

Adaptability of mastication in people with implant-supported bridges

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Abstract

Objectives: We aimed to determine whether people with implant-supported bridges in both jaws, thus lacking periodontal receptors, adjust jaw muscle activity to food hardness during mastication.

Materials and Methods: Thirteen participants with implant-supported bridges in both jaws and 13 with natural dentition chewed and swallowed soft and hard gelatine-based model foods, while electromyographic (EMG) activity of the masseter and temporal muscles was recorded bilaterally together with the position of the mandible. Data were compared by using a mixed-design ANOVA model and a *P*-value < 0.05 was considered statistically significant.

Results: The number of chewing cycles and the duration of the masticatory sequence increased with food hardness in both groups, whereas vertical and lateral amplitude of the jaw movements, and the jaw-opening velocity, increased significantly with food hardness only for the dentate group. Although both groups adapted the EMG activity to the hardness of the food, the implant participants showed a significantly weaker increase in EMG activity with increased food hardness early during the masticatory sequence than the dentate participants did. In addition, the implant group showed significantly less reduction of muscle activity during the progression of the masticatory sequence than the dentate group.

Conclusions: People with implant-supported bridges show an impaired adaptation of the muscle activity to food hardness during mastication. We suggest that a lack of sensory signals from periodontal mechanoreceptors accounts for the impairment.

Key words: chewing adaptation; dental implants; model food; periodontal mechanoreceptors; sensory motor control

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During mastication, the central nervous system (CNS) uses sensory signals to adjust motor output to the physical characteristics of the food through changes in jaw muscle activity, which

in turn alters jaw kinematics and chewing forces. This adaptation occurs continuously during the masticatory sequence as the food properties are modified (Thexton et al. 1980, Schwarts et al. 1989, Lund 1991, Thexton & Hiiemae 1997, Peyron et al. 1997, 2002).

Various properties of the food can influence masticatory behaviour. These include the size, shape and flavour of the foodstuff as well as material characteristics such as texture, elasticity and rheological properties (Woda et al. 2006). Most studies examining effects of the material properties of food have dealt with hardness using natural food (e.g., Sakamoto et al. 1989, Agrawal et al. 1998, Veyrone & Mioche 2000).

However, the material properties of natural foodstuffs are generally not well defined (Woda et al. 2006) because hardness depends on a wide range of factors, including ductility, brittleness, elasticity, plasticity, strain, strength, toughness, viscoelasticity and viscosity (see Foster et al. 2006).

To overcome this problem, edible viscoelastic model foods with controlled hardness have been developed (Lassauzay et al. 2000, Peyron et al. 2002, 2004). In contrast to natural foods, the material properties of these products, including the rheological properties, are well defined. An increased hardness of such viscoelastic model foods is associated with an increase in the

Conflict of interest and source of funding statement

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number of chewing cycles during the masticatory sequence, increased jaw muscle activity and increased amplitude of the jaw-opening movements (Peyron et al. 2002).

The periodontal mechanoreceptors located around the roots of the teeth signal rich information about tooth loads (Trulsson & Johansson 1996, Trulsson 2006) to the CNS (Habre-Hallage et al. 2010, Trulsson et al. 2010) and are involved in the control of the jaw muscles during biting and chewing (Lund 1991, Türker & Jenkins 2000, Trulsson 2006). Because these receptors convey an abundance of information about the forces that arise during contact between teeth and food during biting and chewing (Trulsson & Johansson 1994, Johnsen & Trulsson 2005), they probably provide information about material properties of the food that the CNS can use to adapt jaw muscle activity to the current state of the food. Indeed, complete denture wearers – who lack periodontal receptors – fail to adapt their jaw muscle activity to food hardness during chewing (Veyrone et al. 2007). An early study by Haraldson (1983) suggests that also persons with prostheses supported by dental implants, and thus lack normal innervation of the periodontium, show an impaired regulation of the jaw muscle activity to the gradual changes in food properties that occur during chewing. Any interpretation of these results is, however, open to doubt because natural foods with largely undefined mechanical properties were used and most of the participants had a mix of dental implants and natural teeth. In the present study, we compared the adaptation of jaw muscle activity and movements in participants with implant-supported bridges in both jaws with that of age- and sex-matched participants with natural teeth. Both groups chewed two well-defined viscoelastic model foods of different hardness.

Material and Methods

Participants

The study included eight males and five females with osseointegrated implants (Nobel Biocare AB, Göteborg, Sweden, or Astra Tech AB, Mölndal, Sweden) that supported full bridges in both jaws (58–83 years of age; mean 71.1 years) and eight males and five females with natural dentition (59–79 years of age; mean 66.4 years). The participants with

natural dentition had at least 28 permanent teeth and no known dental pathology. Participants with implants had used their bridges for at least 12 months. For all implanted participants, six implants supported the bridge in the upper jaw. In the lower jaw, four implants supported the bridge in eight participants and five implants supported the bridges in five participants. All implant bridges extended to the second pre-molar or first molar region. All mandibular bridges and 11 of the maxillary bridges were made of a metal frame to which acrylic prosthetic teeth were attached. The metal frame of two of the maxillary bridges was covered with porcelain. The most distal teeth in the bridges always had the size and shape of a molar.

All of the participants had normal occlusion. They did not indicate any problems or dysfunctions with chewing and all stated that they ate comfortably.

All participants gave written informed consent in accordance with the Declaration of Helsinki, and the local research ethics committee had approved the study.

