for chewing on the right side.

3.4. Coherence of the jaw and neck muscles

The coherence of the examined muscles was evaluated while chewing gum exclusively on the left or right side. The coherences were significantly changed among the muscles (Friedman test, $p < 0.001$). When chewing on the right side, the coherence of two jaw closing muscles (NC-Mm and C-Ta) is significantly higher than that of C-/NC-AD (Dunn's Method, $p < 0.05$), while the coherence of three jaw closing muscles (NC-Mm and C-/NC-Ta) is significantly higher than that of C-/NC-SCM (Dunn's Method, $p < 0.05$). Furthermore, the coherence of NC-SCM had broadly distributed features between the low and high coherence values. Fig. 6 shows the results of chewing gum on the right side. The results for chewing on the left side are similar to those on the right side.

3.5. Correlation between the gain, phase, and coherence

The relationships between the gain, phase, and coherence were evaluated in regard to all examined muscles for right and left side gum chewing. For jaw closing and opening muscles (NC-Mm, C-/NC-Ta and C-/NC-AD), none of the combinations (gain vs. phase, gain vs. coherence and phase vs. coherence) are significantly correlated. On the contrary, neck muscles show different correlation results. Although the C-SCM is not significantly correlated for any combination, a significant negative correlation is found between the phase and coherence in the NC-SCM (Fig. 7). The correlative coefficient value between the phase and the coherence for right and left side chewing is $r = -0.729$ (Pearson's correlation coefficient, $p < 0.001$) and $r = -0.715$ (Pearson's correlation coefficient, $p < 0.001$) respectively. Fig. 7 shows the linear regression equation results.

4. Discussion

4.1. Significance of EMG-EMG transfer function and coherence function analyses for evaluating the coordinated features between the jaw and neck muscle activities while chewing

All subjects exclusively showed the first peak frequency throughout all jaw closing, jaw opening, and neck muscle EMG signals; the average peak frequencies were 1.21 Hz (1.16 Hz) for right (left) side chewing (Fig. 3). The power spectrum has several other peaks (Figs. 1B, 2A), which are considered to be harmonics of the first peak [18]. For example, if a sinusoidal signal with frequency *f* is distorted, the frequencies composing the signal are expressed as integer multiples of *f* (i.e., *f*, 2*f*, 3*f*, 4*f*, etc.), and the first harmonic (i.e., *f*) is termed the fundamental frequency and the peaks in the higher frequency bands are called harmonics. The chewing rhythm has been reported at 1.22 Hz [19], 1.01–1.12 Hz [20], 1.00–1.03 Hz [21], and 1.24–1.25 Hz [22]. Based on these

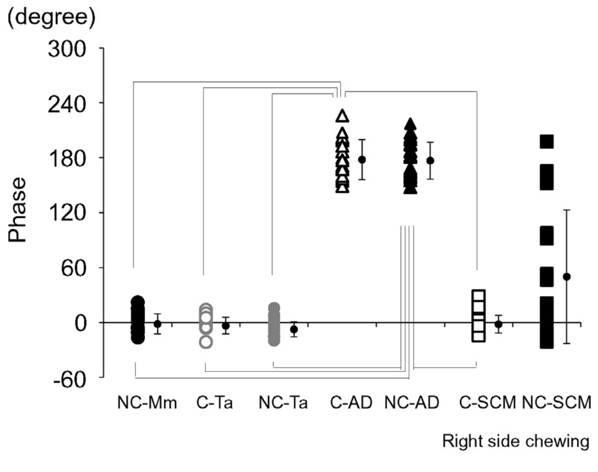

Fig. 5. Phase in the first peak frequency of the jaw and neck muscle activities for individual subjects. Dots and error bars represent the mean values and standard deviation, respectively. Inter-muscle lines show significant differences (Friedman test and Dunn's Method, $p < 0.05$) between the jaw and neck muscle activities. Phases for the jaw closing muscle and C-SCM activities are synchronized, while the phase for jaw opening muscle activity is presented as an anti-phase to jaw closing and C-SCM activities. Furthermore, the phase for the NC-SCM is broadly distributed across the jaw closing and jaw opening phases.

