Electromyographic Evaluation of Masticatory Muscles in Dentate Patients Versus Conventional and Implant-Supported Fixed and Removable Denture Wearers—A Preliminary Report Comparing Model Foods

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Purpose: To evaluate differences in masticatory muscle function during chewing of model foods designed to differ in fracture strength between dentate subjects (n = 5, ages 59 to 68 years) versus patients treated with a maxillary conventional complete denture opposing natural dentition or one of the following types of mandibular complete dentures: conventional, implant-supported overdenture, implant-supported fixed denture (n = 20, ages 45 to 83 years). The authors hypothesized that denture wearers would differ in duration of chewing, frequency of chewing, and masticatory muscle activity while preparing a bolus for swallowing. ***Materials and Methods:*** Surface electromyography was recorded bilaterally from the masseter, anterior temporalis, and anterior digastric. Masticatory muscle activity was evaluated using scaled values of the area under the electromyographic curve, while subjects chewed agar-based model foods with different fracture strengths. Chewing duration and frequency also were calculated from electromyographic recordings. Mixed model analysis of variance with "subject" as a random factor was used during statistical analysis. Logarithmic transformation was required to achieve normalization of residuals for the duration of chewing and the relative masticatory muscles activity, but not for the chewing frequency. ***Results:*** Relative masticatory muscle activity was 2.57 times higher for the denture wearers than for the dentate subjects during chewing of model foods ($P < .0001$). The reduction in masticatory muscle activity from the 1st to the 10th chewing cycle was proportionally less in magnitude and occurred more gradually for denture wearers compared to dentate subjects. While chewing sequence duration increased with food fracture strength, it did not differ significantly in treatment versus dentate groups. Chewing cycle frequency did not differ between groups or with food fracture strength. ***Conclusions:*** The observed increases in relative masticatory muscle activity for denture wearers compared to the dentate subjects during oral food processing likely reflect supplemental mechanical efforts to accommodate the use of dentures for preparing a bolus for swallowing. *Int J Prosthodont 2015;28:79–92. doi: 10.11607/ijp.3931*

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Oral food processing is divisible into three main components, followed by swallowing (ie, clearance).[1] Initially, food is transported from the front of the mouth to posterior teeth, involving low amplitude simple jaw movements in which the posterior teeth typically do not occlude.[2] Next is a reduction phase, where elevated levels of jaw adductor activity occlude the teeth that function to decrease food particle size during rhythmic mastication cycles. During the final segment, the bolus is transported to the back of the tongue in preparation for swallowing.[3] Food transfer is mainly performed by tongue-palate interactions.[4]

The pattern of mastication, as well as chewing function, are different in complete denture wearers as compared with dentate subjects.[5–17] Most of these comparative assessments of dentate versus denture wearers involve mastication of natural foods. While natural foods present the advantage of characterizing

Table 1 Study Population Age and Gender Distribution by Study Group

Group (number of subjects)	Male age (y)	Female age (y)	Age mean(SD)	Male %	Female %
ND/ND (5)	59, 68	61, 61, 63	62.4 (3.43)	40	60
CD/ND (5)	49, 77	67, 79, 83	62.5 (11.12)	40	60
CD/CD (5)	45, 50, 65, 67	66			
CD/OD (5)	–	55, 55, 58, 66, 73			
CD/FD (5)	57, 76	49, 53, 60			

ND/ND = maxillary/mandibular natural dentition; CD/ND = maxillary conventional complete denture/mandibular natural dentition; CD/CD = maxillary/mandibular conventional complete dentures; CD/OD = maxillary conventional complete denture/mandibular implant overdenture; CD/FD = maxillary conventional complete denture/mandibular implant fixed denture.

physiologically relevant mastication, their characteristics are hard to standardize, and fabrication of samples with reproducible properties is particularly difficult, which makes them less appropriate for comparison of masticatory performance.[18]

In this study, the objective evaluation of chewing function relied on novel test foods with consistent, well-characterized properties, and standardized dimensions, color, taste, and smell for administration to different participants across experimental trials.[19,20] Artificial test food substances, although typically not swallowed, are chewed similarly to natural foods with respect to the number of strokes and particle size reduction.[21] The key advantage of agar gels as model foods is that they allow focus on the crushing aspect (brittle fracture) without complications from adhesion to oral surfaces or melting of particles. In a number of previous studies,[11,14,22–26] contributions from noncrushing aspects of oral processing intervened during testing. The resistance in the food comes from viscous and elastic elements, with the relative amounts depending on the food. Our use of model foods will further the continuing development of methods to characterize masticatory function in study participants with various dental states and prosthodontic treatments.

The objective of this study was to evaluate masticatory muscle function in dentate subjects versus denture wearers when the primary food variable is resistance to crushing. The hypothesis was that the level of relative masticatory muscle activity during chewing, measured by electromyography (EMG), will bear directly on differences in masticatory control by the nervous system to accommodate differences in the fracture strength of the model foods as well as putative differences related to prosthodontic treatments. The authors predicted that denture wearers, compared to dentate subjects, would differ in the duration of chewing, the frequency of chewing, and relative masticatory muscle activity while preparing a bolus for deglutition. By using model foods varying in fracture stress, the authors could effectively determine how this property impacts masticatory muscle function in dentate subjects versus denture wearers.

Materials and Methods

Subjects were recruited from the University of North Carolina (UNC) School of Dentistry patients pool. Volunteers, who responded to an email notice addressed to the faculty and staff, also were considered. For those selected, a health history questionnaire, comprehensive oral evaluation, and radiographic examination were consulted to confirm that potential study participants met the inclusion criteria.

The dentate subjects (n = 5, group natural dentition [ND/ND]) were required to have at least 10 occluding natural teeth in each jaw. Missing teeth were only allowed at the distal end of the arches, so that no intercalate edentulous spaces were considered in this study. The denture wearers (n = 20 [subdivided into four groups], maxillary conventional complete denture group [CD/XX]) were all edentulous in the maxilla, wearing maxillary conventional complete denture (at least 10 artificial teeth) and in the mandible presented one of the following:

- At least 10 occluding natural teeth, no intercalate edentulous spaces (5 subjects)
- Conventional complete denture, at least 10 occluding artificial teeth (5 subjects)
- Implant-supported overdenture, minimum 2 implants, at least 10 occluding artificial teeth (5 subjects)
- Implant-supported fixed denture, minimum 3 implants, at least 10 occluding artificial teeth (5 subjects)

All dentures worn by study patients were evaluated and established as acceptable in adaptation and function by the principal investigator (SUT).

Participants' ages ranged from 45 to 83 years. The dentate subject group had a mean age of 62.4 ± 3.43 years, while the mean age for the denture wearer group was 62.5 ± 11.12 years. Within each group, 60% of study participants were female (Table 1). Age and sex composition of both groups was coincidentally matched. All edentulous individuals were required to fall within the description of class II or III of the Prosthodontic Diagnostic Index (PDI)[27] for complete edentulism. Subjects with uncontrolled diabetes, bruxism, class III ridge relationship, or prostheses older than 5 years were excluded. The dentures worn by the patients enrolled in the study were in function for 6 to 50 months at the time of data collection. All study participants were required to be able and willing to follow study procedures and instructions and to give written informed consent. All procedures were approved by the University of North Carolina Institutional Review Board (no. 05-2810).

During a preliminary analysis of the data presented in this study, the authors evaluated differences among the five groups of subjects (n = 5 for each group).[28] Although trends were observed (eg, participants wearing maxillary complete dentures opposing mandibular natural dentitions chewed longer, but presented a lower relative masticatory muscle activity as compared to subjects wearing maxillary and mandibular dentures), no statistically significant differences were detected among the prosthodontically treated individuals due to the small sample sizes. For this reason, the treatment groups were combined for the analysis presented in this article, which focuses on the impact of the fracture stress of model foods on chewing characteristics. The reader is referred to Uram-Tuculescu[28] for further description of other parameters such as the duty cycle of the jaw closing muscles, and timing of contraction.

