A study on the physical properties and reproducibility of marketed foods used to measure continuous masticatory and deglutition functions and the reproducibility and validity of the generated chewing sounds.

（咀嚼音および嚥下音の連続記録に使用する市販食品の物性再現性と発生する咀嚼音の再現性と妥当性に関する研究）

Nihon University Graduate School of Dentistry at Matsudo,

Removable Prosthodontics

Shizuka Tarukawa

(Director: Professor Yasuhiko Kawai)

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Abstract

Study 1 aimed to measure the physical properties of 13 marketed foods and gummy jelly (as a control) to comprehend their physical properties and reproducibility, with the goal of using marketed foods in a new testing method to assess consecutive masticatory and swallowing ability. Gummy jelly (UHA Mikakuto, Japan, Nara) and 13 frequently consumed marketed foods were used to assess the food texture and reproducibility of maximum compressive force. The compressing load and speed were set to 500N at 9.88 mm/s to simulate adults' occlusal force and jaw closing speed during chewing. The pushrod jig pressed the test food 1 mm above the compression plate, and the maximum compressive force was recorded. The means of maximum compressive force were compared between the test foods using a one-way analysis of variance followed by Bonferroni-adjusted multiple comparisons. Hierarchical clustering analysis was conducted with 14 foods using maximum compressive force to interpret relationships between the foods. The reproducibility of foods was assessed by the coefficient of variation (CV). The results suggested that traditional test foods used for assessing masticatory ability, such as gummy jelly and peanuts, exhibited significantly higher maximum compressive force than commonly marketed foods. Hierarchical clustering analysis further indicated dissimilar physical properties between traditional test foods and marketed foods. The foods' reproducibility revealed that gummy jelly exhibited better reproducibility than peanuts. Almonds, kamaboko, and chocolate were identified to have acceptable reproducibility for the new testing method.

Study 2 investigated the reliability and inter-day reproducibility of consecutive sounds from chewing to swallowing under standardized conditions, aiming to establish convergent validity with occluding force and the glucose elution method. Seven males and four females, aged 28.3 ± 2.4 years, participated. Baseline measurements included occlusal force and masticatory performance. In a soundproof room, participants chewed almonds at a set rhythm, with sounds recorded continuously from chewing onset to swallowing. Recordings were processed using time series analysis software,

extracting the first 10 seconds for frequency analysis and dB sum of squares calculation. The process was replicated three times, and the average was used. Inter-day reliability was assessed by replicating the entire procedure on day-1 and day-2. Intraday reliability for the dB sum of squares was evaluated using the intraclass correlation coefficient (ICC: 1,3) separately for each day, with a paired t-test. Simple regression analysis explored associations between dB sum of squares, occlusal force, and glucose elution. Results demonstrated excellent agreement and high reliability across data sets within and between days (day-1: 0.97, day-2: 0.91). A significant negative linear association was observed between the dB sum of squares and occlusal force two, thus, convergent validity was confirmed with occlusal force but not with masticatory performance. These findings suggest potential targets for therapeutic interventions in patients with impaired masticatory function. Future studies will extend examinations across age groups and oral health levels, following the established protocol.

I. Introduction

In Japan's rapidly aging society, maintaining a healthy diet to prevent malnutrition is crucial for extending a healthy life (1, 2). The significant decrease in the number of teeth, especially in older adult individuals, can lead to malocclusion (3, 4). Reduced masticatory functions resulting from impaired occlusion can also impact food intake (5).

Prosthetic intervention, which treats malocclusion and restores functional teeth, plays a crucial role in enhancing masticatory function (6). Accurately assessing each patient's food intake and developing personalized prosthodontic interventions and dietary support advice (7-9) are essential for improving their quality of life. Success in prosthetic intervention relies on optimal treatment planning based on appropriate diagnosis (10). And the assessments of treatment outcomes, masticatory performance, a measure of the comminution of food attainable under standardized testing conditions (11), and swallowing play pivotal roles.

Traditional methods for evaluating masticatory performance (12, 13) and swallowing (14, 15), such as the sieving method (16), color-changeable gum method (17), and glucose elution method via gummy jelly (18) or observing the comminution of gummy jelly (19), are commonly used. However, test foods for masticatory performance, such as peanuts (20, 21), chewing gum (17, 22), and gummy jelly (19, 23, 24), are not regularly consumed. The infrequent consumption of these test foods in daily intake may not adequately represent typical eating habits. Also, these traditional methods have limitations as they require patients to chew test foods for a fixed duration and remove them from the mouth to evaluate crushing or elution. That is to say that these approach captures only a partial aspect of the process, from food intake to swallowing. Therefore, creating a new testing method to consecutively assess masticatory and swallowing function is ideal.