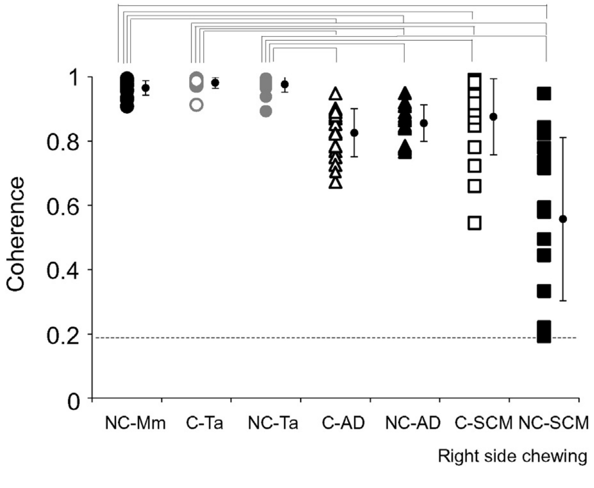

Fig. 6. Coherence in the first peak frequency of the jaw and neck muscle activities for individual subjects. Dots and error bars represent the mean values and standard deviation, respectively. Inter-muscle lines show significant differences (Friedman test and Dunn's Method, $p < 0.05$) between the jaw and neck muscles. Coherence in the jaw closing muscle activity is significantly higher than those in the jaw opening and neck muscle activities. Coherence in the NC-SCM shows broadly distributed features. Horizontal lines show the 95% confidence level (0.19) for the coherence spectrum.

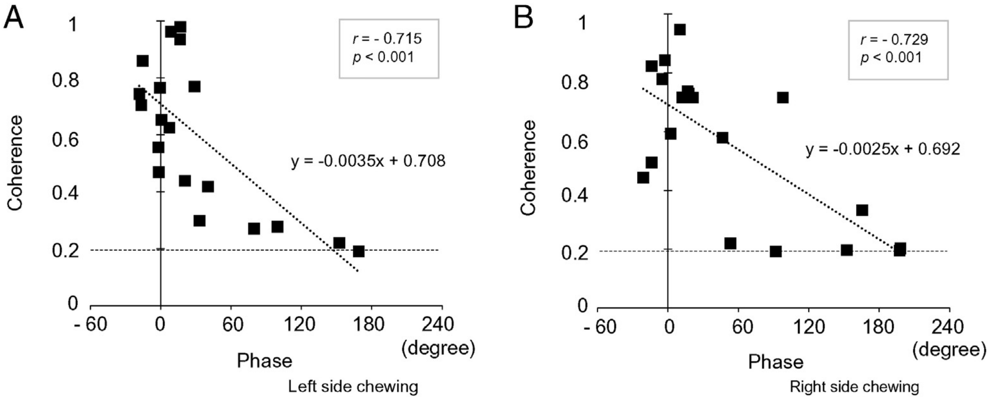

Fig. 7. Correlation between phase and coherence of NC-SCM activities. Graphs representing the correlation between the phase and the coherence of NC-SCM activities in both right (A) and left (B) side chewing. Correlation coefficient, *p*-values, and the linear regression equation are shown. Both left and right side chewing show a significant (Pearson's correlation coefficient, $p < 0.001$) negative correlative coefficient.

previously reported chewing rhythms, the first peak frequency in the present study is interpreted as the aggregation of the chewing rhythm in the jaw and neck muscle activities. Consequently, this study focuses on the first peak frequency.

