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Review Article

Assessment of mastication with implications for oral rehabilitation: a review

A. VAN DER BILT *Department of Oral-Maxillofacial Surgery, Prosthodontics and Special Dental Care, University Medical Center Utrecht, Utrecht, The Netherlands*

SUMMARY During chewing, food is reduced in size, while saliva moistens the food and binds the masticated food into a bolus that can be easily swallowed. Characteristics of the oral system, like number of teeth, bite force and salivary flow, will influence the masticatory process. Masticatory function of healthy persons has been studied extensively the last decades. These results were used as a comparison for outcomes of various patient groups. In this review, findings from literature on masticatory function for both healthy persons and patient groups are presented. Masticatory function of patients with compromised dentition appeared to be significantly reduced when compared with the function of healthy controls. The influence of oral rehabilitation, e.g. dental restorations, implant treatment and temporomandibular disorder treatment, on masticatory function will be discussed. For instance, implant treatment was shown to have a significant positive effect on both bite force and masticatory performance. Also, patient satisfaction with an implant-retained prosthesis was high in comparison with the situation before implant treatment. The article also reviews the neuromuscular control of chewing. The jaw muscle activity needed to break solid food is largely reflexly induced. Immediate muscle response is necessary to maintain a constant chewing rhythm under varying food resistance conditions. Finally, the influence of food characteristics on the masticatory process is discussed. Dry and hard products require more chewing cycles before swallowing than moist and soft foods. More time is needed to break the food and to add enough saliva to form a cohesive bolus suitable for swallowing.

KEYWORDS: mastication, bite force, chewing, swallowing, saliva, food, perception

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Introduction

Chewing, talking, laughing, smiling and yawning are important functions of the oral system. Dentition, tongue, cheeks, lips, jaw muscles, neuromuscular control and saliva are essential to perform these functions adequately. Often, patients are confronted with problems in performing these functions. This may be because of missing teeth or to a malfunction of the jaws and/or jaw joints, jaw muscles or the neural system. The purpose of this review is to report and discuss findings from literature on various aspects of the masticatory process for both healthy persons and patients.

Section 'Masticatory function' focuses on the masticatory process. The stereotyped way of the chewing process is described, and methods to determine masticatory function are introduced. Objective methods (e.g. sieving of chewed food) as well as patient-based methods (questionnaires) to determine masticatory function are discussed. Furthermore, aspects of the swallowing process are described. In section 'Factors influencing masticatory function', oral factors determining the chewing result are discussed. Characteristics of the oral system, like dentition, jaw muscle activity, bite force and salivary flow rate, will influence the masticatory process. This will lead to large variations in

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size reduction of food particles, salivation of food, mixing of food particles into a bolus and swallowing threshold. In section 'Masticatory function in various groups of individuals', the masticatory function of healthy subjects and of various groups of patients is discussed. Furthermore, the influence of oral rehabilitation on masticatory function is examined. In section 'Neuromuscular control of chewing', an overview of the neuromuscular control of chewing and swallowing is presented. The movement of the jaw, and thus the coordination between the various chewing muscles, plays an important role in the fragmentation of the food. Section 'Influence of food characteristics on chewing' deals with the influence of food characteristics on chewing. For instance, water and fat percentage and hardness of the food are known to influence the masticatory process. Food hardness is sensed during mastication and affects jaw muscle activity, masticatory force and movements of the lower jaw. The review ends with a brief summary (section 'Summary').

Masticatory function

Chewing and swallowing

All ingested solid foods, regardless of bite size and initial texture, are processed in a stereotyped way by humans (1–5). After ingestion, the tongue transports the food from the front of the mouth to the occlusal surfaces of the post-canine teeth (Stage I transport) (3). Then, the food is processed by a series of masticatory cycles needed to comminute and soften the food (food processing stage). Large food particles are broken down between the (pre)molar teeth into small pieces, which are mixed with saliva to form a food bolus. Digestive enzymes act on the masticated food, and salivary mucins bind the food particles into a coherent and slippery bolus that can easily slide through the oesophagus without damaging the mucosa (6). When the jaw closes during chewing, two distinct phases occur: the fast close phase and the slow close phase (3). Fast closure occurs directly after the start of jaw closure until the teeth come into contact with the food bolus. The resistance of the food slows down the lower jaw, and the jaw closure muscles become more active to overcome the resistance of the food: the slow close phase. In this phase, the food is compressed and sheared. The fast and slow close phases of chewing are nicely illustrated in Fig. 1 of reference (7). In this Figure, the vertical movement of the mandible is plotted as a function of time for a subject chewing samples of cheese and carrot.

Three characteristic swallowing patterns have been reported: interposed, terminal and spontaneous swallows (8). Interposed swallows occur within a masticatory sequence, while terminal swallows end the masticatory sequence. Spontaneous swallows occur sporadically between masticatory sequences. When food is ready to be swallowed, it is propelled posteriorly into the oropharynx (Stage II transport) (3). Although the initiation of swallowing can be controlled intentionally, swallowing will almost always start unconscious. The initiation of swallowing has been thought to depend on separate thresholds for food particle size and for particle lubrication (9). However, instead of this duality, it has also been suggested that swallowing is initiated when it is sensed that a batch of food particles is bound together under viscous forces so as to form a bolus (10). Recently, it was suggested that bolus rheology, in particular its extensional stretch-ability, had the most important influence on the ease of swallowing (11). Optimal swallow performance requires that discrete swallow events occur in concert with each other to transport the food bolus safely and efficiently through the oral and pharyngeal cavities (12). Swallowing constitutes one of the most complex functions, in that it requires the coordinated, bilateral activation of a large number of alimentary and respiratory muscles (13). A review of the coordination of mastication, swallowing and breathing has been published recently (14). The swallowing process can be divided into three continuous phases (15). The first phase of swallowing is also called the oral or clearing phase. It is under voluntary control and typically takes <1 s to complete (16). Practically, all the intrinsic and extrinsic muscles of the tongue, and the suprahyoid muscles, are active, as the food bolus is positioned in the middle of the tongue. The tongue helps to propel the bolus to the pharynx through an anterior to posterior rolling action, with tongue elevation, distal squeezing against the hard palate and contraction of the pharyngeal constrictor muscles (16). The palatopharyngeal folds are pulled medially to form a slit through which properly masticated food can pass. As the bolus passes the anterior palatopharyngeal folds, the oral stage of the swallow is terminated and the swallowing reflex is triggered (16). As the swallow begins, respiration is reflexly inhibited (8, 17). The second phase of swallowing, the pharyngeal phase, is entirely elicited by reflexes. The pharynx elevates and contracts followed by a peristaltic wave movement of the musculature in a caudal direction, so that the food bolus descends into the oesophagus. Simultaneously, the larynx elevates and moves anteriorly, thereby contributing to laryngeal closure. The epiglottis is folded down to cover the entrance of the laryngeal vestibule and the trachea during swallowing, so that the lower respiratory tract is protected from the entry of saliva or food particles, while they pass through in the pharyngeal phase (6, 18). The third phase of swallowing is the oesophageal phase, which involves a sequential contraction of the oesophagus. This phase is also controlled by reflexes (4). Oesophageal peristalsis carries the food bolus through the cervical and thoracic oesophagus into the stomach.

Masticatory performance and masticatory ability

Masticatory function can be described in terms of the objective capacity of a person to fragment solid food or as the subjective response of a person to questions concerning chewing food. Objective masticatory function (defined as masticatory performance) has often been measured by determining an individual's capacity to grind or pulverise a test food after a fixed number of chewing cycles. Several studies have shown that masticatory performance is reduced in people who have lost post-canine teeth (19–25) and in those who wear removable dentures (26–28). Implant-supported prostheses improve the masticatory function and satisfaction in edentulous patients (29–33). Self-assessed masticatory function (defined as masticatory ability) has been studied by interviewing subjects on their oral function (21, 34–42). The subjective evaluation of masticatory performance includes other aspects of mastication such as adaptational and psychological factors that cannot be obtained from pulverisation tests (34, 43).

