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Coherence Analysis of Jaw and Neck Muscle Coordination during Chewing in Healthy Adults

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Purpose: Coordinated activity between the jaw and neck muscles is important in oral motor tasks such as chewing. This study examined coherence between the jaw and neck muscles during chewing in healthy adults.

Methods: A total of 12 healthy adults underwent electromyography (EMG) of the jaw and neck muscles during right-sided chewing at a frequency of 1 Hz. Surface electrodes were placed over the temporalis (TA), masseter (MS), anterior digastric (DA), and sternocleidomastoid (SM) muscles on the right side. EMG signals were processed for coherence and phase analysis using advanced signal processing techniques.

Results: The MS and TA muscle pair exhibited high synchronization when chewing (median coherence=0.992). Contrarily, the coherence values between the MS and DA, as well as the MS and SM muscle pairs, were relatively low (median coherence=0.848 and 0.957, respectively). Phase analysis revealed minimal temporal differences between the MS and TA muscle pair and the MS and SM muscle pair, whereas substantial phase shifts were observed between the MS and DA muscle pair.

Conclusions: During chewing in healthy adults, the TA muscle works synergistically whereas the DA muscle antagonistically with the MS muscle, and the SM muscle supports the activity of the MS muscle. The observed synchrony and coordination provide insights into the intricate interplay among these muscles during oral motor tasks.

Keywords: Coherence; Electromyography; Masticatory muscles; Muscle coordination; Neck Muscles

INTRODUCTION

Muscle coordination involves the harmonious interplay of various muscle groups, encompassing coactivation, synergistic, and antagonistic relationships [1]. Coordinated actions between the jaw and neck muscles often exhibit functional coupling, where their activities synchronize to facilitate various oral motor tasks [2,3]. The functional relationship between these muscles is important in the coordination of intricate movements associated with mastication and head positioning [4,5].

The masseter is a powerful jaw-closing muscle that elevates the mandible during biting and chewing. It facilitates the initial stages of closing the jaw and exerting force during the power stroke of chewing. During clenching or chewing, the temporalis and masseter muscles exhibit synergistic relationships, facilitating jaw closure [6,7]. Alternatively, the digastric muscle assists in the initial phase of jaw opening, particularly in controlling the descent speed and direction of the mandible. While it is not a direct antagonist to the masseter, the digastric muscle has opposing functions in its primary actions during chewing as it mainly involves jaw opening rather than closing. The sternocleidomastoid (SM) muscle is a neck muscle with various functions, such as flexing, rotating, and tilting the head and neck. In addition, it plays a role in the chewing process as it helps stabilize the head and neck during jaw movements [8-10].

The coordination pattern of the masticatory muscles was evaluated using various indices calculated as the ratio of muscle activity intensity of muscle pairs [11-13]. Recent studies have employed coherence analysis to reveal complex coordination patterns between the jaw and neck muscles [14,15]. This analytical approach reveals the subtle interactions that control orofacial motor tasks by analyzing the synchrony and functional relationships between the involved muscles during various oral and mandibular movements.

Coherence serves as a measure of synchronization between two signals [16]. Coherence analysis involves computation of the average estimates of the cross-power spectrum and power spectra within segments, a method first introduced by Welch [17]. The coherence value reaches one when two signals exhibit complete synchrony at a specific frequency. Conversely, diminishing synchrony between signals causes the coherence values to approach zero. Transfer function analysis evaluates how an input signal interacts with the resulting output signal by considering its relative strengths and temporal alignment. Within this analysis, the gain value quantifies the relative strength, indicating how alterations in the input signal correspond to changes in the variability of the output signal [16,18]. Meanwhile, the phase value reveals the time lag between the signals [16,19]. For example, a phase of 180° at a specific frequency indicates complete inversion of the frequency components between the signals, elucidating their temporal relationship.

Against this background, the present study aimed to explore the coherence, gain, and phase interactions between the jaw and neck muscles during mastication in healthy adults. Specifically, surface electromyography (EMG) was employed to evaluate the relationship between the major jaw and neck muscles to understand their synchrony, interaction strength, and temporal alignment during chewing at a frequency of 1 Hz. For preliminary exploration for expanded follow-up research, this study first attempted to investigate the coordination between the jaw and neck muscles on the ipsilateral side under a unilateral mastication condition. The test hypothesis was that no coherence, gain, or phase interactions exist between the jaw and neck muscles during chewing in healthy adults.

MATERIALS AND METHODS

1. Ethical Approval

Ethical approval was obtained from the Institutional Review Board of Chonnam National University Dental Hospital (CNUDH-2021-002). All experimental procedures were performed in accordance with the principles of the latest revision of the Declaration of Helsinki. Each participant was informed about the study procedure and provided written informed consent before participation.

2. Subjects

The included subjects had no tooth loss except for third molars, no crossbite, an anterior overbite and overjet <4 mm, a dental midline discrepancy <3 mm, and no horizontal tooth mobility. The exclusion criteria were subjects with temporomandibular disorders (TMDs), neck pain, neurological disorders, prolonged medication exceeding 1 month, current orthodontic treatment, and any known history of trauma or surgery in the head and neck regions.

