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Changes in jaw muscle activity and the physical properties of foods with different textures during chewing behaviors

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HIGHLIGHTS

- The number of chewing cycles were greater for steamed rice than for rice cake.
- Muscle activity per cycle was significantly greater for steamed rice than for rice cake.
- Hyoid muscle activity gradually decreased as chewing progressed.
- Changes in adhesiveness and cohesiveness during chewing differed between the foods.
- Changes in masseter activity were affected by salivary flow rate.

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ABSTRACT

This study aimed to investigate how the activity of the masseter (Mas) and suprahyoid (Hyoid) muscles is influenced by the physical properties of food, how changes in the rheological properties of food differ between different foods during the process of food reduction, and how different salivary flow rates affect bolus-making capability during masticatory behavior in healthy humans. Ten healthy adults participated in this study. Electromyographic (EMG) recordings were obtained from the Mas and Hyoid muscles, and 15 g of steamed rice and rice cake was prepared as test foods. In the ingestion test, the subjects were asked to eat each food in their usual manner. The chewing duration, number of chewing cycles before the first swallow, Mas and Hyoid EMG activity, and chewing cycle time were compared between the foods. Total chewing duration was divided into three substages: early, middle, and late; chewing cycle time and EMG activity per chewing cycle of each substage were compared between the foods and among the substages. In the spitting test, the rheological properties of the bolus at the end of each substage were compared between the foods and among the substages. Finally, stimulated salivary flow rates were measured and the relationships between salivary flow rate and chewing duration, EMG activity, and changes in physical food characteristics were investigated. There were significant differences in total chewing duration and the number of chewing cycles, but not in chewing cycle time, between the foods, which had similar hardness values. The EMG activity levels of the Mas and Hyoid per chewing cycle for the rice cake were significantly greater than for the steamed rice throughout the recording periods. While Mas activity did not change among the substages during chewing, Hyoid EMG activity decreased as chewing progressed. Chewing cycle time also gradually decreased as chewing progressed. The hardness of both foods initially increased, then gradually decreased back to baseline. The adhesiveness of the rice cake initially increased, and did not fall throughout the recording period; the adhesiveness of the steamed rice did not significantly change. Cohesiveness barely changed in either of the two foods during chewing, but was significantly greater for the rice cake than for the steamed rice. Finally, a correlation between the stimulated salivary flow rate and chewing performance was evident only in a change in Mas EMG activity. The current results demonstrate that the activities of the Mas and Hyoid muscles changed as chewing progressed, and were affected by hardness, adhesiveness, and cohesiveness. Salivary flow rate may affect the changes in Mas activity during the process of bolus formation.

1. Introduction

Mastication is the first step in the eating process for most mammals, and forms an important part of feeding behavior. During mastication,

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bolus formation is achieved by chewing, which crushes food between the teeth or between the tongue and palate, and mixing with saliva. Once the bolus has reached a condition appropriate for swallowing, the swallowing reflex is initiated.

During mastication, the size, texture, and moisture of the food gradually change. Masticatory muscle activity patterns adapt to these changing characteristics during the process of bolus formation. Previous studies [1–3] have divided the entire sequence of mastication into three substages: early, middle, and late; these studies demonstrated that masticatory muscle activity gradually changed as chewing progressed. Okada et al. [4] analyzed oral behavior during mastication and swallowing of natural food under free-eating conditions from the time of food intake until the terminal swallow. The authors showed that humans need at least two swallows when ingesting food freely, even when only one bite of food has been taken, although most of the food is swallowed during the first swallow. These findings suggest that food processing before the first swallow is critical for completing bolus formation.

Two approaches have been developed to evaluate how the physical characteristics of food affect the process of bolus formation and how the food bolus is handled in the oral cavity during chewing: the rheological approach to food texture and the physiological approach. The physical properties of the bolus that are important in determining the initiation of swallowing are particle-size distribution [5,6] and lubrication with saliva and food fluids [7]. Regarding the latter, a dynamic approach to characterizing the perception of food texture has been proposed [7]. This concept is based on evaluating the breakdown of food during oral processing based on three characteristics: structure, lubrication, and time. However, there have been no quantitative attempts to elucidate how the properties of the food bolus determine the initiation of swallowing during mastication.

In contrast, the role of intra-oral inputs in adapting masticatory behavior to changing bolus conditions has been evaluated by numerous physiological studies. There is no doubt that jaw movement trajectories and related muscle forces during mastication are highly adaptable, and food texture can modulate masticatory forces [6,8-11], jaw movements [12,13], chewing cycle times [14,15], and the number of cycles preceding the swallow [1]. Electromyographic (EMG) recording is the primary technique used to monitor these physiological processes, and its results have shown a clear relationship between muscular activity and food characteristics [16,17]. Moreover, the proprioceptive information obtained from muscle activity, as recorded by EMG, may serve as the sensory basis for food texture perception [17,18].

