J Clin Periodontol 2011; 38: 1137–1146 doi: 10.1111/j.1600-051X.2011.01781.x

Journal of Clinical Periodontology

Impaired force control during food holding and biting in subjects with tooth- or implant-supported fixed prostheses

Krister G. Svensson and Mats Trulsson

Department of Dental Medicine, Karolinska Institutet, Huddinge, Sweden

Svensson KG and 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. doi: 10.1111/j.1600-051X.2011.01781.x.

Abstract

Aim: Our goal here was to assess the ability of subjects with their natural teeth (natural), bimaxillary tooth-supported bridges (bridge) and bimaxillary implant-supported bridges (implant) to control the low contact and high biting forces associated with holding and splitting food between the teeth.

Materials and Methods: Ten subjects in each of these groups performed a task involving holding and splitting morsels of food with different degrees of hardness (biscuits and peanuts) between a pair of opposing central incisors.

Results: The hold force employed by the implant group was significantly higher and more variable than the corresponding force exerted by the bridge group, whereas the natural group used lowest and least variable force. For all three groups, the split force was higher and the split phase duration longer with peanuts than for biscuits. In the case of the natural group, a significantly higher rate of force increase (peak force rate) was observed when splitting peanuts when compared with biscuits, whereas no such difference could be seen for the other two groups.

Conclusion: These findings demonstrate that individuals with bimaxillary tooth- or implant-supported bridges (in whom sensory information provided by the periodontal mechanoreceptors is impaired or missing) are unable to apply low-hold forces at the levels of individuals with natural teeth or to adapt the rate of the split force to the hardness of the food. We thus conclude that adequate sensory information from periodontal mechanoreceptors is essential for normal control of both low contact and high biting forces.

Key words: dental prosthesis; fixed bridge; mastication; mechanoreceptors; periodontal receptor; sensory-motor control; tooth

Accepted for publication 23 July 2011

Conflict of interest and source of funding statement

The authors declare that they have no conflict of interest. This study was supported financially by grants from the Swedish Research Council (Medicine, Grant no. 20612), King Gustaf V's and Queen Victoria's Freemason Foundation, the Swedish Dental Society and Karolinska Institutet.

When forces are applied during biting and chewing, the tooth involved moves in the socket of the alveolar bone, which stretches the periodontal ligament and stimulates the periodontal mechanoreceptors (PMRs) (Cash & Linden 1982). It has been concluded in several studies on human subjects that the PMRs signal important information about the timing, localization, direction and magnitude of force loads exerted on a single tooth (Trulsson et al. 1992, Trulsson 1993, Trulsson & Johansson 1994, Johnsen & Trulsson 2003, 2005). This information is used by the nervous system to regulate the forces exerted when food is positioned and held for biting (Trulsson & Johansson 1996b, Johnsen et al. 2007). In a simple "hold-and-split task" (which involved holding and splitting a morsel of food between a pair of opposing teeth; see Trulsson & Johansson 1996b), subjects seemed to use hold forces large enough to achieve stable contact with the food without compromising the sensitivity of most receptors to force changes (< 1 N for anterior teeth and < 3 N for posterior teeth). However, when sensory input from the teeth was blocked by administration of a local anaesthetic to the periodontium, considerably higher and more variable hold forces were employed (Trulsson & Johansson 1996b, Johnsen et al. 2007, Svensson & Trulsson 2009). Similar impairment of force control during holding and manipulation of food could be observed in individuals lacking PMRs, i.e., patients with fixed prostheses supported by osseointegrated dental implants or with removable complete dentures supported by the oral mucosa (Trulsson & Gunne 1998).

Severe reduction of the support provided by periodontal tissue due to a history of periodontitis enhances the mobility of a tooth when it is loaded, as well as altering the mechanoreceptive innervation, thereby impairing neural regulation of both low- and high-bite forces. Accordingly, in a "hold-and-split task", subjects with reduced periodontal tissue support exhibited hold forces that were almost threefold higher and more variable than those of healthy controls, as well as lower split force rates (Johansson et al. 2006). A detailed analysis of such a task revealed that when higher bite forces are required, both the duration of the split phase and the rate at which the bite force is produced are elevated (Svensson & Trulsson 2009). The lower split force rates obtained following administration of local anaesthetic to the periodontium of healthy natural teeth indicate that adaptation of the bite force rate to the hardness of the food is dependent on information supplied by the PMRs (Svensson & Trulsson 2009).

Missing teeth are commonly replaced with a fixed bridge, supported either by remaining natural teeth or dental implants. Individuals who have lost all of their teeth and been supplied with bridges supported by dental implants lack PMRs (Linden & Scott 1989, Bonte et al. 1993), whereas if the bridge is supported by natural teeth, these still possess intact mechanoreceptors. However, when force is applied to a tooth involved in supporting a bridge, this force will be distributed in a complex manner to the periodontium of all adjoining teeth (Weinberg 1957a,b) and thereby alter the tension on the periodontal ligament of all or many of these teeth and affect their PMR signalling. In the clinic, teeth exhibiting elevated mobility due to loss of support by periodontal tissue are often connected by a cross-arch, dental-supported bridge for enhanced stability (Nyman & Lang 1994).

Individuals with tooth-supported fixed prostheses or implant-supported prostheses have been found to divide food into pieces and prepare it for swallowing as well as those with natural dentition (Laurell 1985, Laurell & Lundgren 1985). Kleinfelder & Ludwigt (2002) reported that experimental splinting of posterior teeth, in subjects with reduced periodontal tissue support (approximately 50% of the periodontal ligament area remaining) or with normal periodontal attachment allowed both groups to exert approximately 40% higher maximal biting force, with no difference with respect to the force levels produced. In addition, another study demonstrated that splinting several healthy anterior teeth together makes it possible to produce higher maximal biting forces (Waltimo & Könönen 1994). At the same time, various investigations on subjects with an implant-supported prosthesis have arrived at divergent conclusions regarding their maximal bite force in comparison with individuals with natural teeth and, in addition, the maximal bite force for implant patients is dependent on the dental status of the opposing jaw and varies over time (e.g., Haraldson & Carlsson 1977, Haraldson et al. 1979, Karlsson & Carlsson 1993, Carlsson & Lindquist 1994, Gartner et al. 2000, Woodmansey et al. 2009).