Volunteers were recruited through a bulletin board posting at the Chonnam National University Dental Hospital. Among the 26 volunteers, 8 who did not meet the inclusion criteria and 6 who had errors in the EMG measurement or problems with the quality of the EMG recordings were excluded, resulting in the inclusion of 12 subjects in the final analysis. The volunteers and participants received differential financial support depending on their participation level. The researcher who led this study took on multiple roles, including overseeing recruitment, conducting screening evaluations, selecting participants, and performing subsequent EMG measurements.

3. Surface EMG Detection

A pair of surface electrodes was placed on the skin of the left and right sides of the anterior portion of the temporalis (TA), superficial masseter (MS), the anterior belly of the digastric (DA), and SM muscles. The positioning of the surface electrodes for the TA and MS muscles was described in a previous study [20]. The electrodes were positioned approximately midway between the mental and hyoid attachments for the DA muscle and halfway between the mastoid process and sternal notch for the SM muscle. Before electrode application, the skin was meticulously cleaned with 83% v/v ethanol. Disposable, monopolar, disc-type, Ag/AgCl surface electrodes with a 10-mm diameter were affixed to the skin using adhesive gel (T246H; Bio Protech). The electrode pairs were spaced at a fixed distance of 20 mm and secured with adhesive tape. As a reference electrode, a single monopolar electrode was placed over the skin over the spinous process of the seventh cervical vertebra. Each circular electrode had a conducting surface diameter of 14 mm.

Myoelectric signals from each electrode setup were amplified using an eight-channel single differential EMG system (WEMG-8 [LXM5308]; Laxtha). The signal was amplified within a bandwidth of 13 to 430 Hz (Butterworth filter; −3-dB response; with slopes of the cutoffs: low-pass 48 dB/octave, high-pass 12 dB/octave), sampled at a rate of 1,024 Hz, and digitized through a 10-bit A/D converter using a differential amplifier. This amplifier had an input impedance exceeding 100 MΩ, a high common-mode rejection ratio (>90 dB), and an input signal amplitude ranging from 312.5 μVp to 5 mVp. The resultant EMG signals were either monitored or stored as data files on the hard disk drive of a personal computer, facilitated by a dedicated software (TeleScan ver. 3.01; Laxtha).

4. Experimental Protocol

The task and EMG recordings for the study subjects were performed in a controlled environment—an isolated, quiet room equipped with a dental chair as well as regulated lighting and temperature. Each participant assumed an upright position in a comfortable chair without a headrest, maintaining a natural and unsupported posture. With their gaze fixed on a wall positioned 2 m in front of them, they were given precise instructions regarding the experimental protocol.

Resting muscle activity was initially recorded for a duration of 10 s, assessing both the relaxation of the monitored muscles and any noise within the recorded myoelectric signals. For the chewing task, the participants were instructed to begin by chewing two pieces of gum (Xylitol Original Gum; Lotte Wellfood). Then, with their eyes closed, they were prompted to chew the gum with their right molars at a frequency of 60 strokes per minute (equivalent to one stroke per second, synchronized with a metronome set at ♩=60) while focusing on the beat of the metronome. Concurrently, EMG signals were continuously recorded for 20 s throughout the chewing task.

5. Signal Processing

Of the eight channels capturing EMG signals during the chewing task, only the four channels on the right side were used for analysis. The raw EMG signals obtained from the recordings underwent digital filtering within a low-pass range of 0-500 Hz and a band-stop frequency of 60 Hz. Subsequently, the filtered signals were converted into text files using a dedicated software (TeleScan version 3.01; Laxtha).

Thereafter, signal analyses were conducted on the EMG datasets using Python 3.9.0 (https://www.python.org/) along with the SciPy (https://scipy.org/) and NumPy (https://numpy.org/) modules. The EMG signals were processed as absolute values, ensuring that all data points were converted to positive numbers (Fig. 1A, B). The power spectrum of the EMG signal within the range of 0-500 Hz was computed using the fast Fourier transform (FFT) algorithm, implemented using the *scipy.fft* function (Fig. 1C, D).

As the segmentation of the EMG record dataset increases, the confidence level in the coherence function analysis diminishes, as observed in a previous study [14]. The low- and high-coherence values become statistically significant due to the reduction in data points per segment when the number of segments increases. Such a reduction results in decreased frequency resolution, as calculated using the following formula:

$$\text{Frequency resolution}=\frac{\text{Sampling frequency}}{\text{Number of data points}}$$

Here, sampling frequency refers to the number of samples taken per unit time, and the number of data points denotes the total number of samples used in the FFT algorithm. Increasing the number of data points (i.e., length of the signal) enhances the frequency resolution. Consequently, data gathering over an extended period yields more data points, improving the frequency resolution of the FFT.

In this study, the 20-s EMG recordings were divided into four segments. As the sampling frequency was 1,024 Hz, 20,480 data points were obtained for 20 s of recordings. Given the segmentation into four parts, each segment comprised 5,120 data points (acquired over 5 s). Consequently, the resulting frequency resolution was 0.2 Hz (1/5 s).

Coherence analysis was employed to evaluate the relationship between the two sets of EMG data in the frequency domain. The coherence function is mathematically expressed as follows and was obtained using the following *scipy.signal.coherence* function:

$$Coherence=\frac{|S_{xy}(f)|^2}{S_{xx}(f)S_{yy}(f)}$$

Here, $S_{xx}(f)$ and $S_{yy}(f)$ denote the power spectral densities obtained using the *scipy.signal.welch* function, whereas $S_{xy}(f)$ denotes the cross-spectral density derived from the *scipy.signal.csd* function. In this study, the reference signal was MS (input signal for the transfer function), whereas TA, DA, and SM were considered as the signals under examination (output signal for the transfer function). Conceptually, TA acts as a synergist with MS, whereas DA functions as an antagonist to MS.