Sounds occur during mastication and swallowing (25-27). Recording consecutive sounds through food intake, mastication, and swallowing, using test food frequently consumed, may address the issues of traditional tests and closely resemble the actual situation. Thus, this study focused on the 'sound' generated during these sequential processes, emphasizing the importance of capturing the entire process from food intake to swallowing (25, 28). While previous studies have explored the sound during tapping occlusion (29) and pseudo-mastication sound (30-32), few have concentrated on evaluating the process from mastication to swallowing. Considering the swallowing assessment, test foods like gum and gummy jelly may not be suitable for evaluating the normality of swallowing functions for a older adult (23). Hence, it is essential to explore methods using widely and safe consumed foods.

To explore widely and safe consumed foods, the food needs to fulfill several requirements. One of the crucial requirements is reproducibility. To use frequently consumed test food, the reproducibility of the physical properties of several foods needs to be investigated compared to control test food, i.e., gummy jelly. Therefore, study 1 aimed to measure the compressive force of 13 marketed foods and gummy jelly (as a control) to understand their physical properties (33, 34) and reproducibility (35) under simulating jaw movement (33, 36). The result of the study is expected to lead to the creation of a new testing method using marketed foods to assess consecutive masticatory and swallowing functions.

With new methods for capturing sounds from food intake to swallowing, ensuring the reproducibility of masticatory sound measurements becomes crucial to avoid systematic error (37). Additionally, assessing the relationship between available masticatory assessments is essential to secure test construct validity (38). Therefore, study 2 aimed to investigate the reliability of the measurements and inter-day reproducibility of consecutive sounds from chewing to swallowing under standardized conditions. The relationship between occluding force and the glucose elution method is also assessed to ensure convergent validity (38).

II. Materials and Methods

1. Study 1

1) Test food

To assess the reproducibility of maximum compressive force, gummy jelly (A test gummy jelly; UHA Mikakuto, Osaka, Japan. hereafter control) and 13 frequently consumed marketed foods were used as the test food to analyze the food texture and reproducibility by maximum compressive force (Figure 1a). The test foods were almond (no salt almond; Clown foods, Yokohama), apple, banana, carrot, cheese (Belcube creamy plane; Bel Japon, Tokyo, Japan), chocolate (Chocolate Bites; Fujiya, Tokyo, Japan), cracker (Nabisco original premium crackers; Mondelēz Japan, Osaka, Japan), cucumber, ham (7 premium loin ham; Premium kitchen, Hyogo, Japan), kamaboko (Kamaboko red; Yuzuki, Tokyo, Japan), konjac (7 Premium namaimo konjac; Akutsu foods, Fukushima, Japan), peanut (Chiba half-roasted peanuts; Kawagoeya, Chiba, Japan), and shallot (Iwashita amarakkyo; Iwashita, Tochigi, Japan). The food was arranged to the standard size (14 mm X 14 mm X 10 mm) using a metal mold（Decorative vegetable cutter; Daiso Industries, Hiroshima, Japan (Figure 1b). The test foods were placed in a sterilized box at room temperature (22°C) and 50% humidity for one hour before measurement to adapt food properties to room temperature and humidity.

2) Maximum compressive force

The maximum compressive force of the test foods and control was measured using a Compact Tabletop Tester (EZ-SX, Shimadzu Corporation, Tokyo) (Figure 2a). Ten maximum compressive force measurements were recorded for each test food and control, with ten samples. The tester has a maximum load capacity of 500N. The crosshead speed ranges from 0.001 to 1000 mm/min, and the maximum return speed is 1500 mm/min. A toothed pushrod jig, similar in shape to a molar, was installed on the tester (Figure 2b), and the test foods were placed on a lower compression plate. The compressing load and speed were set to 500N at 9.88 mm/s to simulate adults' occlusal force and jaw closing speed on chewing (33, 36). The pushrod jig pressed the test food 1 mm above the compression plate, and the maximum compressive force was recorded (Figure 3). The setting of the experimental condition, control of the pressing movement, and data recording were done by Materials Testing Software (TRAPEZIUM X, Shimazu Corporation, Tokyo).