We hypothesize that when teeth contacts food, their PMRs signal detailed information that is required to regulate both manipulative and power aspects of jaw action. Therefore, we predict that impairment or lack of sensory information from the PMRs is associated with higher and more variable levels of hold force and a reduced capacity to adapt the force rate during splitting to the hardness of the food. To test this hypothesis, we allowed subjects with their natural teeth (and intact PMRs), tooth-supported fixed prostheses in both jaws (impaired sensory information from the PMRs) and implant-supported fixed prostheses in both jaws (no PMRs) to perform a straightforward "hold-and-split" task involving two brittle foods with different degrees of hardness (i.e., biscuits and peanuts) and analysed the forces applied during the holding and split phases.

Materials and Methods

Participants

Ten subjects (mean age 70 (range 61–83) years old, five men and five women) with tooth-supported fixed bridges of at least 10 units (including abutment teeth and pontics) in both the upper and lower jaws (the bridge group) (Table 1); 10 subjects (mean age 72 (67–77) years old, seven men and three women) with screw retained implant-supported fixed bridges of at least 10 units (including dental implant abutments and pontics) in both the upper and lower jaws (the implant group); and 10 age-matched controls (mean age 67 (62–72) years old, seven men and three women) with healthy natural dentition (the natural group) were included in this study. The subjects in the bridge and implant groups were recruited from clinics specializing in oral rehabilitation at the Department of Dental Medicine at Karolinska Institutet, Public Dental Service clinics and from associated private practices within the greater Stockholm area, Sweden. The subjects with natural dentition were present, and former staff members at Karolinska Institutet belonged to a local senior citizens organization.

The tooth-supported fixed prostheses were all of the metal-ceramic type, involved 10–13 (mean 10.5) units, were supported by 4–9 (mean 6.7) abutment teeth in each jaw and had been in place for a mean of 53 months (range 8–246 months). Bone support (defined as the percentage of support from the

Table 1. Description and status of the tooth-supported bridges for the participants in the bridge group regarding total number of abutment teeth and pontics, number of abutment teeth and pontics in the anterior part of the bridge and number of root canal treated anterior teeth

Subject no.	Tooth-supported bridge (total)				Anterior part of the bridge (13–23)				Root canal treated anterior teeth (13–23)	
	Maxilla		Mandible		Maxilla		Mandible			
	Abutm. teeth	Pontics	Abutm. teeth	Pontics	Abutm. teeth	Pontics	Abutm. teeth	Pontics	Maxilla	Mandible
B1	7	5	9	3	3	3	4	2	0	0
B2	9	3	4	6	4	2	1	5	0	0
B3	6	4	6	5	5	1	2	4	1	0
B4	7	5	5	5	4	2	3	3	0	0
B5	8	2	8	5	6	0	4	2	0	0
B6	5	5	7	5	3	3	2	4	0	0
B7	9	2	8	2	6	0	6	0	6	6
B8	8	2	6	4	6	0	2	4	0	0
B9	5	5	5	5	2	4	3	3	0	0
B10	7	4	5	7	5	1	2	4	0	0

margin of the metal-ceramic bridge to the apex of the root) was determined by assessment of available intra-oral radiographs employing a Schei ruler (Schei et al. 1959). Mean values from the mesial and distal side of each tooth were calculated and, subsequently, the overall mean for each subject determined. The mean bone support for the subjects with bridges was 79% (range 66–89%).

The implant-supported fixed prostheses were all of the metal-acrylic type (with the exception of one individual with a metal-ceramic type in the upper jaw), extended to the premolar area and were supported by 4–6 (mean 5.0) dental implants (ad modum Brånemark) in each jaw. These bridges had been in place for a mean of 77 months (range 1–240 months).

All participants were in good general health and visited their dentists on a regular basis. They exhibited no symptoms or clinical signs of any dental, oral or oro-facial problem or malfunction at the time of the experiment. Some of the supporting teeth in some of the bridges had been subjected to root canal treatment and equipped with a post and core for retention of the bridge. None of the upper or lower front teeth of the subjects with natural dentition had been subjected to any endodontic or prosthetic treatment (e.g., veneers, partial or full covering crowns, etc.). All subjects in the three groups had a normal intermaxillary relationship. All participants provided their written informed consent in accordance with the Declaration of Helsinki, and this study was pre-approved by the regional ethical review board in Stockholm, Sweden (04-715/4).

A sample size calculation and power analysis based on results from previous studies involving the same behavioural task have been used to calculate the number of subjects included.

Equipment

The custom-built apparatus (Umeå University, Physiology Section, IMB, Umeå, Sweden) employed to measure bite forces during the hold-and-split task (Fig. 1A) consisted of a 11 cm-long, plastic-covered, bar-shaped metal handle (diameter 7 mm) connected to two duralumin blocks that terminated in two parallel, rectangular plates (total weight, 48 g; stiffness between the plates, 50 N/mm), the total length of the apparatus being 17 cm. The upper duralumin block contained strain gauge force transducers for continuous measurement of the forces applied to the plate (DC - 200 Hz), and the apparatus was designed so as to insure that the force measurement was independent of where the force was applied to the plate (Lockerly 1971). The test morsel was placed on the free-end of the plate and a thin (<0.1 mm) piece of plastic-coated fabric tape on the top of the upper plate prevented this morsel from slipping while the apparatus was being positioned. The lower plate was equipped with a piece of plexiglass designed to act as an anterior stop to facilitate positioning of the lower incisors. The distance between the surfaces of the upper and lower plates was 8 mm.

The behavioural task and test foods

After placing the food on the upper plate at the free-end portion of the bar equipped with transducers, each subject used his/her preferred hand to place the apparatus between the upper and lower right central incisors, maintaining the apparatus in a horizontal position. Positioning was facilitated by placing the lower plate on the lower incisor and gently sliding the apparatus until the anterior stop was reached, resulting in the edge of the upper right central incisor being positioned near the middle of the morsel (Fig. 1A).

The subjects were instructed to hold the food between their incisors and not to use more force than necessary to control it. Then, after approximately 3 s, the subjects were told to split the morsel. The forces applied by the teeth were continuously monitored. If the food was lost prior to the split (i.e., dropped during positioning or ejected during tooth contact), the trial was repeated with a new morsel. The test foods used were half of a medium-sized roasted peanut (Estrella salta jordnötter; Estrella AB, Angered, Sweden) and a piece of biscuit (approximately 8×12 mm, with a thickness of 6 mm; Digestive Oliv; Göteborgskex, Kungälv, Sweden).