The model foods were cylindrical samples of agar gels, containing 1.75%, 3.5%, 5.25%, or 7% by weight agar, 60% by weight glycerol and deionized water as the remaining mass. Also, 0.02 g of strawberry flavor (Mother Murphy's) was added to make the model food more palatable. While the model system was a food grade material, the investigators allowed participants to expectorate the bolus rather than swallow. Sets of samples were made prior to testing each subject. The four different concentrations of agar resulted in different fracture stress (a measure of force/area at fracture; an indication of gel fracture strength) that ranged from 85 to 358 kPa. Fracture stress was determined by uniaxial compression using an Instron 5565 Universal Testing Machine equipped with a 500-N load cell (Instron). Samples with agar concentration varying from 1% to 9% were compressed to 20% of their original height at a rate of 15 mm/minute.

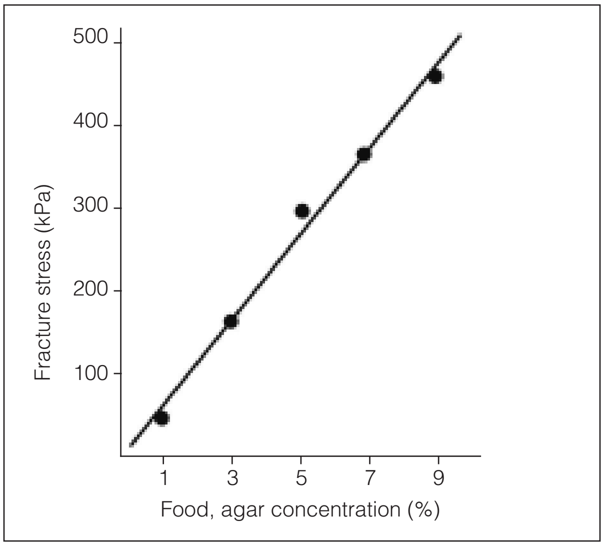

Fig 1 Linear regression plot for fracture stress versus agar concentration in the sample foods.

The point of fracture was seen as an abrupt decrease in force on the force-deformation curve. Fracture stress was calculated assuming no volume change with compression and using the equations described by Hamann et al[29] and Truong and Daubert.[30] True compressive stress at fracture (σ_c, Pa) was calculated as follows:

$$\sigma_c = (F/A)\lambda$$

where F is the force (N), A is cross-sectional area (m^2) of samples before compression, λ is a shape correction factor defined as

$$\lambda = L/L_i$$

where L is the final height (m) of sample after deformation up to fracture and L_i is initial height (m). Final height is calculated by the difference between initial height and deformation (ΔL, m). A plot of fracture stress (kPa; Fig 1) versus agar concentration conformed to the linear equation as follows:

$$\text{Fracture stress (kPa)} = -5.54 + 51.9 \times \text{Agar Concentration} \quad (\%)$$

A cylindrical sample (19-mm diameter x 19-mm height) of the 1.75% agar model food was given to the subject, who was instructed to chew on the right side to the point of swallowing, then expectorate, and rinse with tap water. Then, another 1.75% agar sample was chewed on the left side. Afterwards, similar procedures were observed for the rest of the model foods, following the increasing order of fracture stress (3.5%, 5.25%, and 7% agar), for a total of eight masticatory sequence recordings during a single session of testing, which generally lasted 30 to 45 minutes (including paperwork, instructions, questions and answers, equipment preparation, and actual experimental procedures).

Prior to chewing the samples, surface electrodes were placed on the right and left side superficial masseter, anterior temporalis, and anterior digastric muscle. The amplified EMG signals were recorded at 5,020 Hz using a BioEMG II electromyograph (Bioresearch). The raw EMG data were analyzed by one investigator, while the data files did not contain name identifiers.

Digitized EMG values were filtered and converted to positive waveforms with a root-mean-square (rms) transformation using the LabView graphical software (National Instruments). Values for each rms EMG were output at 2-ms intervals using a 42-ms time constant for averaging raw EMGs.[31] The rms EMG versus time graph for each masticatory sequence was expanded (stretched) along the time axis in order to facilitate identification of each chewing cycle from beginning of jaw-opening phase (firing of anterior digastric muscles) to end of closing phase (firing of masseters and anterior temporalis muscles).

Behavioral measures (duration and frequency of chewing) were determined by analyzing data from all six muscles investigated (right and left anterior digastric, right and left anterior temporalis, right and left masseter). Physiologic measures extracted from EMG activity from the two masseters and the two temporalis anterior muscles (ie, area under the rms EMG curve) also were analyzed.

Separate analyses were performed for the total duration of chewing, the frequency of chewing, and EMG area-under-curve for the jaw-closing muscles. The total duration of the chewing sequence was the time recorded from start of chewing (beginning of first firing of digastric muscles) to expectoration (ie, just before swallowing would have occurred, end of last firing of masseters and temporalis muscles). The chewing cycle frequency was calculated by dividing the total number of chewing cycles in a chewing sequence by the total duration of the said chewing sequence. The EMG area-under-curve for the jaw-closing muscles was calculated in the following manner. From the EMG activity profile for each jaw-closing muscle during individual chewing cycles, the investigators extracted the total integrated area under the rms EMG curve (AUC) calculated using the Simpson's rule.[32] Scaled values (hereafter referred to as relative muscle activity) were calculated for the AUC to minimize the confounding effect of the differences in electrode construction and electrode location on a muscle. The largest AUC value for a given muscle during an experiment was identified. This event was assigned a value of 1.0 and all other values were linearly rescaled to be between 0 and 1.[31,33] The authors based their analyses on the average (across the two masseters and the two temporalis anterior muscles) logged values. If a chewing cycle duration was less than 0.3 seconds, the cycle was considered incomplete and eliminated from all subsequent analyses.[34,35]

Statistical Approach

Given the large number of repeated measures from each subject, mixed model analysis of variance (Proc Mixed, SAS Institute) with "subject" as a random factor was used for analysis of the duration and frequency of chewing and of the relative masticatory muscle activity. Explanatory variables for each analysis included subject group (ND/ND, CD/XX), the fracture stress of model foods (FS), and the participant's age. For the relative masticatory muscle activity, "side" (chewing versus nonchewing), "muscle" (superficial masseter versus anterior temporalis), and chewing cycle number were entered additionally into the model. Because the total number of chewing cycles per sequence varied greatly among individuals, analyses of the relative masticatory muscle activity were limited to the first 10 chewing cycles of each sequence. Logarithmic transformation was required to achieve normalization of residuals for the duration of chewing and the relative masticatory muscle activity, but not for the chewing frequency. The fracture stress of the model foods was expressed as its logarithm and treated as a continuous variable as explained in the following paragraph.

Inspection of the measures from individual subjects and the means of each subject group revealed that the duration of chewing increased with the fracture stress of the food samples. The relationship was empirically described by a power function:

$$D = c_d \bullet (FS)^n \qquad (1)$$

where D is the total sequence duration, c_d represents the multiplicative constant expressing the predicted duration of chewing for samples that fracture at 1 kPa, and n designates the power function exponent, expressing the rate at which the chewing duration increased with increases in fracture stress. The logarithmic form of the power function in equation *(1)* enabled estimates of c_d and n to be obtained by simple linear regression:

$$\log_{10}(D) = \log_{10}(c_d) + n \bullet \log_{10}(FS)$$

where $\log_{10}(c_d)$ is the estimated y-intercept and n is the estimated slope of the log-linear relationship.

Similarly, the relative masticatory muscle activity increased with the fracture stress of the food samples.

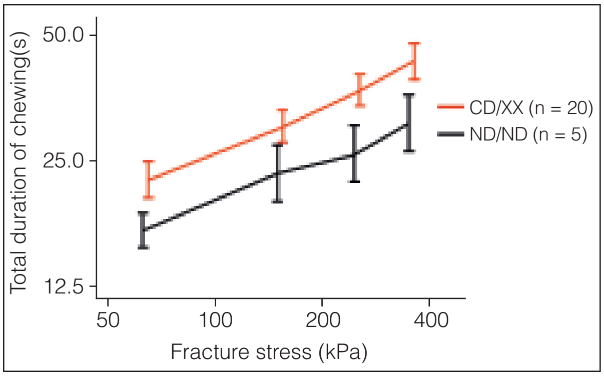

Fig 2 Mean total duration of chewing sequence versus stress at which the food samples fractured for the dentate subjects (ND/ND) and denture wearers (CD/XX). The total duration of the chewing sequence increased as a power function of fracture stress (*P* < .01 for both groups). Denture wearers had longer but not significantly different chewing duration (*P* > .10) as compared to dentate subjects. Vertical bars indicate ± 1 SD of the mean. Note that both axes are scaled logarithmically to illustrate the power function relationship between the two variables (see text).