3) Analysis

The highest and lowest values of ten measured data for individual foods and control were removed to avoid measuring error, and the mean and standard deviation were calculated from the remaining eight data. The maximum compressive force was compared between the test foods by one-way analysis of variance followed by Bonferroni-adjusted multiple comparisons as necessary. Statistical significance was set at a p-value of less than 0.05.

Hierarchical clustering analysis was conducted with 14 foods using maximum compressive force to interpret relationships between the foods. The closest two foods are determined by maximum compressive force average similarity and merged into one group. The process continues until all the observations are merged into one large group, producing a hierarchy of groupings from one group to N groups. A dendrogram was depicted to specify the similarity or dissimilarity among the foods using Euclidean distance to allocate test foods to specific clusters.

The reproducibility of measurements to the control was assessed by the coefficient of variation (CV) calculated from test food data. The calculated CVs were collated with clusters generated from the dendrogram to consider selecting commercial foods for a new testing method to assess consecutive masticatory and swallowing functions. Statistical analysis was performed with statistical software (Stata/SE 17.0 for Mac, TX, USA).

2. Study2

1) Subjects

The study comprised seven males and four females, aged 28.3 ± 2.4 years (ranging between 26 and 35 years). The selection criteria included participants in their 20s to 30s, possessing a complete set of 28 teeth, and without any history of temporomandibular joint disease.

2) Test food

Almonds were chosen as the test food due to their demonstrated reproducibility compared to standardized tests (Tarukawa et al., *in press*). The almonds underwent a one-hour drying process at room temperature (22°C, 50% humidity) before utilization to standardize properties.

3) Measurement of masticatory function

(1) Occlusal force

Occlusal force, a reliable measure associated with masticatory performance (4). Participants inserted a film into their mouths and bit for 3 seconds at their maximum bite force. The Bite Force Analyzer software (Bite Force Analyzer, GC, Tokyo, Japan) calculated the maximum bite force.

(2) Masticatory performance

Participants were instructed to chew glucose-containing gummies (Glucolam, GC, Tokyo, Japan) freely for 20 seconds without swallowing the gummies or saliva. Post-chewing, the mouth was rinsed with 10 mL of water, and the mixture was filtered through a mesh. The filtrate, collected with a brush, underwent glucose content measurement using a glucose meter (GS-II, GC, Tokyo, Japan).

4) Sound recording and analysis

(1) Sound collecting device

A High-performance Sound Level Meter (LA-7000, Ono Sokki, Kanagawa, Japan) was employed to capture sounds from chewing to swallowing. The microphone tip was precisely positioned horizontally at 50 mm from the laryngeal ridge, ensuring contact with the skin surface (Figure 4).

(2) Recording of masticatory sound

In a soundproof room, participants seated with the Frankfurt plane parallel to the floor for masticatory sound measurement were instructed to place one almond on the first molar of the masticatory side. This setup aimed to align the onset of mastication. Participants then initiated chewing at a rhythm synchronized with a metronome set to one beat per second. Sounds generated throughout the entire process, from the onset of chewing to swallowing, were continuously recorded. Measurements were conducted three times, with a one-minute interval between each session.

(3) The dB sum of squares

The recorded sound data, saved in WAVE file format, was imported into time series analysis software (Oscope2, Ono Sokki, Kanagawa, Japan). The visual waveform was presented at a sampling frequency of 64,000 Hz, and the first 10 seconds of sound were extracted (Figure 5). This extracted sound data underwent frequency analysis, revealing the power spectrum. Subsequently, the data was transformed into time-dB notation and saved as a CSV file. The CSV file was then imported into a spreadsheet (Microsoft Excel, Microsoft, WA, USA). In this spreadsheet, the dB sum of squares, approximating sound energy, was calculated. This entire process was iterated three times, and the average of the dB-squared sum was utilized as the dB-squared value. The entire process, including recording and analysis, was replicated on both day-1 and day-2 to assess inter-day reliability.

5) Analysis

Intraday reliability among the three calculated data sets for the dB sum of squares was assessed using the intraclass correlation coefficient (ICC). The dataset encompassed 33 ratings of 11 subjects by three dB sum of squares: ICC (1,3). This analysis was conducted separately for both day-1 and day-2. The consistency of ICC values was evaluated by established guidelines for interpretation (35).

To appraise the inter-day reproducibility between day-1 and day-2, a paired t-test was employed. A simple regression analysis was performed for each obtained dB sum of squares, treating them as independent variables, with occlusal force and glucose elution as dependent variables.

Statistical analyses were executed using Stata/SE 17.0 for Mac (StataCorp LLC, TX, USA). The threshold for statistical significance was set at a p-value less than 0.05.