Amylase in saliva plays a role in the early breakdown of starch components in food; saliva is also essential for smoothing the surface of the food bolus to facilitate its transport through the mouth and pharynx. So far, few attempts have been made to describe the changes in EMG patterns and rheological properties that occur in the process of bolus formation during chewing, or to compare the texture and consistency of foods during different stages of mastication. The present study was designed to investigate: 1) how the rheological properties of foods influence chewing behavior-related muscle coordination and activity patterns and 2) how different salivary flow rates affect bolus-making capability during chewing of steamed rice and rice cake in healthy humans.

2. Materials and methods

2.1. Participants

Ten normal adult females, ranging in age from 20 to 31 years (average age ± SD 23.0 ± 3.0 years) participated in this study. Prior to the start of the study a dentist confirmed that the participants had no abnormalities in the number or position of their teeth, no history of orthodontic treatment or temporomandibular disorders, and no occlusal abnormalities or mastication or swallowing problems. No participant had a history of alimentary, pulmonary or neurological disease. Informed consent was obtained from all participants, and this study was approved by the Ethics Committee of the Niigata University Graduate School of Medical and Dental Sciences (23-R16-11-08).

2.2. Physiological recordings

Paired 8-mm diameter surface electrodes (NT-211u, Nihon Kohden, Tokyo, Japan) were used for surface EMG recordings of both the right and left jaw-closing masseter muscles (Mas) and the jaw-opening suprahyoid muscles (Hyoid). For Mas and Hyoid recordings, the electrodes were attached to the skin bilaterally over the center of each Mas and the anterior belly of each digastric muscle with an inter-electrode distance of 2 cm. A reference electrode was affixed to the earlobe. The signals from the EMG waves were amplified (AB611-J, Nihon Kohden, Tokyo, Japan).

Electroglottography (EGG) was recorded to monitor laryngeal elevation during swallowing using a standard laryngograph processor (Laryngograph, London, UK). For this procedure, the surface electrodes were placed at the level of the larynx and the subject was asked to pronounce the/i/sound. EGG was used only for detection of swallowing movements, but not for quantitative analysis of waveforms [19].

EMG and EGG signals were then converted by an analog-to-digital converter (PowerLab, ADInstruments, Colorado Springs, CO, USA) at sampling rates of 10 kHz. The data were stored on a personal computer, and data analysis was performed using the PowerLab software package (LabChart 6 Pro, ADInstruments).

2.3. Test foods

Steamed rice and rice cake were prepared as test foods and served in 15 g portions. Since steamed rice is a traditional food in Japan, many Japanese studies have used it as a test food for the evaluation of masticatory and swallowing functions [3,4,20-23]. Rice cake or mochi (made by pounding glutinous rice into a paste) is also a very traditional Japanese food; it has a unique texture with extreme adhesiveness and tolerance to elongation [21] and is particularly difficult to chew and swallow. Since rice cake is very pliable, it is difficult to bite into pieces and swallow safely. In a previous study, we determined that 15 g was the appropriate amount of rice cake to be used in each trial.

The physical properties of the foods were measured by a modified two-bite test using a creep meter (RE2-3305, Yamaden, Tokyo, Japan) [3,22]. In this procedure, food samples were placed on the plate (40 mm diameter, 15 mm height) and elevated toward a polyacetal plunger (20 mm diameter, 8 mm height) at a speed of 10 mm/s. The plunger was connected to a load cell that pressed the sample twice (compressibility 66.7%). The following parameters were calculated: hardness (the height of the first peak in the stress–strain curve), adhesiveness (the area of the first negative peak, i.e., the work required to pull the plunger from the food sample), and cohesiveness (the ratio of the area under the second compressive peak/the area under the first compressive peak). This procedure was repeated five times to obtain a mean value for each parameter. Data were analyzed using an analysis software package (Creep analysis version 2.0, Yamaden, Tokyo, Japan). The yield stresses (hardness) for the steamed rice and rice cake were $9.3 \times 10^3 \pm 1.1 \times 10^3$ and $9.9 \times 10^3 \pm 1.6 \times 10^3$ N/m^2, adhesiveness values were $1.0 \times 10^2 \pm 0.3 \times 10^2$ and $2.1 \times 10^2 \pm 0.7 \times 10^2$ J/m^3, and cohesiveness values were 0.39 ± 0.06 and 0.64 ± 0.07, respectively. There were significant differences in the adhesiveness and cohesiveness of the steamed rice and rice cake ($P < 0.05$, t-test), which indicated that the rice cake was initially more adhesive and cohesive than the steamed rice.