The transfer function $H(f)$ was initially derived using the following equation:

$$\text{Transfer function}\quad H(f)=\frac{S_{xy}(f)}{S_{xx}(f)}$$

From this transfer function, both the gain and phase values were obtained. With $H(f)$ being a complex number, the *numpy.abs* function was used to calculate the gain ($|H(f)|$) and the *numpy.angle* function to determine the phase ($\varnothing(f)$):

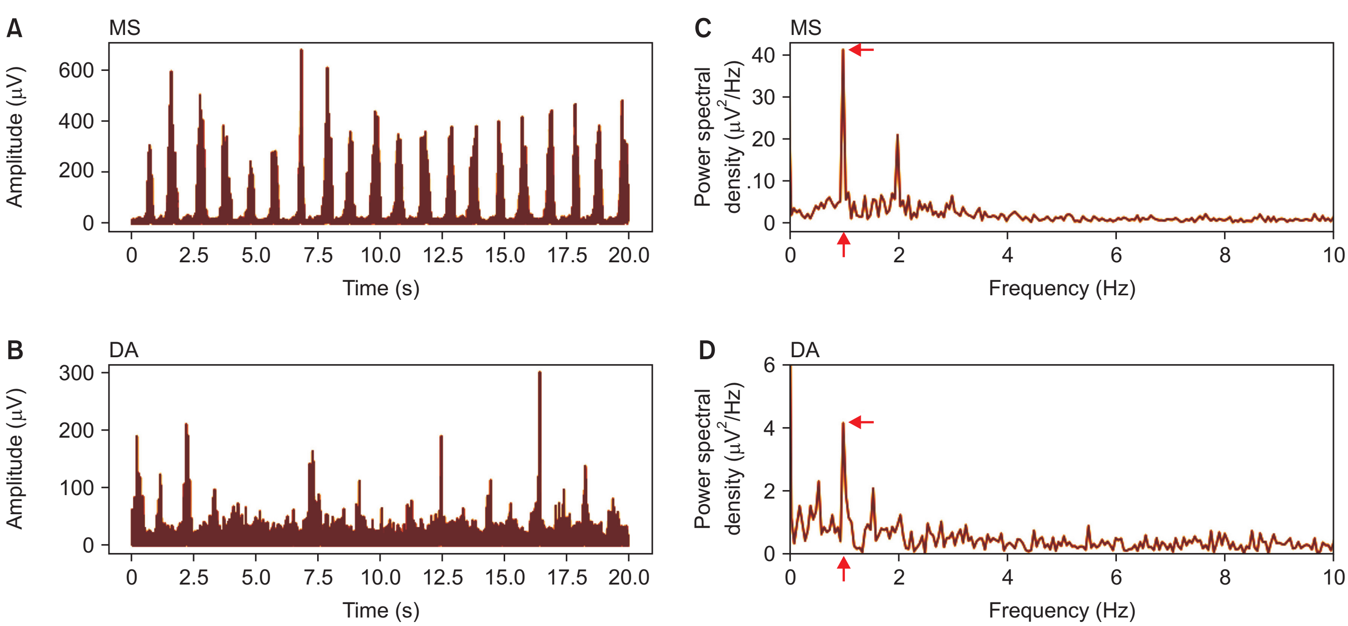


Fig. 1. Example of electromyography recordings of the MS and DA muscles with absolute value processing (A, B) and their power spectrum obtained using the FFT algorithm (C, D). The FFT algorithm converts a time-domain signal into its frequency components. The power spectra (C, D) selectively show the range of 0-10 Hz out of the entire range of 0-500 Hz to examine the low-frequency region. Red arrows indicate data points at 1 Hz corresponding to the chewing rhythm. MS, superficial masseter muscle; DA, anterior belly of the digastric muscle; FFT, fast Fourier transform.

$$\text{Gain} \quad |H(f)| = \frac{H_R(f)^2 + H_I(f)^2}{S_{xx}(f)}$$

$$\text{Phase} \quad \varnothing(f) = tan^{-1}\left(\frac{H_I(f)}{H_R(f)}\right)$$

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

In the power spectrum where MS was the reference signal, the primary peak distinctly emerged at 1 Hz (Fig. 1C), corresponding to the chewing rhythm frequency. Hence, all the coherence, gain, and phase (unit: rad) values were determined at a frequency of 1 Hz within the power spectrum. Fig. 2 presents an example of the coherence, gain, and phase relationship between the EMG signals of the MS and DA muscles. The analysis encompassed coherence, gain, and phase evaluations across the following muscle pairs: MS and TA, MS and DA, and MS and SM. Notably, the phase values were converted from radians to degrees before statistical analysis.

6. Statistical Analysis

The normality assessment using the Shapiro–Wilk test showed that not all data followed a normal distribution. Consequently, medians and interquartile ranges were used as measures of central tendency and dispersion. Given the nonnormal distribution, nonparametric statistical tests were employed for all subsequent analyses.