A wide variety of methods have been used to determine masticatory performance, e.g. measuring colour change in chewing gum (44, 45), sugar loss from chewing gum (46), a colorimetric method to determine the release of dye when chewing raw carrots (47), photometric methods to quantify changes in colour (48, 49) and optical scanning of chewed particles (50, 51). However, in the majority of the studies on chewing performance, the degree of breakdown of a food has been determined by sieving the comminuted food (24, 32, 52–55). Both natural foods, such as peanuts, almonds and carrots, and synthetic materials have been used as test materials in experiments determining the masticatory performance. A natural test food has the advantage that it is normally consumed, so that subjects are accustomed to it. However, the consistency of the food may vary owing to seasonal and geographical influences. To avoid these variations in consistency, artificial food is a good alternative, which has often been used (28, 32, 53, 55–57). Some authors have used test sieving with only one sieve (20, 52, 58–60). In these studies, the masticatory performance was defined by the weight percentage of masticated food that would pass a sieve with a fixed aperture after a fixed number of chewing cycles. Sieving methods, which use more than one sieve, give more detailed information on the distribution of particle sizes of the chewed food (19, 25, 28, 32, 53–55). From the distribution of particle sizes, the median particle size can be determined. For the multiple sieve method, the masticatory performance was defined as the median particle size obtained after a fixed number of chewing cycles (61). A small median particle size after a fixed number of chewing cycles indicates that the food has been well fragmented, and thus, the masticatory performance is high. Recently, the single and multiple sieve methods were compared (62). It was concluded that the multiple sieve method yields better results than the single sieve method. Large individual differences in masticatory performance were observed among healthy subjects (19, 23, 43, 60, 63, 64). For instance, the standard deviation of the masticatory performance of a group of 631 dentate subjects, determined after chewing 20 strokes on peanuts, was nearly half the value of the mean: 59 ± 25% (Table 2 of reference 60).

Another method to determine masticatory performance, which is now widely used, evaluates the ability to mix and knead a food bolus. Two-coloured chewing gum (65–67) and paraffin wax (68–71) have been used as test foods for the quantification of the masticatory performance. The degree of mixing of the two colours was determined by optical methods (65, 68, 71), by visual inspection (72) or by both (66). Validity and reliability studies showed that chewing on two-coloured wax paraffin is a reliable alternative for comminution tests (71, 73). The correlation coefficient between outcomes of the comminution and the mixing ability tests was 0·66 ($P < 0{\cdot}001$) (71). It was concluded that the mixing ability test is more suitable for, and discriminates better between, persons with compromised masticatory performance than the comminution test (71).

Self-assessed masticatory function, or masticatory ability, can be determined from questionnaires or personal interviews (74). Questionnaires on oral function have been used in epidemiologic surveys (34, 35, 39–43, 75–77). These studies addressed questions on masticatory function, dental state, food selection patterns and nutrient intake. Masticatory ability appeared to be closely related to the number of teeth and dental status. The change in subjectively evaluated masticatory function with increasing age was best explained by the number of teeth, while age *per se* had only marginal influence on masticatory ability (75). Maintaining 20 or more natural teeth and at least eight functional tooth units is important in reducing the likelihood of self-assessed chewing difficulties (21, 34, 39, 41, 76). Self-assessed chewing ability and the results of functional tests (masticatory performance) correlated only weakly or not at all (25, 78–80). Correlation coefficients reported in these studies ranged between 0·12 and 0·34 in a study on complete denture wearers (79), and between 0·11 and 0·36 in a study on patients treated with fixed dentures on implants (80). Many individuals with a compromised dentition and dentures judge their masticatory function as 'good' while a comminution test resulted in values much lower than dentate subjects (75). It is probable that self-assessment of chewing ability is, in general, too optimistic when compared with the results of objective tests (75). Denture wearers have most probably got used to their dentures and feel comfortable with chewing. In a recent article, methods commonly used to measure masticatory function of patients wearing conventional and implant prostheses were reviewed (81). Outcomes of laboratory-based methods and patient-based methods were compared. Patient-based outcomes were recommended by the authors as the most appropriate variables of masticatory performance, as these are based on the patients' perceptions. This may be true for the evaluation of the masticatory function of individual patients. However, self-assessed masticatory function does not explain the mechanisms of the chewing process. Therefore, laboratory-based methods will be necessary to quantify masticatory function in various groups of patients and to evaluate changes in masticatory function in groups of patients as a result of dental treatment.

Swallowing threshold

The urge to swallow food could be triggered by a threshold level in the food particle sizes as well as by the degree of lubrication of the food bolus (9, 10, 82). The distribution of food particle sizes swallowed after mastication has been termed the 'swallowing threshold' (64, 83). The swallowing threshold can be determined by sieving a food bolus, which is expectorated just before a subject felt the need to swallow (63, 84). The number of chewing cycles needed to prepare food for swallowing was rather constant within a subject for one type of food (85), whereas large variations in the number of chewing cycles until swallowing were observed among subjects for one type of food (63, 64, 84). High measurement–remeasurement correlations were reported for the number of chewing cycles until swallowing ($0{\cdot}82 < r < 0{\cdot}95$), although there was a shift towards a slightly larger number of chewing cycles at the second measurement (32·6 vs. 34·2 cycles) (85). The number of chewing cycles used before swallowing 9·1 cm^3 of peanuts varied between 17 and 110 in a group of 87 dentate subjects (86). Large standard deviations in the number of chewing cycles before swallowing various natural foods were also reported for a group of 10 young healthy subjects (84). Furthermore, the number of chewing cycles until swallowing among seven natural foods appeared to be strongly correlated for a group of 87 dentate subjects (86). Correlation coefficients ranged between 0·44 and 0·90. This means that subjects who used a small number of chewing cycles before swallowing one food consistently also used small numbers for all other types of food. This implies that there are 'slow' and 'fast' swallowers (subjects who swallow any food after a relative low or high number of cycles, respectively). This is partly the result of the individual's physiology, but possibly also the result of the social context. Figure 1 illustrates the large variation in chewing behaviour among people. The jaw movement, rectified muscle activity (sum of right and left masseter and temporalis muscles) and muscle work (muscle activity integrated over jaw displacement of masseter and temporalis muscles measured bilaterally) are shown for two healthy subjects (A and B). The subjects were instructed to chew and swallow a piece of bread (13 cm^3). Subject A chewed eight times on the bread and then swallowed it (upper three rows), whereas the second subject chewed the bread 34 times, thus more than four times longer,

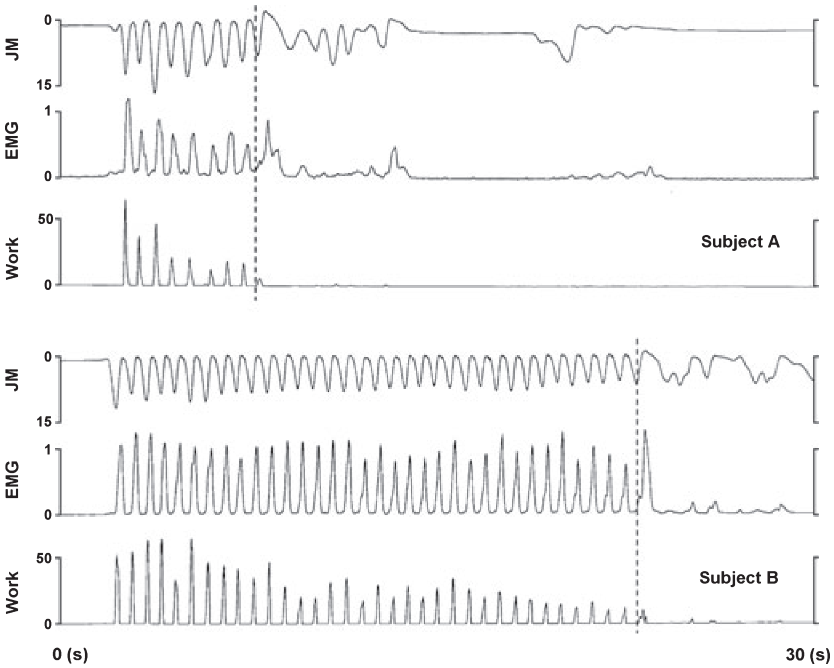

Fig. 1. Vertical jaw movement (JM in mm), rectified muscle activity of right and left masseter and temporal muscles (muscle activities of masseter and temporalis muscles were summed; EMG in mV), and instantaneous muscle work (work in mV mm s^{-1}) of two subjects chewing a piece of bread (13 cm^3). The jaw gape was measured by recording the position of two infrared light-emitting diodes, one on the chin and one on the forehead. The areas of the bursts of the instantaneous work signal represent the work performed by the jaw muscles during the various cycles. EMG and work bursts occur while the jaw is closing. The work bursts decline while mastication proceeds and the food bolus is softened. The dashed lines indicate the moments before the food was swallowed. Subject B chewed the bread more than four times longer than subject A. EMG, electromyography.

before he swallowed it (lower three rows). Figure 1 clearly illustrates that muscle work decreases while mastication proceeds and the food bolus is softened. Another example of the large inter-individual differences can be found in Fig. 2 of a recent review article on masticatory function (87).