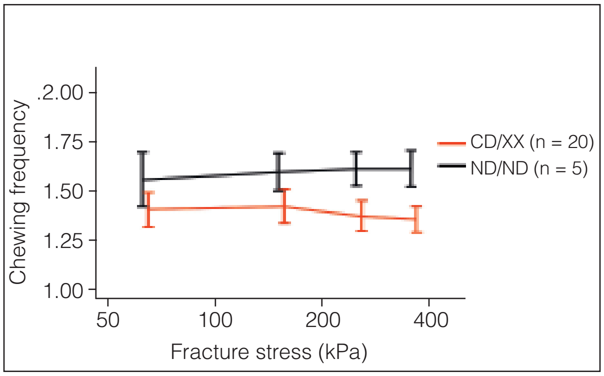

Fig 3 Mean frequency of chewing (chews per second) versus fracture stress for the dentate subjects (ND/ND) and denture wearers (CD/XX). The frequency of chewing did not differ significantly with fracture stress in either group (*P* > .81 for effect of fracture stress, *P* > .29 for subject group × fracture stress interaction). Denture wearers had slower but not significantly different (*P* > .21) chewing frequency as compared to dentate subjects. Vertical bars indicate ± 1 SD of the mean. Note that only the x-axis is scaled logarithmically.

The relationship was empirically described by a power function:

$$\text{Masticatory muscle activity} = c_a \cdot (FS)^m \qquad (2)$$

where masticatory muscle activity is based on the scaled EMG AUC, c_a designates the multiplicative constant expressing the predicted masticatory muscle activity required for samples that fracture at 1 kPa, and m designates the power function exponent, expressing the rate at which relative masticatory muscle activity increased with increasing fracture stress. As for the duration of the chewing sequence, the logarithmic form of the power function in equation *(2)* enabled estimates of c_a and m to be obtained by simple linear regression. For both the duration of chewing and the relative masticatory muscle activity, mixed model analyses of variance with "subject" as a random factor were explored to determine whether the same or different y-intercepts and whether the same or different slopes applied to the two groups of subjects.

Estimates of c_a and m were obtained additionally for each of the 10 chewing cycles for each subject of both groups. Each of these parameters was analyzed with mixed model analysis of variance with "subject" as a random factor to determine whether the power function relationship between relative masticatory muscle activity and food fracture stress varied across chews in an increasing or decreasing manner, and, if so, whether the variation was different for the two groups of subjects. *P* values were not adjusted to account for the multiple statistical analyses performed on each of the duration and frequency of chewing and the relative masticatory muscle activity.

Results

Total Duration of Chewing Sequence

On average, the denture wearers tended to chew longer (45% longer) than the dentate subjects; however, the difference failed to attain statistical significance (*P* > .10). The duration of the chewing sequence did not vary with the subjects' age (*P* > .12).

For each group of subjects, the mean total duration of the chewing sequence increased as a power function of fracture stress as shown in Fig 2 (denture wearers: $c_d = 2.99$, $n = 0.456$, $R^2 = 0.99$, $P < .01$; dentate subjects: $c_d = 2.94$, $n = 0.400$; $R^2 = 0.99$, $P < .01$). The exponents of the power functions did not differ significantly for the two groups of subjects (*P* > .37), indicating that both groups responded similarly to increases in perceived hardness of the gel samples.

Chewing Frequency

The mean chewing frequency for the dentate subjects was 1.58 chews per second (SD = 0.19), while the denture wearers averaged 1.38 chews per second (SD = 0.36). Mean chewing frequency mean was 1.42 chews per second (SD = 0.34) across all subjects.

On average, the denture wearers tended to chew slower (0.20 chews per second slower) than the dentate subjects; however, the difference in chewing frequency was not statistically significant (*P* > .21). The chewing frequency did not vary with the subjects' age (*P* > .46). Unlike the total duration of the chewing sequence, the frequency of chewing (chews per

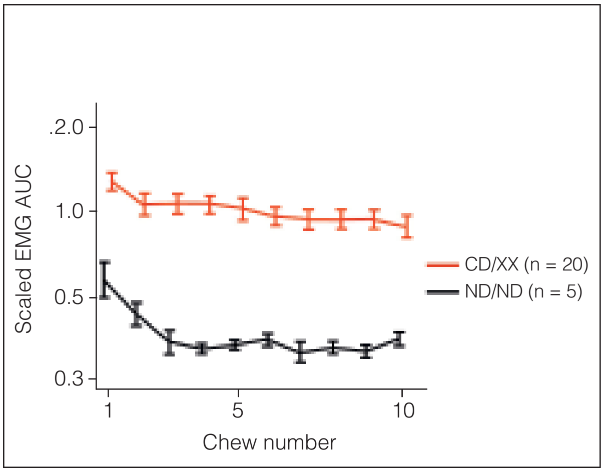

Fig 4 Mean masticatory muscle activity, as measured by scaled area under the EMG curve, for each of the first 10 chews of the dentate subjects (ND/ND) and denture wearers (CD/XX) for the first 10 cycles. The relative masticatory muscle activity was 2.57 times higher for the denture wearers as compared to the dentate subjects (P < .0001). Relative masticatory muscle activity varied with chewing cycle number (see text, P < .0001), and the pattern of variation was different for the two groups (P < .0001). Vertical bars indicate ± 1 SD of the mean. Note that the y-axis is scaled logarithmically.

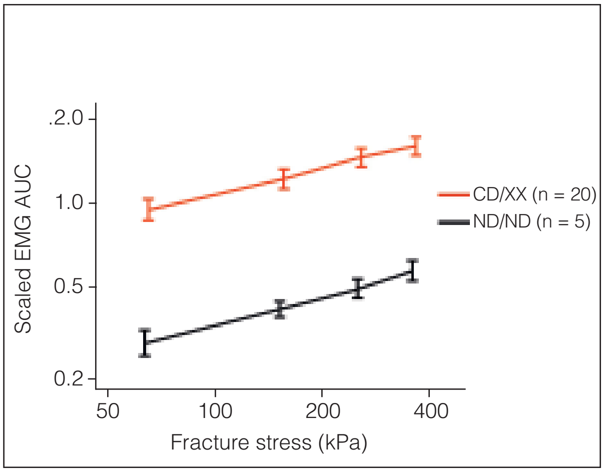

Fig 5 Mean masticatory muscle activity per chew, as measured by scaled area under the EMG curve, versus fracture stress for the dentate subjects (ND/ND) and denture wearers (CD/XX). Relative masticatory muscle activity increased as a power function of the fracture stress (P < .005) and was higher in denture wearers as compared to dentate subjects (P < .0001). Vertical bars indicate ± 1 SD of the mean. Note that both axes are scaled logarithmically.

second) did not differ significantly with fracture stress in either group as shown in Fig 3 (P > .81 for effect of FS, P > .29 for subject group x FS interaction).

EMG Area-Under-Curve for the Jaw-Closing Muscles

Overall, the relative masticatory muscle activity, calculated as average of logged values for the four jaw-closing muscles investigated, was 2.57 times higher for the 20 denture wearers than for the five dentate subjects over the first 10 cycles (mean logarithm = 0.041 [SD = 0.140] versus –0.369 [SD = 0.052], P < .0001). Moreover, relative masticatory muscle activity varied with chewing cycle number (P < .0001), and the pattern of variation was different for the two groups of study participants (subject group by chew number interaction: P < .0001; Fig 4). Mainly, the reduction in masticatory muscle activity from the 1st to the 10th chewing cycle appeared proportionally less in magnitude and occurred more gradually from cycle to cycle for the denture wearers. The relative masticatory muscle activity did not vary with the subjects' age (P > .32).