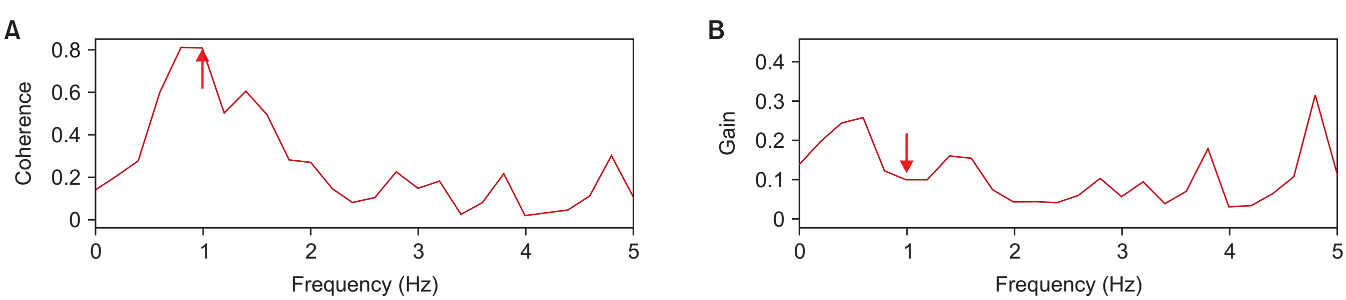
The pairwise median differences between the experimental conditions were evaluated using the Friedman test along with *post hoc* Wilcoxon signed-rank tests, incorporating the Bonferroni correction for multiple comparisons. The Friedman test was explicitly used to detect significant differences in coherence, gain, and phase among the following muscle pairs: MS and TA, MS and DA, and MS and SM. In the Friedman ANOVA tests, $p<0.05$ was considered to indicate statistical significance. Furthermore, for *post hoc* analyses with Bonferroni correction, the significance threshold was set at $p<0.017$. Statistical analysis was conducted using IBM SPSS Statistics for Windows, Version 21.0 (IBM Co.).

Following the Friedman test conducted across three muscle pairs for coherence with 12 participants, post-analysis evaluation using G*Power 3.1 [21] revealed a significant effect size (partial η^2=0.617, Cohen's d=1.269), and the actual power of 0.941 achieved exceeded the desired threshold (1-β) of 0.9. These results confirm the adequacy of the sample size for detecting significant effects within this experimental setup.

RESULTS

1. Participants

A total of 12 healthy young adult subjects (eight female participants and four male participants; mean age, 26.6±2.4 years) were included in the final analysis after screening.



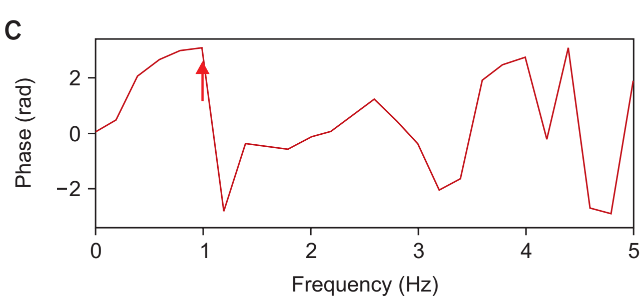


Fig. 2. Example of coherence (A), gain (B), and phase (C) between the superficial masseter and the anterior belly of the digastric muscles. Red arrows indicate data points at the 1-Hz frequency corresponding to the chewing rhythm.

The mean±standard deviation (SD) height and weight of the subjects were 168±6 cm and 61.3±10.0 kg, respectively. Furthermore, their mean±SD body mass index (BMI) was 21.5±2.4 (range, 19.0 to 27.3) kg/m^2.

2. Coherence of the Jaw and Neck Muscles

The median coherence value for the MS and TA muscle pair was 0.992, almost reaching 1.0. Contrarily, the median values for the MS and DA muscle pairs and MS and SM muscle pairs were 0.848 and 0.957, respectively, which were lower than those of the MS and TA muscle pair (Table 1, Fig. 3). Significant differences were observed in coherence values among the muscle pairs ($\chi^2(2)=17.167$, $p<0.001$). *Post hoc* analysis revealed that both MS and DA (Z=–3.059, p=0.002) and MS and SM (Z=–2.981, p=0.003) muscle pairs exhibited significantly lower coherence than the MS and TA muscle pair. However, no statistically significant difference was observed between the MS and DA or between the MS and SM muscle pair (Z=–1.726, p=0.084) (Fig. 3).

3. Gain of the Jaw and Neck Muscles

The MS and TA muscle pair exhibited a median gain of 0.458, followed by the MS and DA muscle pair with a median gain of 0.201. The MS and SM muscle pair had the smallest median gain at 0.025, nearly approaching 0 (Table 1, Fig. 4). Significant differences in gain values were observed across muscle pairs ($\chi^2(2)=20.667$, $p<0.001$). *Post hoc* analysis revealed that both the MS and DA (Z=–2.824, p=0.005) and MS and SM (Z=–3.059, p=0.002) muscle pairs had significantly lower gain values than the MS and TA pair. In addition, the MS and SM pair exhibited significantly lower gain values than the MS and DA pair (Z=–3.059, p=0.002) (Fig. 4).