III. Results

1. Study 1

1) Maximum compressive force

Gummy jelly exhibited the highest average value (271.1N) and was significantly higher than the other 13 test foods ($p<0.01$). Peanuts showed the next highest value (177.4N), significantly higher than the other 12 test foods ($p<0.01$). The maximum compressive force results for other foods and their intergroup differences are illustrated in Figure 6. Alphabetical labels above each bar indicate significant differences, with the same alphabet indicating no significant differences between the foods.

2) Hierarchical clustering analysis

The dendrogram of hierarchical clustering is shown in Figure 7. It is estimated to produce a hierarchy of groupings into four clusters. A similarity was observed between peanuts and gummy jelly, considered as traditional test foods (Cluster 1). Shallot and almond are merged (Cluster 2). Bananas, cheese, and konjac were merged (Cluster 3), and cracker cucumber, apple, carrot, and chocolate were merged together (Cluster 4). In summary, Cluster 1 comprised foods with the highest compressive force, followed by Clusters 2 and 4, while Cluster 3 represented foods with the lowest compressive strength.

3) Reproducibility of measurement

The reproducibility of measurements relative to the control was assessed using the coefficient of variation (CV) calculated from test food data (Figure 8). The calculated CVs were compared for each cluster generated from the dendrogram to inform the selection of commercial foods. The control, Gummy jelly, showed a CV of 11.8%. Foods with CVs lower than the control included chocolate (3.6%), kamaboko (4.2%), carrots (8.7%), and konjac (10.5%). In Cluster 1, Gummy jelly exhibited a smaller CV than peanuts. In Cluster 2, almonds had a smaller CV than shallot. In Cluster 3, kamaboko showed a smaller CV than the other four foods. In Cluster 4, chocolate demonstrated a better CV than the other foods.

2. Study 2

1) Intraday and inter-day reliability of the dB sum of squares

Figure 9 illustrates the individual ratings of the three data sets for the dB sum of squares of 11 subjects on day-1 and day-2. The estimated correlation between individual ratings was 0.97 (95% confidence interval 0.92 to 0.99) for day-1 and 0.91 (95% confidence interval 0.78 to 0.97) for day-2, indicating excellent agreement and high reliability of individual ratings for the three data sets (35).

The paired t-test revealed no significant difference between day-1 and day-2 (day-1: average 3,789,871, day-2: average 3,634,430 dB sum of squares, $p = 0.181$), indicating the consistency across the different day.

2) Regression analysis

Figure 10 illustrates the scatterplot of obtained dB sum of squares as independent variables (y) and occlusal force as dependent variables (x). A significant negative linear association was observed between the two variables, indicating that occlusal force can predict sound ($y = -1065.74x + 5.1e+06$, Adjusted R-squared: 0.436, $p = 0.02$).

In contrast, Figure 11 illustrates no significant linear association between the dB sum of squares and masticatory function ($y = -3995.08x + 4.7e+06$, Adjusted R-squared: 0.039, $p = 0.56$).

IV. Discussion

Study 1 aimed to measure the compressive force of 13 marketed foods and gummy jelly (as a control) to understand their physical properties and reproducibility, with the goal of creating a new testing method to assess consecutive masticatory and swallowing ability.

The results indicated that traditional test foods, including gummy jelly and peanuts, exhibited significantly higher maximum compressive force than commonly marketed foods. The hierarchical clustering analysis provides valuable insights into the grouping of foods based on their physical properties, offering a clearer understanding of the relationships and differences among the tested items. Reproducibility assessment, employing coefficient variances and clustering, demonstrated that gummy jelly exhibited better reproducibility than peanuts. Additionally, among commonly marketed foods, almonds, kamaboko, and chocolate showed acceptable reproducibility for the new testing method. These observed differences align with the study's goals, offering valuable insights into assessing masticatory and swallowing ability using marketed foods.

The evaluation of masticatory ability is increasingly crucial in a super-aging society, given its impact on general health and the associated risks of frailty and death in older adults (1-5, 20). Nevertheless, variations in masticatory ability between dentate and edentulous individuals, as well as between younger and older adults (5, 20), highlight the complexity of this assessment. Gummy jelly (24) is intended for testing masticatory ability in dentate and edentulous individuals, which may present challenges for some edentulous individuals in dividing it into two pieces. Therefore, alternative methods or test foods, such as half-size gummy jelly, have been investigated for edentulous or frail individuals (5, 23).