Mean relative masticatory muscle activity, similar to the total duration of chewing, increased as a power function of the stress at which the food samples fractured (P < .005, R^2 > 0.99 for each subject group; Fig 5). Consistent with the greater relative masticatory muscle activity observed in the denture patients noted above, the parameter $\log_{10}(c_a)$ was greater for the denture wearers than the dentate subjects (mean: –0.708 [SD = 0.47] versus –1.19 [SD = 0.479], P < .05). However, the parameter m did not differ significantly for the two groups (means = 0.327 [SD = .182] versus 0.360 [SD = 0.207], P > 0.72), indicating an equal sensitivity to changes in food firmness.

Analysis of the parameters for the relationship between relative masticatory muscle activity and food fracture stress revealed that for each group, the multiplicative constant c_a varied in no consistent manner from chewing cycle 1 to 10 (P > .31 for effect of chew number, P > .71 for subject group by chew number interaction; Fig 6). However, the exponent m varied significantly among chews (P < .0001), decreasing in mean value from chew 1 to subsequent chews (Fig 7). The pattern of variation was similar for the two groups (P > .72 for effect of subject group, P > 0.74 for subject group by chew number interaction).

Discussion

The use of flavored artificial test foods provided the advantage of controlling food properties for detecting functional differences in dentate subjects versus denture wearers during chewing. The authors suggest that agar gels are a suitable model food because they can be predictably engineered. In this study, different concentrations of agar and glycerol generated variation in fracture strength without altering

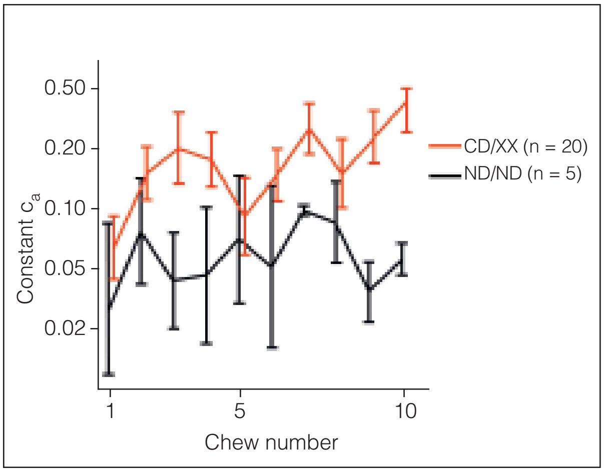

Fig 6 The constant c_a of the power functions describing the relationship between scaled masticatory muscle activity and fracture stress by chew number. Multiplicative constant c_a varied in no consistent manner from chewing cycle 1 to 10 (see text, $P > .31$ for effect of chew number, $P > .71$ for subject group by chew number interaction). Vertical bars indicate ± 1 SD of the mean. Note that the y-axis is scaled logarithmically. ND/ND = dentate subjects; CD/XX = denture wearers.

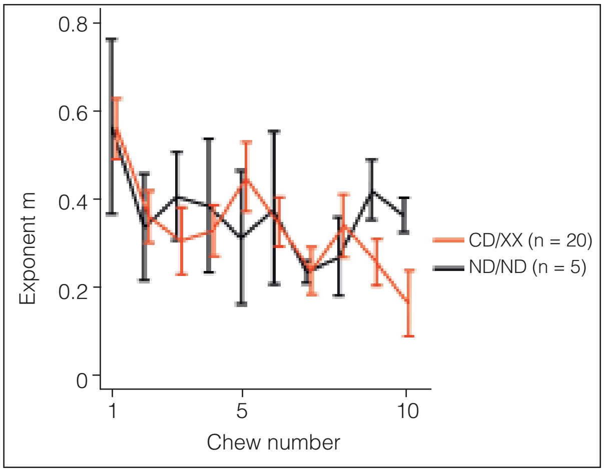

Fig 7 The exponent m of the power functions describing the relationship between scaled masticatory muscle activity and fracture stress by chew number. Exponent m decreased significantly from chew 1 to subsequent chews (see text, $P < .0001$). The pattern of variation did not differ between groups ($P > .72$). Vertical bars indicate ± 1 SD of the mean. ND/ND = dentate subjects; CD/XX = denture wearers.

deformability.[20] The authors then compared surface EMGs from the jaw muscles to assess how dentate and denture wearers responded to differences in fracture strength of model foods.

EMG activity of skeletal muscles is of considerable interest to clinicians, as is a representation of the outflow of motoneurons in the spinal cord to muscles as a result of voluntary or reflex contraction.[36] EMG, including surface EMG, is widely applied also in human research.[36–45]

As opposed to intramuscular EMG, surface EMG is a noninvasive and painless procedure that has been widely applied in sports, ergonomics, and medicine.[37] However, it was suggested that surface EMG is usually more prone to electrical artifacts (noise), mechanical artifacts, and contamination from the activity of other muscles (cross talk) than intramuscular EMG.[36] It is also limited to use on large, superficial muscles.[38] Good ways to reduce the electrical noise include the use of active surface electrodes, short leads,[46] bipolar recording technique,[47] and grounding the subject.[39] A better signal detection can be obtained by lowering the skin-electrode complex impedance.[37] Mechanical artifacts (movement of electrodes, wires) can be controlled by taping electrodes/wires to skin surface[38] and removing the stratum corneum of the skin.[48] Signal filtering is also an effective way to reduce or eliminate such artifacts.[36] Analysis of raw data after each acquisition is critical in detecting artifacts, which could be addressed by replacing electrodes, improving skin preparation, or modifying cable configuration.[37] Influence of cross talk can be dealt with once the extent of it and the conditions that initiate cross talk are known so long as the experimental conditions stay constant.[40] Considering that EMG signals may contain noise that cannot be eliminated, it was suggested that surface EMG cannot be used to determine the start of the activity of a muscle.[38] On the other hand, some maintain that the start or finish of the muscle activity can be determined by surface EMG[41] so long as the investigator is aware of the differences in the waveforms of genuine muscle signals and the artifacts.[39] The surface EMG signals generally present a narrow frequency range, whereas noise signals have either very fast components or slow, regular undulations.[39] In order to make quantitative assessments from surface EMG, the raw signals should be full-wave rectified and high-cut filtered.[42,43] Then, quantitative measurements can be made by using integration to measure the area under the curve.[32,46,47] The area under the curve recognizes a linear or nonlinear relationship with the force generated in the muscle,[32,44] being the preferred method for quantifying surface EMG. For within- and among-subjects comparison, the EMG records should be normalized to a known variable, with level of contraction of the muscle under study being the most commonly used.[36] Finally, it appears that despite a long list, most of the error sources can be controlled by proper skin treatment, using small electrodes with adequate adhesion, placing the electrodes according to protocols, and carefully examining the raw data before processing.[37] Surface electromyography is, in principle, a suitable tool in the field of dentistry and can provide objective, documentable, valid, and reproducible data on the functional condition of the masticatory muscle.[45]

Consistent with the literature,[5–11,13–15,17,22,49–53] this study's findings indicated deficits in functioning of the masticatory apparatus in denture wearers as compared to dentate subjects.

Total Duration of Chewing

While for each group the total duration of the chewing sequence increased with the stress values at which the food samples fractured, the investigators found no statistically significant difference in chewing duration between dentate subjects and denture wearers.

Other research also found an increased duration for chewing foods that are more mechanically challenging.[2,9,12,15,17,18,23,54–63] This means that one adaptive step in chewing harder foods is to increase the total masticatory effort by adding chewing cycles to the masticatory sequence.

Foster et al[24] made a direct comparison between elastic (using gelatin-based foods) and plastic (using caramels) rheological properties and confirmed that the masticatory apparatus adapts to increases in food hardness by elevating both the chewing duration and masticatory muscle activity.[24] Ideally, the range of hardness values is similar in the elastic and plastic foods from this study. Moreover, the influence of additional rheological properties on masticatory parameters should be minimized to allow the identification of how food hardness, rather than other textural characteristics, influences oral physiology.[24] Model foods can better isolate hardness as a study parameter, virtually eliminating the influence of other properties of natural foods, which are complex materials (elasticity, plasticity, stickiness).[24]

In the present study, chewing sequence duration was not significantly increased in denture wearers, as compared to dentate subjects. Veyrune and Mioche[22] found no significant differences in chewing duration between dentate subjects and complete denture wearers when chewing beef. However, beef posed a significant challenge to chewing for the complete denture wearers, who exhibited a consistently higher percentage of food rejection, as compared to the dentate subjects.[22] In such circumstance, denture patients may reduce their masticatory muscle activity in both intensity and duration to limit discomfort or even pain.