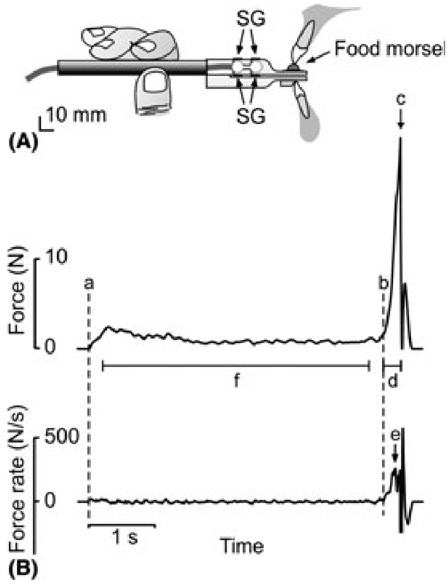

Fig. 1. (A) The hand-held apparatus, employed to record the bite forces exerted on the morsel of food during the hold-and-split task. The morsel rested on the upper horizontal plate, and this apparatus was positioned between the upper and lower right central incisors. The lower plate had an anterior stop designed to facilitate positioning in the mouth. SG, strain gauges. (B) A representative force profile (upper trace) and force rate profile (lower trace) for a subject holding and splitting a peanut. (a) initial contact with the food; (b) initiation of splitting; (c) the split force and end of the split phase; (d) duration of the split phase; (e) peak rate of split force; and (f) hold phase, interval beginning 0.2 s after initial contact with the food and ending 0.2 s prior to the onset of the split phase.

The experimental procedure

The subjects were seated comfortably upright in a dental chair in a quiet room, with the armrest supporting the elbow of their preferred arm. After receiving the instructions, each subject performed at least six practice trials to become familiar with the task before the actual experimental trials, which involved performing the hold-and-split task 10 times each with peanuts and biscuits in a semi-random order. The subjects were aware at all times of the type of test food being used.

Measurements

The bite force as a function of time was collected and analysed using a microcomputer-based data acquisition and analysis software system (WinSC/WinZoom v1.52.0.1; Umeå University, Physiology Section, IMB, Umeå, Sweden), with 12-bit resolution at 800 Hz. Force rates were obtained by symmetrical numerical time differentiation (± 5 points) of the force signal. Several force and time measurements were obtained from each individual trial (Fig. 1B).

The hold force was defined as the mean force exerted during the interval (f) beginning 0.2 s after initial contact with the food (a) and ending 0.2 s before onset (b) of the split phase. As the split phase was characterized by a distinct and rapid elevation of force (b to c), which eventually split the morsel, the moment of initial contact (a) and onset of the split phase (b) could both be reliably identified from the force-rate signal. The beginning of the split phase was defined as the point at which the force rate exceeded 5 N/s, the minimum rate of increase that could be reliably detected in single trials. The split force (c) was defined as the peak force prior to the moment the morsel split, as indicated by a rapid decrease in the force, which also indicated the end of the split phase. The duration of the split phase (d) was defined as the time from the onset (b) to the end (c) of this phase. The mean force rate was defined as the increase in force from the onset (b) to the end (c) of the split phase, divided by the duration of this same phase (d), and the peak force rate during the split phase (e) was identified by the computer.

The force increase during the early stage of the split phase was analysed by measuring the time required for the force to increase 1, 2 and 3 N from the start of the split phase.

For each subject, data from all 10 trials with each food were combined providing a subject mean for each measurement, and the data were further on expressed as a group mean and standard deviation (SD) for normal distributed data and median (25–75 percentile) for skewed distributions as specified in the results section.

Statistical analysis

Linear mixed models were employed to evaluate the effect of dental status and type of food on the different outcomes – hold force, variability of hold force, split force, duration of the split phase and peak and mean split force rates. An interaction term was included in all analyses to assess whether any differences between parameters with the biscuit and peanut were the same for all groups and in cases of significant interaction, planned pairwise comparisons were subsequently performed. The hold force and duration of the split phase displayed a right-skewed distribution and were therefore analysed on a log-scale.

Pearson r correlation analysis was performed to determine correlations between the two foods.

To take into account within-subject differences in repeated measures on the two foods, a covariance structure was fitted in all analyses (Brown & Prescott 2006). Thus, for each analysis, four different covariance structures were employed and evaluated using the Bayes Information Criterion (BIC) (Weiss 2005). These covariance structures were compound symmetry (equal variance for food) and compound symmetry heterogenous (unequal variance for food), with or without separate estimates of variations among the three dental groups. For each covariance model the within-factor levels with regard to the food were assumed to be correlated. Finally, the covariance model that displayed the lowest BIC

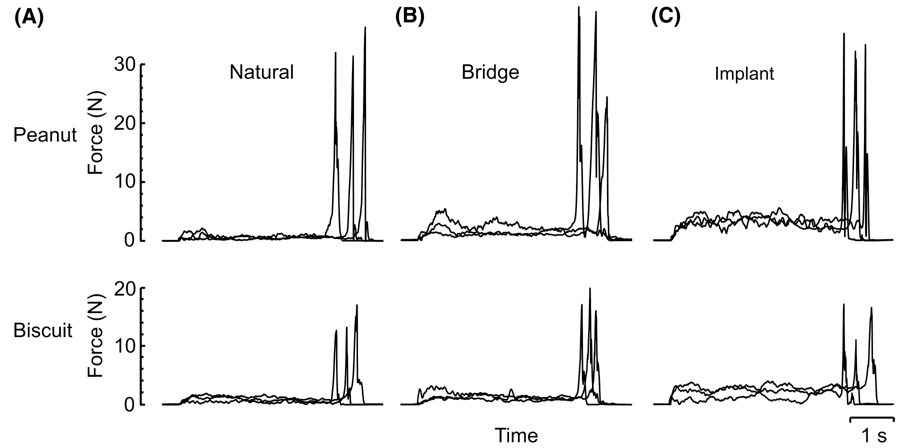

Fig. 2. Representative force recordings during the hold-and-split phases with biscuits and peanuts for subjects with natural teeth (A), tooth-supported bridges (B) or implant-supported bridges (C). Three superimposed recordings from one subject are shown in each case.