Model foods

Two viscoelastic model foods, identical in size and shape, but of different hardness, were prepared according to the recipe of Peyron et al. (2002). The foods were based on gelatin (Gelita Sweden AB, Klippan, Sweden) of two different grades, one with 25 g of 150 bloom and one with 41.5 g of 250 bloom, to which glucose (132 g), sugar (111 g), water (84 g) and citric acid were added. The two foods were coloured yellow and green, respectively; so they could be distinguished by the experimenter during the mastication trials. The soft and hard model foods were prepared in a water bath at 80°C for 2 and 4 h, respectively. The mixtures were then put into cylindrical Plexiglas molds for 24 h and finally in an airtight box for 72 h. Each food sample was 20 mm in diameter and 10 mm in height.

We performed duplicate measurements of the mechanical properties of 10 samples from each of 12 batches of model food of each type using a universal testing machine (AG-G, Shimadzu Co., Kyoto, Japan). The food was uni-axially compressed 5 mm at 50 mm/min. while the force was measured continuously (250 samples/s). Oil was applied to the contact plates before each test to reduce adhesion between the food and the plates. The hardness of the

two model foods, assessed as maximal stress during the compression, differed with a factor of around two. The gauged hardness of the hard food was 131 ± 22 and 127 ± 20 kPa (mean \pm 1 SD; $N = 120$) in the first and the second compression test, respectively. The corresponding values for the soft food were 63 ± 14 and 61 ± 12 kPa ($N = 120$). That the maximal stress recorded during the two compression cycles differed only modestly, verified that both foods showed essentially viscoelastic properties.

Recording jaw movements and muscle activity

Participants sat in a relaxed position in an electrically and magnetically shielded room. We measured the vertical, lateral and anterior–posterior movements of the lower jaw with reference to the upper jaw using a custom-built apparatus (Umeå University, Physiology Section, IMB, Umeå, Sweden). A small magnet (10 × 5 × 5 mm) was attached to the labial surfaces of the mandibular incisors with dental composite cured with a led lamp. A lightweight frame attached to the head and equipped with an array of magnetic sensors tracked in three dimensions the position of the magnet (accuracy: 0.1 mm; bandwidth: DC – 100 Hz). The frame rested on the upper part of the bridge of the nose and was fixed to the head with spectacle frames, the ends of which were joined by a strap around the head. The apparatus allowed normal head movement while the participants were chewing.

Surface electromyograms were recorded from the centres of the masseter and temporal muscles using shielded preamplifiers (bandwidth 6 Hz to 2.5 kHz) mounted on the skin directly above the surface electrodes; these electrodes were 2 mm in diameter and 12 mm apart. They were coated with electrode jelly and then firmly attached to the skin using double-sided adhesive tape after the skin had been rubbed gently with an alcohol solution. Throughout the experiments, we carefully monitored the electromyographic (EMG) signals for stability, artifacts and noise.

All signals recorded were stored and analysed using the SC/ZOOM micro-computer-based data acquisition and analysis system (SC/ZOOM, v.3.1.02, Umeå University, Physiology Section, IMB, Umeå, Sweden). The EMG signals were sampled at 3.2 kHz and the vertical and lateral position of the lower jaw

with reference to the upper jaw was sampled at 800 Hz.

Experimental protocol

Each participant chewed and swallowed four soft and four hard model foods. They were presented in an unpredictable order to the participants, who were informed neither about the aim of the study nor about the properties of the test foods. Before each trial, the experimenter placed a model food on the extended tongue of the participant. The experimenter concealed the food from the participant's view to eliminate visual cues. The participants were instructed to hold the test food between the tongue and palate with the mouth closed and the teeth in the inter-cuspal position (reference point for the kinematic analysis). Two to four seconds after the food was placed on the tongue, the experimenter signalled to the participant to start chewing. Once done with the chewing (and swallowing), the participants were instructed to return to the inter-cuspal position. Between trials, the participants were free to drink, rest, speak and rinse the mouth. The experimenters always asked the participants if they were ready to continue with the next trial. Before the trials, the participants were asked if they had a preferred side for chewing and were instructed to chew on this side, termed the chewing side.

The participants performed the same experimental protocol on two different days. The purpose of the first visit was to familiarize them with the general procedure, equipment and task; the data used for analysis were collected on the second day. After the end of the chewing trials the second day, we asked the participants to comment on their experiences during the trials. Specifically, we asked if they experienced any trouble during the trials and if the apparatus might have disturbed the chewing. However, we asked no questions that alluded to the properties of the food. After giving their comments, the participants judged the hardness of four test foods of each type after chewing on each of them for five cycles. To eliminate visual cues, the participants were instructed to close their eyes before spitting the food out into a bowl. After completion of each trial, the participants marked the perceived hardness of the food on a visual analogue scale (VAS, 100 mm) where 0 and 100 represented the softest and the hardest food imagin-

able, respectively. In these trials, the two types of food were again presented in an order that the participant could not predict.

Data analysis

Phases of chewing cycles

Based on the recorded kinematic signals, we defined a chewing cycle as consisting of an opening phase followed by a closing phase and an occlusal phase (Fig. 1a). The opening phase began when the jaw had opened from the occlusal state by 10% of the maximum opening as measured in the vertical dimension and averaged across all chewing cycles of each sequence. For each participant, we defined the occlusal state as the minimum jaw opening (maximum jaw elevation) recorded during each trial, including the periods when the participant was asked to fit the teeth together in the inter-cuspal position. The opening phase ended at peak jaw opening, where the closing phase thus began. The latter ended at the same vertical jaw position as where the opening phase began, i.e., at a jaw opening corresponding to 10% of the average maximum opening. Finally, the occlusal phase lasted from the end of the closing phase to the beginning of the opening phase of the subsequent chewing cycle.