4. Phase of the Jaw and Neck Muscles

The median phase values for the MS and TA and MS and SM muscle pairs were 1.40° and –0.05°, respectively, approaching 0°. Contrarily, the median phase for the MS and DA muscle pair was –192.85°, close to –180° (Table 1, Fig. 5). A significant discrepancy in phase values was observed among muscle pairs ($\chi^2(2)=18.000$, $p<0.001$). The phase values of the MS and DA muscle pair were significantly

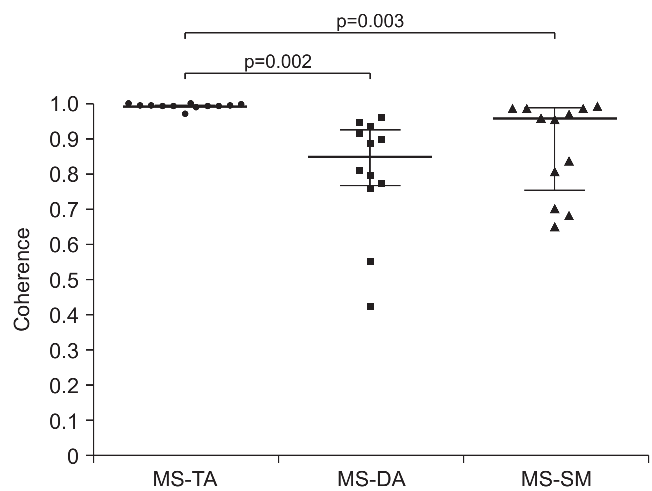


Fig. 3. Coherence values of the three muscle pairs at the 1-Hz frequency. In the scatterplot of each muscle pair, the thick horizontal line represents the median, and the two thin horizontal lines represent the first and third quartile values, respectively. MS, superficial masseter muscle; TA, anterior portion of the temporalis muscle; DA, anterior belly of the digastric muscle; SM, sternocleidomastoid muscle. The "–" sign between two muscles indicates a pair of those two muscles. Friedman one-way ANOVA with *post hoc* Wilcoxon signed-rank test.

Table 1. Descriptive statistics of the coherence, gain, and phase values

Muscle pair	Coherence			Gain			Phase (°)		
	MS-TA	MS-DA	MS-SM	MS-TA	MS-DA	MS-SM	MS-TA	MS-DA	MS-SM
Maximum	0.998	0.958	0.990	1.110	0.394	0.054	11.0	–101.5	44.5
Third quartile	0.996	0.927	0.984	0.658	0.258	0.032	7.38	–174.85	18.55
Median	0.992	0.848	0.957	0.458	0.201	0.025	1.40	–192.85	–0.05
First quartile	0.991	0.762	0.726	0.395	0.082	0.013	–2.43	–207.35	–2.73
Minimum	0.969	0.423	0.648	0.288	0.022	0.004	–12.5	–273.2	–21.0
Range	0.029	0.535	0.342	0.822	0.372	0.050	23.5	171.7	65.5

MS, superficial masseter muscle; TA, anterior portion of the temporalis muscle; DA, anterior belly of the digastric muscle; SM, sternocleidomastoid muscle.
The "–" sign between two muscles indicates a pair of those two muscles.

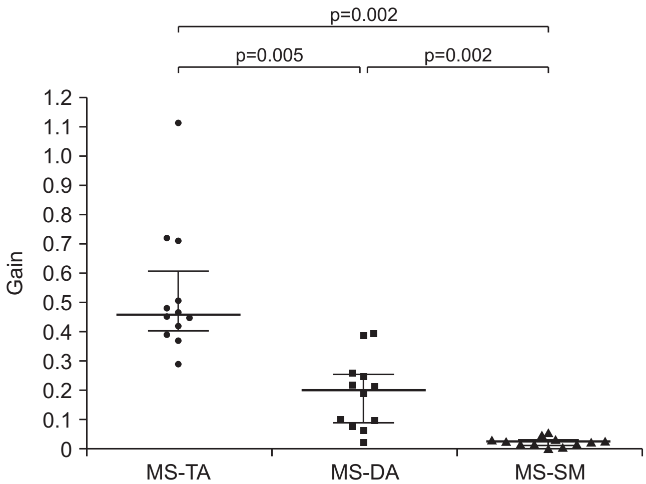


Fig. 4. Gain values of the three muscle pairs at the 1-Hz frequency. In the scatterplot of each muscle pair, the thick horizontal line represents the median, and the two thin horizontal lines represent the first and third quartile values, respectively. MS, superficial masseter muscle; TA, anterior portion of the temporalis muscle; DA, anterior belly of the digastric muscle; SM, sternocleidomastoid muscle. The "–" sign between two muscles indicates a pair of those two muscles. Friedman one-way ANOVA with *post hoc* Wilcoxon signed-rank test.

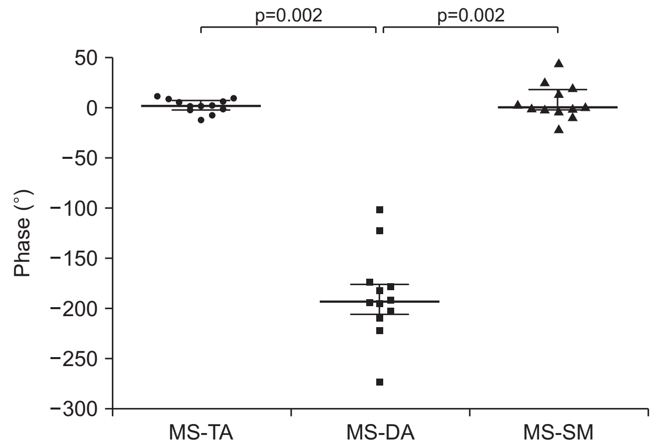


Fig. 5. Phase values of the three muscle pairs at the 1-Hz frequency (unit: °). In the scatterplot of each muscle pair, the thick horizontal line represents the median, and the two thin horizontal lines represent the first and third quartile values, respectively. MS, superficial masseter muscle; TA, anterior portion of the temporalis muscle;DA, anterior belly of the digastric muscle; SM, sternocleidomastoid muscle. The "–" sign between two muscles indicates a pair of those two muscles. Friedman one-way ANOVA with *post hoc* Wilcoxon signed-rank test.

lower than those of the MS and TA muscle pair (Z=–3.059, p=0.002) and MS and SM muscle pair (Z=–3.059, p=0.002). However, no statistically significant difference was observed between the MS and TA muscle pair and the MS and SM muscle pair (Z=–0.628, p=0.530) (Fig. 5).