Although the number of chewing cycles needed to prepare food for swallowing largely varied among healthy dentate people, this number was shown to be only weakly correlated with the chewing performance (19, 63, 83). Thus, a subject with a high masticatory performance does not necessarily swallow food after a smaller number of chewing strokes than a subject with a less high masticatory performance. This is illustrated in Fig. 2. The number of chewing cycles until swallowing the food is plotted as a function of the masticatory performance (median particle size after 15 chewing cycles) for 87 subjects (63). Low values of the median particle size (left part of figure) indicate that the food was well fragmented and thus the masticatory performance was good, whereas large values (right part of

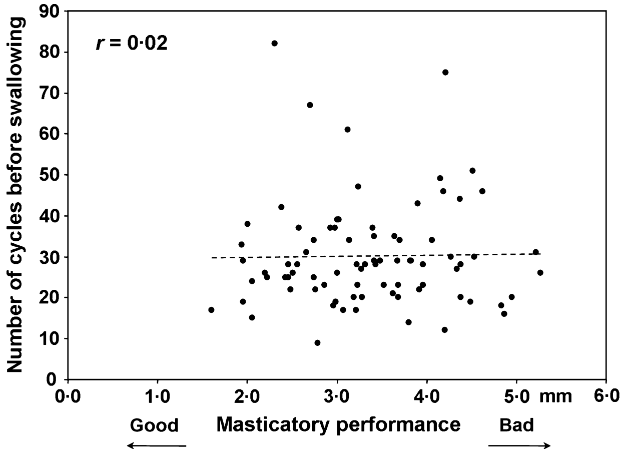

Fig. 2. The number of chewing strokes before swallowing the test food (Optocal) as a function of the median particle size obtained after 15 chewing strokes (masticatory performance). The data were obtained from 87 healthy adult subjects. Dashed line shows linear regression. A very low correlation ($r = 0{\cdot}02$) was observed, which indicates that there is no relationship between the number of chewing strokes until swallowing and the masticatory performance. Reproduced from (63).

figure) indicate that the food was not broken into small particles (bad chewing performance). As can be seen from Fig. 2, there is no significant correlation (r = 0·02) between the number of chewing cycles up to swallowing and the masticatory performance. In contrast to the results of the above-mentioned studies (19, 63, 83), a significant correlation (r = 0·69) between the number of chewing cycles and masticatory performance has been reported for a group of 35 dentate subjects chewing carrots (64). The contrasting result may be because of the test food. Carrot particles are relatively difficult to swallow, as the consistency of carrot does not change during the chewing process. Therefore, subjects with a less good masticatory performance must continue chewing until the carrot particles are small enough to be safely swallowed. It was recently reported that the upper limit of the median particle size of carrot particles swallowed by a group of young persons with good oral health was 4·0 mm (88).

It is interesting to relate chewing performance with the actual size of particles that an individual is willing to swallow. If there is no relationship between the number of chewing cycles until swallowing and masticatory performance, then subjects with a high masticatory performance will, on average, swallow finer food particles than subjects with a less high performance. This is illustrated in Fig. 3, where the median size of the swallowed food of a group of 87 dentate subjects is plotted as a function of masticatory performance (median size after 15 chewing cycles) (63). A significant correlation between the median particle size of the bolus ready for swallowing and the masticatory performance was observed (r = 0·59, P < 0·001). Similar results have been reported previously for dentate subjects: the particle size of the swallowed food was found to be directly related to the masticatory performance of the subjects (24, 75, 83, 89). In contrast to the results of these studies, no inter-individual variability was observed in the particle size distributions of a group of 10 subjects with normal dentition at the end of the chewing process for six different foods, nuts and vegetables (90). Based on this result, the authors suggested that the requirements that the food bolus must meet before it is ready to be swallowed are similar for everyone. The suggestion contradicts the results for the group of dentate subjects shown in Fig. 3: median particle sizes of the boluses ready for swallowing varied from 5·23 mm (hardly fragmented particles) down to 0·92 mm (very fine grains) (63). The puzzling result about the absence of inter-individual variability in particle size distributions may be caused by the relative small number of participants in that study (90). In a later study, the authors reported significant differences (P < 0·001) in particle size distributions of the bolus ready for swallowing among 10 young subjects (84).

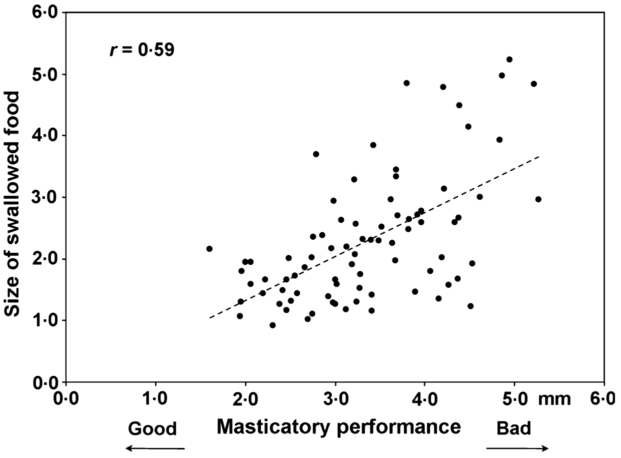

Fig. 3. Median particle size of the swallowed food as a function of the median particle size obtained after 15 chewing strokes (masticatory performance). The data were obtained from 87 healthy adult subjects. Dashed line shows linear regression. A significant correlation (r = 0·59; P < 0·001) was observed, which indicates that subjects with a good masticatory performance swallow finer food particles than subjects with a less good performance. Note that the median sizes of swallowed food vary from 5·23 mm (hardly fragmented particles) down to 0·92 mm (very fine grains), which indicates the large differences in chewing behaviour among the 87 healthy dentate subjects. Reproduced from (63).

Factors influencing masticatory function

Many factors are known to influence masticatory performance, such as loss and restoration of post-canine teeth, occlusal contact area, malocclusion, bite force, salivary flow, age, gender, sensory feedback and oral motor function. The main factors influencing masticatory performance were determined simultaneously in only a few of these studies (23, 60, 91). A number of functional tooth units and bite force were confirmed as the key determinants of masticatory performance (60, 91).

Dentition

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 teeth. Many people have deficiencies in masticatory function because of loss of teeth, malocclusion or periodontal disease (92). However, in spite of their handicap, most people manage to eat without much problem even though they are unable to comminute their food perfectly before swallowing. Declining masticatory function becuase of compromised dentition is responsible for swallowing poorly chewed food (20, 24, 63, 75, 83, 89, 93–95) and for chewing longer before swallowing (19, 21, 64, 75, 89, 95). Furthermore, compromised masticatory performance results in consuming predominantly soft, easy to chew foods. This may induce poor dietary practices and marginal nutritional intakes (36, 40, 93, 96–102). To improve masticatory function, missing teeth are often replaced by fixed or removable prosthodontic appliances. A clear relationship was found between dental state and masticatory performance as determined from chewing tests (19–25, 43, 56, 60, 75, 91, 95, 103–105).

The variation in masticatory performance may be related to many different dental factors, such as the number of teeth present, the number of occluding pairs of teeth, the total occlusal surface, the occlusal contact area, tooth shape and the preferred side of chewing. In studies on oral function, dental status has been quantified in various ways: number of teeth (20, 34, 36, 43), number of occluding tooth contacts (19, 106), number of occluding pairs of teeth (19, 21, 23, 25, 39, 43, 60, 93), total occlusal area (22, 91) or occlusal contact area (57, 89, 91, 104, 107–109). The number of occluding posterior teeth can be expressed in occlusal units. An occluding molar pair is counted as two occlusal units, whereas a premolar pair is counted as one occlusal unit (21). Thus, the maximum number of occlusal units is 12 for a subject with full dentition. The number of occlusal units per side has also been determined because the distribution of occlusal units is known to influence chewing performance (20, 21). The number of occlusal units appeared to be a good predictor of chewing performance (19, 24, 25, 43, 60). About 50% of the variance in masticatory performance was explained by the number of occlusal units (60).

In a study on the influence of occlusal factors on the masticatory performance in 32 young dentate subjects, it was found that masticatory performance was most highly correlated with the occlusal area of the post-canine teeth ($r = 0{\cdot}55$, $P < 0{\cdot}01$) (22). This finding was confirmed in a study in which the occlusal area was experimentally changed by varying the width of a food platform mounted on mandibular removable partial dentures (110). Reduction in the width of the food platform significantly impaired masticatory function. An even more important factor controlling the masticatory performance of people with natural teeth proved to be the amount of occlusal contact area of molar and premolar teeth, which is on average one-fifth of the total occlusal surface (103). Multiple regression analysis was used to predict the masticatory performance from occlusal factors (23, 43). The number of occluding teeth was the best single variable in the regression analysis and could predict 20% of the variation in masticatory performance ($P = 0{\cdot}0009$) (43). The explained variance increased to 49% when more variables were added: age, gender and orthodontic treatment need. In another study, a combination of occlusal factors (number of teeth in occlusal contact and orthodontic treatment priority index) could explain 48% of the variation in masticatory performance, which indicates that other factors will also affect masticatory performance (23). Indeed, adding bite force in the regression model raised the explained variance in masticatory performance to 70% (60, 91).