These results could be incorporated into future assessments utilizing marketed foods as test subjects. The findings unveiled four clusters from 12 foods. Notably, shallots and almonds emerged as the second food clusters with the highest compressive strength, following gummy jelly and peanuts. Almonds exhibit advantageous reproducibility, potentially unaffected by temperature or humidity. However, it is essential to note that shallots may influence physical stability due to their high-water content.

In the third cluster, comprising banana, cheese, konjac, ham, and kamaboko, these foods exhibited the lowest compressive strength among those tested, with kamaboko showing the highest reproducibility. Kamaboko, a processed seafood product, possesses a natural elasticity. Its texture resembles gummy jelly, with significantly lower compressive strength than gummy jelly.

Consequently, kamaboko could be a viable substitute for gummy jelly, particularly for older adults with diminished masticatory function or oral frailty.

The fourth cluster comprised chocolate, carrot, apple, cucumber, and crackers, which were less elastic and required more effort to bite off. Chocolate exhibited the highest reproducibility, closely followed by carrot. Chocolate and carrots have the potential as test foods available in the market. However, it is crucial to note that chocolate is temperature-sensitive and may require precise control under certain conditions. In contrast, being less susceptible to external factors, carrot proves to be more manageable.

Study 1 acknowledges several limitations. One significant factor is the unknown condition of the crosshead speed used to measure the compressive force of foods, simulating adults' jaw-closing movement. The available data suggests a crosshead speed of 8.1 mm/sec for subjects in their 20s (36). However, reports from the literature on textural profile analysis of tofu using mechanical compression tests show variations in crosshead speeds, ranging from 10 to 300 mm/min (34). Some studies indicate that higher crosshead speeds (e.g., 10 mm/sec vs. 0.8 mm/sec) may decrease rupture stress values (33). In this study, anticipating assessments of older adults in the future, a temporary crosshead speed of 10 mm/second was set to simulate jaw-closing speed. Additionally, the size of testing foods varied, including almonds, cheese, chocolate, crackers, peanuts, and shallots. The diverse sizes and shapes of these foods may influence the value of compressive force.

Since this study primarily compared commercial foods, focusing on comminution, and biting as observed in test foods like gummy jellies and peanuts, another limitation raised in this study is the need to consider other food characteristics, such as maximum compressive force, cohesiveness, and elasticity. The stickiness of food can also impact masticatory efficiency, especially in patients wearing prostheses. However, factors like cohesion, elasticity, and stickiness are crucial in understanding masticatory performance but have yet to be explicitly addressed. Thus, future studies will incorporate these aspects for a more comprehensive analysis.

Despite these limitations, the novel findings of this study highlight that marketed foods exhibit different physical properties compared to traditional test foods that are easier to chew. The classification into three categories and clarifying which foods to use, based on reproducibility comparable to the control food (gummy jelly), provide valuable insights. Consequently, the results of this study can be applied to a new testing method using marketed foods to assess consecutive masticatory and swallowing functions.

Study 2 aimed to investigate the reliability of measurements and the inter-day reproducibility of consecutive sounds from chewing to swallowing under standardized conditions to minimize systematic errors. Additionally, the relationship between occluding force and the glucose elution method is assessed to ensure convergent validity. The results indicated excellent agreement and high reliability of individual ratings for the three measurement datasets within day-1 and day-2. Furthermore, the absence of a significant difference between day-1 and day-2 suggests consistency in measurements across different days. Convergent validity was confirmed with occlusal force but not with masticatory performance.

Another challenging aspect involves utilizing waveforms of the collected data to observe sound characteristics over time. The data are then aggregated as a sum of squares in decibels (dB) to capture the actual state of sound over a certain period, effectively responding to the ups and downs of sound fluctuations.

The data obtained through multiple measurement methods and analyses may be susceptible to systematic errors. The primary emphasis of the present study was on the repetition of the entire process, including the subject settings and the collection and analysis of masticatory sounds, which were performed three times in one day. The results remained consistent even when the same procedures were repeated on a subsequent day, providing a basis for future studies. Additionally, the test must be manageable for the patient with a single measurement; in this respect, we have made a step towards making the test practical.