Jaw movement variables

For analysis of jaw movements, we extracted 10 variables from the kinematic signals (see left column in Table 1). For each trial, we measured (1) the duration of the masticatory sequence (between the go signal and the swallowing) and (2) the number of chewing cycles performed. For each chewing cycle, we extracted the duration of (3) the chewing cycle, (4) the jaw-opening phase, (5) the jaw-closing phase and (6) the occlusal phase. For each chewing cycle, we also measured (7) the peak-to-peak amplitude of vertical jaw movement, (8) the peak-to-peak amplitude of lateral jaw movement, (9) the peak velocity in the vertical dimension of the jaw during the jaw-opening phase and (10) during the jaw-closing phase.

Segmentation of the masticatory sequence

To analyse changes in chewing behaviour during the masticatory sequences,

we used data from three segments of each sequence that represented its beginning, middle and end (Fig. 1b). These segments each included three chewing cycles, across which data were averaged. The second to fourth cycle represented the beginning of the sequence and the second to fourth cycle from the end of the sequence represented its end; neither the very first nor the very last cycle of the sequence was included because of great intra-individual variance across trials.

Normalization of EMG signals

The EMG signals were root mean square (r.m.s.) processed over a moving time window corresponding to ± 100 samples (± 31 ms; see Figs 1a and b). The r.m.s.-processed signals were then integrated during each phase of each chewing cycle, rendering for each phase a measure corresponding to the area under the r.m.s.-processed EMG signal. We also computed the total EMG activity for each chewing cycle as the sum of the integrated electromyograms for each of the three phases. To make EMG data comparable across participants, for each muscle we normalized the integrated EMG data obtained for each phase to the total EMG activity averaged across all chewing cycles. That is, for each participant, muscle and phase of each chewing cycle, we divided the integrated EMG activity by the average value of the total EMG activity recorded from the muscle during all chewing cycles performed by the participant. This normalization allowed us to examine relative effects of food type, segment of the masticatory sequence and phase of chewing cycle on the activity in each of the four muscles recorded.

Statistical analyses

For each variable used to characterize the jaw movements, we assessed differences between the two groups of participants (dentate and with implants) using mixed-design ANOVAS where data from participants within each group were subjected to repeated measures on the segment of the masticatory sequence (beginning, middle and end) and type of food (hard and soft). To evaluate possible effects of dental implants on the use of the chewing muscles during the masticatory sequences, we ran a single rather complex mixed-design ANOVA on the normalized EMG signals. Also in

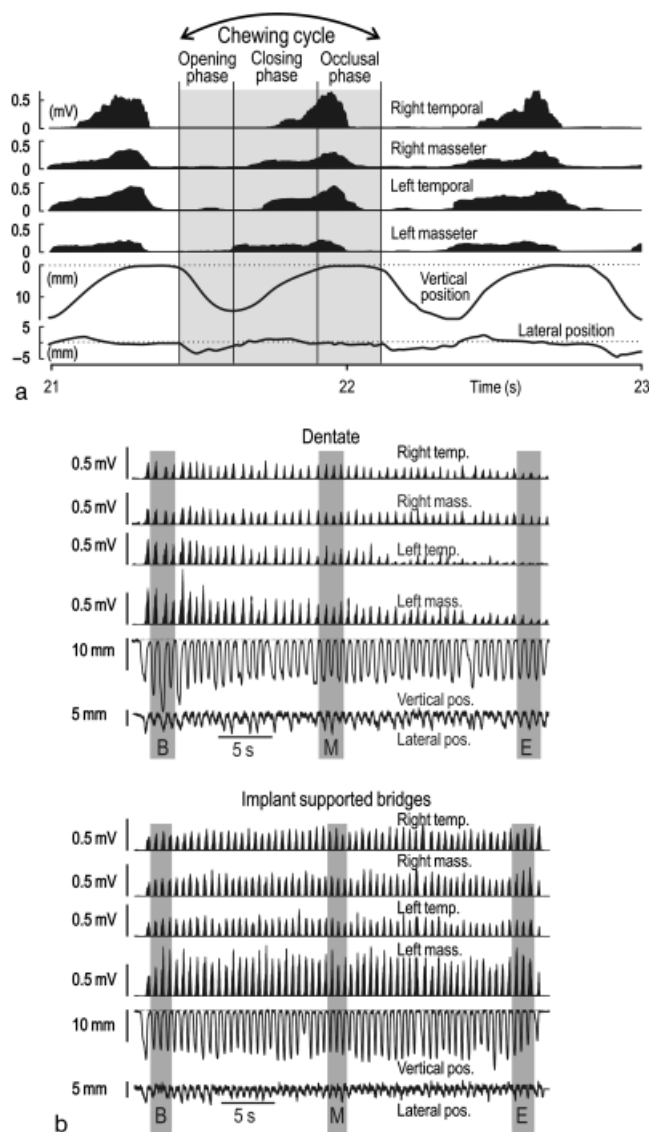


Fig. 1. Activity in the masseter and temporal muscles (root mean square-processed electromyographic signals) and the vertical and lateral position of the mandible of subjects chewing on the harder food sample. (a) Definition of the opening, closing and occlusal phase of a chewing cycle. A value of zero in the vertical position indicates the jaw position during the occlusal state. (b) One masticatory sequence (trial) performed by a dentate and one performed by an implant participant. The three triplets of chewing cycles representing the beginning (B), middle (M) and end (E) segments are indicated.

this ANOVA, participant group constituted the between-group effect while the segment of the masticatory sequence and food type constituted repeated measures within participants. To address differences in activation patterns depending on muscle, both muscle (masseter, temporal) and the side of the jaw where the muscle was situated (chewing side, non-chewing side) were subjected to repeated measures. Furthermore, to examine possible effects related to the phase of the chewing cycle, phase was also subjected to repeated measures.