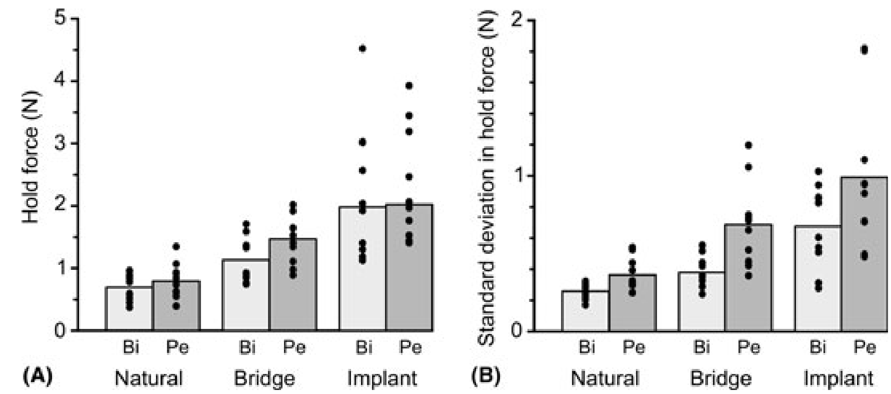

Fig. 3. Median hold force (A) and mean intra-trial variability (B) during the hold phase of the hold-and-split task with biscuits (Bi) and peanuts (Pe) performed by the subjects with natural teeth (Natural), tooth-supported bridges (Bridge) or implant-supported bridges (Implant). Each filled circle indicates the mean value for an individual subject.

value was considered to represent the best fit to the data.

As a result of positively skewed distribution of the time measurements obtained during the early stage of the split phase, planned comparisons were performed using Wilcoxon's signed ranks test to compare time needed for a force increase of 3 N between biscuit and peanut within the groups.

Normal probability plots were used to evaluate the assumption of normally distributed residuals. Cook's distance was applied to detect observations that exerted a strong impact on the estimates of parameter values. All analyses were performed using SAS 9.2 (SAS Institute Inc., Cary, NC, USA), and P-values of < 0.05 were considered to be statistically significant.

Results

Subjects with natural teeth, as well as those with tooth- or implant-supported bridges exerted relatively steady forces during the hold phase for both types of food (peanuts and biscuits), followed by a rapid elevation in force until the morsel was split (split phase) (Fig. 2). However, some noteworthy differences in this respect were observed between these groups. Compared with the natural group, the bridge and implant groups exerted significantly higher and more variable forces during the hold phase. Furthermore, during the split phase, only the natural group adapted their force rate to the hardness of the food.

Hold phase

Measured over all three groups, the hold force was lower for biscuits than peanuts ($p < 0.001$) (Fig. 3A). Although this difference was most evident in the case of the bridge group, no interaction between food and group was observed ($p = 0.203$). In the case of the biscuit, the hold forces were 0.69 N (0.52–0.88) (median (25–75 percentile)) for the natural group, 1.13 N (0.85–1.36) for the bridge group and 1.98 N (1.30–3.01) for the implant group. With the peanut, the corresponding hold forces were 0.79 N (0.62–0.93), 1.47 N (1.11–1.65) and 2.02 N (1.53–3.19)

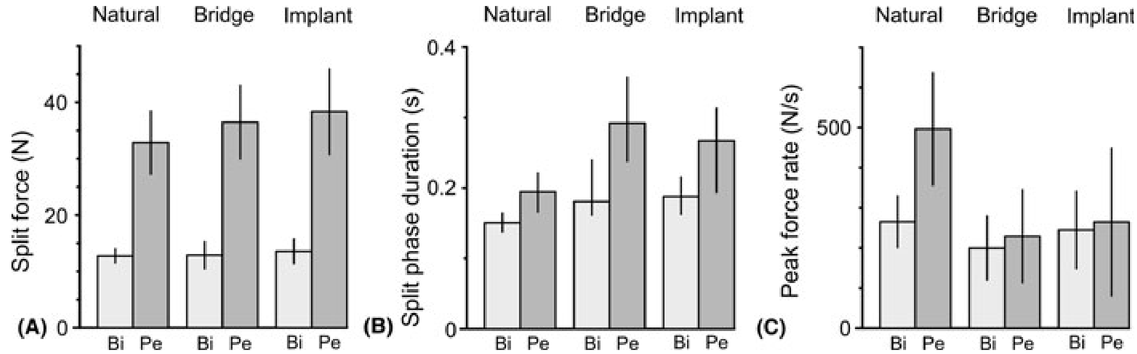

Fig. 4. Mean split forces (A), median duration of the split phase (B) and mean peak force rate (C) employed to split the biscuits (Bi) and peanuts (Pe) by subjects with natural teeth (Natural), tooth-supported bridges (Bridge) or implant-supported bridges (Implant). The vertical lines in A and C indicate ±standard deviations and the vertical lines in B indicate 25–75 percentiles.

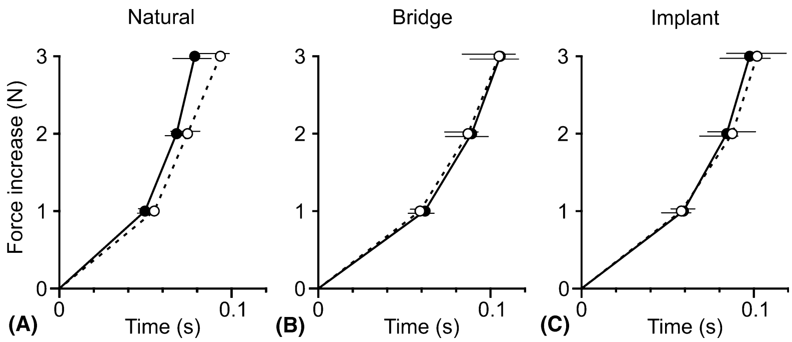

Fig. 5. Force trajectories during the early stage of the split phase (from initiation to achievement of a 3 N increase in force) for subjects with natural teeth (Natural), tooth-supported bridges (Bridge) or implant-supported bridges (Implant). Filled circles connected with a line indicate median values for peanuts, whereas unfilled circles connected with a dashed line indicate biscuits. The horizontal lines (upper=biscuits and lower=peanuts) indicate 25–75 percentiles. Note the shorter time needed for the natural group to reach the 3 N level for peanuts compared to biscuits (p = 0.010).

respectively. Over both foods, the subjects in the bridge and implant groups exerted significantly higher hold forces than those with natural teeth ($p < 0.001$) and, in addition, these forces were significantly greater in the case of the implant group than the bridge group (p = 0.003).

