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REVIEW

Influence of oral characteristics and food products on masticatory function

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Abstract
Mastication is a complex process that involves activities of the facial muscles, the elevator and suprahyoidal muscles, and the tongue. These activities result in patterns of rhythmic mandibular movements, food manipulation, and the crushing of food between the teeth. Saliva facilitates mastication by moistening food particles, making a bolus, and assisting swallowing, whereas food consistency modifies masticatory forces, the mandibular jaw movements, the duration of the mastication cycle, and the number of cycles preceding the first swallow. Jaw elevator EMG activity research shows a clear relation between muscular activity and food properties. The teeth, masticatory muscles, and temporomandibular joints are also important because together they form the mechanism by which the food particles are fragmented. Hard and dry foods require more chewing cycles and a longer time in the mouth until swallowing for sufficient breakdown to take place and for enough saliva to be added to form a coherent bolus safe enough for swallowing. Product characteristics, the amount of saliva, dentition, and bite force affect the chewing performance. This study presents an update and synopsis of the effects of saliva, food, dentition, muscle force, and temporomandibular disorders on the masticatory process.

Key Words: *Bite force, chewing efficiency, dental state, swallow, texture perception*

Introduction

Mastication is the first step in the process of digestion. The food is prepared for swallowing, with further processing in the digestive system. Chewing is a complex sensory-motor activity whereby the ingested food is first transported to the post-canine teeth by the tongue and then processed into a bolus suitable for swallowing [1]. During chewing, the food particles are reduced in size, while saliva is produced to moisten and lubricate the food. The water in the saliva moistens the food particles, whereas the salivary mucins bind masticated food into a coherent and slippery bolus that can be easily swallowed [2]. Taste and texture of the food are perceived and have their influence on the chewing process. The relationship between food texture and the masticatory process was recently reviewed in a special issue of the *Journal of Texture Studies* [3].

The control of mastication is exerted by a rhythmic activity in the brain stem [4] that can be overridden by the higher centers and modified by peripheral information [5]. The urge to swallow food can be triggered by a threshold level in the food particle size as well as by the degree of lubrication of the food bolus [6–8]. During mastication it is likely that mechanoreceptors in the gingival tissues will be stimulated, which may result in salivary flow [9,10]. At chewing forces as low as 5% of comfortable chewing forces, the masticatory-salivary reflex could already be elicited [9]. Evidence from animal and human studies suggests that increased mastication increases salivary output, whilst reductions in the masticatory effort have the reverse effect [11]. An increase in the salivary flow rate of rats was observed

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after implementation of a diet which required more mastication [12]. In humans, reduced flow rates of both unstimulated and stimulated whole saliva were found after subjects started to consume a liquid diet [13].

There are several factors determining the chewing result. The teeth are important in the masticatory system. They form the occlusal area where the food particles are fragmented. This fragmentation depends on the total occlusal area and thus on the number of post-canine teeth in occlusion [14–17]. Bite force, also one of the components of the chewing function, is exerted by the jaw elevator muscles. Bite force depends on muscle volume, jaw muscle activity, and the coordination between the various chewing muscles [18]. Measurement of the maximum bite force is an attempt to quantify the total force which can be developed by the jaw-closing muscles [19].

Decreased chewing performance is expected in patients with problems in the temporomandibular joint (TMJ) [20]. Restoration of chewing performance is therefore an important goal in the treatment of temporomandibular disorders (TMD) [21].

In addition to reflex control, cognition can influence food perception and breakdown in the mouth [2]. Mastication may depend on the type of food and its interaction with saliva, teeth, and the biomechanical system. The aim of this study was to present an update and synopsis of the influences of saliva, food, dentition, muscle force, and TMD on the masticatory process.

