Effect of the Occlusal Profile on the Masticatory Performance of Healthy Dentate Subjects

Nikolaos N. Giannakopoulos, Dr Med Dent, MSc[a]/Alexander Wirth, DDS[b]/Sebastian Braun, DDS[b]/
Lydia Eberhard, Dr Med Dent[a]/Hans J. Schindler, Dr Med Dent[c]/Daniel Hellmann, Dr Med Dent[a]

Purpose: The purpose of this study was to examine, on the basis of masticatory performance (MP), total muscle work (TMW), and range of movement (RoM), whether reduction of the profile of the cusps results in loss of the biomechanical effectiveness of chewing by healthy dentate patients. **Methods:** Twenty healthy patients (10 female, mean age: 24.1 ± 1.2 years) chewed standardized silicone particles, performing 15 masticatory cycles. Three experimental conditions were investigated: chewing on *(1)* the natural dentition (ND), *(2)* splints with structured occlusal profiles simulating the patient's natural dentition (SS), and *(3)* splints with a plane surface (PS). The expectorated particles were analyzed by a validated scanning procedure. The size distribution of the particles was calculated with the Rosin-Rammler function and the mean particle sizes (X_{50}) were determined for each experimental condition. The target variables of the experimental conditions were compared by repeated measures analysis of variance. **Results:** X_{50} values calculated for MP differed significantly (P <.002) between PS and SS, and between ND and SS. Conversely, no significant differences (P > .05) were observed between SS and ND. Regarding muscle work the EMG activity of the masseter differed significantly (P < .001) between the left and right sides, with higher values for the right (chewing) side. No significant differences (P > .05) were observed for TMW and RoM under the three test conditions. **Conclusions:** The results confirm the biomechanical significance of structured occlusal surfaces during chewing of brittle test food by young dentate subjects. *Int J Prosthodont 2014;27:383–389. doi: 10.11607/ijp.3793*

The human masticatory system has a remarkable capacity to comminute a wide range of food textures. Mastication is a physiologic process controlled by the central nervous system and modulated by sensory input from the involved tissues. The primary objective of the chewing process is the formation of a safe bolus.[1] The structures constituting the masticatory system—eg, the teeth, jaws, lips, cheeks, masticatory muscles, and temporomandibular joints—interact with different food textures and modulate mastication.[2] The effects of test food texture, initial particle size, bolus hardness, and volume of mouthful on mastication have been examined in numerous experimental settings.[3–13]In addition, the modulating effect of proprioception, salivary glands, sex, age, occlusal surface, dental status, and temporomandibular disorders on chewing has also been investigated.[14–29] The results of these investigations have revealed the varying effects of extrinsic and intrinsic factors on mastication.[30]

In contrast, little information is available regarding the adaptive behavior of the masticatory system in response to alteration of the occlusal profiles of dentate subjects. Loss of the original tooth shape, and thus loss of essential biomechanical characteristics, can result from either natural attrition and abrasion, which stem from parafunctional activity and nutritional habits, respectively, or prosthodontic rehabilitation, which often results in a flatter occlusal surface. Natural degradation is associated with long-term wear of tooth structure, which allows gradual adaptation of complex neuromuscular control mechanisms. Prosthodontic reconstruction, on the other hand, occurs over a short time period and requires immediate adaptation. The effect of flattening the occlusal profile, which implies reduction of shear occlusal forces,

[a]Assistant Professor, Department of Prosthodontics, University of Heidelberg, Heidelberg, Germany.
[b]Private Practice, Heidelberg, Germany.
[c]Professor, Department of Prosthodontics, University of Heidelberg, Heidelberg, Germany and Research Group Biomechanics, Institute for Mechanics, Karlsruhe Institute of Technology, Karlsruhe, Germany.