DISCUSSION

The present study investigated the intricate coordination between the jaw and neck muscles during chewing in healthy adults, examining the coherence, gain, and phase relationships between specific muscle pairs.

The results indicated a closely intertwined functional relationship between the TA and MS muscle pair, suggesting that their synchronized and coordinated activity is crucial for efficient chewing movements. High-coherence values between these muscles imply robust synchronized activity, a strong functional relationship that facilitates efficient and coordinated jaw movements. Gain values possibly reflect the influence or dominance of one muscle over the other, where a higher gain from the MS to the TA muscle may indicate a significant impact or control during chewing. Furthermore, consistent phase alignment between the two muscles implies coordinated temporal relationships, potentially facilitating smooth and synchronous muscle contractions important for effective chewing.

The phase difference between the activity of the DA muscle and that of the MS muscle was –193°, close to –180°. This suggests that the DA muscle exhibits an antiphase to the MS muscle, potentially antagonizing the activity of the MS muscle and preceding it in initiating the opening motion during each stroke. In this study, the negative phase values for the MS and DA muscle pair are contrary to the positive values reported in other studies [3,14,22]. As the phase repeats in a 360° cycle, both –180° and 180° indicate an antiphase relationship. Lower coherence levels may imply insufficient simultaneous or coordinated action between the DA and MS muscles. Lower gain values can indicate a balanced or less-dominant influence of the MS muscle over the DA muscle. These findings may be partially due to the characteristics of surface EMG signal obtained from the attachment site of the DA muscle. Due to the crosstalk phenomenon [23], signals from adjacent suprahyoid muscles possibly influence the signals from the DA muscle; as a result, signals obtained from this location may not purely reflect the activity of the DA muscle.

As regards the SM and MS muscle pair, higher coherence values between these muscles suggest synchronized or coordinated activity during chewing. Low gain values indicate that the SM muscle facilitates the action of the MS muscle during chewing, whereas consistent phase alignment signifies synchronized temporal relationships, contributing to coordinated jaw movements important for efficient chewing. Comparable studies conducted under similar experimental conditions reported coherence, gain, and phase values of the jaw and neck muscles on the chewing side that were closely consistent with the findings of this study [3,14].

Chewing rhythm defines an individual's chewing pattern and speed and is often observed to fall within the range of 1.0-1.25 Hz [24-26]. Coherence analysis revealed that the frequency of the chewing rhythm closely aligns with that in previous studies using other existing methods. In adults with normal teeth, coherence analysis revealed an average first peak frequency of the jaw and neck muscles during gum chewing of 1.15 to 1.25 Hz [3,14,22]. For denture wearers, this peak was observed at 1.37 Hz [22]. Ishii et al. [14] reported that this initial peak in the power spectrum is consistent with the chewing rhythm, providing insights into the power, temporal, and synergistic relationships between the jaw and neck muscles in healthy subjects.

However, in our study, the subjects exclusively chewed gum at a frequency of one stroke per second, synchronized with a metronome set at 1 Hz. Comparison of our findings with those of studies conducted under habitual chewing conditions may not be directly feasible. The coherence patterns observed might differ for several reasons. Habitual gum chewing involves natural muscle coordination, whereas chewing at a specified frequency imposes a rhythm that may adjust muscle synchrony or desynchrony, potentially altering coherence levels [27]. Furthermore, chewing at a frequency of 1 Hz may prompt specific muscle responses, leading to detectable changes in synchronization patterns. In this study, the first peak at 1.0 Hz was evident in the power spectra of all three muscle pairs. Moreover, habitual chewing engages a wider range of muscles due to varying food textures and intensities [28]. Chewing at a controlled frequency can limit muscle recruitment, influencing coherence patterns because of altered muscle engagement [29]. Additionally, rhythmic chewing might induce motor control adaptations [30,31], potentially affecting the observed muscle coordination dynamics in coherence analysis. Further studies should delve deeper into these inferences to elucidate the nuances.

Coherence analysis finds diverse applications across various conditions. Ishii et al. [3] reported that chewing rhythm, quantitative and temporal coordination, and functional coordination in jaw and neck muscle activities remained unchanged during soft and hard gum chewing or increased jaw and neck muscle activities. Narita et al. [22] demonstrated that gain values in individuals wearing dentures for jaw closing and opening decreased compared with those without dentures. Denture wearers exhibited comparable gain values for these activities to young subjects but had higher coherence values for neck muscle activities on the chewing and nonchewing sides. Additionally, Fassicollo et al. [15] investigated muscle coordination in patients with TMDs. Their findings indicated prolonged chewing stroke duration as well as impaired differential recruitment and coherence among the TA, MS, and SM muscles. Furthermore, they observed peak timing delays and temporal asynchrony between the jaw and neck muscles.