Jaw muscle activity and bite force

Chewing requires muscle activity to make the movements of the jaw and to exert forces to cut or grind the food. The amount of muscle activity has been shown to depend on the texture of the food: more muscle activity is observed for harder foods (111–114). Thus, the amount of muscle activity is an indication of how forcefully a subject can chew or clench the teeth together. Furthermore, a positive and near linear relationship has been shown to exist between surface electromyography (EMG) of the jaw elevator muscles and a steady level of bite force during isometric contractions (115–122). The relationship between EMG and bite force as obtained during clenching experiments (static condition) may be used to estimate bite forces from recordings of EMG during function (dynamic condition). However, the relationship between EMG and force during mastication may be different from the observed relation under isometric conditions, because the force-length and the force-shortening velocity relationships of muscles play a role during dynamic conditions (123–125). It was demonstrated that the use of isometric data for dynamic biting may cause overestimation when chewing force is predicted from masticatory data (125).

Maximum voluntary bite force is an important variable to assess the functional state of the masticatory system. Bite force has been used to evaluate masticatory function in relation with occlusal factors (126–129), dentition (109, 130), dental prostheses (27, 131), implant treatment (33, 80, 132), orthognatic surgery (133, 134), oral surgery (135–137), temporomandibular disorders (TMDs) (118, 138) and neuromuscular disease (139, 140). Bite force has been reported to have a large influence on masticatory performance in subjects with overdentures, full dentures as well as natural dentitions (32, 60). Correlation coefficients up to 0·8 were reported, and thus, bite force explains over 60% of the variance in masticatory performance.

Maximum bite force is influenced by factors related to the recording technique (128), like the location of the measurement within the dental arch [incisors vs. (pre)molars] (27, 132, 141), number of teeth included (130, 142), dimensions of the bite force transducer (thin pressure-sensitive sheet vs. strain gauge bite transducer) (106, 143) and unilateral versus bilateral measurements (106, 118, 132, 144, 145). Therefore, one should be careful when comparing bite forces obtained with different recording techniques. For instance, bilaterally measured maximum force was on average 30%–40% larger than the unilaterally measured force (118, 144, 145). An overview of maximum voluntary bite forces reported for healthy subjects is given in Table 1 (27, 32, 60, 106, 118, 126, 138, 141, 143–153).

Significantly higher maximum bite forces are reported for men than for women (126, 132, 141, 143, 145, 153). Furthermore, maximum bite force tends to decrease with age for adult subjects (27, 60, 109, 126, 130, 143, 145). The decrease in bite force may be a direct effect of age on muscle strength, or it may be caused by changes in food choice because of deteriorated dentition. This may lead to less-trained jaw muscles. Although the correlation between age and bite force is significant, it should be realised that the effect of age on bite force is small. Correlation coefficients between −0·22 and −0·31 were reported, which means that age explains <10% of the variance of bite

Table 1. Overview of average maximum voluntary bite force and standard deviation as measured unilaterally and/or bilaterally in the molar region of dentate adult subjects

Reference	Unilateral*		Bilateral*		Number of subjects‡ (*n*)
	Male or all†	Female	Male or all†	Female	
Ahlberg *et al.* (138)	878 (194)	690 (175)			196/188
Bakke *et al.* (118)	480 (163)		694 (263)		19
Bakke *et al.* (126)	522 (123)	441 (113)			59/63
Braun *et al.* (146)			814 (209)	615 (138)	86/56
Clark and Carter (147)	354 (73)	—			10 (males)
Ferrario *et al.* (141)	306 (42)	234 (71)			36/16
Fontijn-Tekamp *et al.* (32)	398 (103)				19
Gibbs *et al.* (148)			725		20
Hagberg (149)		395 (93)			9 (females)
Haraldson *et al.* (150)	383 (164)				10
Hatch *et al.* (60)	583 (281)				631
Helkimo *et al.* (27)	444 (157)	357 (159)			28/16
Ikebe *et al.* (143)			512 (318)	442 (275)	444/376
Miyaura *et al.* (151)			491 (277)		590
Shinogaya *et al.* (106)	553 (105)		1110 (288)		17
Thompson *et al.* (152)	520 (190)				13
Tortopidis *et al.* (144)	429 (132)		579 (235)		8 (males)
van der Bilt *et al.* (145)	490 (192)	418 (138)	652 (151)	553 (170)	13/68
Waltimo and Könönen (153)	847 (131)	597 (94)			22/24

*All bite forces are expressed in Newtons (N).

†Refers to all subjects if there is no separate value for females.

‡Number of male/female subjects or all subjects.

force. In a study on the determinants of masticatory function, it was reported that age had a direct effect on bite force and on occlusal units (60). Furthermore, an indirect effect of age on bite force was reported, which was caused by a decrease in the number of occlusal units.

Salivary flow rate

The production of sufficient saliva is indispensable for good chewing. The water in saliva moistens the food particles, whereas the salivary mucins bind masticated food into a coherent and slippery bolus that can be easily swallowed (6). It has been suggested that the swallowing process initiates when the cohesive forces that bind food particles together into a bolus are strongest (10). The important role of saliva for chewing and swallowing is demonstrated by the finding that the number of chewing strokes, hence time in the mouth, needed for swallowing significantly increases after experimentally induced oral dryness (154). Additionally, significantly more saliva is required for oral manipulation of powdered crisp bread than for pieces of crisp bread (155), 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 (156). 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 (157). While saliva and chewing have been shown to be interrelated, the relationship between amount of saliva and mastication has not been studied extensively (158). During mastication, it is likely that mechanoreceptors in the gingival tissues will be stimulated which may result in salivary flow (159, 160). At chewing forces as low as 5% of comfortable chewing forces, the masticatory-salivary reflex could already be elicited (159).

Mechanically stimulated salivary flow rate can be determined in a standardised way from chewing on a piece of tasteless Parafilm. Over a period of 5 min, a subject expectorates saliva at 30-s intervals into a pre-weighed container, and flow rate (mL min^{-1}) is then calculated. Flow rates of mechanically stimulated whole saliva between 0·52 and 4·55 mL min^{-1} have been reported for healthy subjects (161). In a group of 266 healthy subjects, salivary flow rates ranged from 0·16 to 3·8 mL min^{-1} (86). In that study, it was shown that the number of chewing cycles until swallowing was only weakly correlated ($r = -0{\cdot}13$; $P = 0{\cdot}04$) with the salivary flow rate of a subject. The results of that study are shown in Fig. 4. Salivary flow rate only explains 2% of the variance in the number of chewing cycles. This means that a subject with a relatively high salivary flow rate does not necessarily swallow food after fewer chewing cycles than a subject with less saliva. As a consequence, subjects with relative high salivary flow rates are used to swallow better moistened food than subjects with less saliva. This may have an influence on the perception of food. However, it was reported that there was no relationship between a subject's salivary flow rate and sensory ratings (162). Thus, a subject with a larger salivary flow rate during eating did not rate food differently from a subject with less salivary flow.

Masticatory function in various groups of individuals

Natural dentition

Chewing efficiency decreases as the natural dentition deteriorates (19, 23, 32, 35, 43, 60, 163). In most studies on the relation between dental state and masticatory function, subjects with a poor dental state were compared with subjects who have a complete

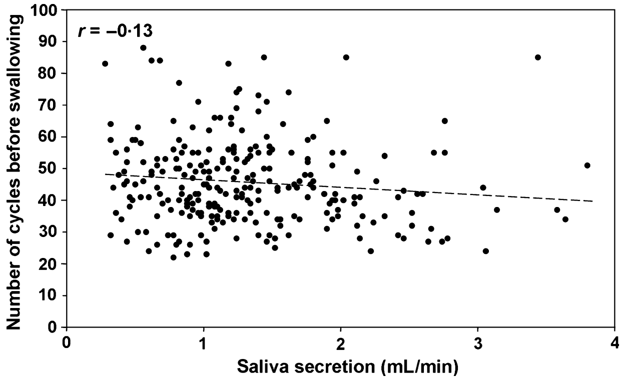

Fig. 4. Number of chewing strokes needed before swallowing Melba toast as a function of the salivary flow rate. The data were obtained from 266 healthy adult subjects. Dashed line shows linear regression. A small, but significant correlation was observed ($r = -0{\cdot}13$; $P = 0{\cdot}04$; 2% explained variance only), which indicates salivary flow rate hardly influences the number of chewing cycles. Reproduced from (86).

dentition. However, there have been few studies that directly determined the influence on masticatory function of prosthodontic treatment. Masticatory performance improved immediately after prosthodontic treatment (95). Thereafter, a further gradual increase in masticatory efficiency occurred until after a month the masticatory function was optimal. The masticatory performance of partially edentulous patients has been studied before and after completion of prosthetic restoration (25). The results of the patient group were compared with data obtained for a control group of subjects having a full dentition. This approach allowed quantification of the extent to which masticatory function could be restored. The total number of occluding post-canine teeth increased as a result of the prosthodontic treatment, yielding a significantly improved objective masticatory function. The average masticatory performance was found to approach the level of a control group of subjects with a complete dentition, if all occlusal units of the longest posterior side were replaced. Subjects with an incomplete dentition tended to chew predominantly at the side of the longest posterior arch (21, 25, 35). Rehabilitation of post-canine teeth restores some of the objective masticatory function and leads to an increased appreciation of the masticatory function, although no correlation between the change in objective and self-assessed masticatory function was found (25, 78–80).