Mastication

Mastication is a process in which pieces of food are ground into a fine state, mixed with saliva, and brought to approximately body temperature in readiness for transfer to the stomach where most of the digestion begins [22]. Fragmentation and moistening of food is the main function of mastication, but it also imparts enjoyable sensations related to taste and the pleasure of eating. All ingested solid foods, regardless of bite size and initial texture, are processed in a stereotyped way by humans [1,23,24]. After ingestion the food is transported from the front of the mouth to the occlusal surfaces of the post-canine teeth (Stage I transport). Then the food is processed by a series of masticatory cycles needed to comminute and soften the food (food-processing stage). The number of processing cycles increases as foods become more difficult to chew. When food is ready to be swallowed it is propelled posteriorly into the oropharynx (Stage II transport). Food accumulates in the oropharynx until it is finally swallowed.

The masticatory function has been extensively investigated. Objective masticatory function (defined as masticatory performance) has often been measured by determining an individual's capacity to grind or pulverize a test food. Several studies have shown that masticatory function is reduced in people who have lost post-canine teeth, e.g. [15,25–29] and in those who wear removable dentures, e.g. [30,31]. Implant-supported prostheses improve the oral function and satisfaction in edentulous patients, e.g. [19,32–35]. Subjective masticatory function (defined as masticatory ability) has been studied by interviewing subjects on their own assessment of that function, e.g. [36–40]. Masticatory ability appears to be closely related to the number of teeth. Impairment of chewing ability occurs when fewer than 20 well-distributed teeth are present [36].

Mastication is a complex process, involving activities of the facial muscles, the elevator and suprahyoidal muscles, and the tongue. These activities result in patterns of rhythmic mandibular movements, food manipulation, and the crushing of food between the teeth. Integral motor control is a requirement for the ability to masticate foods but an intact dentition is also important. Basic chewing rhythms are generated centrally in the absence of sensory feedback by the so-called central pattern generator (CPG) which has been suggested to be located in the medial bulbar reticular formation [4,41–44]. However, mastication is a behavior that has to adapt to environmental demands through the mediation of both peripheral and central inputs to the CPG. Mechanoreceptors in the oral cavity and jaw-closing muscle spindles serve as important sensory inputs for regulation of jaw-movement pattern and masticatory force [5,45–47].

The function of the CPG of rhythmical masticatory movements can be divided into three processes: (a) generation of the masticatory rhythm, (b) generation of a pattern of activities of the jaw, tongue, and facial muscles, and (c) coordination of the activities of these muscles [4]. There are several lines of evidence showing that the masticatory CPG is functionally subdivided into two neuronal groups: one for generation of masticatory rhythm, giving the timing signal for rhythmical alteration of jaw closing and jaw opening (central rhythm generator (CRG)), and the other for generation of the spatio-temporal pattern of activities of the jaw, tongue, and facial muscles. The central motor command for the actual pattern of the masticatory movement is assumed to be generated by a certain neuronal population, which receives rhythmical input from the CRG, integrates the input with other central and peripheral inputs, and sends the command to cranial motoneurons innervating the jaw, tongue, and facial muscles (review: [48]).

At it simplest, mastication consists of rhythmic activity of the jaw-opening and -closing muscles regulated by a central pattern generator [41]. This basic rhythm is modulated by sensory inputs throughout the chewing sequence, allowing adjustment of the masticatory process to the bolus texture at any moment according to a precise feedback control [5,49–51]. During mastication, the major jaw elevator muscles (masseter, temporalis, and pterygoid) are used to overcome food resistance [5,52].