Ensuring that the test measures valid values require verification. For this purpose, the relevance to existing tests needs confirmation. The results confirmed a significant negative association with occlusal force, assessing the initial stage of the process up to swallowing. Notably, the higher the bite force, the fewer masticatory sounds are produced, as indicated by dB square, an approximation of sound energy. Although no relationship between masticatory sound and masticatory efficiency was found, the results suggest a potential negative linear relationship within the range of masticatory efficiency below 220 mg/dl. In the future, we aim to extend the initial 10-second recordings and reevaluate the relationship with masticatory efficiency. The negative association between acoustics and masticatory parameters was also found in previous research (28), which aligns with the findings of this study.

Study 2 acknowledges several limitations. While the ultimate aim is to collect sounds from chewing to swallowing, the reproducibility has been confirmed for 10 seconds after chewing starts. The collection of sounds during swallowing will be part of the next stage. Despite these limitations and based on the confirmed reproducibility of the initial period, we plan to implement multiple sound collection methods, from ingestion to swallowing, to achieve optimal reproducibility.

A second limitation is the age range of the subjects, who are in their 20s and 30s, leaving uncertainties about how older adults might respond. In this study, masticatory sounds were collected at a rhythm of once per second using a metronome. However, the method of sound collection may vary under the influence of different oral health levels in older adults. This aspect is addressed in the study's protocol, where we will examine the impact of oral health status on masticatory sounds and measurement methods. Building on the current study's results, we plan to extend our examination to edentulous and dentulous subjects aged 60 years and over who wear complete dentures. Furthermore, reliability when different raters are involved in testing must be considered.

Despite these limitations, the novel findings from this study, which demonstrate the reproducibility of specific sound collection methods and data obtained can inform future research from the start of feeding to swallowing. The significant association with occlusal force, an existing examination item in the maxillofacial system, and the suggestion that masticatory sounds may be enhanced by reduced occlusal force are considered valuable insights. These findings may lead the way for improved targets in therapeutic interventions for patients with impaired masticatory function. In the future, following the study protocol, we aim to conduct further examinations across all age groups and various levels of oral health.

V. Conclusion

In this study, the physical properties and reproducibility of 13 marketed foods alongside gummy jelly, as a control, were examined. Additionally, the reliability and inter-day reproducibility of consecutive sounds from chewing to swallowing were investigated under standardized conditions to minimize systematic errors. The conclusions drawn from the results are as follows:

1. Traditional test foods used for assessing masticatory ability, such as gummy jelly and peanuts, exhibited significantly higher maximum compressive force compared to commonly marketed foods.
2. Hierarchical clustering analysis revealed dissimilar physical properties between traditional test foods and marketed foods.
3. Reproducibility assessments showed that gummy jelly exhibited better reproducibility than peanuts, while almonds, kamaboko, and chocolate demonstrated acceptable reproducibility for the new testing method.

4. Inter- and intraday reliability of consecutive sounds from chewing to swallowing was found to be sufficient.
5. A significant negative linear association was observed between the dB sum of squares and occlusal force, confirming convergent validity with occlusal force but not with masticatory performance.

The results of this study can be applied to a new testing method using marketed foods may lead the way for improved targets in therapeutic interventions for patients with impaired masticatory function by assessing consecutive masticatory and swallowing functions.

VI. Figure Legends

Figure 1 The test foods (a; control and marketed) and molding metal used in the study (b)

Figure 2 Schematic diagram of Compact Tabletop Tester (EZ-SX): (a) and a toothed pushrod jig (b)

Figure 3 Conditions for maximum compressive force measurement: The compressing load and speed were set to 500N at 9.88 mm/s to simulate adults' occlusal force and jaw closing speed during chewing. The pushrod jig pressed the test food 1mm above the compression plate, and the data were recorded.

Figure 4 Setup of the High-performance Sound Level Meter (LA-7000, Ono Sokki, Kanagawa, Japan) for recording masticatory sounds. The microphone tip was precisely positioned horizontally at 50 mm from the laryngeal ridge, ensuring contact with the skin surface.

Figure 5 Visualization of the masticatory sound waveform at a sampling frequency of 64,000 Hz. The waveform illustrates the sound characteristics during chewing, and the first 10 seconds were specifically extracted for further analysis, highlighting key features in the early phase of mastication.

Figure 6 Maximum compressive force results of foods and their differences. Alphabetical labels above each bar indicate significant differences, with the same alphabet indicating no significant differences between the foods.

Figure 7 The dendrogram of hierarchical clustering analysis

Figure 8 Assessment of reproducibility of measurements relative to the control using coefficient of variation (CV) for maximum compressive force data. CVs were compared within each cluster generated from the dendrogram.