However, in the analyses of EMG data, we only considered the jaw closing and the occlusal phases, because the chewing muscles were virtually silent during the jaw-opening phase (Fig. 1). Because this ANOVA was based on EMG data normalized for each muscle we recorded from, it did not allow us to compare EMG activity across muscles; the ANOVA showed no main effect of muscle. All ANOVAs were based on mean values computed for each participant and combination of factorial levels. A P -value < 0.05 was considered statis-

tically significant and under "Results" we report all significant main effects and significant interactions observed in the ANOVAs. Post hoc comparisons were performed with the Tukey HSD test.

Results

Participants' comments and assessment of hardness

In the periods between the mastication trials, almost all dentate participants (12/13) spontaneously commented that some model foods were harder than others, but only one participant from the implant group did so. After the end of the trials, when we asked the participants to comment on their experiences during the trials, all dentate participants responded that some model foods were harder, *versus* only six from the implant group. However, when requested to judge the hardness of the food during the VAS test, all participants in both groups made a distinction between hard and soft food in a similar way. A mixed-design ANOVA on the VAS scores revealed a main effect of food ($F_{1:24} = 151.5$, $P < 0.0001$), while there was no effect of group (dentate *versus* implant participants; $F_{1:24} = 1.12$, $P = 0.90$) and no interaction between food type and group ($F_{1:24} = 0.02$, $P = 0.90$). Interestingly, during the VAS trials, the experimenters noted that 5 of the 13 participants in the implant group had failed to divide most food samples into pieces after five chewing cycles. Nineteen of the 20 pieces of hard food were not even cut through and 12 of 20 soft food samples. In contrast, all dentate participants successfully separated the food samples into several pieces. All participants in both groups indicated that the task was easy to perform and felt natural, and none said that the apparatus had interfered with the chewing.

Jaw movements

We assessed possible differences in jaw behaviour between implant and dentate participants using factorial ANOVAs run on the 10 jaw movement variables selected for analysis (see Table 1). In addition to main effects of the experimental factors on the jaw behaviours, this analysis also enabled us to detect interaction effects between participant group, food hardness (hard and soft test

Table 1. Results of the mixed-design ANOVAS applied to analyse effects of the experimental factors on jaw movements

Jaw movement variable	Effect				
	food type (main effect)	segment (main effect)	group (main effect)	group × food type (interaction)	group × segment (interaction)
1. Duration of the masticatory sequence	$F_{1:24} = 62.6$ $P < 0.0001$	–	NS	NS	–
2. Number of chewing cycles during the masticatory sequence	$F_{1:24} = 61.8$ $P < 0.0001$	–	NS	NS	–
3. Duration of the chewing cycle	NS	$F_{2:48} = 5.7$ $P < 0.01$	NS	NS	NS
4. Duration of jaw-opening phase	NS	NS	NS	NS	NS
5. Duration of jaw-closing phase	NS	$F_{2:48} = 19.3$ $P < 0.0001$	NS	NS	NS
6. Duration of occlusal phase	NS	$F_{2:48} = 25.8$ $P < 0.0001$	NS	NS	NS
7. Amplitude of vertical jaw movement	$F_{1:24} = 28.6$ $P < 0.0001$	$F_{2:48} = 14.6$ $P < 0.0001$	NS	$F_{1:24} = 6.2$ $P < 0.05$	NS
8. Amplitude of lateral jaw movement	$F_{1:24} = 18.1$ $P < 0.001$	NS	NS	NS	NS
9. Velocity of jaw opening	$F_{1:24} = 18.3$ $P < 0.001$	$F_{2:48} = 17.4$ $P < 0.0001$	NS	NS	$F_{2:48} = 4.6$ $P < 0.05$
10. Velocity of jaw closing	$F_{1:24} = 16.7$ $P < 0.001$	$F_{2:48} = 10.0$ $P < 0.001$	NS	$F_{1:24} = 5.3$ $P < 0.001$	NS

‘‘Food type’’ refers to soft *versus* hard test food; ‘‘segment’’ to the beginning, middle and end of the masticatory sequence; and ‘‘group’’ to dentate *versus* implanted participants. $P \geq 0.05$. No three-way interaction was present in any of the ANOVAS. NS, not significant.

food) and segment of the masticatory sequence (beginning, middle and end).