Compromised dentition

The anterior and premolar regions of the dental arch are functionally and aesthetically indispensable and are considered a priority in rehabilitation (164). The (pre)molar regions play an important role in mastication. The literature indicates that masticatory ability (self-assessed masticatory function) is closely related to the number of teeth, and it is considered to be impaired when the patient has <20 well-distributed teeth (21, 34, 39, 41, 76). In that case, subjects reported complaints on chewing function: they had to chew longer, swallowed coarser food particles and could not chew hard foods (41). A dentition where most of the posterior teeth are missing was defined as a shortened dental arch (21). In a study on 725 adults with shortened dental arches in Tanzania, it was observed that shortened dental arches with intact premolar regions and at least one pair of occluding molars provided sufficient chewing ability (41). These subjects could chew 20 common Tanzanian foods with hardly any complaints. Shortened dental arches with 3–4 pairs of occluding premolars and asymmetric arches resulted in impairment of chewing ability, especially for hard foods. Such a dentition was inadequate for chewing hard foods and resulted in more complaints about chewing function (41). It is difficult to quantify the minimum number of teeth needed to satisfy functional demands because these demands vary from individual to individual (165). Furthermore, both dental and financial considerations influence the treatment plan. The question of replacement of missing molar teeth by cantilevers, resin-bonded fixed partial dentures, implant-supported prostheses or distal extension removable partial dentures becomes less and less one of the effectiveness of treatment and more of a financial decision (164–166). However, a study on objective masticatory function showed that persons with a shortened dental arch needed twice as many chewing strokes as persons with a complete natural dentition to comminute a test food to a certain size (32). Although persons with a shortened dental arch tend to be satisfied with their oral function, improvement of oral function may still be able to be obtained from dental treatment. Patients' needs and demands vary much and should be individually assessed (164, 166).

Complete dentures

Retention and stability problems of the mandibular prosthesis often cause complaints of masticatory function in complete denture wearers. The ability of denture wearers to break down test food is very poor when compared with that of persons with natural dentitions. Complete denture wearers needed on average four times, (32, 52), six times, (26) and even eight times (167) the number of chewing strokes of dentate persons to achieve the same degree of pulverisation. It was found that the difference in chewing efficiency between dentates and denture wearers depends on the consistency of the food (28). The poor chewing performance of denture wearers was compensated by chewing longer and swallowing coarser food particles (19, 35, 64, 94, 168, 169). One of the factors leading to the decrease in chewing performance is the reduced bite force that denture wearers can develop owing to a lack of retention and stability of the denture. The bite force of these subjects obtained with maximum clenching (unilateral) ranges from 77 to 135 N (27, 32, 75, 131, 150, 170), whereas the average maximum bite force (unilaterally measured) for dentate persons varies from 306 to 847 N (see Table 1). The maximum bite forces of denture wearers may be even lower than the forces needed to penetrate natural foods, such as boiled meat (80 N), raw carrot (118 N) and rye bread (167 N) (170). Thus, denture wearers might have difficulties in biting and incising such foods. As a consequence, full denture wearers select only a few food particles at a time, so the total force needed to crush the food is limited (28). We may conclude that edentulous persons are handicapped in masticatory function, and even clinically satisfactory complete dentures are poor substitutes for natural teeth. Although the objective masticatory performance of complete denture wearers was reported to be low, approximately 80% of the complete denture wearers considered their self-assessed chewing ability to be good (42, 171). The future of complete dentures in oral rehabilitation was recently reviewed (172).

Implant-retained overdentures

Mandibular implant overdenture treatment is a successful treatment modality for complete denture wearers. Reviews on the effects of implant treatment on masticatory function were recently published (81, 173). Furthermore, different functional aspects of oral implants and future recommendations were published in a recent issue of the *Journal of Oral Rehabilitation* (174). Patients who have had implant treatment reported high levels of satisfaction regarding various aspects of their denture function, and they were more satisfied than patients with similar problems who received a conventional complete denture without implant support (30, 175–181). Furthermore, mandibular implant treatment provides significant improvement over conventional treatment in oral-health-related quality of life (182). Patients' appreciation of their implant-retained denture was remained high for a long period of time as was demonstrated in a 10-year evaluation of implant-retained mandibular dentures (183). Improvement of the oral function after implant treatment was also demonstrated by objective methods. The maximum bite force of subjects with a mandibular denture supported by implants was 60–200% higher than that of subjects with a conventional denture (33, 80, 132, 184–187). In a group of 12 patients with implant-supported mandibular overdentures, the average maximum bite force increased from 116 N before implant treatment to 200 N three months after treatment (187). Five years later, the average maximum bite force was still at that high post-treatment level (193 N). The masticatory performance also significantly improved after implant treatment (29, 32, 187–191). However, not all studies did report significant improvement of masticatory function after implant treatment (59, 186). There appeared to be little difference in oral function and patient satisfaction between mainly tissue-supported and implant-supported mandibular overdentures (29, 31, 132), and the same applies to removable versus non-removable prosthetic appliances (176, 192).

The average number of chewing cycles needed to halve the initial size of a test food was reported to decrease from 47 to 25 cycles after implant treatment (189). Thus, after implant treatment, subjects needed only about half the number of chewing cycles as before treatment to comminute their food to half the initial size. Jaw muscle activity during chewing did not significantly change after implant treatment (193, 194). A decrease in masseter muscle activity during swallowing was observed after implant treatment, which may indicate adaptation to the new condition of more stability of the mandibular denture (194). The long-term effects of implant treatment on oral function also proved to be promising (80, 185, 195–197). Ten years after implant treatment, jaw muscle activity parameters and kinesiographic parameters (vertical opening, frontal extension and closing velocity) approached the values of normal dentate subjects (196). Furthermore, maximum bite force and masticatory performance significantly increased after implant treatment and remained unaltered during the following 10-year period (197). Thus, implant treatment greatly improves masticatory function and patient satisfaction for a long period of time.

Temporomandibular disorders

Temporomandibular disorders is a collective term embracing a number of clinical problems that involve the masticatory musculature, the temporomandibular joint and associated structures or both (198). Main TMD subgroups are classified as muscle-related and temporomandibular joint-related conditions. Mastication may be hampered by TMDs (199–202). As a result, limited masticatory function is one of the problems that patients with TMDs encounter. Rehabilitation to improve masticatory function is therefore one of the goals in the treatment of TMD (203). Most of the TMD studies deal with self-assessed masticatory function 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, the three most frequent jaw disabilities were found to be: eating hard foods (77·6%), yawning (75·7%) and chewing (64·5%) (204). Masticatory ability has also been evaluated from questionnaires regarding the various types of food. Scores on masticatory ability significantly correlated with temporomandibular joint pain (negative correlation) and mouth opening capacity (positive correlation), but not with temporomandibular joint noise and muscle tenderness (203). Multiple regression analysis could explain 37% of the variation in masticatory ability from eight independent factors (gender, age and six TMD parameters).

Masticatory function of patients with TMD has been objectively determined, and these include masticatory performance, bite force, bite force endurance, EMG and jaw kinematics. Changes over time of masticatory performance and chewing movement were examined in patients who had been diagnosed with non-reducing disc displacement of the temporomandibular joint, but who had not received any treatment (205). Two years after the initial visit, it appeared that masticatory performance and chewing movement had improved spontaneously, although these parameters did not reach the level of healthy controls.