Saliva

Saliva plays an important role in bolus formation and hence is important for safe swallowing. In addition to water, one of the components of saliva is mucins, which cover and protect the oral cavity [53,54]. Mucins also provide saliva with its lubricative properties and facilitate manipulation, mastication, and swallowing [55]. The presence of food in the mouth is a powerful stimulus to salivation and it is generally accepted that the main components of this effect are gustatory stimulation and masticatory movements [56–62]. Whole saliva flow rates in man vary from 0.5 ml/min at rest to 5 ml/min during chewing [58] and even 7 ml/min in response to citric acid stimulation [60]. At rest, the amount of saliva in the mouth before and after swallowing is 1.1 and 0.8 ml, respectively [63]. The important role of saliva for chewing and swallowing was demonstrated by the finding that the number of chewing strokes, hence time in the mouth needed for swallowing, significantly increased after experimentally induced oral dryness [64]. In addition, significantly more saliva is required for oral manipulation of powdered crispbread than for pieces of crispbread [56], as the larger surface area of the powder requires more saliva for lubrication and cohesive binding in preparation for deglutition. In a study on rabbits, it was demonstrated that greater amounts of saliva were produced for dry food than for moist food [65]. The amount of saliva also plays a role in the chewing of meat, with more saliva being incorporated into a food bolus of tough meat, than into tender meat before the bolus is swallowed [66]. Owing to circadian rhythms, variations in individual salivary flow rates can be as high as 50% over a day [67,68].

A mutual association exists between salivary flow and diet: food not only influences salivary flow, but saliva can also affect sensory perception [62]. It was demonstrated that short-term reductions in salivary flow have very little impact on taste perception [69], while long-term deficiency of saliva resulted in lower taste sensitivity and altered preferences [70]. Saliva is thought to be involved in our perception of taste, flavor, and texture of foods. The effects of saliva on food leading to changes in perception are plentiful. Mixing of saliva with food can have a diluting effect; moreover, it can influence flavor release [71]. Furthermore, it was demonstrated that salivary flow rate correlated positively with the perception of some texture and mouth-feel attributes [72].

Research on semi-solids has shown that there was no relationship between a subject's salivary flow rate and sensory ratings (flavor and mouth feel) of a vanilla custard dessert [73]. Thus, a subject with a larger salivary flow rate during eating did not rate the custard dessert differently from a subject with lesser salivary flow. A possible explanation for this could be that subjects have their own references and that ratings are relative rather than absolute, and probably a result of experience. Subjects are apparently used to the volumes of saliva in their mouths. Assuming this is the case, it can be hypothesized that an artificial increase in the amount of saliva could influence the sensory ratings. In fact, an artificial increase of 0.5 ml saliva significantly influenced the sensory ratings of semi-solids [74]. The addition of a fluid affected the mouth-feel attributes of thickness and melting of vanilla custard dessert.

The effect on the sensory ratings of adding fluid to a solid food is unknown. Food properties may be modified by the additional fluid, which may lead to changes in chewing force, mandibular jaw movements, and number of chewing cycles to prepare the food for swallowing. Therefore, an artificial increase in the amount of saliva mixing with food may also influence the perception of the food. Preliminary results of a study in which various fluids (water, solution of α-amylase, or artificial saliva containing mucins) were added to solid food showed a significant influence of these fluids on oral physiology parameters as well as on textural and sound attributes [75]. For dry foods like melba toast and cake, the addition of 5 ml water to the food significantly reduced the muscle activity and the number of chewing cycles until swallowing. Several texture and sound attributes were also significantly lower after water had been added. The effect of the mucins and α-amylase in the solutions was limited. Doubling the volume of tap water had a greater effect. Adding a fluid to solid food clearly facilitates the chewing of dry foods, e.g. melba toast and cake. However, no significant influences on oral physiology and perception of the additional water were observed for carrot (90% water) and cheese (35% water and 31% fat).

Food properties

Food has a considerable influence on mastication [51,76,77]. A clear relationship between muscular activity and food properties has been reported [78,79]. The number of chewing cycles preceding the first swallow is also related to the type of food [7]. A firm, dry food, such as, for instance, nuts, requires many chewing cycles to fragment it before it can be swallowed [7]. Although it may be surmised that the taste of food also has a considerable influence on the chewing process, it is disappointing to find that there is a paucity of experiments and thus data on this question [80]. A recent study showed that an increase in the bitter taste of a gelatine-based gel caused a significant decrease in the number of chewing cycles [81]. It is suggested that the influence of taste on the chewing process runs via its relation with salivary flow rate. Flavor release from food may be related to the surface of the fragmented food particles and thus it will be related to masticatory performance [82].