The number of chewing cycles and the duration of the masticatory sequence did not differ between implant and dentate participants (Table 1, rows 1 and 2). Both groups used more cycles and longer masticatory sequences when chewing the hard food than the soft food (Fig. 2a). Neither the duration of the chewing cycles nor that of the various phases of the chewing cycles differed between the groups of participants (Table 1, rows 3, 4, 5 and 6). When participants were chewing soft food, the duration of the chewing cycles was 0.80 ± 0.11 s (mean \pm SD) and 0.83 ± 0.16 s for the natural and implant groups, respectively, and with hard food it was 0.79 ± 0.12 and 0.82 ± 0.17 s (mean \pm SD of means computed for each participant). The duration of the chewing cycle changed for both groups during the progression of the masticatory sequence. Averaged across both groups of participants and types of food, it was 0.73 ± 0.14 , 0.76 ± 0.16 and 0.88 ± 0.25 s in the beginning, middle and end of the masticatory sequence, respectively. Although a significant effect was observed on both the jaw-closing phase and the occlusal phase (Table 1, rows 5 and 6), the effect on the occlusal phase was most conspicuous. Its duration increased from, on

average, 0.27 ± 0.05 s in the beginning to 0.41 ± 0.17 s at the end of the sequence.

In accord with previous observations (Lassauzay et al. 2000, Peyron et al. 2002), the amplitude of the vertical jaw moments was overall greater with the hard than with the soft food (Table 1, row 7 – main effect of food type) and it declined during the progression of the masticatory sequence (Table 1, main effect of segment). However, hardness had a smaller influence on the vertical amplitude in the implanted than in the dentate participants (cf. right and left panels in Fig. 2b; Table 1, interaction between group and food type). In fact, a post hoc analysis revealed that hardness did not reliably affect the vertical amplitude in the implant group ($P = 0.25$) but did so in the dentate group ($P < 0.001$). Food type also affected the amplitude of the lateral jaw movements during the masticatory sequence (Table 1, row 8), but there was no effect that involved participant group. As with the vertical movements, the lateral movement was greater with the hard than with the soft test food.

As expected from the main effect of hardness on the amplitude of jaw movements, food hardness affected both the jaw-opening and jaw-closing velocity (Table 1, rows 9 and 10 – main effects of food type). Likewise, both velocities

declined during the progression of the masticatory sequence (main effect of segment). However, the implant group showed a weaker decline in the jaw-opening velocity during the masticatory sequence than the dentate group did (Fig. 2c; Table 1, row 9 – interaction between group and segment), and a post hoc analysis failed to indicate a significant effect of segment on the jaw-opening velocity in the implant group ($P > 0.37$). Moreover, the implant group showed a weaker effect of food hardness on the jaw-closing velocity than did the dentate group (Fig. 2d; Table 1, row 10 – interaction between group and food type). Indeed, a post hoc analysis revealed that hardness did not reliably influence the jaw-closing velocity in the implant group ($P = 0.38$) whereas it did in the dentate group ($P < 0.002$).

Taken together, these results regarding jaw movements indicate that participants with implants poorly adapted the jaw kinematics to food properties and changes in these properties during the chewing sequences.

Muscle activity

We assessed possible differences between implant and dentate participants' use of the chewing muscles by using a factorial ANOVA of the same general design as with the analysis of the jaw movements,

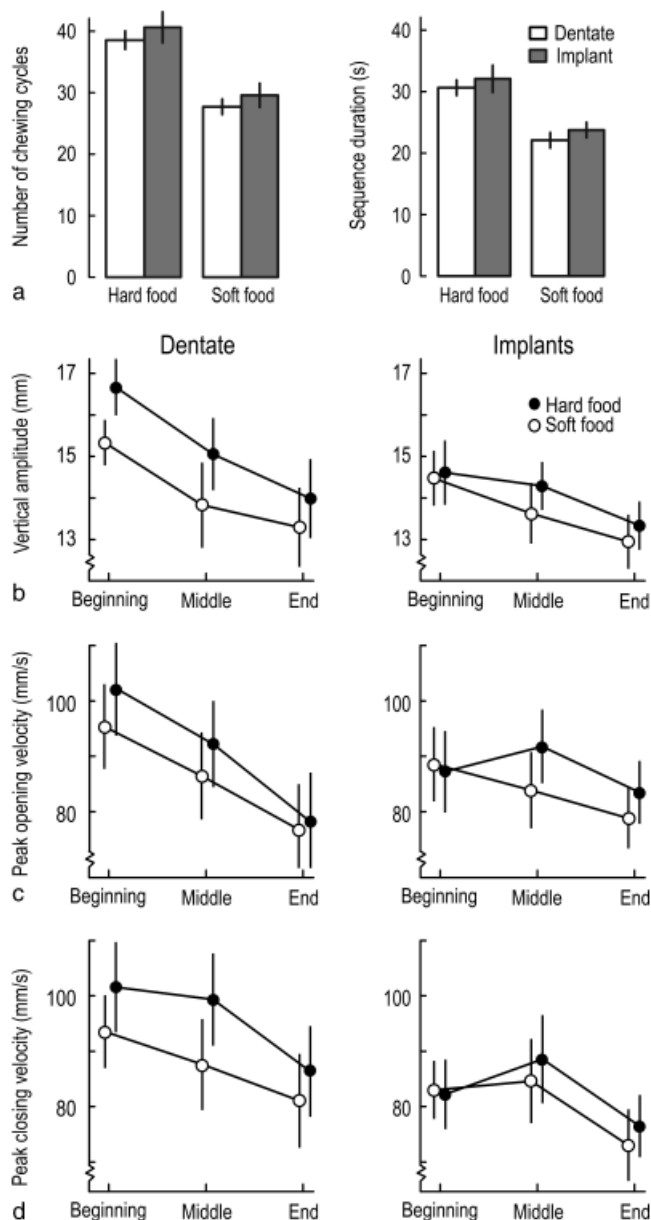


Fig. 2. Jaw movement variables during the masticatory sequences for dentate and implant participants. (a) Number of chewing cycles (left panel) and duration of the masticatory sequence (right panel) for dentate and implant participants chewing hard and soft food. Column height gives the mean value of means computed for each participant and the error bars indicate SEM ($N = 13$ in all cases). (b–d) Vertical amplitude, peak opening velocity and peak closing velocity of the jaw movement for dentate (left panels) and implant participants (right panels) during the three segments (beginning, middle and end) of the masticatory sequence when chewing hard and soft food. Symbols give the mean value of means computed for each participant and the error bars indicate SEM ($N = 13$).

but with the muscle (masseter, temporal) and the side of the jaw at which the muscle was located (chewing side *versus* the non-chewing side) as additional factors.