The gain presented the values below 1.0, referred to C-Mm activity (Fig. 4), and which is supporting the past basic concept that C-Mm is the predominant jaw and neck muscle activity while chewing [23–27]. In the analysis of the bio-signals using the transfer function, the relationships between the input signal to the bio-system and the output signals from the bio-system have been investigated and described as the relationships between input and output variabilities [9], the relative amplitude [6,7] and transmissibility [28]. This study also presented a significant positive correlation is observed between the power ratio and the gain in all examined muscles except for the non-chewing side neck muscle (NC-SCM). These positive correlations in jaw muscles and C-SCM activities suggest that the gain can be interpreted as the power coordination and relative amplitude relationships referred to the C-Mm activity while chewing. On the other hand, the relationship between the power ratio and gain for NC-SCM is insignificant. Hence, we speculate that NC-SCM poorly aggregated into the first peak frequency fits the chewing rhythm. Thus, NC-SCM may be involved not only in the jaw function but also other motor functions such as head movements and/or head stabilization during rhythmical chewing [29].

The phase indicated that bilateral jaw closing muscles and C-SCM activities are synchronized, but bilateral jaw opening muscles are activated with anti-phase synchronization while chewing (Fig. 5). Rilo et al. [21] reported that jaw closing muscles (right and left side masseter and temporalis muscles) activities are synchronized, and Vitti and Basmajian [23] reported that the jaw opening muscle act in antagonism with the jaw closing muscles while chewing. Additionally, Plesh et al. [30] reported that the temporal aspects of activity in the masseter and anterior temporalis muscles are very similar while chewing gum. Moreover, it has been reported that C-SCM activities are concomitant with jaw closing muscle activities in rhythmic chewing [1,3,4]. These previous findings and our novel data in Fig. 5 suggest that the phase parameter in EMG-EMG transfer function analysis may elicit the temporal relationships in jaw and neck muscle activities during rhythmic chewing. The phase in the present study also reveals novel findings; the NC-SCM activity is broadly distributed across jaw closing and jaw opening muscle activities in rhythmic chewing, implying a personal variability in the phase characteristics in NC-SCM activities.

The coherence in synergistic activities occurred between bilateral jaw muscles and C-SCM activities (Fig. 6). However, similar to the phase characteristics (Fig. 5), NC-SCM has a broad distribution in coherence (Fig. 6). In addition, the coherence and phase in NC-SCM activities display significant negative relationships (Fig. 7), indicating that different types of coordination of neck muscle activities can be estimated while chewing. Thus, when the NC-SCM is co-activated with jaw closing muscle activities, bilateral coordination between the jaw and neck muscle activities can be estimated. In contrast, the synchrony of the NC-SCM activity deteriorates when the NC-SCM activity deviates from closing activity (Fig. 7). Hence, we propose that bilateral or unilateral (chewing side predominant) synchronized coordination between jaw and neck