Appearance, flavor, and texture are the three main acceptability attributes of food that provide enjoyment in eating. Whatever form the food takes, it must be converted into a sufficient bolus during the process of mastication to allow it to be swallowed [22].

Food texture modifies masticatory forces [83], the mandibular jaw movements [84], the duration of the mastication cycle, and the number of cycles preceding the first swallow [85,86]. Jaw elevator EMG activity research showed a clear relation between muscular activity and food properties (Figure 1) [77,78]. Moreover, the salivary flow rate can also be related to the texture of food.

Salivary flow during mastication depends on both the type and weight/size of the food stimulus [61]. Indeed, in a study on rabbits, higher salivary flow rates were observed with dry food (dry pellets) than with moist food (pieces of carrot) [65]. The salivary flow rates observed with natural foods are much higher than when chewing unflavored test materials (Parafilm) to induce salivation. Parafilm is an inert and tasteless material, so it does not cause gustatory secretory stimulation. The effect of gustatory stimulation of food has been found to be more important for the saliva flow rate than the mechanical stimulation of chewing [87,88]. Recent research has shown that the amount of saliva secreted per gram of product differed significantly among the different types of foods. The food with the lowest percentage of water and fat (toast) elicited the highest levels of saliva, which indicates that a dry product needs more saliva to moisten and form a cohesive bolus suitable for swallowing [85].

Food properties modify the transport duration of the bolus between the oral cavity and the oropharynx, but the duration of swallowing itself is not affected [89]. The number of chewing cycles needed to prepare the food for swallowing has been shown to be rather constant within a subject for one type of food, whereas wide variations in the number of chewing cycles until swallowing are observed among subjects [29,85,90,91]. Food can vary widely in, for example, thickness, hardness, fat, and moisture content. These differences are reflected in the force needed to shear food, the breakdown pattern of the food, the ease with which it is manipulated, formed into a bolus, and swallowed. The type of food product has a significant effect on the number of chewing cycles until swallowing (Figure 2). Dry and hard products require more chewing cycles before swallowing [86]. Evidently, more time is needed to break the food down and to add enough saliva to form a cohesive bolus suitable for swallowing. Buttering dry foods significantly reduces the number of chewing cycles until swallowing [86].

The number of chewing cycles needed to prepare food for swallowing is fairly constant within a subject for one type of food, whereas wide variations in the number of chewing cycles until swallowing were observed among subjects [91,92]. For instance, the number of chewing cycles needed to swallow 9.1 cm^3 of peanuts varied between 17 and 110 in a group of 87 dentate subjects [86]. Furthermore, the moment of swallowing appeared to be strongly correlated among various natural foods [86,92]. This means that subjects who used a small number of chewing cycles for one food consistently also used small numbers for all types of food. This implies that there are "slow" and "fast" swallowers (subjects who swallow any food after a relatively low or high number of cycles, respectively). This is partly the result of the individual's physiology, but possibly also of the social context. Subjects who need a relatively low number of chewing strokes may be in the habit

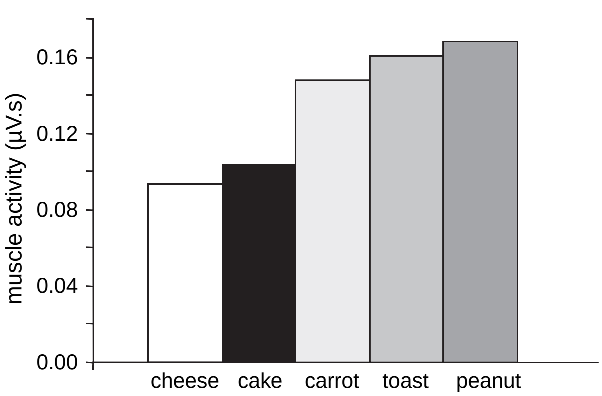

Figure 1. Averages for 20 subjects of the integrals of muscle activity bursts when five different foods were chewed (unpublished data).