The variability for each individual trial (expressed as the standard deviation (SD) of the hold force) is documented in Fig 3B. For the biscuit, this variability was 0.26 (0.05) N (mean (SD)) for the natural group, 0.38 (0.10) N for the bridge group and 0.68 (0.26) N for the implant group. In the case of the peanut, the corresponding variabilities were 0.36 (0.11) N, 0.69 (0.27) N and 0.99 (0.48) N, respectively, with an evident interaction between food and group (p = 0.023). Significant differences with respect to biscuit and peanuts were observed between all groups ($p < 0.003$ for all pairwise comparisons), except for the values for peanuts obtained with the bridge and implant groups (p = 0.091). Significant differences within each group were also observed for these two types of foods ($p < 0.002$ for all pairwise comparisons).

Split phase

During the split phase, all subjects increased the force exerted rapidly until the food morsel split, following which the force fell sharply. All groups employed higher split forces with peanuts than biscuits ($p < 0.001$ over all groups) (Fig. 4A). In the case of the natural group, this force was 12.7 (1.2) N (mean (SD)) for the biscuits and 32.9 (5.6) N for the peanuts, with similar values for the other two groups (for the bridge group 12.9 (2.4) N and 36.5 (6.5) N, respectively, and for the implant group 13.6 (2.2) N and 38.3 (7.5) N, respectively). There were no statistical significant differences between the groups (p = 0.210) or interactions between food and group (p = 0.192). A positive correlation (Pearson) for the split forces with biscuits and peanuts (r = 0.53) was observed, indicating that subjects who employed a high split force on one of these foods also exhibited a high split force for the other.

The duration of the split phase was longer with the peanuts than the biscuits over all three groups ($p < 0.001$) (Fig. 4B). In the case of the natural group, this duration was 0.15 s (0.14–0.17) (median (25–75 percentile)) for biscuits and 0.20 s (0.16–0.22) for peanuts, whereas the corresponding values for the bridge group were 0.18 s (0.16–0.25) and 0.29 s (0.24–0.38), respectively, and for the implant group 0.19 s (0.16–0.22) and 0.27 s (0.19–0.32) respectively. Even though the difference in this duration between the two test foods appeared to be larger for the bridge and implant groups, there was no significant interaction between food and group ($p = 0.132$). A positive correlation (r = 0.79) between the duration of the split phases for biscuits and peanuts was observed.

The peak force rate during the split phase is illustrated in Fig. 4C. For the natural group, this peak force rate was 265 (64) N/s (mean (SD)) for biscuits and 496 (140) N/s for peanuts, with corresponding values of 200 (79) N/s and 229 (115) N/s, respectively, for the bridge group and 245 (96) N/s and 265 (184) N/s, respectively, for the implant group. Only the subjects in the natural group demonstrated significantly higher peak force rates ($p < 0.001$) for the harder food (peanuts) and this peak force rate was significantly higher than the corresponding rates for peanuts exhibited by the bridge ($p = 0.002$) and implant groups ($p < 0.001$). A positive correlation (r = 0.57) between the peak force rates for biscuits and peanuts was observed.

The mean split force rate (i.e., mean rate of increase in the force during the split phase) for the natural group was 87 (22) N/s (mean (SD)) for biscuits and 181 (45) N/s for peanuts, with corresponding values for the bridge group of 65 (24) N/s and 126 (51) N/s, respectively, and for the implant group 78 (38) N/s and 161 (64) N/s respectively. All three groups exhibited significantly higher mean split force rates for peanuts than biscuits ($p < 0.001$), but no interaction between food and group was found ($p = 0.100$). A positive correlation (r = 0.85) between the mean force rates for biscuits and peanuts was observed.

The force increase during the early stage of the split phase was analysed by measuring the time required to obtain 1, 2 and 3 N increases from the initial value at start of the split phase. A separation of the force trajectories for the two foods is evident for the natural group, whereas no such separation can be seen for the bridge or implant groups (Fig. 5). To statistically evaluate the force increase during this early stage of the split, the time needed for the force to increase 3 N was compared between biscuit and peanut within each group. The subjects in the natural group needed 0.093 s (0.078–0.098) (median (25–75 percentiles)) to obtain a 3 N force increase when splitting the biscuits, whereas a significantly shorter time (0.079 s (0.067–0.089)) was needed for the peanuts ($p = 0.010$). No such difference between the biscuits and peanuts could be observed for the bridge group (0.105 s (0.083–0.116) for biscuits and 0.106 s (0.089–0.118) for peanuts, $p = 1.000$) or the implant group (0.102 s (0.084–0.120) and 0.095 s (0.080–0.111), respectively, $p = 0.432$).

Discussion

This investigation reveals that subjects with tooth- or implant-supported bridges in both jaws demonstrate clear impairment in their regulation of the low contact force required to hold a morsel of food between anterior teeth before splitting it. Furthermore, the subjects with tooth-supported bridges exhibited lower and more stable hold forces than those with implant-supported bridges. While splitting food, the participants with natural dentition adjusted their force rate to the hardness of the morsel, i.e., their force increased more rapidly when splitting peanuts than biscuits. However, no such adjustment was demonstrated by the other two groups.

Holding food with fixed dental prostheses

The median hold forces of 0.69 N for biscuits and 0.79 N for peanuts employed by our subjects with natural dentition are comparable with earlier reports of hold forces of 0.59–0.72 N (Trulsson & Johansson 1996b, Trulsson & Gunne 1998, Johnsen et al. 2007, Svensson & Trulsson 2009). Such hold forces below 1 N in individuals with natural teeth are easily explained by the pronounced sensitivity of PMRs at these low levels (<1 N in the case of anterior teeth). Apparently, individuals with natural teeth automatically adjust the bite force during the hold phase to optimize the information supplied by PMRs (see Trulsson & Johansson 1996a, Trulsson 2006).