Slagter et al[14] also found no differences in chewing duration between dentate subjects and denture wearers while chewing artificial materials. Two artificial foods were tested: a high viscosity dental silicone (putty) and a softer, more flexible and ductile material also based on silicone. Although an accurate physical comparison between the test foods and the silicones used in this study cannot be deducted due to different shapes, sizes, and strength testing methodology, estimates indicated that even the softer silicone used by Slagter et al[14] was much harder than the hardest test food in this study. The authors also recognized that "relatively speaking, the denture wearers needed exceptionally large forces to overcome the resistance to deformation and fracture of Optosil particles."[14] In a previous study, the same investigators also detected large proportions of almost intact Optosil particles in the boluses chewed by complete denture wearers, a finding that was partly explained by the relatively high fracture strength of Optosil as compared with natural foods.[64] Olthoff et al[65] also found that the force needed to crush Optosil is much larger than for the natural foods, but it is well within the physiologic range of healthy study participants.[65] Again, the use of foods with hardness beyond the range of comfortable mastication of denture wearers may cut short their masticatory sequence.

Grigoriadis et al[9] also found no significant difference in masticatory sequence duration between dentate subjects and implant-supported denture wearers while chewing viscoelastic model foods based on gelatin. The study group was represented by patients wearing maxillary and mandibular implant-supported fixed dentures, which is very different from the present study sample (maxillary conventional dentures opposing natural dentition or different types of dentures—conventional, implant overdenture, implant fixed denture). Their gelatin-based model foods also had a different hardness range (61 to 131 kPa) compared to the agar gels (85 to 358 kPa) in this study. Though the authors cannot directly compare their findings to the results of Grigoriadis et al,[9] they may speculate that the unparalleled stability of maxillomandibular implant-supported fixed dentures accounted for good chewing efficiency, allowing chewing sequence durations to remain comparable to those of dentate subjects.

A number of studies[5,10,11,13,15,17,51,52,64] did detect significant increases in chewing sequence duration for denture wearers versus dentate subjects. The authors can attribute their opposite findings to the fact that the denture-wearers group included not only maxillomandibular conventional complete denture wearers, but also mixed dental states. These mixed dental states (including combinations of maxillary conventional dentures opposing mandibular natural dentition, implant overdentures, and implant fixed dentures) are expected to function better than maxillomandibular complete denture wearers, as they do not have the challenge of a lower conventional denture, but still not as well as dentate subjects. The small sample size could also constitute a limitation in identifying a significant difference in chewing sequence duration among subject groups.

This study did not detect a significant increase of the total duration of chewing with age, which is in contrast with other findings.[10,55,66–68] One explanation for this could be related to the heterogeneity of the sample, in terms of dental state and prosthodontic treatments. On the other hand, previous studies utilized different foods. Peyron et al[55] used model viscoelastic jellies, which would be processed differently because of the elastic component. Other studies used natural foods: meat[66]; rice, beef, cheese, crisp bread, apple, and peanuts[68]; carrots.[67] Some of these natural foods may pose additional challenges to the masticatory apparatus of elderly people, which would explain, in part, the different findings. Also, since the authors did not perform masticatory performance measurements, it is possible that they had "bad chewers" among the older participants, who prepared a more coarse bolus during a period of time comparable to that used by younger subjects.

Chewing Frequency

Chewing frequency is regarded as an important factor in detecting impaired mastication, as it can decrease when food hardness exceeds the limits imposed by prosthodontic treatments.[12] Otherwise, frequency is the chewing parameter with the most repeatable values between trials in a single individual.[23,25,69]

For the dentate individuals, the average chewing frequency in this study (1.58 chews per second) is comparable with data from the literature (Table 2).[10–12,23–25,55,70–72] The closest value to the authors' findings—1.52 chews per second[23]—was measured while subjects chewed jelly confectionery products. Lower values were found in studies using model foods viscoelastic gum drops,[11] caramels,[24] gelatin,[25,55] and silicone.[70–72] Higher values were measured while using natural foods, such as carrots and nuts.[10,12]

For the denture wearers, the average chewing frequency in the current study (1.38 chews per second) was comparable with data from the literature (see Table 2),[10,11,71] being closest to the findings of Witter et al,[71] who used silicone as model foods. Lower values were obtained with viscoelastic gum drops,[11] while the use of natural foods (nuts, carrots) rendered higher values.[10]

It appears that the use of different foods can explain at least in part why various studies reached different results in measuring chewing frequency. This parameter also exhibits a large interindividual variability.[25,73]

Table 2 Chewing Frequency in Dentate Subjects and Denture Wearers While Using Different Test Foods (Review of Literature)

Subjects	Test food	Chewing frequency (chews/s)	Reference
Dentate	Caramel	1.26	Foster et al[24]
	Silicone	1.32	Buschang et al[70]
	Gum drops	1.33	Veyrune et al[11]
	Gelatin	1.38	Peyron et al[55]
	Silicone	1.41	Witter et al[71]
	Gelatin	1.44	Foster et al[24]
	Silicone	1.47	Kreulen et al[72]
	Gelatin	1.48	Lassauzay et al[25]
	Gelatin	1.52	Peyron et al[23]
	Peanuts	1.71	Woda et al[12]
	Ground nuts	1.73	Mishellany-Dutour et al[10]
	Carrots	1.80	Mishellany-Dutour et al[10]
	Carrots	1.80	Woda et al[12]
Denture wearers	Gum drops	1.25	Veyrune et al[11]
	Silicone	1.33	Witter et al[71]
	Ground nuts	1.66	Mishellany-Dutour et al[10]
	Carrots	1.67	Mishellany-Dutour et al[10]

In the present study, chewing frequency did not vary significantly with the hardness of the model foods. This is in accord with other research.[14,23,55,59,74] On the other hand, Plesh et al[26] found that the chewing frequency in dentate subjects becomes slower with harder chewing gums[26]; Woda et al[12] observed a reduction in masticatory frequency in denture wearers chewing carrots and peanuts, and Jemt[17] found a lower frequency in denture wearers chewing crisp bread as compared to dentate subjects.

Gum chewing should be viewed as a completely different phenomenon. It has two components: First, deformation of a 100% cohesive material (stretching without fracture). Second, jaw opening and replacement of gum on occlusal table, which may involve adhesion between gum and surfaces, requires supplemental masticatory muscle activity and jaw movement, with increased masticatory cycle time. Finally, there is no particle effect. Considering the significant differences in the materials used for testing (agar gels, chewing gums), investigators from the present study could not compare their results with the findings from Plesh et al.[26]

The hardest model food also was not comparable to carrots—as used by Woda et al[12]—or crisp bread—as used by Jemt[17]—and did not pose such heavy challenges to masticatory function. This may explain why the authors did not detect significant changes in chewing frequency with food hardness, as some authors have found.

Foster et al[24] found no difference in chewing frequency with changing hardness using elastic foods (jellied confectionery products, based on gelatin), but did find a decrease in frequency with increase in hardness of plastic foods (caramel confectionery products).[24] The authors of the present study believe that use of caramels introduce specific rheological properties (as they are sticky foods) that may explain longer masticatory cycles for their "hardest" products.

Their findings also indicated that chewing frequency does not differ significantly for the dentate subjects and denture wearers, which is in accordance with other studies.[5,14,75] Mishellany-Dutour et al[10] and Woda et al[12] observed a significant decrease in masticatory cycle frequency when comparing denture wearers with dentate subjects for raw carrots. While raw carrots are generally a normal constituent in the dentate subjects' diet, such hard foods may pose significant challenges for some denture wearers, which may result in more careful jaw movements, with prolonged masticatory cycles and decreased chewing frequency.

Veyrune et al[11] also found a lower masticatory frequency for denture wearers as compared to dentate subjects while chewing laboratory-developed gumdrops (gelatin-based) demonstrating viscoelastic properties. Unlike gelatin gels, the agar-based model foods used in this study did not melt, so chewing reflects just the process of particle reduction. Denture wearers could also have spent more energy and time per cycle in repositioning a viscoelastic (mainly elastic) food on the occlusal table, given that few natural foods exhibit elastic properties. Finally, as the denture wearers recognized a mixture of prosthetic reconstructions, it is hard to relate these findings to those of studies assessing maxillomandibular conventional complete denture wearers.