Correspondence to: *Dr Nikolaos N. Giannakopoulos, Department of Prosthodontics, University of Heidelberg, Im Neuenheimer Feld 400,D-69120 Heidelberg, Germany. Fax: 49 6221 565371; Email: nik.giannakopoulos@med.uni-heidelberg.de*

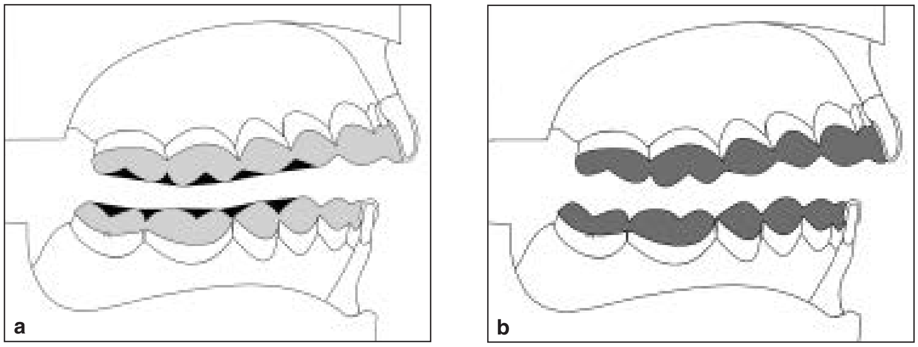

Fig 1 Schematic representation of the **(a)** splint with a plane surface and **(b)** structured splint.

is not well understood for fully dentate subjects. In vitro studies performed with single vertical loading have indicated an essential effect of the occlusal profile on the mincing process.[31] However, clinical investigations of the immediate effect of a flattened tooth profile on the kinetic behavior of the masticatory system throughout the entire chewing cycle are missing.

This in vivo study aimed to examine, on the basis of masticatory performance, whether reduction of the occlusal profile results in loss of biomechanical effectiveness during chewing sequences in healthy dentate subjects. The hypothesis was that an intact occlusal profile results in better masticatory performance than a flattened occlusion. This study also investigated the characteristics of the short-term neuromuscular control response to the changing occlusal profile.

Materials and Methods

Subjects

A convenience sample of 20 healthy participants (10 women and 10 men; mean age: 24.1 ± 1.2 years) were enrolled in this study. All of them were naturally, fully dentate (irrespective of the third molars), without need for dental treatment and without any pain or dysfunction, as assessed using the Research Diagnostic Criteria for Temporomandibular Disorders.[32] The study was approved by the Ethics Committee of the University Medical Centre, Heidelberg, Germany (S-174/2011). All participants provided written consent prior to the study. The experimental procedures were conducted in accordance with the Declaration of Helsinki. Prior to the experiments, all participants were asked about their preferred chewing side.

Experimental Occlusion

For the experimental setup, casts of the participants were mounted in a semi-adjustable articulator (SAM 2PX, SAM Präzisionstechnik) using an arbitrary facebow (Axioquick Anatomic Transferbow, SAM Präzisionstechnik). The articulator was programmed with individual kinematic data acquired using a telemetric jaw-motion registration device (JMA, Zebris Medical). On the basis of the mounted casts, two pairs of thin (0.3 mm) vacuum-formed copolyester splints (Erkodent) were fabricated for both arches. The first pair of splints followed the occlusal profile of the patients' natural dentition. The second pair was produced after the posterior occlusal surface of the mounted casts had been modified into a flat occlusion by means of acrylic resin (Trim Plus, Harry J. Bosworth). To obtain identical vertical distances between the arches for both pairs of splints, the mandibular splint was relined directly in the mouth with acrylic resin. This procedure was accomplished using a removable frontal jig, which equalized the incisal jaw gap for both types of splints to approximately 4 mm compared with intercuspation. Fine intraoral adjustment ensured both pairs of splints were shaped appropriately to guarantee chewing cycles without interference. The two experimental occlusal conditions are depicted in Fig 1.

Masticatory Performance

Standardized artificial test food (Optosil Comfort, Heraeus Kulzer) was used to measure masticatory performance via the assessment of particle size distribution.[33,34] The portions comprised 15 cubes with a 5.6-mm edge length and weight of approximately 3.0 g.