Counselling, occlusal appliances and physiotherapy are often used treatment modalities to restore joint and muscle function (206–210). A maxillary stabilisation splint used during sleep for 6 weeks did not alter the jaw movements when chewing soft food (211). There was no difference regarding masticatory performance and bite force between patients presenting anterior disc displacement with and without reduction (200). Patients with mainly arthrogenous TMD for longer than 3 years tended to display less reduction of their masticatory performance (201). Again, comparison with controls showed that these patients still had a significantly reduced masticatory performance. Maximum bite force was also used to quantify oral function in patients with TMD (138, 212, 213). Significant (negative) correlations ($r = -0{\cdot}55$, $P = 0{\cdot}01$) were found between maximum bite force and TMD discomfort scores. An increase in bite force from 37% pre-operatively up to 93% of normal levels 1 year after joint surgery has been reported in patients with temporomandibular joint disorders (214). The insertion of a stabilisation splint immediately reduced the muscle activity of masseter and temporalis during maximum voluntary clenching ($P < 0{\cdot}005$), whereas the symmetry between left and right ($P < 0{\cdot}05$) and also between masseter and temporalis ($P < 0{\cdot}01$) increased (215).

Orthognathic surgery patients

Functional deficits in orthognathic surgery patients were recently reviewed (216). Dentofacial deformities might hamper the function of the masticatory system. Indeed, many studies have reported lower than normal maximum bite forces in orthognathic surgery patients before treatment (217–221). Also, significantly lower masticatory performances were shown for orthognathic patients than for controls (217, 219, 220, 222, 223). The mean masticatory efficiency of a pre-operative group of 54 patients with mandibular prognathism was reported to be approximately half that of the control group (222). Surgical correction of a dentofacial deformity often leads to an increase of maximum bite force (133, 218, 220, 221, 224). In a study on 15 female retrognathic patients, maximum bite forces had increased significantly after surgery, approaching normal values within 2 years (221). However, the consequences of a surgical correction for masticatory performance are inconsistent. In a group of patients with mixed dentofacial deformities, 3 years after surgery, the masticatory performance had not increased (225). Surgical correction of mandibular prognathism often leads to an increase of masticatory performance, but control values are not reached (134, 220, 226). Correlations between masticatory performance and estimated masticatory forces were weak, suggesting that jaw muscle force is not the primary factor that determines masticatory performance (217). Other factors contributing to masticatory performance might include occlusal relationships and mechanical advantage.

Ageing and nutrition

Elderly people may have deficiencies in masticatory performance, because of deteriorated muscle strength, loss of teeth, malocclusion, periodontal disease and decrease of motor skill (32, 143, 227–232). Also, salivary flow rate may decrease for the elderly, although the decrease appeared to be moderate in fit healthy unmedicated subjects (100, 233–235). However, substantial changes in salivary composition and flow rate were reported for elderly people as a result of diseases and conditions associated with age (100). It is well established that sensory acuity diminishes with age and that within the chemical senses, the sense of smell is more prone to losses with age than is the sense of taste (236, 237). It is also widely assumed that such losses inevitably lead to less pleasure derived from eating (238), and to a preference for stronger flavoured/tasting products (239). As a consequence, age-related changes in sensory perception and preference are believed to have a major impact on appetite and food intake (237). Oral sensation, as measured with two-point discrimination, oral stereognosis, vibrotactile detection, proprioception and thermal sensitivity, was shown to remain stable with ageing and showed only a slight decline after age 80 (240, 241).

The deterioration of masticatory performance and salivary flow may lead to changes in the diet, because some foods become troublesome to eat (93, 96, 98–100, 100, 101, 242). A review of the influence of impaired mastication on nutrition has been published some years ago (97). The altered food choice, predominantly soft and easy to chew foods, may result in lower intakes for key nutrients as iron and fibre (36, 93, 96, 243). As a result, the quality of life could be influenced by the deteriorated oral status in the elderly (244, 245). Tailored nutrition intervention aimed to increase the fruit and vegetable intake of edentulous older people may positively change dietary behaviour (246). A comparison between a group of dentate subjects and denture wearers demonstrated that dentate subjects consumed significantly more fruit and vegetables, although the differences were small (40). Perceived chewing ability explained only 4% of the variance in the intake of fruit and vegetables. Attitude, self-identity and knowledge explained a further 20%. Chewing-related variables are not predictors of overall diet quality (77). If the diet of denture wearers is to be improved, psychological factors, as well as perceived chewing ability, must be addressed.

In a recent study, the impact of age on masticatory function was assessed (94). The oral function of a group of 14 young fully dentate subjects (37 years) was compared with the function of 14 aged individuals with similar dentition (69 years). Aged subjects used significantly more chewing strokes to reach the swallowing threshold than younger subjects, and as a result, they swallowed finer food particles than the young subjects. Similar results were reported in a study on a large group ($n = 863$) of subjects with either natural teeth or fixed replacement of their missing teeth (20). That study demonstrated persistence of high masticatory performance despite age. Older subjects increased the number of chewing strokes used to prepare the food for swallowing. Aged denture wearers made significantly more chewing strokes before swallowing than aged dentate subjects (94). However, the median particle size of the swallowed food was significantly larger for aged dentures wearers than for aged dentate subjects, despite the increase in the number of chewing cycles. Masticatory function was thus adapted to ageing, but was impaired in denture wearers, who failed to compensate for their compromised masticatory performance (94). Recently, a literature review was published with the goal to investigate the relationship between mastication and cognition, with a special focus on ageing and dementia (247). A causal relationship between mastication and cognition was suggested. Furthermore, correlations were reported between mastication and activities of daily living and nutritional status (247).

Neuromuscular control of chewing

The movement of the jaw, and thus the neuromuscular control of chewing, plays an important role in the comminution of food. Chewing requires muscle activity to make the movements of the jaw and to exert forces to cut or grind the food. A relatively low level of muscle activity is observed in the surface EMG of the closing muscles of subjects making pseudo-chewing movements without food. More muscle activity is generated if the closing movement is counteracted by food resistance (4, 248). Apparently, a small part of the muscle activity observed during chewing is needed just for the basic rhythmic movements of the jaw, and additional muscle activity is required to overcome the resistance of the food. The masticatory forces are controlled very precisely, and these forces change from bite to bite and depend on the consistency of the food: more muscle activity is observed for harder foods (111–114). Jaw muscle motoneurons are activated by three sources: the cortical masticatory area, which initiates and stops mastication and delivers pre-programmed movement patterns depending on expectations and feedback, the central pattern generator (CPG), which provides basic rhythmic activity to the jaw muscles, and peripheral feedback, which modifies jaw muscle activity (249, 250). Reviews were published on: the generation of the central masticatory pattern and its modification by sensory feedback (251), the adaptation of masticatory patterns to the biomechanical properties of food (252), the reflex control of human jaw muscles (253) and the functional roles of oral reflexes in chewing and biting (254).

Cortical masticatory area

Site-specific repetive stimulation of the cortical masticatory area induces various patterns of rhythmic jaw movements in mammals (13, 255, 256). The activity of most neurons in the masticatory cortex is higher during ingestion than during mastication, which suggests that the masticatory cortex plays a major role in setting the parameters of the first bite (251). The pathways that originate from the masticatory cortex are used for the conscious initiation and termination of mastication (253). The masticatory cortex may also contribute to the continuous modulation of the masticatory pattern evoked by the CPG. The masticatory cortex may set the effectiveness of the synaptic input to motoneurons that innervate jaw muscles or release a pre-programmed movement pattern, depending on the food resistance encountered in the previous bite (253).

Central pattern generator

Experiments on animals have established the existence of a rhythm generator for mastication which consists of a group of cells located in the brain stem, known as the CPG (249, 257). The basic rhythmic activity of the jaw-opening and jaw-closing muscles is known to be generated by the CPG. Cortically evoked rhythmic trigeminal activity remained present in animals after elimination of sensory feedback from peripheral receptors (249, 258). This shows that neither muscle spindle afferents nor periodontal afferents are essential to the basic rhythmic activity patterns of mastication. Cortical stimulation of the anaesthetised rabbit induced rhythmical mandibular movements in the awake animal (259). The CPG may be switched on by activity of higher centres or by intra-oral stimuli (260, 261). The existence of the masticatory CPG in human subjects has not been directly shown, but rather has been assumed from circumstantial evidence, such as the existence of the suckling reflex in infants (262), phase-dependent modulation of mastication (263), phase-dependent modulation of mandibular stretch reflex sensitivity (264), phase-dependent modulation of exteroceptive jaw reflex (265, 266) and the interaction among mastication, respiration and swallowing (267).