According to the BMI standards of the World Health Organization [32], 1 subject in this study who had a BMI of 27.3 kg/m^2 was classified as overweight whereas the remaining 11 subjects were classified as normal. In general, individuals with higher BMI values tend to have a higher proportion of body fat, including both subcutaneous and visceral fats. Subcutaneous fat can influence the amplitude and mean frequency estimates of surface EMG signals [33,34]. Although BMI can be a contributing factor, its direct influence on EMG signals might not follow a linear or easily quantifiable pattern. Other individual variations, such as muscle structure, hydration levels, and electrode placement precision, also contribute to signal variability [35-38]. Similarly, the coherence, gain, and phase of surface EMG signals are believed to be indirectly affected by BMI or subcutaneous fat thickness and influenced by multiple factors. Upon reviewing the coherence, gain, and phase data of the subject with an overweight BMI in this study, the gain value of the MS and SM muscle pair was an outlier, whereas the others were not.

This study has several limitations. First, the sample size was relatively small, limiting the ability to discern potential gender-based differences in coherence between women and men within jaw and neck muscle coordination. Second, the study employed a single chewing task to explore the coordination between the jaw and neck muscles. Examination of various mastication movements would have provided a more comprehensive understanding of the complexity of muscle coordination. In addition, analysis of the coordination of muscles on only one side of the body associated with chewing on the right side limited an expanded assessment of bilateral muscle interactions. Third, the surface EMG device used for the measurements exhibited inherent limitations. For example, crosstalk effects could have reduced the accuracy of the signal from the muscles to be monitored. This is particularly true for the DA muscle, as it has a small volume and the suprahyoid muscles are nearby. Finally, the inclusion of only healthy adults in this study made it difficult to generalize the results to populations with disease conditions such as TMDs or oral motor disorders.

Future studies should have a larger sample size and include healthy individuals and populations with various diseases. Furthermore, future investigations should explore various oral motor tasks using improved EMG equipment and techniques to understand the broader dynamics of muscle coordination and increase the accuracy of muscle activity assessment.

In conclusion, this study provides valuable insights into the coherence, gain, and phase relationships between the jaw and neck muscles during chewing movements in healthy adults. The TA muscle synergistically coordinates with the MS muscle, whereas the DA muscle exhibits antagonistic characteristics. Additionally, the SM muscle facilitates the activity of the MS muscle. The observed patterns of synchrony and coordination among specific muscle pairs highlight the intricate interplay involved in oral motor tasks. Understanding the nuanced interactions between these muscle groups holds promise for elucidating normal oral motor function and potential implications for therapeutic interventions in orofacial movement disorders.

CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

DATA AVAILABILITY STATEMENT

Participants in this study did not provide written consent for the public sharing of their data. Because of the sensitive nature of the research, supporting data are not available for public access.

FUNDING

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AUTHOR CONTRIBUTIONS

Conceptualization: YGI. Formal analysis: HJS, SHH, YGI. Funding acquisition: YGI. Methodology: HJS, SHH, YGI. Project administration: YGI. Writing - original draft: HJS, YGI. Writing - review & editing: HJS, SHH, JYK, YGI.

REFERENCES

1. Latash ML. Muscle coactivation: definitions, mechanisms, and functions. J Neurophysiol 2018;120:88-104.
2. Zafar H, Nordh E, Eriksson PO. Temporal coordination between mandibular and head-neck movements during jaw opening-closing tasks in man. Arch Oral Biol 2000;45:675-682.
3. Ishii T, Narita N, Endo H, et al. Coordinated features in jaw and neck muscle activities induced by chewing of soft and hard gum in healthy subjects. Clin Exp Dent Res 2021;7:868-876.
4. Eriksson PO, Häggman-Henrikson B, Nordh E, Zafar H. Co-ordinated mandibular and head-neck movements during rhythmic jaw activities in man. J Dent Res 2000;79:1378-1384.
5. Zafar H. Integrated jaw and neck function in man. Studies of mandibular and head-neck movements during jaw opening-closing tasks. Swed Dent J Suppl 2000:1-41.
6. Allami Sanjani M, Tahami E, Veisi G. Synchronous muscle synergy evaluation of Jaw muscle activities during chewing at different speeds, a preliminary study. Brain Sci 2023;13:1344.
7. Farella M, Palumbo A, Milani S, Avecone S, Gallo LM, Michelotti A. Synergist coactivation and substitution pattern of the human masseter and temporalis muscles during sustained static contractions. Clin Neurophysiol 2009;120:190-197.
8. Shimazaki K, Matsubara N, Hisano M, Soma K. Functional relationships between the masseter and sternocleidomastoid muscle activities during gum chewing. Angle Orthod 2006;76:452-458.
9. Giannakopoulos NN, Hellmann D, Schmitter M, Krüger B, Hauser T, Schindler HJ. Neuromuscular interaction of jaw and neck