The finding that our subjects with implant-supported bridges employed 2.5-fold as much force as those with natural teeth to hold food morsels between a pair of anterior teeth (2.00 N *versus* to 0.74 N over both foods) is consistent with the report by Trulsson & Gunne that subjects with prostheses supported by the oral mucosa or dental implants use approximately fourfold higher hold force (means of 2.21 and 2.63 N respectively) during the same hold-and-split task (1998).

As shown previously, the hold forces exerted by natural teeth are elevated two to threefold (on an average of 1.41–1.96 N) after application of a local anaesthetic (Trulsson & Johansson 1996b, Johnsen et al. 2007, Svensson & Trulsson 2009). Thus, the force used by subjects with anaesthetized natural teeth (where input of information from the PMRs is blocked) is comparable to that of subjects with bimaxillar prostheses supported by dental implants (who lack PMRs).

This is the first reported analysis of the variation in the forces employed during a hold-and-split task by individuals with tooth-supported bridges. Our present findings indicate significant impairment of the fine sensory-motor regulation of low contact forces, with such subjects employing almost twice the hold forces used by those with natural dentition (1.13 *versus* 0.69 N for biscuits and 1.47 *versus* 0.79 N for peanuts, respectively). The higher and more variable hold forces with tooth-supported bridges might reflect various factors. First, the reduced support provided by periodontal tissue for the abutment teeth, which was rather common among our subjects with tooth-supported fixed prostheses, most likely give rise to higher hold forces. Indeed, Johansson et al. found that subjects with an average reduction in periodontal tissue support of 45% exhibited threefold higher hold forces than those with healthy dentition (2006). Secondly, rigid mechanical coupling between the abutment teeth involved results in lower mobility (enhanced stiffness) of these individual teeth when force is applied to the prosthesis (Picton 1990, Nyman & Lang 1994). Thus, when teeth are coupled together in a fixed bridge, higher bite (hold) forces are required to generate the same amount of tooth movement and thus the same degree of PMR stimulation. Finally, a force applied to the incisors in a full fixed bridge will affect not only the anterior abutment teeth but also the posterior abutment teeth (premolars and molars) (Weinberg 1957a,b), where the PMRs are less sensitive (Johnsen & Trulsson 2005). Anterior PMRs saturate at force levels of approximately 1 N, whereas the corresponding value for posterior PMRs is around 3 N. This difference explains why the hold forces employed during a hold-and-split task increase distally along the dental arch (from 0.60 N for incisors to 1.74 N for 1st molars) (Johnsen et al. 2007). Thus, the differing sensitivities of PMRs associated with different types of teeth may influence the hold forces produced by subjects with tooth-supported bridges. In addition, for two subjects in the bridge group in the present study, one or more of the anterior abutment teeth were root canal treated (see Table 1). However, the behaviour of the two subjects did not differ compared with the other subjects in the same group. Nevertheless, the effect of root canal treatment (non-vital teeth without intra-pulpal receptors) on the parameters analysed in this task is not fully known and further research is therefore needed.

Interestingly, our subjects with tooth-supported bridges employed significantly lower hold forces (1.30 N over both foods) than those with implant-supported bridges (2.00 N over both foods). It seems reasonable to propose that this difference reflects a difference in the availability of sensory information concerning the bite forces applied. Subjects with tooth-supported bridges still obtain sensory information from PMRs, even if these are stimulated to a reduced extent by any given applied force (see above). On the other hand, subjects with dental implants lack PMRs and must rely on some other, less sensitive sensory system for the regulation of hold forces. Such sensory systems could involve, e.g., mechanoreceptors located in the mucosa, periosteum, bone sutures, temporomandibular joints or muscle spindles in the jaw muscles. In monkeys, the primary afferents from muscle spindles are highly active shortly after contact with food, and may very well be able to signal information about contact forces (Lund et al. 1979, Larson et al. 1981). Another possible source of information may be acoustic receptors in the inner ear, which may be directly activated through bone conduction and provide sensory information concerning impact forces on the teeth.

In the present investigation, the median hold force for biscuits was slightly lower than for peanuts over all three groups. The fact that such a difference in hold force for different types of food during the hold-and-split task has not been reported earlier (Trulsson & Johansson 1996b, Svensson & Trulsson 2009) may be explained by our observation that the largest difference of this kind was among the subjects with tooth-supported bridges (see Fig. 3A), a group that has not been studied previously. Possible explanations for the use of higher-hold forces with peanuts may be related to differences in the form and surface structure of the two test foods employed. The rounded, more slippery surface of the peanut may trigger more firm holding between the teeth, to reduce the risk of slippage. Alternatively, auditory cues might have signalled slight cracking of the more brittle surface of the biscuits, indicating adequate food contact.

Considered together, our present findings on hold forces support the hypothesis that the PMRs play a key role in regulating the delicate forces employed to manipulate and hold food prior to biting and chewing. Although both individuals with bimaxillary bridges supported by teeth or implants demonstrate impaired control of these low contact forces, those with tooth-supported bridges behave in a somewhat more natural manner.

Splitting food with fixed dental prostheses

The forces at the moment of split (split forces) for peanuts and biscuits did not differ among the three groups examined here, indicating that these forces are determined primarily by the properties of the food item itself. However, to a certain extent, the anatomical shape (sharpness) of the occluding incisors also influences the force required to split morsels. Thus, the positive correlation observed between the split forces for biscuits and peanuts indicates that individuals who require a strong biting force to split one type of food must also develop strong force to split the other. We assume that subjects who had to apply high force to split the food had less sharp incisors. Importantly, however, as there was no difference between the groups with respect to split forces, we assume that the cutting effect of the incisors of the individuals in these groups was similar.

The split forces observed here were higher (13.1 N for biscuits and 35.9 N for peanuts, averages for all three groups) than those reported earlier for the same items of food (Trulsson & Johansson 1996b, Svensson & Trulsson 2009). In the case of the biscuits, this can easily be explained by the use of larger pieces here (8×12 mm) than in earlier studies (6×8 mm). Although the peanuts we used were of the same brand and sort as in previous investigations, different batches may well vary in texture and hardness. Origin, year of harvest, roasting time, salt content and other manufacturing parameters are known to influence the hardness of peanuts (Smyth et al. 1998, McKiernan & Mattes 2010).