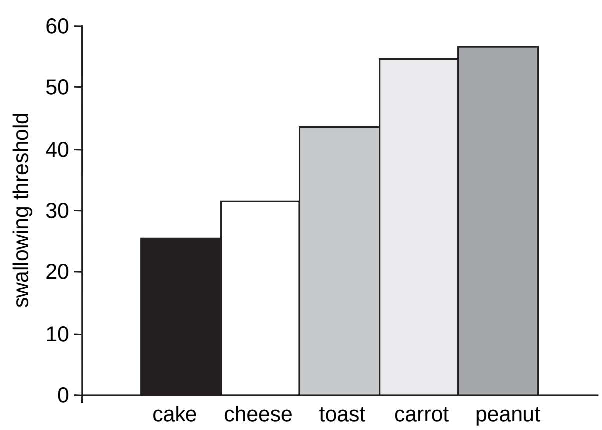

Figure 2. Averages for 20 subjects of the number of chewing cycles prior to swallowing (swallowing threshold) for five different foods (unpublished data).

of eating faster, take less time to finish their meals, or might feel less discomfort from distension of the soft tissues of the pharynx and esophagus when they swallow a large bolus [7].

Dental status and muscle force

Masticatory performance results from a complex interplay of direct and indirect effects. Muscle (bite) force and the number of functional tooth units are the key determinants of masticatory performance, which suggests that their maintenance may be of important for promoting healthful functional status [17].

Many factors related to dentition are known to have a considerable influence on masticatory performance, such as number of teeth, loss and restoration of post-canine teeth, and the number of occlusal contact areas [15,25,26,28,29,93–95]. The relationship between masticatory performance and the number of occluding teeth was found to be linear [29]. However, it was shown that subjective oral function did not correlate with the objective masticatory performance. In recent research, the correlation between number of chewing strokes before swallowing and dental state was tested and the results showed that masticatory performance was significantly influenced by dentition, but not by age or gender [92]. In fact, a clear relationship exists between dental state and masticatory performance as determined by a chewing test [16,17,26,27,94,96,97].

It was believed that subjects with an incomplete dentition, and thus a reduced masticatory performance, on average use more chewing strokes to prepare the food for swallowing than subjects with a complete natural dentition [91]. They would compensate for their reduced capacity by chewing longer, but this could not prevent them from swallowing larger food particles [29]. However, it was shown recently that subjects with a low masticatory performance did not necessarily chew longer before swallowing than subjects who had a better masticatory performance [92]. As a consequence, subjects with a high masticatory performance will, on average, swallow finer food particles (median particle size of about 1 mm) than subjects with a less high performance (median particle size of about 3 mm; see Figure 3 of [92]). It could well be that this will influence the perception of the food. If so, chewers with a high performance would, on average, perceive food in a different way than would subjects with a less high chewing performance.

Subjects with a reduced dentition cannot pulverize their food to the same extent as subjects with more post-canine teeth, in a fixed number of chewing strokes. According to Fontijn-Tekamp et al. [92], the number of occlusal units was the only factor that affected the median particle size after mastication and the swallowing threshold. An occluding molar pair was counted as two occlusal units, whereas a premolar pair was counted as one occlusal unit [95]. The number of occlusal units, however, explained only 16% of the variance. A better determinant of masticatory function is the bite force [17] which alone could explain 40% of the variation in chewing efficiency [19].

Previous studies have shown that individuals usually use a certain percentage of their maximum bite force during chewing [98,99]. Therefore, a subject with a high muscle force will also use more force while chewing, especially for hard foods. This indicates that a higher bite force may lead to a better fragmentation of the food. Significant correlations were reported between masticatory performance and muscle force for subjects with natural dentition, subjects with a shortened arch, and denture wearers [19]. Maximum bite forces, measured bilaterally at the premolars, range from on average 220 N for subjects with conventional prostheses, to about 340 N for subjects with implant-retained dentures [100]. Subjects with a complete dentition have maximum bite forces of nearly 500 N [101].