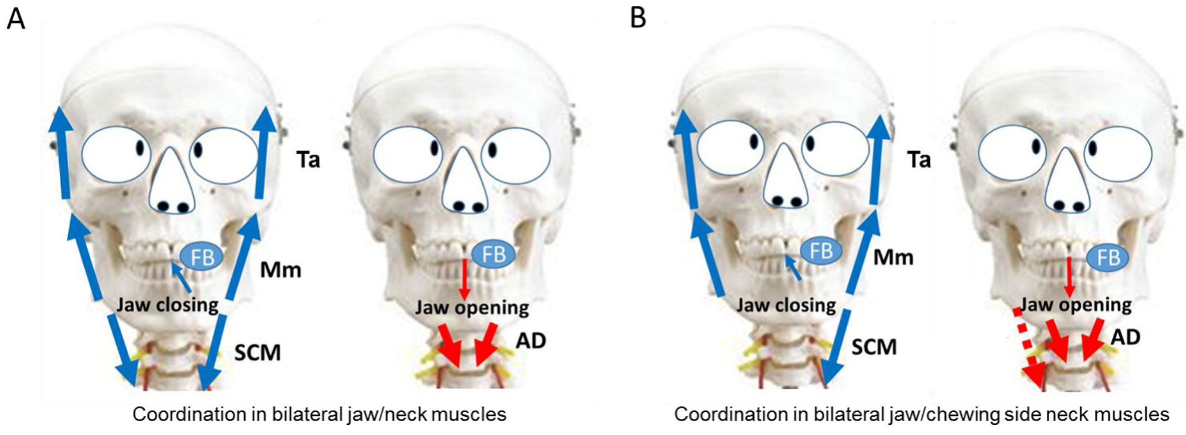

Fig. 8. Schema of jaw and neck muscle coordination while chewing gum on the left side in healthy controls. Schema (A) showing possible coordination among bilateral jaw and neck muscles when the NC-SCM is activated in the jaw closing phase during rhythmic chewing. Contrasting schema (B) showing possible coordination among the unilateral jaw and chewing side neck muscles when the NC-SCM is irregularly activated in the jaw opening phase during rhythmic chewing. FB = food bolus on the chewing side.

muscle activities while chewing corresponds to the phase characteristics in the NC-SCM activity while chewing (Fig. 8).

4.2. Physiofunctional backgrounds in the coordination between jaw and neck muscle activities while chewing and its clinical implications

It has been reported that the SCM activities while chewing do not differ significantly between the working and non-working sides in subjects with mediotrusive tooth contact of the non-working side, whereas the SCM activities in the working side is higher than that in non-working side in the subjects without the mediotrusive tooth contact in the non-working side [31]. Considering other orofacial motor task performances such as jaw clenching, jaw opening and closing task performances, bilateral jaw clenching produces the bilateral neck muscle activation, while unilateral jaw clenching produces unilateral and clenching side predominant neck muscle activity [32]. The neck muscle and jaw opening muscle activities are concomitant in the jaw-opening phase [33]. Further, the head extends during jaw opening and head flexion during the jaw closing phase in cyclic jaw movement performance [34]. Taking these neck muscle activations in other orofacial motor task performances in healthy subjects into account, the SCM activity in rhythmic chewing may be influenced by the personal variabilities in occlusion as well as jaw and head movement characteristics, reflecting the broadly distributed phase and coherence characteristics of the NC-SCM activities in rhythmical chewing.

In addition, it has also been reported that patients with TMD show disabilities not only in jaw functions but also in the remote sensorimotor function in the cervical region [19,35–37]. With regard to the jaw and neck muscle EMG findings in TMD, Ries et al. [36] found that a smaller symmetry of the temporalis muscle, masseter muscle, and sternocleidomastoid muscle activities in the TMD, while Ferreira et al. [19] reported a greater variability in the coordination of jaw muscle activities and the less accurate recruitment of the jaw muscle activities while chewing in the TMD. Furthermore, patients with WAD, who complain of pain and dysfunction in mouth opening [38] and avoid tough or large pieces of food [39], also present greater fluctuations of head movements as well as jaw opening and closing movement cycles [34]. Considering these pathological features in the jaw and neck muscle activities in TMD and WAD, clinical application of EMG-EMG transfer function analysis and EMG-EMG coherence function analysis may quantitatively present the patho-functional relationships between jaw and neck muscle activities by means of the gain as the amplitude relationship, the phase as the temporal relationship, and the coherence as the synchrony in TMD and WAD patients while chewing.

5. Conclusion

We quantitatively investigated the coordinated features in the jaw and neck muscle EMG signals during rhythmic chewing using EMG-EMG transfer function and EMG-EMG coherence function analyses. Well-coordinated jaw and neck muscle activities are present when the non-chewing side neck muscle activation is synchronized with jaw closing muscle activities while chewing. In contrast, chewing side predominant coordination occurs when the non-chewing side neck muscle activity is irregularly activated in the jaw opening phase. These findings suggest that EMG-EMG transfer function and EMG-EMG coherence function analyses may be useful to quantitatively assess the pathological in-coordinated jaw and neck muscle activities while chewing.

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Disclosure

The authors declare no conflicts of interest.

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