The chewing frequency recorded in this study did not vary significantly with age, in accordance with other studies.[10,12,55,76] It appears that age, per se, exhibits only limited impact on masticatory function in this sample, as compared with the number of remaining functional teeth.[77]

Relative Masticatory Muscle Activity: EMG Area-Under-Curve for the Jaw-Closing Muscles

Since maximal occlusal forces are not generated during normal chewing, it appears more relevant to evaluate masticatory muscle activity during chewing in assessing the effect of prosthodontic treatments on masticatory performance.[78] Evaluation of masticatory muscle activity by measuring the area under the EMG curve offers a more pertinent variable as compared to simple EMG parameters, like peak masticatory muscle activity, as it also takes into account the duration of contraction.[25]

A major observation in the present study was that relative masticatory muscle activity, similar to the total duration of chewing, increased with the fracture stress of the food samples following a power function relationship. Other studies[2,4,9,14,23,24,26,54,59–63,79–83] documented similar variation in EMG masticatory muscle activity with increased hardness of foods. Masticatory muscle activity is reported as significantly affected by increases in food hardness.[24] However, Veyrune et al[11] found that complete denture wearers failed to increase EMG masticatory muscle activity per cycle in response to hardness of food. They used four gelatin-based viscoelastic (mainly elastic, but non-sticky) model foods, which differed in hardness (maximum deformation ranging from 39 to 114 kPa).[25] The authors can speculate that the limited range of food hardness may explain, at least in part, why a significant relationship between masticatory muscle activity and food hardness was not detected for denture wearers.[11] The same study did identify a direct relationship between masticatory muscle activity and food hardness in dentate subjects, in accord with Peyron et al,[23] using the same gelatin-based model foods. Thus, the difference among studies in the amount of variation in EMG masticatory muscle activity with increase in food hardness may be related to differences in food characteristics and/or measurement variance while using surface electrodes.

The findings follow previous observations that masticatory muscle activity decreases as a chewing sequence proceeds.[23,25,79,84,85] The dentate subjects and denture wearers demonstrated a similar response in reducing relative masticatory muscle activity throughout the initial 10 cycles of a chewing sequence. The higher values of the exponent m of the power functions describing the relationship between scaled masticatory muscle activity and fracture stress for both groups for the initial chewing cycles reflect the need for proportionally greater amounts of masticatory muscle activity to comminute the larger food pieces when the samples were whole or had been fractured only once or twice.

Although both groups of participants were similarly responsive to increases in the hardness of the food samples, the relative masticatory muscle activity was 2.57 times higher for the denture wearers than for the dentate subjects, suggesting that the masticatory muscle of the denture wearers used a greater proportion of their maximum observed activity during most chewing cycles.

It is worth noting that higher relative recruitment does not necessarily indicate that the denture wearers recruited overall higher levels of masticatory force during mastication. If denture wearers used more similar but recruited absolutely smaller forces from their masticatory muscle compared to dentate subjects—a possibility that cannot be addressed by EMG alone—they were not necessarily generating larger muscle forces during mastication. It is possible that the denture wearers were “working safer” by recruiting consistently smaller amounts of force. Hück et al[50] hypothesized that complete denture wearers may adopt a “safer” masticatory cycle in order to mitigate the effects of destabilizing forces produced by the bolus with a dual aim of stabilizing their dentures and avoiding pain. Veyrune and Mioche[22] also pointed out that masticatory patterns in denture wearers may become limited, while Veyrune et al[11] suggested that part of masticatory muscle activity in these patients may be directed to denture stabilization.

In the present study, the reduction in masticatory muscle activity from the 1st to the 10th chew was proportionally less in magnitude for the denture wearers than the dentate subjects and occurred more gradually from cycle to cycle, which is in accordance with other studies.[9,11,16] This difference would likely reflect the fact that dentate subjects are generally more efficient during chewing, accomplishing most of the comminution of food early in the chewing sequence (or at least sooner than denture wearers), then significantly reducing the amount of masticatory muscle activity per chew. In contrast, denture wearers, being less efficient and presenting a slower progression in food breakdown, exhibited a slower reduction in masticatory muscle activity per chew.

The authors also hypothesized that, for the dentate subjects, the amount of masticatory muscle activity per chew was more closely related to the consistency of the forming bolus, as masticatory muscle activity sharply decreases during the first three chews. It probably follows a cycle by cycle adaptation to the information from receptors in the mouth while food is being processed.[6,7,9,86] For the denture wearers, the variation in masticatory muscle activity per chew is less marked from chew 1 to chew 10. This likely indicates a slower progression in food breakdown. It also may indicate that denture wearers have less sensitivity to new information, as lack of inputs from periodontal receptors may impair adaptability on a chew by chew basis.

Although a number of studies also found increased masticatory muscle activity in complete denture wearers compared to dentate subjects,[10–12] Veyrune and Mioche[22] reported less masticatory muscle activity for denture wearers as compared with dentate subjects, while chewing beef samples. Also, the masticatory muscle activity of denture wearers during chewing beef was poorly adapted to food texture. The authors hypothesized that denture wearers may limit the maximal crushing force that occurs just before and during tooth contact due to pain from the oral mucosa if it is pinched by the denture.

A reduced masticatory muscle activity in denture wearers as compared to dentate subjects was also found by Kapur and Garrett[87] and Slagter et al.[14] Such findings can be explained by the fact that the test foods used (peanuts, carrots,[87] and dental silicones[14]) were challenging the denture wearers beyond their masticatory comfort, so they limited their chewing force and masticatory muscle activity.

Once again, since the present study included participants with various prosthodontic treatments (not only maxillomandibular conventional complete dentures), differences in outcomes (as compared to research comparing dentates to conventional complete denture wearers) are expected. We can further speculate that, in general, denture wearers will respond in two distinct ways to food properties. When food properties are within the range of their masticatory comfort, they will adapt by increasing both chewing duration (adding extra masticatory cycles) and relative masticatory muscle activity, as difficulty in chewing increases. As compared to dentate subjects, denture wearers will chew for longer periods, use more cycles, and exhibit increased relative masticatory muscle activity. Chewing frequency is not expected to vary with hardness of food, neither will it be significantly different as compared to dentate subjects for the same foods.

When food properties extend beyond the range of their comfortable mastication, the denture wearers may limit their chewing time (with decreased number of cycles) and relative masticatory muscle activity, sometimes to the point of rejecting food.[22] In these instances, denture wearers may show similar, or decreased chewing duration and relative masticatory muscle activity compared to dentate subjects. Furthermore, chewing frequency can also decrease with hardness of foods, indicating impaired mastication for these challenging foods.

Study Limitations and Future Directions

The reduced sample size and age range, along with a heterogenous denture wearers group (various dental states and prosthodontic treatments pooled into a single group), constitute limitations of this preliminary study. Other limiting factors included imposed unilateral chewing sequences and imposed order of chewing samples. No post-hoc tests were conducted. As the hypothesis was partially confirmed, future research is needed to better characterize the complex process of mastication and how this function is influenced by dental state and food properties. Observing a larger sample size with more homogenous groups and use of free mastication (instead of imposed one-sided chewing) while subjects are processing different foods in a random manner will likely help to detect additional meaningful differences on the outcomes of various prosthodontic treatments. It is also desirable that a number of occlusal factors (occlusal scheme, number of occluding pairs, occlusal surface, and anatomy) be included in the analyses, or closely controlled. The addition of a jaw-tracking system to the investigation would better characterize the mandibular movements and help validate behavioral measurements while chewing. Statistical analyses will benefit from using post-hoc tests.

Conclusions

Denture wearers treated with a maxillary conventional complete denture opposing natural dentition or one of the several types of mandibular complete dentures (conventional, implant-supported overdenture, implant-supported fixed denture) displayed increased relative masticatory muscle activity as compared to dentate subjects while chewing standardized model foods. In the denture wearers, the relative masticatory muscle activity did not decrease from chew to chew in the manner observed for dentate subjects. The observed increases in relative masticatory muscle activity for denture wearers compared to the dentate subjects likely reflect supplemental mechanical efforts during oral food processing to accommodate the use of dentures for preparing a bolus for swallowing.