Electromyographic Activity

The electromyographic (EMG) activity of the masseter and temporalis anterior muscles was measured with silver/silver chloride bipolar surface electrodes (conducting surface diameter: 14 mm; distance from center to center of the two electrodes: 20 mm; Noraxon Dual Electrodes, Noraxon; Fig 2). The center of the muscle bulk was located by palpation, and the electrodes were placed parallel to the longitudinal axis of the muscle. Before electrode application, the skin was cleaned with 70% ethanol. A single surface electrode placed over the seventh vertebra served as the common electrode. The EMG signals were differentially amplified (Zebris EMG Bluetooth Measuring System, Zebris Medical), recorded at a sampling rate of 900 Hz, and saved and analyzed on a personal computer equipped with suitable software (WinJaw 10.6.77, Zebris Medical).

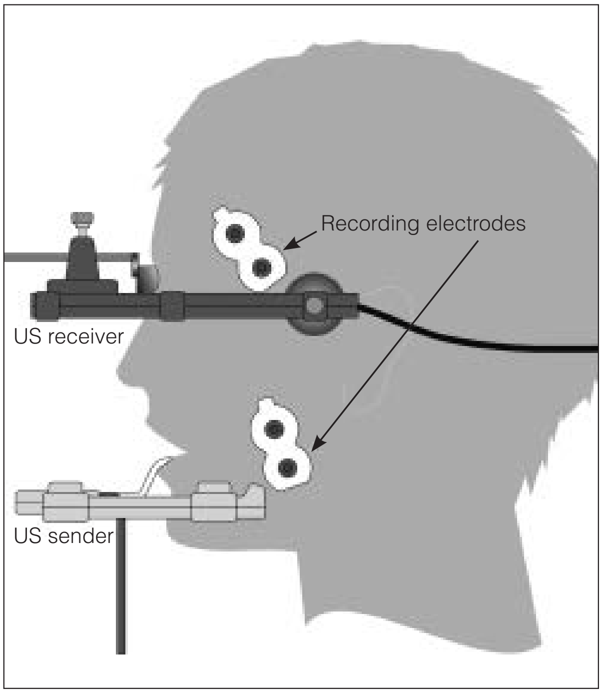

Fig 2 Schematic representation of the experimental setup for assessment of the mandibular kinematics and EMG activity of the temporalis anterior and masseter muscles. US = ultrasound.

Mandibular Movement

Kinematic data for the mandible were recorded with an ultrasonic telemetric device (Jaw Movement Analysis [JMA], Zebris Medical; see Fig 2). The labial side of the mandibular splint was reduced to allow attachment of the mandibular facebow to the teeth using a special paraocclusal device. The device was attached to the mandibular anterior teeth with cyanoacrylate adhesive, and the measurement system was calibrated according to the subjects' individual geometric anatomy. The JMA enabled the measurement of the spatial displacement of any point of the mandible; for this study, the trajectory of the point of the incisor during movement was selected.

Experimental Procedure

Chewing was performed under three experimental conditions: *(1)* chewing on natural dentition (ND), *(2)* chewing on splints with structured occlusal profiles simulating the participants' natural dentition (SS), and *(3)* chewing on splints with a plane surface (PS; see Fig 1). The participants minced the artificial test food with 15 chewing cycles on the right side only. The experiments were replicated twice per experimental condition in the same order (ND-SS-PS). The first chewing sequence was carried out to familiarize the participants with the test food and splint conditions; the second chewing sequence was used for measuring the particle size distribution. The sequence of the test conditions was chosen to provide the greatest "training" effect for the most unfamiliar condition (PS).