Figure 3a shows, for the dentate participants (left panel) and implant participants (right panel), the normalized EMG activity for the jaw-closing

phase averaged over all four muscles of all participants when they chewed on the two different food types. Figure 3b shows the corresponding EMG data for the occlusal phase. Overall, the EMG activity was greater when the participants chewed on hard than on soft food (Table 2, main effect of food type) and it declined during the progression of the

masticatory sequence (main effect of segment). A decrease in the activity during the closing phases accounted for this decline, whereas the activity during the occlusal phases rather tended to increase (cf. Figs 3a and b; Table 2, interaction between segment and phase). However, the decline in EMG activity was smaller in the implant than in the dentate group (cf. left and right panels in Fig. 3; Table 2, interaction between group and segment). Furthermore, this smaller decline in the implant participants was mainly accounted for by a smaller decline in muscle activity during the closing phases of the chewing cycles (cf. right and left panels in Fig. 3a; Table 2, three-way interaction involving group, segment and phase). Indeed, a corresponding ANOVA run on data from the occlusal phase alone showed no effect of group and no interactions involving group ($P > 0.78$ in all instances).

Overall, the EMG activity was greater when the participants chewed on hard than on soft food (Table 2, main effect of food type). However, the difference in EMG activity between the hard and soft food decreased during the progression of the masticatory sequence (Fig. 3; Table 2, interaction between food type and segment). For the closing phase, the difference was practically gone at the end of the sequence (Fig. 3a). As can be gleaned from a comparison of the left and the right panels of Fig. 3, the muscle activity in the implant group was less affected by food hardness than that in the dentate group. Accordingly, there was a significant interaction between participant group and food type (Table 2). Moreover, a three-way interaction on the muscle activity of segment in addition to food type and group (Table 2) indicated that the weaker response to food hardness in the implant group was present essentially only at the beginning of the masticatory sequence.

The design of the ANOVA used to analyse the normalized EMG signals from the chewing muscles also allowed evaluation of possible differences in the pattern of muscle activation depending on muscle (temporal and masseter) and the side of the jaw where the muscle was situated (chewing *versus* non-chewing side). Because we found no significant effects on this pattern that involved participant group and either of these factors (muscle, side) (Table 2), we just briefly describe the findings based on data pooled across the two groups of

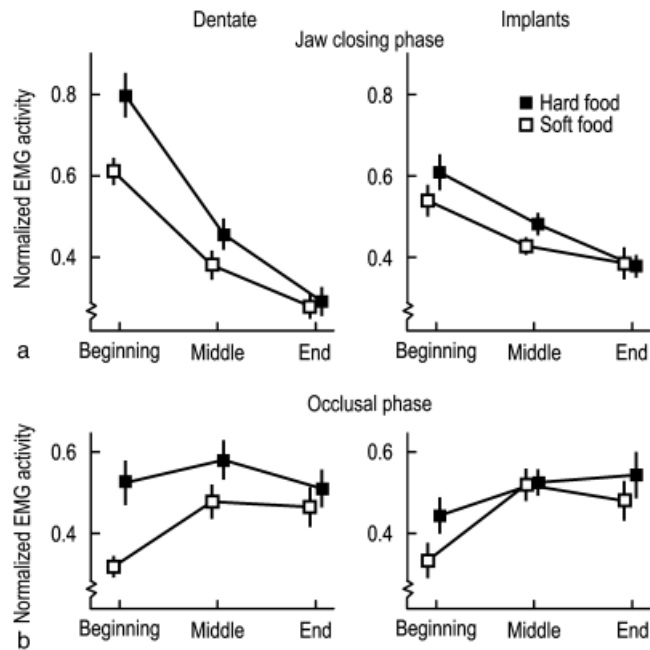


Fig. 3. Normalized electromyographic activity averaged across all four muscles from dentate participants (left panels) and implant participants (right panels) during the three segments (beginning, middle and end) of the masticatory sequence when chewing hard and soft test foods. (a and b) Data obtained for the jaw-closing phase and the occlusal phase, respectively. Symbols give the mean value of means computed for each participant and the error bars indicate SEM ($N = 13$).

Table 2. Statistically significant main effects and interaction effects on the normalized EMG activity assessed by the mixed-design ANOVA (see "Material and Methods")

Effect	F-value	P-value
Segment (main effect)	$F_{2:48} = 11.4$	<0.001
Segment \times phase	$F_{2:48} = 72.1$	<0.001
Segment \times group	$F_{2:48} = 5.3$	<0.01
Segment \times phase \times group	$F_{2:48} = 3.3$	<0.05
Food type (main effect)	$F_{1:24} = 40.0$	<0.001
Food type \times segment	$F_{2:48} = 16.4$	<0.001
Food type \times group	$F_{1:24} = 5.2$	<0.05
Food type \times segment \times group	$F_{2:48} = 3.3$	<0.05
Segment \times food type \times muscle	$F_{2:48} = 3.3$	<0.05
Segment \times phase \times muscle	$F_{2:48} = 3.3$	<0.05
Phase \times side \times muscle	$F_{1:24} = 6.9$	<0.05
Segment \times phase \times side \times muscle	$F_{2:48} = 7.7$	<0.01

"Segment" refers to the beginning, middle and end of the masticatory sequence; "group" to dentate *versus* implanted participants; "food type" to soft *versus* hard test food; "phase" to closing *versus* occlusal phase of the chewing cycles; "muscle" to masseter *versus* temporal muscle; "side" to the location of the muscle on the chewing side *versus* on the non-chewing side of the jaw.