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References

1. Foster KD, Grigor JMV, Cheong JN, Yoo MJY, Bronlund JE, Morgenstern MP. The role of oral processing in dynamic sensory perception. J Food Sci 2011;76:R49–R61.
2. Hiiemae KM, Palmer JB. Food transport and bolus formation during complete feeding sequences on foods of different initial consistency. Dysphagia 1999;14:31–42.
3. Heath MR, Prinz JF. Oral processing of foods and the sensory evaluation of texture. In: Rosenthal AJ, ed. Food Texture: Measurement and Perception. Gaithersburg, MD, Aspen, 1999: 18–29.
4. Hiiemae K, Heath MR, Heath G, et al. Natural bites, food consistency and feeding in man. Arch Oral Biol 1996;41:75–89.
5. Witter DJ, Woda A, Bronkhorst EM, Creugers NHJ. Clinical interpretation of a masticatory normative indicator analysis of masticatory function in subjects with different occlusal and prosthodontic status. J Dent 2013;41:443–448.
6. Trulsson M, Van der Bilt A, Carlsson GE, et al. From brain to bridge: Masticatory function and dental implants. J Oral Rehabil 2012;39:858–877.
7. Svensson KG, Trulsson M. Impaired force control during food holding and biting in subjects with tooth- or implant-supported fixed prostheses. J Clin Periodontol 2011;38:1137–1146.
8. Bersani E, Regalo SCH, Siessere S, et al. Implant-supported prosthesis following Branemark protocol on electromyography of masticatory muscles. J Oral Rehabil 2011;38:668–673.
9. Grigoriadis A, Johansson RS, Trulsson M. Adaptability of mastication in people with implant-supported bridges. J Clin Periodontol 2011;38:395–404.
10. 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;99:21–28.
11. Veyrune JL, Lassauzay C, Nicolas E, Peyron MA, Woda A. Mastication of model products in complete denture wearers. Arch Oral Biol 2007;52:80–85.
12. Woda A, Mishellany A, Peyron MA. The regulation of masticatory function and food bolus formation. J Oral Rehabil 2006; 33:40–49.
13. Fontijn-Tekamp FA, Slagter AP, van der Bilt A, et al. Biting and chewing in overdentures, full dentures, and natural dentitions. J Dent Res 2000;79:19–24.
14. Slagter AP, Bosman F, van der Glas HW, van der Bilt A. Human jaw-elevator muscle activity and food comminution in the dentate and edentulous state. Arch Oral Biol 1993;38:195–205.
15. Wayler AH, Muench ME, Kapur KK, Chauncey HH. Masticatory performance and food acceptability in persons with removable partial dentures, complete dentures and intact natural dentition. J Gerontol 1984;39:84–89.
16. Haraldson T. Comparisons of chewing patterns in patients with bridges supported on osseointegrated implants and subjects with natural dentition. Acta Odontol Scand 1983;41:203–208.
17. Jemt T. Chewing patterns in dentate and complete denture wearers—Recorded by light-emitting diodes. Swed Dent J 1981;5: 199–205.
18. Shiau YY, Peng CC, Hsu CW. Evaluation of biting performance with standardized test-foods. J Oral Rehabil 1999;26:47–52.
19. Foegeding EA, Daubert CR, Drake MA, et al. A comprehensive approach to understanding textural properties of semi- and soft-solid foods. J Texture Studies; 2011 42:3–29.
20. Barrangou LM, Drake MA, Daubert CR, Foegeding EA. Sensory texture related to large-strain rheological properties of agar/glycerol gels as a model food. J Texture Studies 2006;37:41–62.
21. Fontijn-Tekamp FA, van der Bilt A, Abbink JH, Bosman F. Swallowing threshold and masticatory performance in dentate adults. Physiol Behav 2004;83:31–36.
22. Veyrune JL, Mioche L. Complete denture wearers: Electromyography of mastication and texture perception whilst eating meat. Eur J Oral Sci 2000;108:83–92.
23. Peyron A, Lassauzay C, Woda A. Effects of increased hardness on jaw movement and muscle activity during chewing of visco-elastic model foods. Exp Brain Res 2002;142:41–51.
24. Foster KD, Woda A, and Peyron MA. Effect of texture of plastic and elastic model foods on the parameters of mastication. J Neurophysiol 2006;95:69–79.

25. 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;108:84–92.
26. Plesh O, Bishop B, McCall W. Effect of gum hardness on chewing pattern. Exp Neurol 1986;92:2–12.
27. McGarry TJ, Nimmo A, Skiba JF, Ahlstrom RH, Smith CR, Koumjian JH. Classification system for complete edentulism. J Prosthodont 1999;8:27–39.
28. Uram-Tuculescu S. Masticatory Function of the Dentulous Versus Prosthodontically Treated Edentulous Mandible [master's thesis]. Chapel Hill, North Carolina: University of North Carolina at Chapel Hill, 2008.
29. Hamann DD, Zhang J, Daubert CR, Foegeding EA, Diehl KC. Analysis of compression, tension and torsion for testing food gel fracture properties. J Texture Stud 2006;37:20–39.
30. Truong VD, Daubert CR. Comparative study of large strain methods for assessing failure characteristics of selected food gels. J Texture Stud 2000;31:35–53.
31. Hylander WL, Johnson KR. Modelling relative masseter force from surface electromyograms during mastication in non-human primates. Arch Oral Biol 1993;38:233–240.
32. Loeb GE, Gans C. Signal processing and display. In: Electromyography for Experimentalists. Chicago: The University of Chicago Press, 1986:244–262.
33. Hylander WL, Ravosa MJ, Ross CF, Wall CE, Johnson KR. Symphyseal fusion and jaw-adductor muscle force: An EMG study. Am J Phys Anthropol 2000;112:69–92.
34. Bhatka R, Throckmorton GS, Wintergerst AM, Hutchins B, Buschang PH. Bolus size and unilateral chewing cycle kinematics. Arch Oral Biol 2004;49:59–66.
35. Throckmorton GS, Buschang BH, Hayasaki H, Phelan T. The effect of chewing rates on mandibular kinematics. J Oral Rehabil 2001;28:28–34.
36. Türker KS. Electromyography: Some methodological problems and issues. Phys Ther 1993;73:698–710.
37. Merlo A, Campanini I. Tehnical aspects of surface electromyography for clinicians. Open Rehab J 2010;3:98–109.
38. Basmajian JV, De Luca C. Muscles Alive–Their Functions Revealed by Electromyography. 5th ed. Baltimore, MD: Williams & Wilkins, 1985.
39. Loeb GE, Gans C. Noise and artifact. In: Electromyography for Experimentalists. Chicago: The University of Chicago Press, 1986: 175–188.
40. Turker KS, Miles TS. Cross-talk from other muscles can contaminate elecromyographic signals in reflex studies of the human leg. Neurosci Lett 1990;111:164–169.
41. Moller E. Evidence that the rest position is subject to servocontrol. In: Anderson DJ, Matthews B, eds. Mastication. Bristol, England: John Wright & Sons, 1976:72–80.
42. Miles TS, Türker KS. Decomposition of human electromyogramme in an inhibitory reflex. Exp Brain Res 1987;65:337–342.
43. Yang JF, Winter DA. Electromyography reliability in maximal and submaximal isometric contractions. Arch Phys Med Rehabil 1983;64:417–420.
44. Bigland-Ritchie B. Electromyography/force relations and fatigue of human voluntary contractions. Exerc Sport Sci Rev 1981;9: 75–119.
45. Hugger S, Schindler HJ, Kordaß B, Hugger A. Clinical relevance of surface EMG of the masticatory muscles (part 1): Resting activity, maximal and submaximal voluntary contraction, symmetry of EMG activity. Int J Computerized Dent 2012; 15:297–314.
46. Soderberg GL, Cook TM. Electromyography in biomechanics. Phys Ther 1984;64:1813–1820.
47. Soderberg GL. Selected Topics in Surface Electromyography for Use in the Occupational Setting: Expert Perspectives. Washington, DC: U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health, 1992.
48. Tam H, Webster JG. Minimizing electron motion artifact by skin abrasion. IEEE Trans Biomed Eng 1977;31:823–826.
49. Van der Bilt A. Assessment of mastication with implications for oral rehabilitation: A review. J Oral Rehabil 2011;38:54–80.
50. Hück NL, Abbinck JH, Hoogenkamp E, van der Bilt A, van der Glas HW. Exteroceptive reflexes in jaw-closing muscle EMG during rhythmic jaw closing and clenching in man. Exp Brain Res 2005;162:30–38.
51. Lucas PW, Luke DA. Is food particle size a criterion for the initiation of swallowing? J Oral Rehabil 1986;13:27–36.
52. Gunne H-SJ. Masticatory efficiency and dental state. A comparison between two methods. Acta Odontol Scand 1985;43:39–46.
53. Carlsson GE. Masticatory efficiency: The effect of age, the loss of teeth and prosthetic rehabilitation. Int Dent J 1984;34:3–7.
54. Cakir E, Koc H, Vinyard CJ, et al. Evaluation of texture changes due to compositional differences using oral processing. J Texture Stud 2011;43:257–267.
55. Peyron MA, Blanc O, Lund JP, Woda A. Influence of age on adaptability of human mastication. J Neurophysiol 2004;92: 73–79.
56. Peyron MA, Maskawi K, Woda A, Tanguay R, Lund JP. Effect of food texture and sample thickness on mandibular movement and hardness assessment during biting in man. J Dent Res 1997; 76:89–95.
57. Duizer LM, Gullett EA, Findlay CJ. The relationship between sensory time-intensity, physiological electromyography and instrumental texture profile analysis measurements of beef tenderness. Meat Sci 1996;42:15–24.
58. Slagter AP, Olthoff LW, Bosman F, Steen WH. Masticatory ability, denture quality, and oral conditions in edentulous subjects. J Prosthet Dent 1992;68:299–307.
59. Horio T, Kawamura Y. Effects of texture of food on chewing patterns in the human subject. J Oral Rehabil 1989;16:77–83.
60. Mioche L. Mastication and food texture perception: Variation with age. J Texture Stud 2004;35:145–158.
61. Pereira LJ, de Wijk RA, Gaviao MBD, van der Bilt A. Effect of added fluids on the perception of solid food. Physiol Behav 2006;88:538–544.
62. Woda A, Foster K, Mishellany A, Peyron MA. Adaptation of healthy mastication to factors pertaining to the individual of to the food. Physiol Behav 2006;89:28–35.
63. De Wijk RA, Zijlstra N, Mars M, de Graaf C, Prinz JF. The effects of food viscosity on bite size, bite effort and food intake. Physiol Behav 2008;95:527–532.
64. Slagter AP, Olthoff LW, Steen WH, Bosman F. Comminution of food by complete-denture wearers. J Dent Res 1992;71:80–86.
65. Olthoff LW, van der Bilt A, De Boer A, Bosman F. Comparison of force-deformation characteristics of artificial and several natural foods for chewing experiments. J Texture Stud 1986;17:75–89.
66. Mioche L, Bourdiol P, Monier Sandra, Martin J-F, Cormier D. Changes in jaw muscles activity with age: Effects on food bolus properties. Physiol Behav 2004;82:621–627.
67. Feldman RS, Kapur KK, Alman JE, Chauncey HH. Aging and mastication: Changes in performance and in the swallowing threshold with natural dentition. J Am Geriatric Soc 1980;28:97–103.
68. Kohyama K, Mioche L, Martin JF. Chewing patterns of various texture foods studied by electromyography in young and elderly populations. J Texture Stud 2002;33:269–283.