Peripheral feedback

Comparison of the movements and the activity patterns in the motor nerves evoked by cortical stimulation of the paralysed animal with those of natural chewing before paralysis has demonstrated the important role of somatosensory feedback in mastication (250). During cortical stimulation, the CPG produces stereotyped open–close cycles, whereas during natural chewing, the movement trajectories of the consecutive chewing cycles vary considerably (250). Moreover, the activity of the jaw-closer α-motoneurons is much smaller in fictive mastication than during natural chewing. This suggests that to adequately fulfil the motor tasks of the mandible during chewing, the central nervous system requires information about the position and velocity of the mandible, about the forces acting on the mandible and on the teeth, and about the length and contraction velocity of the muscles involved. An increase of the amplitude and the duration of the activity of the jaw-closing muscles of the rabbit was observed, when cortically induced rhythmic open–close movements were obstructed by a steel ball or a foam strip between antagonistic teeth (259, 268, 269). This effect was reduced after elimination of feedback from the periodontal pressoreceptors by deafferentation. When spindle cell bodies were also destroyed, the facilitation of the jaw-closing muscles disappeared almost completely (270). It was concluded that periodontal pressoreceptors and muscle spindles provide positive feedback to the jaw-closing muscles during mastication.

Simulated chewing experiments

The neuromuscular control of chewing in humans has been studied during simulated masticatory movements (248, 271, 272). In these studies, food resistance was simulated by a computer-controlled external load,

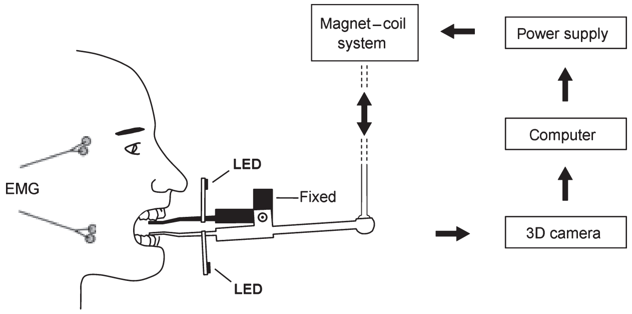

Fig. 5. Experimental setup for external loading of jaw muscles. Reproduced from (299).

acting on the mandible in a downward direction during closing (Fig. 5). During the experiments, the subjects made rhythmic open–close movements at their natural chewing frequency, controlled by a metronome (248). Sequences of cycles with a load were unexpectedly alternated with sequences of cycles without a load. Jaw movement, and EMG of the masseter, temporalis and digastric muscles were recorded. It was demonstrated that the additional muscle activity, needed to counteract the external load, consists of two components: an anticipating component starting before the onset of the food simulating load and a peripherally induced component starting after the onset of the load. The anticipating component was generated only if a counteracting load was expected. The onset of the anticipating muscle activity occurred immediately after the moment that the jaw started closing. Peripherally induced muscle activity was generated on average 25 ms after the onset of the load. About 85% of the muscle activity needed to overcome the external load was peripherally induced, which indicated that the muscle activity was mainly of sensory origin. However, when the movement rate of chewing was doubled (fast chewing with 120 cycles per min), the contribution of peripherally induced muscle activity decreased to only 40%. Therefore, as jaw movement speed increased, emphasis in the control of the muscle activity shifted from sensory induced (closed-loop) to feed forward (open-loop) control (273). Muscles spindles are primarily responsible for the peripherally induced muscle activity as was demonstrated in an experiment on anaesthetised rabbits (269). An experiment with rhythmic arm movements, comparable to the rhythmic jaw movements described above, showed that arm and jaw muscles responded differently to loading (274). In the arm muscles, there was little reflex activity, but a large anticipatory response, which indicates that the role of reflexes in these rhythmic arm movements was less important than the role of reflexes in rhythmic jaw movements. Furthermore, symmetrical responses were observed in biceps and triceps, which indicate similar motor control in both arm muscles. In contrast, large differences in reflex activity between masseter and digastric muscles were observed, indicating fundamental differences in sensory feedback to the jaw-closing and jaw-opening muscle (271).

The masticatory system is mainly closed-loop controlled. A reason for this may be the fact that the relatively large forces needed for food fragmentation must be controlled under uncertain conditions. First, no optical feedback is available in the chewing process. Furthermore, food resistance may vary largely from cycle to cycle. Thus, immediate muscle response is necessary to maintain a constant chewing rhythm. Furthermore, damage to the dental elements must be avoided when biting through hard and brittle food. Force-velocity properties of the jaw-closing muscles have been proposed as the principal factors responsible for halting jaw closure in the situation where the food resistance suddenly disappears (275). The force of the jaw-closing muscles will decrease when they shorten, while the force of the jaw-opening muscles will increase when they are stretched. This will result in a vanishing of the chewing force (275). The limitation of the chewing force by reflex mechanisms [latency of 8–9 ms between the EMG inhibitory period and the reduction of force (276)] would be too slow to limit the jaw velocity at tooth contact. The force-velocity properties of the muscles provide a quick mechanism for dealing with unexpected closing movements and so avoid damage to the dental elements (275).

The muscle spindles of the jaw-closing muscles provide positive feedback to the alpha motoneurons. It is generally assumed that the feedback is modulated during chewing so that counterproductive forces of the jaw-closing muscles can be avoided during jaw opening (277). Muscle spindle feedback should be suppressed during jaw opening. Indeed, jaw-jerk reflexes elicited during simulated chewing appeared to be modulated (264). Pronounced reflexes were observed at the onset of jaw closing, during the closing phase, and at occlusion. No or only weak jaw-jerk reflexes were present during jaw opening. The modulation of masticatory reflexes during simulated chewing has also been studied by delivering mechanical taps (1 and 2 N) to the upper left central incisor with a tooth stimulator (272). The taps were delivered each time the jaw passed through the mid-gape point during jaw closing and opening. Reflexes were also elicited during a static task with the jaw at mid-gape position. Periodontal mechanoreceptor- and muscle spindle-mediated reflex components were differentiated by performing experiments without and with periodontal anaesthesia. Both periodontal mechanoreceptor and muscle spindle reflexes were reduced during simulated masticatory chewing when compared to the static condition (272). Modulation of exteroceptive jaw muscle reflexes, elicited by light noxious electrical stimulation of the lower lip, has also been studied during simulated chewing (265, 266). Reflexes in response to mildly painful stimuli were 'gated' during simulated mastication: as the teeth moved closer towards occlusion, the inhibitory response was progressively reduced. Conversely, responses to moderately painful stimuli became stronger, as the teeth moved closer towards occlusion (265). The modulation of jaw muscle reflexes allows smooth mastication to occur, as it gates out mildly painful signals while stronger responses occur when the signal indicates potential or actual damage closer to occlusion (265).

Influence of food characteristics on chewing

Characteristics of the food are known to influence the masticatory process. When we chew for instance a crispy food, the jaw decelerates and accelerates as a result of resistance and breakage of food particles. The characteristic breakage behaviour of a food is essential for the sensory sensation. Food hardness is sensed during mastication and affects jaw muscle activity, masticatory force and mandibular jaw movements. Food characteristics have a large influence on the number of chewing cycles needed to prepare the food for swallowing. Dry and hard foods require more chewing cycles as more time is needed to break the food down and to add enough saliva to form a cohesive bolus suitable for swallowing.

Influence of food type on muscle activity, chewing force and jaw movement

A clear relationship between food hardness and jaw muscle activity has been reported in numerous studies. Increased jaw muscle activity and longer burst duration of the muscle activity were observed for harder foods (111–114, 278–281). It was shown that the hardness of chewing gum (soft or hard gum) influenced the chewing cycle duration and the amplitude of the muscle activity. The subjects chewed slower and with more muscle activity on the hard gum (278). In another study, muscle activity was measured while subjects chewed on 15 different types of food (various kinds of cheese, nuts and carrots), which largely varied in mechanical properties (112). Young's modulus and toughness were measured for each food. Young's modulus (or elastic modulus) was determined from the slope of a force–deformation curve of the material. Toughness is the resistance to fracture of a material when stressed and was measured by a wedge test. Muscle activity needed to chew the various food types turned out to be inversely related to the square root of the ratio of food toughness and the modulus of elasticity ($r = -0{\cdot}86$; $P < 0{\cdot}0001$). The influence of food characteristics on chewing was also studied using model foods (280). Two model food types were used, presenting either elastic or plastic rheological properties. Each model food type consisted of four products of different hardness. The elastic model food was an edible jellied confectionery product, and the plastic model food was an edible caramel confectionery product. Muscle activity was significantly affected by an increase in hardness regardless of the food type, whereas the shape of the chewing cycles depended on the rheological properties. The products with plastic rheological properties were chewed at a slower frequency than the elastic foods. Chewing tests were also performed with meat of two different textures: tough and dry versus tender and juicy meat (157). The mean muscle activity needed for chewing the tough meat was significantly higher than for chewing the tender meat. As a consequence, when the bolus was ready to be swallowed, more saliva had been incorporated into the tough meat samples (mean weight increase 36%) than the tender meat samples (mean weight increase 30%).