Figure 9 Intraday reliability comparison of three calculated data sets for the dB sum of squares on day-1 and day-2. The estimated ICC (1, 3) for individual ratings was 0.97 for day-1 and 0.91 for day-2, signifying excellent agreement and high reliability. The values are expressed in scientific notation, where "e" represents an exponent that multiplies the preceding number by 10 to the power of 6.

Figure 10 Scatterplot and regression equation depicting the relationship between obtained dB sum of squares (independent variable, y) and occlusal force (dependent variable, x)

Figure 11 Scatterplot and regression equation depicting the relationship between obtained dB sum of squares (independent variable, y) and masticatory performance (dependent variable, x)

VII. References

1. Okada K, Enoki H, Izawa S, Iguchi A, Kuzuya M: Association between masticatory performance and anthropometric measurements and nutritional status in the elderly. Geriatr Gerontol Int, 10: 56-63, 2010.
2. Robinson SM: Improving nutrition to support healthy ageing: what are the opportunities for intervention? Proc Nutr Soc, 77: 257-264, 2018.
3. Ansai T, Takata Y, Soh I, Awano S, Yoshida A, Sonoki K, Hamasaki T, Torisu T, Sogame A, Shimada N, Takehara T: Relationship between tooth loss and mortality in 80-year-old Japanese community-dwelling subjects. BMC Public Health, 10: 386, 2010.
4. Ikebe K, Matsuda K, Kagawa R, Enoki K, Yoshida M, Maeda Y, Nokubi T: Association of masticatory performance with age, gender, number of teeth, occlusal force and salivary flow in Japanese older adults: is ageing a risk factor for masticatory dysfunction? Arch Oral Biol, 56: 991-996, 2011.
5. Oura R, Mantyla P, Saarela R, Hiltunen K: Oral hypofunction and association with need for daily assistance among older adults in long-term care. J Oral Rehabil, 49: 823-830, 2022.
6. van der Bilt A: Assessment of mastication with implications for oral rehabilitation: a review. J Oral Rehabil, 38: 754-780, 2011.
7. Amagai N, Komagamine Y, Kanazawa M, Iwaki M, Jo A, Suzuki H, Minakuchi S: The effect of prosthetic rehabilitation and simple dietary counseling on food intake and oral health related quality of life among the edentulous individuals: A randomized controlled trial. J Dent, 65: 89-94, 2017.
8. Komagamine Y, Kanazawa M, Iwaki M, Jo A, Suzuki H, Amagai N, Minakuchi S: Combined effect of new complete dentures and simple dietary advice on nutritional status in edentulous patients: study protocol for a randomized controlled trial. Trials, 17: 539, 2016.
9. Suzuki H, Kanazawa M, Komagamine Y, Iwaki M, Jo A, Amagai N, Minakuchi S: The effect of new complete denture fabrication and simplified dietary advice on nutrient intake and masticatory function of edentulous elderly: A randomized-controlled trial. Clin Nutr, 37: 1441-1447, 2018.
10. Zitzmann NU, Krastl G, Hecker H, Walter C, Waltimo T, Weiger R: Strategic considerations in treatment planning: deciding when to treat, extract, or replace a questionable tooth. J Prosthet Dent, 104: 80-91, 2010.
11. The Glossary of Prosthodontic Terms: Ninth Edition. J Prosthet Dent, 117: e56, 2017.
12. Bunpu P, Changsiripun C: Assessment of masticatory performance in patients undergoing orthognathic surgery: A systematic review and meta-analysis. J Oral Rehabil, 50: 596-616, 2023.
13. Fan Y, Shu X, Leung KCM, Lo ECM: Associations of general health conditions with masticatory performance and maximum bite force in older adults: A systematic review of cross-sectional studies. J Dent, 123: 104186, 2022.
14. Boaden E, Burnell J, Hives L, Dey P, Clegg A, Lyons MW, Lightbody CE, Hurley MA, Roddam H, McInnes E, Alexandrov A, Watkins CL: Screening for aspiration risk associated with dysphagia in acute stroke. Cochrane Database Syst Rev, 10: CD012679, 2021.

15. McIntyre M, Doeltgen S, Dalton N, Koppa M, Chimunda T: Post-extubation dysphagia incidence in critically ill patients: A systematic review and meta-analysis. Aust Crit Care, 34: 67-75, 2021.

16. Manly RS, Braley LC: Masticatory performance and efficiency. J Dent Res, 29: 448-462, 1950.

17. Hama Y, Kanazawa M, Minakuchi S, Uchida T, Sasaki Y: Properties of a color-changeable chewing gum used to evaluate masticatory performance. J Prosthodont Res, 58: 102-106, 2014.