Data Analysis

After chewing, the particles were expelled from the mouth and analyzed using a validated scanning procedure described elsewhere.[35] The particle size distribution was computed using the Rosin-Rammler function,[36] and X_{50} values[33] were determined for each of the experimental conditions. The X_{50} value is the median particle size or the size of the aperture of a theoretical sieve (in millimeters) through which 50% of the volume of chewed particles can pass. Optical scanning can be used to estimate the particle size by applying specially developed image-analysis algorithms that calculate geometrically defined particle volumes, thus avoiding time-consuming sieving procedures.[35]

The raw EMG data obtained from the four muscles were rectified using the root-mean-square algorithm. The individual cycles were identified using semiautomatic software developed in-house,[37] which also computed the sum under the curve (integral) for each chewing burst of a specific muscle; the values obtained were added together to determine the specific muscle work (SMW). The target variable was the total muscle work (TMW) for all muscles investigated, representing the area under the curve of the rectified EMG recordings. The total amount of time (TT) needed for the 15 chewing cycles was also determined.

The cumulative length of the incisor point movement path (IMP) during the 15 chewing cycles was selected as a global target variable for the kinematic behavior of the neuromuscular system. This variable is considered the most appropriate measure of the movement effort of the mandible.

Table 1a Total Muscle Work (TMW) and X_{50} Values for Each Experimental Condition

	X_{50} (mm)		TMW (µV × s)	
	Range	Mean (SD)	Range	Mean (SD)
ND	3.80–5.14	4.53 (0.37)	640.75–3013.75	1276.04 (528.39)
SS	3.80–4.93	4.55 (0.31)	694.25–3364.25	1313.87 (573.21)
PS	4.26–5.27	4.77 (0.31)	604.5–2913.25	1259.63 (500.24)

ND = natural dentition; SS = structured splint; PS = plane splint.

Table 1b Total Time (TT) and Incisor Point Movement Path (IMP) Values for Each Experimental Condition

	IMP (mm)		TT (s)	
	Range	Mean (SD)	Range	Mean (SD)
ND	490.1–926.6	682.75 (119.59)	9.08–18.68	15.12 (2.39)
SS	474.0–962.0	678.65 (134.91)	11.35–20.02	14.67 (2.18)
PS	491.9–999.6	676.22 (144.99)	10.22–19.06	14.36 (2.56)

ND = natural dentition; SS = structured splint; PS = plane splint.

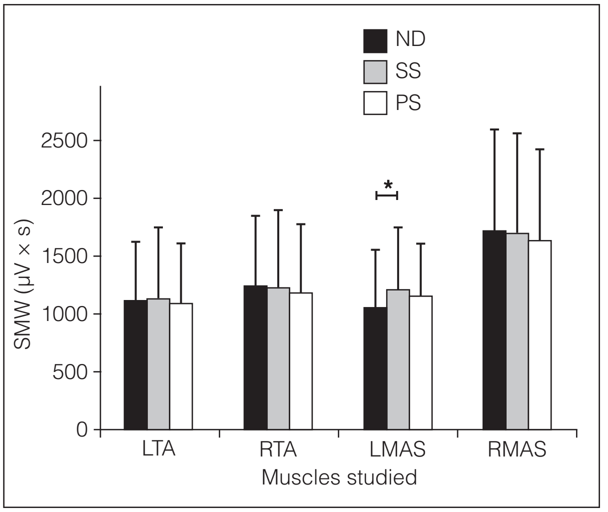

Fig 3 Specific muscle work (SMW) of the studied muscles for each experimental condition. LTA = left temporalis anterior; RTA = right temporalis anterior; LMAS = left masseter; RMAS = right masseter; ND = natural dentition; SS = structured splint; PS = plane splint. *Statistically significant difference ($P < .02$).

Statistics

The target variables (primary variable: X_{50}; secondary variables: TMW, TT, IMP) for the different test conditions were compared by one-way repeated-measures analysis of variance (ANOVA). The SMW values for the homonymous muscles and three test conditions were analyzed by one-way repeated-measures ANOVA. Data distribution was assessed with the Kolmogorov-Smirnov test. The statistical power was evaluated post hoc.

Results

The results for all variables analyzed under the experimental conditions are summarized in Tables 1a and 1b. All data were normally distributed, and the post hoc power for the target variable (X_{50} value) was greater than 0.80. Approximately 80% of the study participants preferred chewing on their right side; the rest had no chewing side preference.