69. Youssef RE, Throckmorton GS, Ellis EI, Sinn DP. Comparison of habitual masticatory patterns in men and women using a custom computer program. J Prosthet Dent 1997;78:79–86.
70. Buschang PH, Throckmorton GS, Travers KH, Johnson G. The effects of bolus size and chewing rate on masticatory performance with artificial test foods. J Oral Rehabil 1997;24:522–526.
71. Witter DJ, Tekamp FA, Slagter AP, Kreulen CM, Creugers NHJ. Swallowing threshold parameters of subjects with complete dentures and overdentures. Open J Stomatol 2011;1:69–74.
72. Kreulen CM, Witter DJ, Tekamp FA, Slagter AP, Creugers NHJ. Swallowing threshold parameters of subjects with shortened dental arches. J Dent 2012;40:639–643.
73. Steiner JE, Michman J, Litman A. Time sequence of the activity of the temporal and masseter muscles in healthy young human adults during habitual chewing of different test foods. Arch Oral Biol 1974;19:29–34.
74. Jemt T, Hedegard B. Reproducibility of chewing rhythm and of mandibular displacements during chewing. J Oral Rehabil 1982;9:31–37.
75. Shi CS, Ouyang G, Guo T. A comparative study of mastication between complete denture wearers and dentate subjects. J Prosthet Dent 1991;66:5–9.
76. Karlsson S, Carlsson GE. Characteristics of mandibular masticatory movement in young and elderly dentate subjects. J Dent Res 1990;69:473–476.
77. Kohyama K, Mioche L, Bourdiol P. Influence of age and dental status on chewing behaviour studied by EMG recordings during consumption of various food samples. Gerodontol 2003;20:15–23.
78. Feine JS, Lund JP. Measuring chewing ability in randomized controlled trials with edentulous populations wearing implant prostheses. J Oral Rehabil 2006;33:1–8.
79. Van der Bilt A, Engelen L, Abbink JH, Pereira LJ. Effects of adding fluids to solid foods on muscle activity and number of chewing cycles. Eur J Oral Sci 2007;115:198–205.
80. Mioche L, Bourdiol P, Martin J-F, Nöel Y. Variations in human masseter and temporalis muscle activity related to food texture during free and side-imposed mastication. Arch Oral Biol 1999;44:5–12.
81. Agrawal KR, Lucas PW, Bruce IC, Prinz JF. Food properties that influence neuromuscular activity during human mastication. J Dent Res 1998;77:31–38.
82. Mathevon E, Mioche L, Brown WE, Culioli J. Texture analysis of meat cooked at various temperatures by mechanical measurements, sensory assessments and masticatory muscle electromyography. J Texture Stud 1995;26:75–92.
83. Feine JS, Maskawi K, de Grandmont P, Donohue WB, Tanguay R, Lund JP. Within-subject comparisons of implant-supported mandibular prostheses: Evaluation of masticatory function. J Dent Res 1994;73:46–56.
84. 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 Stud 2004;35:395–414.
85. Yven C, Bonnet L, Cormier D, Monier S, Mioche L. Impaired mastication modifies the dynamics of bolus formation. Eur J Oral Sci 2006;114:84–90.
86. Lund JP, Kolta A, Westberg KG, Scott G. Brainstem mechanisms underlying feeding behaviours. Curr Opin Neurobiol 1998;8:18–24.
87. Kapur KK, Garrett NR. Studies of biologic parameters for denture design. Part II: Comparison of masseter muscle activity, masticatory performance, and salivary secretion rates between denture and natural dentition groups. J Prosthet Dent 1984;52:8–13.

Literature Abstract

Oral manifestations of hepatitis C virus infection

Based on a review of the literature, the article reported an update on the relationship between hepatitis C virus (HCV) infection with oral lichen planus (OLP), Sjogren-like sialadenitis (SjS) and oral squamous cell carcinoma (OSCC). The authors found that there was strong and convincing evidence that HCV was associated with OLP, whereas the relationship between HCV and SjS was controversial and that HCV could represents an etiologic agent of OSCC in certain countries. The article, however, did not present the inclusion criteria of the reviewed articles.

Carrozzo M, Scally K. *World J Gastroenterol* 2014;20:7534–7543. **References:** 125. **Reprints:** Dr Marco Carrozzo, Professor of Oral Medicine, Centre for Oral Health Research, Oral Medicine Department, University of Newcastle upon Tyne, Framlington Place, Newcastle upon Tyne NE2 4BW, United Kingdom. Email: marco.carrozzo@ncl.ac.uk—*Huong Nguyen, Ann Arbor, Michigan, USA*