18. Nokubi T, Yoshimuta Y, Nokubi F, Yasui S, Kusunoki C, Ono T, Maeda Y, Yokota K: Validity and reliability of a visual scoring method for masticatory ability using test gummy jelly. Gerodontology, 30: 76-82, 2013.

19. Igarashi K, Watanabe Y, Kugimiya Y, Shirobe M, Edahiro A, Kaneda K, Hasegawa Y, Ito M, Hirano H, Sakurai K, Ono T, Inagaki H, Awata S, Kawai Y: Validity of a visual scoring method using gummy jelly for evaluating chewing efficiency in a large-scale epidemiological survey. J Oral Rehabil, 46: 409-416, 2019.

20. Limpuangthip N, Somkotra T, Arksornnukit M: Modified retention and stability criteria for complete denture wearers: A risk assessment tool for impaired masticatory ability and oral health-related quality of life. J Prosthet Dent, 120: 43-49, 2018.

21. Lucas PW, Luke DA: Optimum mouthful for food comminution in human mastication. Arch Oral Biol, 29: 205-210, 1984.

22. Tarkowska A, Katzer L, Ahlers MO: Assessment of masticatory performance by means of a color-changeable chewing gum. J Prosthodont Res, 61: 9-19, 2017.

23. Murakami K, Yoshimoto T, Hori K, Sato R, Sta Maria MT, Marito P, Takano H, Khaing AMM, Nokubi T, Ono T: Masticatory Performance Test Using a Gummy Jelly for Older People with Low Masticatory Ability. J Clin Med, 12: 593, 2023.

24. Nokubi T, Nokubi F, Yoshimuta Y, Ikebe K, Ono T, Maeda Y: Measuring masticatory performance using a new device and beta-carotene in test gummy jelly. J Oral Rehabil, 37: 820-826, 2010.

25. Nakamura A, Saito T, Ikeda D, Ohta K, Mineno H, Nishimura M: Automatic Detection of Chewing and Swallowing. Sensors (Basel), 21: 3378, 2021.

26. Sazonov E, Schuckers S, Lopez-Meyer P, Makeyev O, Sazonova N, Melanson EL, Neuman M: Non-invasive monitoring of chewing and swallowing for objective quantification of ingestive behavior. Physiol Meas, 29: 525-541, 2008.

27. Takahashi K, Groher ME, Michi K: Methodology for detecting swallowing sounds. Dysphagia, 9: 54-62, 1994.

28. Xia Y, Wang L: Study of occlusal acoustic parameters in assessing masticatory performance. BMC Oral Health, 22: 74, 2022.

29. Prinz JF: Computer aided gnathosonic analysis: distinguishing between single and multiple tooth impact sounds. J Oral Rehabil, 27: 682-689, 2000.

30. Endo H, Ino S, Fujisaki W: The effect of a crunchy pseudo-chewing sound on perceived texture of softened foods. Physiol Behav, 167: 324-331, 2016.

31. Endo H, Ino S, Fujisaki W: Texture-dependent effects of pseudo-chewing sound on perceived food texture and evoked feelings in response to nursing care foods. Appetite, 116: 493-501, 2017.

32. Kaneko H, Endo H, Ino S: A pseudo-mastication sound presentation device to improve the texture of nursing care foods. J Texture Stud, 51: 389-397, 2020.

33. Michiwaki Y, Kinumatu Y, Yokoyama M, Michi K, Ohkosi H, Takahashi T: Changes of Food Texture at Various Compression Speed. The Japanese Journal of Dysphagia Rehabilitation, 3: 16-20, 1999.

34. Yuan S, Chang SK: Texture profile of tofu as affected by instron parameters and sample preparation, and correlations of instron hardness and springiness with sensory scores. J Food Sci, 72: S136-145, 2007.

35. Cicchetti DV: Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. Psychological Assessment, 6: 284-290, 1994.

36. Miyazaki J, Shiga H, Kobayashi Y: The Reliability of Evaluating Masticatory Function by Masticatory Analysis. J Jpn Prosthodont Soc, 45: 283-294, 2001.

37. Hibbert DB: Systematic errors in analytical measurement results. J Chromatogr A, 1158: 25-32, 2007.

38. Brundle C, Heaven A, Brown L, Teale E, Young J, West R, Clegg A: Convergent validity of the electronic frailty index. Age Ageing, 48: 152-156, 2019.