muscles during jaw clenching. J Orofac Pain 2013;27:61-71.
10. Häggman-Henrikson B, Nordh E, Eriksson PO. Increased sternocleidomastoid, but not trapezius, muscle activity in response to increased chewing load. Eur J Oral Sci 2013;121:443-449.
11. Naeije M, McCarroll RS, Weijs WA. Electromyographic activity of the human masticatory muscles during submaximal clenching in the inter-cuspal position. J Oral Rehabil 1989;16:63-70.
12. Ginszt M, Zieliński G. Novel functional indices of masticatory muscle activity. J Clin Med 2021;10:1440.
13. Ferrario VF, Sforza C, Miani A Jr, D'Addona A, Barbini E. Electromyographic activity of human masticatory muscles in normal young people. Statistical evaluation of reference values for clinical applications. J Oral Rehabil 1993;20:271-280.
14. Ishii T, Narita N, Endo H. Evaluation of jaw and neck muscle activities while chewing using EMG-EMG transfer function and EMG-EMG coherence function analyses in healthy subjects. Physiol Behav 2016;160:35-42.
15. Fassicollo CE, Garcia DM, Machado BCZ, de Felício CM. Changes in jaw and neck muscle coactivation and coordination in patients with chronic painful TMD disk displacement with reduction during chewing. Physiol Behav 2021;230:113267.
16. Zhang R, Zuckerman JH, Giller CA, Levine BD. Transfer function analysis of dynamic cerebral autoregulation in humans. Am J Physiol 1998;274:H233-H241.
17. Welch P. The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. IEEE Transactions on Audio and Electroacoustics 1967;15:70-73.
18. Ehara T, Ogawa Y, Kato J, Aoki K, Ogawa S, Iwasaki K. The effect of dexmedetomidine on arterial-cardiac baroreflex function assessed by spectral and transfer function analysis. J Anesth 2012;26:483-489.
19. Sakagami J, Ono T, Hasegawa Y, Hori K, Zhang M, Maeda Y. Transfer function analysis of cerebral autoregulation dynamics during jaw movements. J Dent Res 2011;90:71-76.
20. Im YG, Han SH, Park JI, Lim HS, Kim BG, Kim JH. Repeatability of measurements of surface electromyographic variables during maximum voluntary contraction of temporalis and masseter muscles in normal adults. J Oral Sci 2017;59:233-245.
21. Faul F, Erdfelder E, Buchner A, Lang AG. Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. Behav Res Methods 2009;41:1149-1160.
22. Narita N, Endo H, Ishii T, et al. Effects of denture wearing on coordinated features of jaw and neck muscle activities during chewing in partially edentulous elderly patients. J Prosthodont Res 2021;65:235-242.
23. Mesin L. Crosstalk in surface electromyogram: literature review and some insights. Phys Eng Sci Med 2020;43:481-492.
24. Youssef RE, Throckmorton GS, Ellis E 3rd, Sinn DP. Comparison of habitual masticatory patterns in men and women using a custom computer program. J Prosthet Dent 1997;78:179-186.
25. Rilo B, da Silva JL, Gude F, Santana U. Myoelectric activity during unilateral chewing in healthy subjects: cycle duration and order of muscle activation. J Prosthet Dent 1998;80:462-466.
26. Tartaglia GM, Testori T, Pallavera A, Marelli B, Sforza C. Electromyographic analysis of masticatory and neck muscles in subjects with natural dentition, teeth-supported and implant-supported prostheses. Clin Oral Implants Res 2008;19:1081-1088.
27. Kravchenko A, Weiser A, Hugger S, Kordass B, Hugger A, Wanke E. Variability and reliability of muscle activity measurements during chewing. Int J Comput Dent 2014;17:21-33.
28. Turcio KH, Zuim PR, Guiotti AM, Dos Santos DM, Goiato MC, Brandini DA. Does the habitual mastication side impact jaw muscle activity? Arch Oral Biol 2016;67:34-38.
29. Hodson-Tole EF, Wakeling JM. Motor unit recruitment patterns 2: the influence of myoelectric intensity and muscle fascicle strain rate. J Exp Biol 2008;211:1893-1902.
30. Thor M, Strohmer B, Manoonpong P. Locomotion control with frequency and motor pattern adaptations. Front Neural Circuits 2021;15:743888.
31. Almotairy N, Kumar A, Trulsson M, Grigoriadis A. Development of the jaw sensorimotor control and chewing - a systematic review. Physiol Behav 2018;194:456-465.
32. Obesity: preventing and managing the global epidemic. Report of a WHO consultation. World Health Organ Tech Rep Ser 2000;894:i-xii, 1-253.
33. Kuiken TA, Lowery MM, Stoykov NS. The effect of subcutaneous fat on myoelectric signal amplitude and cross-talk. Prosthet Orthot Int 2003;27:48-54.
34. Lowery MM, Stoykov NS, Taflove A, Kuiken TA. A multiple-layer finite-element model of the surface EMG signal. IEEE Trans Biomed Eng 2002;49:446-454.
35. Kawase T, Sakurada T, Koike Y, Kansaku K. A hybrid BMI-based exoskeleton for paresis: EMG control for assisting arm movements. J Neural Eng 2017;14:016015.
36. Bartuzi P, Tokarski T, Roman-Liu D. The effect of the fatty tissue on EMG signal in young women. Acta Bioeng Biomech 2010;12:87-92.
37. Minetto MA, Botter A, Šprager S, et al. Feasibility study of detecting surface electromyograms in severely obese patients. J Electromyogr Kinesiol 2013;23:285-295.
38. Nordander C, Willner J, Hansson GA, et al. Influence of the subcutaneous fat layer, as measured by ultrasound, skinfold calipers and BMI, on the EMG amplitude. Eur J Appl Physiol 2003;89:514-519.