The X_{50} values for masticatory performance differed significantly ($P < .002$) between PS and SS and between ND and PS. Conversely, no significant differences ($P > .05$) were observed between SS and ND.

Regarding SMW, the EMG activity of the masseter differed significantly ($P < .001$) between the left and right sides, with higher values for the right side. This difference between sides was not observed for the temporalis, and no differences were detected between the test conditions for the temporalis. As a result, no significant differences ($P > .05$) were observed regarding TMW and TT under the test conditions. Within the left masseter, however, significant differences ($P < .02$) between ND and SS were detected for SMW (Fig 3).

The IMP, selected as the kinematic target variable, showed no significant differences ($P > .05$) among the experimental conditions.

Discussion

The results confirmed the initial hypothesis, as demonstrated by the numerically small but statistically significant differences found regarding masticatory performance. To the authors' knowledge, these findings substantiate, for the first time in a realistic in vivo chewing experiment, the assumption that the structured occlusal profile in young, healthy humans is biomechanically more effective at breaking friable test food particles than a flattened occlusion. This result is in accordance with a previous in vitro study using an identical test food, which showed that force-deformation properties are significantly affected by the cusp shape of a chewing simulator.[30] The other variables investigated (TMW, TT, and IMP), however, did not change significantly under the different experimental conditions.

Methodologic Considerations

One limitation of this study is the use of occlusal splints to simulate different occlusal surfaces in vivo. Possible reduction of proprioceptive feedback may have compromised the masticatory system.[38] Previous studies, however, found no effect of the absence of periodontal feedback in terms of kinematic and dynamic values for mastication.[39] Moreover, a previous study showed that the consequent change of the vertical dimension of occlusion (less than 6 mm) through the splints is not expected to alter chewing performance.[40] This claim is in agreement with the present study, which did not detect performance differences between the ND and SS conditions. The EMG differences observed between ND and SS for the left masseter while chewing on the right side with the structured splint can be attributed to the unfamiliar chewing conditions with SS, which led to altered balancing behavior that involved stiffening of the chewing system against jaw displacement. This phenomenon disappeared gradually for the third experimental condition (PS), possibly indicating the onset of training effects.

It could be argued that training effects are a consequence of the sequentially performed tasks in this trial. However, this experiment was intentionally designed to avoid an unrealistic size effect of the PS profile caused by the two unfamiliar conditions, ie, the unfamiliar test food and drastically changed occlusal profile. In this context, the sequential procedure should contribute to a realistic experimental model that is comparable with common clinical settings in prosthodontic rehabilitation. Use of standardized experimental conditions (eg, artificial test food with constant volume and particle size, unilateral chewing, and paraocclusal application of recording devices) may have weakened the comparability to natural chewing. Nonetheless, it is suggested that fundamental short-term responses of the masticatory system to intrinsic changes were modeled sufficiently because all test conditions were affected similarly by the experimental requirements.

Masticatory Performance, TMW, TT, and IMP

The decreased masticatory performance caused by the flat profile, without significant changes in TMW, TT, or IMP, must be discussed. Semiautomatic masticatory movements are controlled by neuronal programs[41] and modified by peripheral feedback, which depends on the texture and fragmentation status of the food. Another consistent observation is that elderly individuals, particularly those with slightly compromised masticatory ability (but who still succeed in forming a normal food bolus), adapt their masticatory function mainly by increasing the number of chewing cycles.[1,16,42] In the present experiment, in which occlusal changes occurred abruptly, one might have expected the force output of the masticatory system to increase to compensate for the flat occlusion. Previous experimental studies have shown that force generation during the individual chewing cycle depends on the hardness and thickness of the texture[12,43] and is modulated by the anticipation and resistance of the texture as perceived by proprioception.[44] To explain the uniform response of TMW, TT, and IMP under all experimental conditions, the authors assume that the biomechanical properties of the bolus did not induce additional occlusal force to achieve the swallowing threshold, despite less effective fragmentation produced by the flat occlusion. A possible cause could be that the optimum cohesiveness of the bolus, which is the crucial variable responsible for initiation of swallowing,[45,46] does not provoke readjustment of the chewing force. This explanation can be inferred from validated computational models predicting comparable numbers of chews until swallowing for foods with different biomechanical properties.[47]