Note that neither "group" nor "phase" had a significant main effect on the normalized EMG activity.

participants. First, the change in EMG activity during the progression of the masticatory sequence was more pronounced in the masseter than the temporal muscles, and this difference between the muscles was most pronounced when the participant chewed hard food (Fig. 4a; Table 1, interaction between segment, food type and mus-

cle). Second, the use of the muscles depended on whether they were situated on the chewing *versus* the non-chewing side (Table 2, interactions involving segment, phase and muscle in addition to side). The temporal and masseter muscles located on the chewing side showed similar changes in activity during the masticatory sequence both dur-

ing the closing and occlusal phases (Fig. 4b, left panel). However, on the non-chewing side, the relative activation of the masseter muscle was greater than that of the temporal muscle during the closing phase, whereas the activation of the temporal muscle was greater during the occlusal phase (Fig. 4b, right panel). Finally, the difference between the masseter and the temporal muscle during the closing phase declined during the progression of the masticatory sequence, which explained the involvement of the segment in the interactions reported in Table 2.

Discussion

We have compared how individuals with natural dentition and with implant-supported bridges in both jaws adapt their chewing behaviour to food hardness during mastication. Our results show that whereas food hardness had no reliable effect on the amplitude and velocity of the jaw movements of participants with implants, it did have an effect in the dentate group. Furthermore, the implant participants did not increase their jaw muscle activity with increased food hardness to the same extent as the dentate participants. Likewise, the implant participants showed a reduced ability to adapt muscle activity during the progression of the masticatory sequence.

Effect of implant-supported bridges on mastication

The duration of the masticatory sequence and the number of chewing cycles were similar in dentate and implant participants. Previous data showing that masticatory sequences in people with removable prostheses supported by the oral mucosa include more chewing cycles and last longer than in people with natural teeth (Slagter et al. 1993, Veyrune et al. 2007, Mishellany-Dutour et al. 2008) suggest that chewing is less affected by implant-supported bridges than by removable prostheses. However, our data show that the jaw movements were affected in the group with dental implants. That is, in contrast to the dentate participants, in whom the amplitude and velocity of mandibular movements reliably increased with food hardness (see also Horio & Kawamura 1989, Agrawal et al. 1998, Lassauzay et al. 2000, Peyron et al. 2002, Foster et al. 2006), the participants with implants

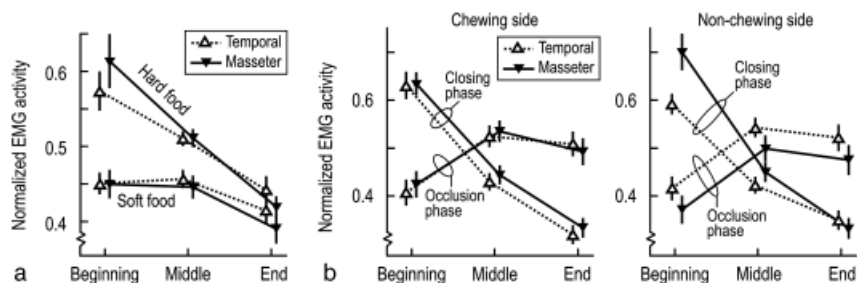


Fig. 4. Difference in patterns of normalized muscle activity depending on muscle (masseter, temporal) and on the side where the muscle was situated (chewing *versus* non-chewing side). (a) Changes in activity of the masseter and temporal muscles during the masticatory sequence (beginning, middle and end) depending on food hardness. Data averaged across the closing and occlusal phases of the chewing cycles and across the homologous muscle of the left and right side. (b) Changes across the masticatory sequence in activity of the masseter and temporal muscles during the closing and occlusal phase depending on whether the muscle was located on the chewing side and the non-chewing side. Data averaged across both food types. (a and b) Symbols give the mean value of means computed for each participant and the error bars indicate SEM ($N = 26$; data from both participant groups pooled).

tended to use similar mandibular movements irrespective of food type. Furthermore, they did not adapt their jaw movements to the changing food properties during the progression of the masticatory sequence as much as the dentate participants did.

Normal chewing behaviour is characterized by an overall greater jaw muscle activity when chewing hard than soft food and by a gradual decrease in activity during the masticatory sequence (Horio & Kawamura 1989, Slagter et al. 1993, Feine et al. 1994, Hiiemae et al. 1996, Agrawal et al. 1998, Lassauzay et al. 2000, Peyron et al. 2002). Both groups in the present study adapted their muscle activity to the hardness of food, but the effect of food type was significantly weaker in the implant group. Although the behaviour of participants with implants was similar to that of dentate participants when chewing on soft food, their impaired ability to adapt muscle activity became more obvious with hard food. That the implant participants adapted the muscle activity poorly over the masticatory sequence corroborates the results of an early study in which the author (Haraldson 1983) stated: ‘‘Patients with implant-supported bridges chewed with approximately the same muscle activity during the whole masticatory sequence, whereas the control participants had a reduced activity at the end of the chewing act’’.