Chewing force has been measured using a multiple-point sheet-type sensor (282). The sensor was a flexible sheet, thinner than 0·1 mm, which had many pressure-sensing points (269 sensing cells) on it. Each sensing cell detects pressure in real time. With this method, both chewing force and contact area between the teeth are obtained. Three silicone rubber model foods of varying hardness were used. The study clearly indicated that sample hardness modified chewing force of humans. The masticatory force during chewing samples of silicon rubber was shown to increase from 100 to 150 N, when the hardness of the samples increased by a factor of 2 (282). Chewing force was also determined for five natural foods in the first chew (283). Force–time curves largely varied for both foods and subjects. Various peaks occurred in the force–time curves of cracker and rice cracker, whereas only two peaks were observed for carrot. The authors suggested that the first peak corresponded to sample rupture. The regulation of bite force increase during the splitting of food morsels of different hardness and the role of periodontal mechanoreceptors in this control was studied in a group of 15 subjects (284). They were instructed to hold and split food samples (peanuts and biscuits) between a pair of opposing central incisors before and during anaesthesia of the teeth. When higher bite forces were needed to split the food (on average 18 N for peanut and 9 N for biscuit), the duration of the split phase was longer and the split force rate was higher. During anaesthesia of the teeth, the duration of the split phase increased and the mean split force rate decreased. It was concluded that adaptation of the bite force rate to the hardness of the food was dependent on information from periodontal mechanoreceptors.

Jaw movement was reported to be influenced by food hardness (7, 279, 285–287). Larger jaw opening was observed when subjects chewed on harder foods. Similar results were reported for edible model foods (114). Four gelatine-based visco-elastic foods identical in shape but differing in hardness were used. The amplitude of the mandibular movements increased for harder foods, especially in the first five chewing cycles ($F = 19$; $P < 0{\cdot}01$). Jaw movement was shown to be also influenced by food size: larger food sizes led to larger jaw gapes and larger jaw velocities during chewing (288, 289). These results suggest that humans chew food such that the mandibular teeth that come into contact with the food open to a height equivalent to that of the food bolus. Sample thickness of the food also influences chewing force. The force needed to chew a piece of apple increased with sample thickness ($P < 0{\cdot}05$) (290).

During chewing, the food bolus or food particles are reduced in size, and saliva is produced to moisten the food. The food is softened by structure breakdown to smaller particles (brittle foods), by temperature raising (fatty foods) and by action of the water and α-amylase of saliva (dry foods and foods containing starch). As a result, jaw muscle activity, muscle work, jaw amplitude and cycle duration decrease while mastication proceeds (114, 231, 281, 291, 292). The decrease in muscle work during the chewing process is also illustrated in Fig. 1. The change in the pattern of jaw movement during the chewing process suggests continuous sensory modulation of the motor output to the mandibular musculature (287). Muscle activity could thus act as a sensory clue for certain food sensory properties such as tenderness of meat (293).

Influence of food type and food volume on swallowing threshold

Food characteristics do have a large influence on the number of chewing cycles needed to prepare the food for swallowing (84, 86, 157, 281, 287). In a group of 87 dentate subjects, the number of chewing cycles varied from on average 17 cycles for a portion of 8 cm^3 of cake up to 61 cycles for an equal portion of carrots (86). A significant linear relationship between the number of chewing cycles until swallowing and the yield force was recently demonstrated for five natural foods (294). A harder food will generally require more chewing cycles before it is ready to be swallowed. This is illustrated in Fig. 6. Also, the volume of the food largely influences oral physiology. For larger portion sizes, subjects needed more time and chewing strokes before they swallowed the food (63, 295–297). The number of

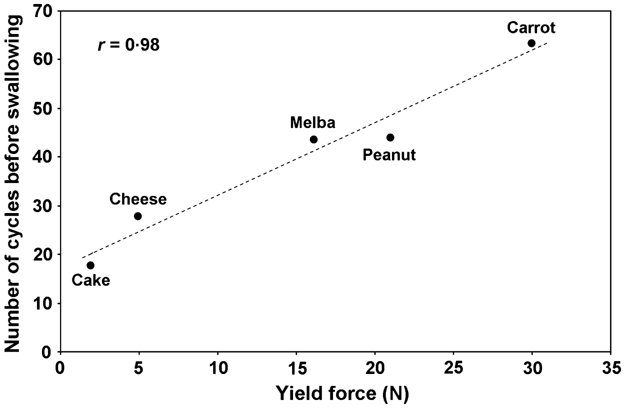

Fig. 6. Relationship between the number of chewing cycles until swallowing and the mechanical properties of the food (yield force). A fixed volume (8 cm^3) of cake, cheese, Melba toast, peanuts and carrots were fed to 87 healthy dentate subjects (42 ± 12 years). Reproduced from (294).

chewing strokes needed to prepare the food for swallowing linearly increased as a function of the food volume ($P < 0{\cdot}001$) (63). When the volume of carrots was doubled (from 2·8 up to 5·6 cm^3), the number of chewing cycles until swallowing increased by 40% (from on average 35 up to 49 chewing cycles).

Dry and hard products require more chewing cycles before swallowing, than moist and soft products. Evidently, more time is needed to break the food down and to add enough saliva to form a cohesive bolus suitable for swallowing (156). Thus, a dry product needs a longer time in the mouth to allow for enough secretion of saliva. Confirming this, buttering dry foods (cake, Melba toast and toast) significantly reduced the number of chewing cycles of these foods (86). The reason for this is probably that butter enhances lubrication and bolus formation of dry products, decreasing the time needed in the mouth to form a coherent bolus. Similar results were observed in a study in which lubrication of the food bolus had been experimentally varied (82). In a recent study, it was shown that adding small volumes of water (5 or 10 mL) to a food significantly lowered the number of chewing cycles and total muscular work until swallowing (281, 298). The largest effects were observed for melba and cake, which are dry products requiring sufficient saliva to form a coherent bolus safe for swallowing. More facilitation of the chewing process was observed after adding fluid to breakfast cake for subjects with relatively low salivary flow rates. Subjects with a relatively low salivary flow rate apparently benefit more from the addition of water than subjects with a larger flow rate.

In a recent article, the particle size distributions of the food boluses suitable for deglutition and the number of chewing cycles until swallowing were determined for 10 natural foods (84). The number of cycles, sequence duration and particle size distributions significantly differed among subjects and foods. Large differences in average median particle size of the bolus ready to swallow were observed, ranging from 0·82 mm for peanuts (hard food) to 3·04 mm for gherkins (soft food). Foods that were rapidly swallowed were both soft and characterised by a high water content (egg white, gherkins, mushrooms and olives). The boluses obtained from these foods contained many large particles. Harder foods needed more chewing cycles before swallowing, so a better particle fragmentation and bolus salivation was achieved (coconut, carrots).

Summary

Dentition and bite force were confirmed as the key determinants of masticatory performance: number of occluding (pre)molar teeth and bite force could explain 70% of the variance in masticatory performance. Also, the production of sufficient saliva is indispensible for good chewing. Masticatory function has been assessed in many patient groups. Patients with compromised dentition or with complete dentures reported many complaints on chewing function. They had to chew longer, swallowed coarser food particles and were not able to chew hard foods. Complete denture wearers needed on average four times the number of chewing strokes of dentate subjects to achieve the same degree of pulverisation of their food. Implant overdenture treatment was reported to be a successful treatment for complete denture wearers. After mandibular implant treatment, both maximum bite force and masticatory efficiency had doubled. Also, long-term clinical results of dental implants were reported to be excellent. Elderly people may have deficiencies in masticatory function, because of loss of teeth, periodontal disease, deteriorated muscle strength, decreased salivary flow rate and decrease of motor skill. This may lead to changes in the diet, because some foods become troublesome to eat. The altered food choice, predominantly soft and easy to chew foods, may result in lower intakes for key nutrients as iron and fibre. Tailored nutrition intervention aimed to increase the fruit and vegetable intake of edentulous older people may positively change dietary behaviour. Simulated chewing experiments have demonstrated that about 85% of the jaw muscle activity needed to crush the food was peripherally induced, which indicates that sensory feedback plays an important role in chewing. Jaw muscle reflexes were shown to be modulated, so that smooth jaw movements can be made during chewing. Food characteristics have a large influence on the amount of muscle activity, number of chewing cycles until swallowing and jaw movement.

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Correspondence: Andries van der Bilt, Department of Oral-Maxillofacial Surgery, Prosthodontics and Special Dental Care, University Medical Center Utrecht, G05.122, PO Box 85500, 3508 GA Utrecht, The Netherlands. E-mail: a.vanderbilt@umcutrecht.nl