A variety of kinematic data have been obtained in experimental settings similar to that used in this investigation. Vertical and lateral movement amplitude,[7] duration of chewing cycles,[48] and jaw velocity[49] have been analyzed in previous trials.[5,50] These measures characterize the proprioceptive response of mechanoreceptors to food texture variability during fragmentation. The present study only compared the IMP, which is a global variable that characterizes the kinematic performance of the masticatory system. In accordance with the EMG performance (used as a surrogate for the chewing force), this measure indicated no significant difference between the test conditions. This result, in accordance with the unaltered TT of the chewing cycles, supports the finding that the power output of the neuromuscular system did not vary substantially.

Clinical Significance

This study examined the effects of altered occlusal profiles on the masticatory performance of young, healthy patients with excellent neuromuscular adaptability. The biomechanically small (approximately 5%) but statistically significant differences found do not necessarily indicate a clinically relevant difference because they do not account for the changes in the surface, volume, and configuration of the particles, which have a considerable impact on bioavailability (the contact surface for enzymatic degradation). In particular, the configuration of the particles may be influenced by the mincing instruments, ie, the plane or structured tooth surface.

Naturally, due to the study sample and control of the many variables that arise in a clinical setting, the results cannot be extrapolated to other patient or age groups or to the long-term behavior of chewing performance. Most notably, the short-term effects detected cannot be applied directly to the target population of most prosthetic rehabilitations, ie, functionally compromised elderly patients for whom occlusal force and motor adaptability are often limited. Thus, the results of this study must be interpreted with caution. The authors speculate, however, that the reduced performance might be even more pronounced for elderly patients than for the sample investigated due to their age-related limited adaptive capacity. Further studies are needed to address this issue. Additional open questions concern the long-term effect of compromised masticatory performance caused by flattened occlusion on the kinetic behavior of the neuromuscular system. Investigations addressing this issue are in progress.

Conclusions

Within the limitations of this study, the results confirmed the short-term biomechanical significance of structured occlusal surfaces during the chewing of a friable artificial test food by young dentate study participants. The structured occlusal profile led to significantly superior masticatory performance compared to the flattened occlusal profile. The neuromuscular control of mastication did not vary significantly between the test conditions, demonstrating that neuromuscular motor behavior tailored for a specific food texture is not influenced by the biomechanical deficiency induced by occlusal flattening.

Acknowledgments

The authors reported no conflicts of interest related to this study.