The time required to split the morsel of food (split phase duration) was significantly longer for peanuts than biscuits for all of our groups – 33% longer for the natural group, 61% longer for the bridge group and 42% longer for the implant group. These findings are consistent with our earlier report on individuals with natural teeth, both without (36% longer duration for the peanuts) and with (38% longer for the peanuts) application of a local anaesthetics to the teeth (Svensson & Trulsson 2009). Thus, regardless of the presence or absence of sensory information from PMRs, the split phase for harder food is longer.

In our ealier study (Svensson & Trulsson 2009), a significant prolongation of split phase duration for the harder food (peanuts) was observed after anaesthetizing the teeth. Although no statistically significant differences in this duration between the different groups could be confirmed here, there was a tendency towards longer split phase durations for the peanuts in subjects with tooth- or implant-supported bridges (see Fig. 4B).

When assessed as the mean force rate during the split phase, the split force rate was significantly higher (103% higher on the average for all three groups) for the peanuts than the biscuits. However, measured as the peak force rate, this split force rate was higher (87%) for the peanuts only in the case of the natural group. For the subjects with tooth- or implant-supported bridges, the peak force rates between the two test foods were surprisingly similar (see Fig. 4C). Furthermore, the peak force rates for the peanuts were significantly lower for these latter two groups than the natural group. Apparently, only individuals with intact dental sensitivity (intact PMRs) apply higher peak force rates when splitting harder food. The very high peak force rates for the peanuts in this natural group provides a reasonable explanation for their tendency towards relatively short split phase durations for this food item (cf. Fig. 4B and 4C).

Overall, the peak and mean force rates documented here are higher than those reported previously for the same types of food. For subjects with natural teeth, peak force rates of 127–158 N/s for biscuits and 171–196 N/s for peanuts have been reported earlier (Trulsson & Johansson 1996b, Svensson & Trulsson 2009), whereas the corresponding values here were 265 and 496 N/s, respectively. Our higher force rates can be explained simply by the much higher forces required to split the food in the present case. If the force accelerates during the split phase, higher split forces will result in higher peak and mean force rates.

Analysis of the time required for the force increase during the early stage of the split phase revealed that the subjects in the natural group exhibited a significantly shorter time for peanuts than biscuits, up to 3 N force increase. However, no such difference was observed for the other two groups. These results are in line with our earlier findings on subjects with natural dentition both with and without anaesthesia of the teeth (Svensson & Trulsson 2009). With normal dental sensitivity, those subjects demonstrated a steeper force trajectory when splitting peanuts than biscuits, but local anaesthesia eliminated this difference. Thus, individuals with intact dental sensitivity adjust the force trajectory during the early split phase to the hardness of the food.

These observations confirm that when individuals with natural dentition split harder morsels of food, they elevate both the duration and rate of the force produced to attain higher split forces. Thus, when the PMRs are intact, the nervous system can adapt the rate at which the force is increased to the level required for splitting for efficient handling of different types of food during biting (see Svensson & Trulsson 2009). This adaptive mechanism appears to be absent from both subjects with anaesthetized teeth and individuals with bridges supported by teeth or dental implants. In addition, in a recent study by Grigoriadis et al. (2011) the adaptation of jaw muscle activity to the hardness of food during chewing has also been shown to be dependent on sensory signals from the PMRs.

We propose that soon after contact is established, the PMRs signal information concerning the security of this contact between the food and teeth. This information is then utilized, in a feed-forward manner to trigger the release of motor commands to the masticatory muscles that create the forces required during the split phase. Thus, during this early phase of contact, information related to the hardness of the food is employed to determine the magnitude of the coming bite forces (Trulsson & Johansson 1996a, Trulsson 2006). Most probably, signals from other oro-facial receptors, such as muscle spindles, also contribute to this "early state information". However, our present findings suggest that when sensory signals from the PMRs are impaired or lacking, signals from other oro-facial mechanoreceptors cannot compensate sufficiently to achieve a normal adaptation of the force rate during splitting of food.

Conclusions

This study demonstrates that intact sensory information from the PMRs is required for normal regulation of both low contact and high biting forces. Consequently, individuals with tooth- or implant-supported fixed prostheses in both jaws exhibit significantly impaired regulation of both the low forces used to manipulate and hold food between the teeth and the higher forces utilized to split food.

Acknowledgements

The authors thank Mr Jakob Bergström, statistician at Department of Learning, Informatics, Management and Ethics (LIME), Karolinska Institutet for assistance with the statistical analyses.

References

Bonte, B., Linden, R. W., Scott, B. J. & van Steenberghe, D. (1993) Role of periodontal mechanoreceptors in evoking reflexes in the jaw-closing muscles of the cat. *The Journal of Physiology* **465**, 581–594.

Brown, H. & Prescott, R. (2006) Applied mixed models in medicine, 2nd edition, pp. 215–223. Chichester: John Wiley & Sons.

Carlsson, G. E. & Lindquist, L. W. (1994) Ten-year longitudinal study of masticatory function in edentulous patients treated with fixed complete dentures on osseointegrated implants. *The International Journal of Prosthodontics* **7**, 448–453.

Cash, R. M. & Linden, R. W. A. (1982) The distribution of mechanoreceptors in the periodontal ligament of the mandibular canine tooth of the cat. *Journal of Physiology-London* **330**, 439–447.

Gartner, J. L., Mushimoto, K., Weber, H. P. & Nishimura, I. (2000) Effect of osseointegrated implants on the coordination of masticatory muscles: a pilot study. *The Journal of Prosthetic Dentistry* **84**, 185–193.

Grigoriadis, A., Johansson, R. S. & Trulsson, M. (2011) Adaptability of mastication in people with implant-supported bridges. *Journal of Clinical Periodontology* **38**, 395–404.

Haraldson, T. & Carlsson, G. E. (1977) Bite force and oral function in patients with osseointegrated oral implants. *Scandinavian Journal of Dental Research* **85**, 200–208.

Haraldson, T., Carlsson, G. E. & Ingervall, B. (1979) Functional state, bite force and postural muscle activity in patients with osseointegrated oral implant bridges. *Acta Odontologica Scandinavica* **37**, 195–206.

Johansson, A. S., Svensson, K. G. & Trulsson, M. (2006) Impaired masticatory behavior in subjects with reduced periodontal tissue support. *Journal of Periodontology* **77**, 1491–1497.