The poor adaptation of the muscle activity to the hardness of the food during the closing phase, especially in the beginning of the masticatory sequence, explains why implant participants had difficulty cutting through the

food early when chewing. Reduced efficiency at comminuting the food might also explain the modest decrease in muscle activity during the masticatory sequence. In the same vein, it is reasonable to assume that the implant participants generally swallowed larger pieces of food than the dentate participants did.

The differences in chewing behaviour between the participants with natural teeth and dental implants presumably resulted from differences in the neural control of jaw actions. However, differences in the morphology of the occlusal surfaces might also have contributed. That is, the fact that the implant-supported bridges had smaller occlusal surfaces than natural teeth and that the number of occluding teeth were fewer might have affected the ability of the implant participants to comminute the food during the masticatory sequence. However, it seems unlikely that smaller occlusal areas could explain the reduced ability of the implant participants to cut through food early when chewing. Hence, we argue that the observed differences in chewing behaviour between the two groups primarily relate to differences in the neural control of the jaw muscles.

Lack of signals from periodontal mechanoreceptors

During mastication, periodontal mechanoreceptors encode information about spatial, temporal and intensity aspects of tooth loads, and the resultant afferent signals contribute to the regulation of jaw actions in humans (Trulsson & Johansson 1996, Trulsson 2006). Given

that the majority of periodontal receptors are particularly sensitive to force changes at low tooth loads, they faithfully encode forces that develop early after contact with food (Trulsson & Johansson 1994, Johnsen & Trulsson 2005). Because the mechanical properties of the food influence the dynamics of the contact forces, the signals that arise in periodontal afferents when during each chewing cycle presumably contain information related to the current mechanical state of the food, including hardness. We believe that such information, presumably together with proprioceptive information about jaw position and velocity at the contact events, is used in adaptation of subsequent jaw actions to the properties of the food. Studies in anaesthetized rabbits performing rhythmic chewing-like jaw movements induced by electrical stimulation of the cortical masticatory area support this notion. That is, destruction of either periodontal or muscle afferents reduces the increase in jaw muscle activity in response to increased food hardness, and the effect of hardness is virtually wiped out after combined destruction of both types of afferents (Lavigne et al. 1987, Inoue et al. 1989, Morimoto et al. 1989). In humans, proprioceptive signals may be conveyed not only in muscle afferents but also in afferents supplying mucosal and cutaneous mechanoreceptors (Johansson et al. 1988).

A function of periodontal receptors in providing early information about the mechanical state, the food for use in the control of forthcoming jaw actions brings to mind the functional role of tactile receptors in the human fingertips in control of fingertip forces during object manipulation tasks. Immediately following contact with an object, tactile afferents encode various mechanical properties of the object, including frictional characteristics and the shape of the surface being touched (Johansson & Westling 1987, Jenmalm et al. 2003, Johansson & Birznieks 2004). This information is used not only to adapt finger forces to the properties of the object currently being manipulated, but also to update memory representations of these properties to improve predictive control of forces in forthcoming interactions with the object (Johansson & Flanagan 2009). Similar principles have been demonstrated during chewing-like movements in humans (Ottenhoff et al. 1992a,b) and in anaesthetized rabbits (Komuro et al. 2001). Thus, periodontal

afferent information acquired early after contact during each chewing cycle may be used not only in scaling muscle activity to the prevailing hardness of the food during the power phase of the current chewing cycle, but also for predictions that can influence muscle activity in subsequent cycles. Hence, the lack of inputs from periodontal afferents presumably explains the impaired capacity to adapt chewing behaviour to food hardness that we have observed in people with implant-supported bridges.

For the participants with implants, the lack of signals from periodontal mechanoreceptors as well as the changes in the masticatory behaviour following loss of the teeth might have caused neuroplastic changes in the sensorimotor system that supports mastication. In general, neuroplastic changes following peripheral deafferentation occur in subcortical structures, including the brainstem and thalamus, as well as at cortical levels (Jones 2000, Sanes & Donoghue 2000, Kaas 2002). For the trigeminal system, evidence from animal studies suggests that dental denervation can bring about plastic changes at all these levels (Linden & Scott 1989; Hu et al. 1999, Henry et al. 2005, Avivi-Arber et al. 2010), which all are engaged in sensorimotor control of jaw actions (Lund & Kolta 2006, Sessle et al. 2007). Such plastic changes might reflect useful functional adaptations to the lack of tooth innervation but might also lead to functional impairment. To our knowledge, no studies have addressed whether loss of teeth induces neuroplastic changes in the trigeminal sensorimotor system in humans. Likewise, it is not known whether implant-supported bridges might cause such changes. Thus, further clarification of the role of neuroplastic mechanisms of the masticatory system in people with implant-supported bridges could provide important knowledge for improved therapeutic regimes for the restoration of oral functions.

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Clinical relevance

Scientific rationale for study: People with natural teeth efficiently adjust their jaw muscle activity to the hardness of food during chewing. Because people with full implant-supported bridges in both jaws lack

periodontal receptors, we asked if these persons could adapt their muscle activity to food hardness.

Principal findings: People with dental implants showed an impaired ability to adapt muscle activity to

food hardness. This impairment was most pronounced with hard food.

Practical implications: The present results emphasize the importance of retaining natural teeth with healthy periodontal function whenever possible.