References

1. Woda A, Hennequin M, Peyron MA. Mastication in humans: Finding a rationale. J Oral Rehabil 2011;38:781–784.
2. Peyron MA, Mishellany A, Woda A. Particle size distribution of food boluses after mastication of six natural foods. J Dent Res 2004;83:578–582.
3. Agrawal KR, Lucas PW, Bruce IC, Prinz JF. Food properties that influence neuromuscular activity during human mastication. J Dent Res 1998;77:1931–1938.
4. Bourne M. Relation between texture and mastication. J Texture Studies 2004;35:125–143.
5. Chew CL, Lucas PW, Tay DKL, Keng SB, Ow RKK. The effect of food texture on the replication of jaw movements in mastication. J Dent 1988;16:210–214.
6 Horio T, Kawamura Y. Effects of texture of food on chewing patterns in the human subject. J Oral Rehabil 1989;16:177–183.
7. Kohyama K, Mioche L. Chewing behavior observed at different stages of mastication for six foods, studied by electromyography and jaw kinematics in young and elderly subjects. J Texture Studies 2004;35:395–414.
8. Lucas PW, Prinz JF, Agrawal KR, Bruce IC. Food texture and its effect on ingestion, mastication and swallowing. J Texture Studies 2004;35:159–170.
9. Mathevon E, Mioche L, Brown WE, Culioli J. Texture analysis of beef cooked at various temperatures by mechanical measurements, sensory assessments and electromyography. J Texture Studies 1995;26:175–192.
10. Mioche L, Bourdiol P, Martin JF, Noël Y. Variations in human masseter and temporalis muscle activity related to food texture during free and side-imposed mastication. Arch Oral Biology 1999;44:1005–1012.
11. Nishinari K. Rheology, food texture and mastication. J Texture Studies 2004;35:113–124.
12. Peyron MA, Maskawi K, Woda A, Tanguay R, Lund JP. Effects of food texture and sample thickness on mandibular movement and hardness assessment during biting in man. J Dent Res 1997;76:789–795.
13. Piancino MG, Bracco P, Vallelonga T, Merlo A, Farina D. Effect of bolus hardness on the chewing pattern and activation of masticatory muscles in subjects with normal dental occlusion. J Electromyogr Kinesiol 2008;18:931–937.
14. Bakke M, Holm B, Jensen BL, Michler L, Moller E. Unilateral, isometric bite force in 8-68-year-old women and men related to occlusal factors. Scand J Dent Res 1990;98:149–158.
15. Carlsson GE. Masticatory efficiency: The effect of age, the loss of teeth and prosthetic rehabilitation. Int Dent J 1984;34:93–97.
16. Feldman RS, Kapur KK, Alman JE, Chauncey HH. Aging and mastication: Changes in performance and in the swallowing threshold with natural dentition. J Am Geriatr Soc 1980;28:97–103.
17. Garcia RI, Perlmuter LC, Chauncey HH. Effects of dentition status and personality on masticatory performance and food acceptability. Dysphagia 1989;4:121–126.
18. Hatch JP, Shinkai RS, Sakai S, Rugh JD, Paunovich ED. Determinants of masticatory performance in dentate adults. Arch Oral Biol 2001;46:641–648.
19. Helkimo E, Carlsson GE, Helkimo M. Bite force and state of dentition. Acta Odontol Scand 1977;35:297–303.
20. Lassauzay C, Peyron MA, Albuisson E, Dransfield E, Woda A. Variability of the masticatory process during chewing of elastic model foods. Eur J Oral Sci 2000;108:484–492.
21. Neill DJ, Howell PG. A study of mastication in dentate individuals. Int J Prosthodont 1988;1:93–98.
22. Ngom PI, Diagne F, Aïdara-Tamba AW, Sene A. Relationship between orthodontic anomalies and masticatory function in adults. Am J Orthod Dentofacial Orthop 2007;131:216–222.
23. Peyron MA, Blanc O, Lund JP, Woda A. Influence of age on adaptability of human mastication. J Neurophysiol 2004;92:773–779.
24. Proschel P, Hofmann M. Frontal chewing patterns of the incisor point and their dependence on resistance of food and type of occlusion. J Prosthet Dent 1988;59:617–624.
25. Wayler AH, Muench ME, Kapur KK, Chauncey HH. Masticatory performance and food acceptability in persons with removable partial dentures, full dentures and intact natural dentition. J Gerontol 1984;39:284–289.
26. Youssef RE, Throckmorton GS, Ellis E 3rd, Sinn DP. Comparison of habitual masticatory patterns in men and women using a custom computer program. J Prosthet Dent 1997;78:179–186.
27. Sato S, Ohta M, Sawatari M, Kawamura H, Motegi K. Occlusal contact area, occlusal pressure, bite force, and masticatory efficiency in patients with anterior disc displacement of the temporomandibular joint. J Oral Rehabil 1999;26:906–911.
28. Ishijima T, Koshino H, Hirai T, Takasaki H. The relationship between salivary secretion rate and masticatory efficiency. J Oral Rehabil 2004;31:3–6.
29. Chen L, Xie Q, Feng H, Lin Y, Li J. The masticatory efficiency of mandibular implant-supported overdentures as compared with tooth-supported overdentures and complete dentures. J Oral Implantol 2002;28:238–243.