Johnsen, S. E., Svensson, K. G. & Trulsson, M. (2007) Forces applied by anterior and posterior teeth and roles of periodontal afferents during hold-and-split tasks in human subjects. *Experimental Brain Research* **178**, 126–134.

Johnsen, S. E. & Trulsson, M. (2003) Receptive field properties of human periodontal afferents responding to loading of premolar and molar teeth. *Journal of Neurophysiology* **89**, 1478–1487.

Johnsen, S. E. & Trulsson, M. (2005) Encoding of amplitude and rate of tooth loads by human periodontal afferents from premolar and molar teeth. *Journal of Neurophysiology* **93**, 1889–1897.

Karlsson, S. & Carlsson, G. E. (1993) Oral motor function and phonetics in patients with implant-supported prostheses. In: Naert, I., van

Steenberghe, D. & Worthington, P. (eds). Osseointegration in Oral Rehabilitation, pp. 123–132, London: Quintessence Pub. Co.

Kleinfelder, J. W. & Ludwigt, K. (2002) Maximal bite force in patients with reduced periodontal tissue support with and without splinting. *Journal of Periodontology* **73**, 1184–1187.

Larson, C. R., Smith, A. & Luschei, E. S. (1981) Discharge characteristics and stretch sensitivity of jaw muscle afferents in the monkey during controlled isometric bites. *Journal of Neurophysiology* **46**, 130–142.

Laurell, L. (1985) Occlusal forces and chewing ability in dentitions with cross-arch bridges. [Thesis]. *Swedish Dental Journal Suppl* **26**, 160.

Laurell, L. & Lundgren, D. (1985) Chewing ability in patients restored with cross-arch fixed partial dentures. *The Journal of Prosthetic Dentistry* **54**, 720–725.

Linden, R. W. & Scott, B. J. (1989) The effect of tooth extraction on periodontal ligament mechanoreceptors represented in the mesencephalic nucleus of the cat. *Archives of Oral Biology* **34**, 937–941.

Lockerly, H. E 1971 inventor. BLH Electronics, assignee. Halfbridge moment desensitization of parallelogram-type beams. US patent 3,576,128. April 27.

Lund, J. P., Smith, A. M., Sessle, B. J. & Murakami, T. (1979) Activity of trigeminal alpha- and gamma-motoneurons and muscle afferents during performance of a biting task. *Journal of Neurophysiology* **42**, 710–725.

McKiernan, F. & Mattes, R. D. (2010) Effects of peanut processing on masticatory performance during variable appetitive states. *Journal of Nutrition and Metabolism*. doi:10.1155/2010/487301

Nyman, S. R. & Lang, N. P. (1994) Tooth mobility and the biological rationale for splinting teeth. *Periodontology 2000* **4**, 15–22.

Picton, D. C. (1990) Tooth mobility–an update. *European Journal of Orthodontics* **12**, 109–115.

Schei, O., Waerhaug, J., Lovdal, A. & Arno, A. (1959) Alveolar bone loss as related to oral hygiene and age. *Journal of Periodontology* **30**, 7–16.

Smyth, D. A., Mach, C., Holloway, O. E., Deming, D. M., Slade, L. & Levine, H. (1998) Evaluation of analytical methods for optimizing peanut roasting for snack foods. *Peanut Science* **25**, 70–76.

Svensson, K. G. & Trulsson, M. (2009) Regulation of bite force increase during splitting of food. *European Journal of Oral Sciences* **117**, 704–710.

Trulsson, M. (1993) Multiple-tooth receptive fields of single human periodontal mechanoreceptive afferents. *Journal of Neurophysiology* **69**, 474–481.

Trulsson, M. (2006) Sensory-motor function of human periodontal mechanoreceptors. *Journal of Oral Rehabilitation* **33**, 262–273.

Trulsson, M. & Gunne, H. S. (1998) Food-holding and -biting behavior in human subjects lacking periodontal receptors. *Journal of Dental Research* **77**, 574–582.

Trulsson, M. & Johansson, R. S. (1994) Encoding of amplitude and rate of forces applied to the teeth by human periodontal mechanoreceptive afferents. *Journal of Neurophysiology* **72**, 1734–1744.

Trulsson, M. & Johansson, R. S. (1996a) Encoding of tooth loads by human periodontal afferents and their role in jaw motor control. *Progress in Neurobiology* **49**, 267–284.

Trulsson, M. & Johansson, R. S. (1996b) Forces applied by the incisors and roles of periodontal afferents during food-holding and -biting tasks. *Experimental Brain Research* **107**, 486–496.

Trulsson, M., Johansson, R. S. & Olsson, K. A. (1992) Directional sensitivity of human periodontal mechanoreceptive afferents to forces applied to the teeth. *Journal of Physiology* **447**, 373–389.

Waltimo, A. & Könönen, M. (1994) Bite force on single as opposed to all maxillary front teeth. *Scandinavian Journal of Dental Research* **102**, 372–375.

Weinberg, L. A. (1957a) Force distribution in splinted anterior teeth. *Oral Surgery, Oral Medicine and Oral Pathology* **10**, 484–494.

Weinberg, L. A. (1957b) Force distribution in splinted posterior teeth. *Oral Surgery, Oral Medicine and Oral Pathology* **10**, 1268–1276.

Weiss, R. E. (2005) Modeling longitudinal data, pp. 146–151. New York: Springer.

Woodmansey, K. F., Ayik, M., Buschang, P. H., White, C. A. & He, J. (2009) Differences in masticatory function in patients with endodontically treated teeth and single-implant-supported prostheses: a pilot study. *Journal of Endodontics* **35**, 10–14.

Address:
K. Svensson
Department of Dental Medicine
Karolinska Institutet
P.O. Box 4064
SE-141 04 Huddinge
Sweden
E-mail: krister.svensson@ki.se

Clinical Relevance

Scientific rationale for study: In individuals with a healthy natural dentition sensory information from PMRs is used by the nervous system to control masticatory forces.

Principal findings: Individuals with tooth- or implant-supported fixed bridges in both jaws exhibit impaired regulation of the low forces utilized to manipulate and hold food between the teeth. In addition, during splitting of food, they do not adapt the rate of bite force production to the hardness of the food.

Practical implications: The present findings demonstrate that intact sensory information from the PMRs is required for normal regulation of both low contact and high biting forces.