The chewing performance has also been studied in subjects with oral prostheses. Denture wearers reach only 25% of dentate chewing performance. Chewing efficiency has been proven to be significantly better in patients with overdentures on dental implants than in patients with full dentures. However, subjects with natural roots under their overdentures performed significantly better compared with subjects with dental implants. After implant treatment, bite force and chewing performance almost doubled [35,100]. Edentulous groups were clearly less efficient than subjects with a natural dentition [19]. Individuals rate their chewing comfort and ability more highly after implant treatment [7,33,102–106]. However, there appeared to be no significant correlation between the improvement after implant treatment as measured with an objective method (maximum bite force) and a subjective method (questionnaire) [107]. Hence, subjects with higher maximum bite forces after implant treatment were not necessarily more satisfied.

Temporomandibular disorders

Mastication is also influenced by disorders of the TMJs, although this influence is not well described in the literature. Decreased masticatory function is one of the most important problems which patients with TMDs encounter and restoration of masticatory function is therefore an important goal in the treatment of TMD [21]. Most of the TMD studies deal with masticatory ability (subjective measure obtained from questionnaires), whereas only a limited number of studies on masticatory performance (objective measure obtained from chewing tests) have been performed.

Using questionnaires and clinical examination, pain-related disabilities in TMD were investigated and the three most frequent jaw disabilities were: eating hard foods (77.6%), yawning (75.7%), and chewing (64.5%) [108]. The TMJ disorders reach a steady state 2–4 years after the onset of dysfunction, few signs and symptoms persist and these do not influence chewing ability [109]. Chewing ability has been evaluated from questionnaires on the ability to chew various types of food. Scores on chewing ability significantly correlated with TMJ pain and mouth-opening capacity but not with TMJ noise and muscle tenderness [21].

Objective oral function of TMD patients has been determined from masticatory performance, bite-force endurance, bite force, and chewing movement. Changes in chewing movement and masticatory performance were examined in patients who had been diagnosed with non-reducing disc displacement of the TMJ but had not received any treatment [110]. Two years after the initial visit it appeared that the masticatory performance had improved spontaneously, although it did not reach the level of healthy controls. Patients who had a TMJ disorder for more than 3 years tended to display less reduction in their masticatory performance [20]. Again, comparison with controls showed that these patients still had a significantly reduced masticatory performance. Both masticatory performance and masticatory ability depended on TMD scores [111]. The endurance time of a submaximal bite force was measured in TMD patients and compared with controls [112]. The mean endurance time in the patient group was significantly shorter than that of the control group. Treatment had a positive effect on the masticatory function, the endurance time significantly increased after treatment of TMD patients [113]. It was concluded that this test is a good complementary tool in assessing the functional capacity of the masticatory system. Furthermore, maximum bite force was used to quantify oral function in TMD patients [114,115]. Significant correlations were found between maximum bite force and TMJ discomfort scores.

Conclusions

This review shows that the characteristics of food products and oral characteristics such as bite force, dentition, and amount of saliva affect the chewing process. Hard and dry products require more chewing cycles and a longer time in the mouth until swallowing for sufficient breakdown to take place and for enough saliva to be added to form a coherent bolus safe enough for swallowing. Masticatory performance is significantly influenced by dental state and bite force. A significant reduction of masticatory function is observed after the loss of teeth. However, chewing performance can be improved by a dental prosthesis, especially one supported by implants, although levels of dentate controls will not be reached. TMJ disorders negatively influence chewing behavior. Changes in subjective and objective measures of oral function after dental treatment are not well correlated and therefore quantification of oral function is essential to evaluate the function of the masticatory system.

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