30. Woda A, Foster K, Mishellany A, Peyron MA. Adaptation of healthy mastication to factors pertaining to the individual or to the food. Physiol Behav 2006;89:28–35.
31. Slagter AP, van der Glas HW, Bosman F, Olthoff LW. Force-deformation properties of artificial and natural foods for testing chewing efficiency. J Prosthet Dent 1992;68:790–799.
32. Dworkin SF, LeResche L. Research diagnostic criteria for temporomandibular disorders: Review, criteria, examinations and specifications, critique. J Craniomandib Disord 1992;6:301–355.
33. Olthoff LW, Van Der Bilt A, Bosman F, Kleizen HH. Distribution of particle sizes in food comminuted by human mastication. Arch Oral Biol 1984;29:899–903.
34. Slagter AP, Olthoff LW, Steen WHA, Bosman F. Comminution of food by complete-denture wearers. J Dent Res 1992;71:380–386.
35. Eberhard L, Schindler HJ, Hellmann D, Schmitter M, Rammelsberg P, Giannakopoulos NN. Comparison of particle-size distributions determined by optical scanning and by sieving in the assessment of masticatory performance. J Oral Rehabil 2012;39:338–348.
36. Rosin P, Rammler E. Gesetzmassigkeiten in der Kornzusammensetzung des Zementes. Zement 1933;31:427–433.
37. Giannakopoulos NN, Hellmann D, Schmitter M, Krüger B, Hauser T, Schindler HJ. Neuromuscular interaction of jaw and neck muscles during jaw clenching. J Orofac Pain 2013;27:61–71.
38. Lavigne G, Kim JS, Valiquette C, Lund JP. Evidence that periodontal pressoreceptors provide positive feedback to jaw closing muscles during mastication. J Neurophysiol 1987;58:342–358.
39. Schindler HJ, Stengel E, Spiess WEL. Feedback control during mastication of solid food textures—A clinical-experimental study. J Prosthet Dent 1998;80:330–336.
40. Olthoff LW, van der Glas HW, van der Bilt A. Influence of occlusal vertical dimension on the masticatory performance during chewing with maxillary splints. J Oral Rehabil 2007;34:560–565.
41. Lund JP, Kolta A. Generation of the central masticatory pattern and its modification by sensory feedback. Dysphagia 2006;21:167–174.
42. Mishellany-Dutour A, Renaud J, Peyron MA, Rimek F, Woda A. Is the goal of mastication reached in young dentates, aged dentates and aged denture wearers? Br J Nutr 2008;99:121–128.
43. Morimoto T, Nakamura O, Ogata K, et al. Autoregulation of masticatory force in the anesthetized rabbits. In: Morimoto T, Matsuya T, Takada K, eds. Brain and Oral Functions: Oral Motor Function and Dysfunction. Amsterdam: Elsevier;1995: 115–124.
44. Ottenhoff FA, van der Bilt A, van der Glas HW, Bosman F. Peripherally induced and anticipating elevator muscle activity during simulated chewing in humans. J Neurophysiol 1992;67:75–83.
45. Alexander RM. News of chews: The optimization of mastication. Nature 1998;391:329–329.
46. Nagatomi H, Yoshimine M, Miura H, Tanaka Y, Arai I. Multivariate analysis of the mechanical properties of boluses during mastication with the normal dentitions. J Med Dent Sci 2008;55:197–206.
47. Prinz JF, Lucas PW. An optimization model for mastication and swallowing in mammals. Proc Biol Sci 1997;264:1715–1721.
48. Lucas PW, Ow RKK, Ritchie GM, Chew CL, Keng SB. Relationship between jaw movement and food breakdown in human mastication. J Dent Res 1986;65:400–404.
49. Anderson K, Throckmorton GS, Buschang PH, Hayasaki H. The effects of bolus hardness on masticatory kinematics. J Oral Rehabil 2002;29:689–696.
50. Brown WE, Eves D, Ellison M, Braxton D. Use of combined electromyography and kinesthesiology during mastication to chart the oral breakdown of foodstuffs: Relevance to measurement of food texture. J Texture Studies 1998;29:145–167.