In Vivo Horizontal Bending Moments on Implants

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To date, transverse and vertical forces applied eccentrically to the axis of dental implants in the molar area during oral function have not been quantified. A specially designed load cell placed directly in the implant allowed for measurements of bending moments. Results of both load directions were compared to each other and to the loads applied vertically along the implant axis. The stress in the bone-implant interface area caused by these three different types of loads was calculated by finite element analysis. The transverse loads during chewing resulted in the highest bending moments (170 Nmm mean maximum) and the highest stress in the bone ($\sigma_{max} \approx 6.2$ MPa) at the crest to the buccal side. Mesial implant moment was significantly less (52 Nmm mean maximum moment; $\sigma_{max} \approx 1.3$ MPa). Clenching in centric occlusion caused a bending moment either to the lingual or to the buccal side, depending on the occlusal contour (140 Nmm maximum).

(INT J ORAL MAXILLOFAC IMPLANTS 1998;13:232–244)

Key words: bending moments, chewing forces, clenching, implant loading, interface, measuring device, occlusion, premature contact

Dental implants of various types have achieved high success rates in completely edentulous patients, supporting either a fixed-detachable prosthesis or a removable bar-retained overdenture.[1–4] They seem to function nearly as well in partially edentulous dentitions,[5–9] where the shortened dental arch, especially in the mandible, is a major area of indication for implants. Here, the alternative treatment modalities from a prosthodontic standpoint are a freestanding implant-supported fixed partial prosthesis, a tooth-to-implant fixed restoration (Figs 1a to 1c), or (similar to the natural dentition) nonsplinted implant crowns.[10]

From a biomechanical standpoint, an implant-supported prosthesis is said to have two major advantages. First, differences in the mobility between teeth and implants are avoided, reducing the risk of overloading the implant. Second, it is believed that the load-bearing capacity, as well as the load distribution, is greater using an implant-supported fixed restoration rather than a tooth-implant–supported fixed prosthesis.

However, this hypothesis is questionable. Using mechanical calculations, Rangert et al[11] demonstrated that forces are shared almost equally between a tooth and a Brånemark implant, and that neither implant nor gold-screw fracture will occur. In an intra-individual prospective study, Olsson et al[12] reported no differences between freestanding implant-supported fixed suprastructures and tooth-implant–supported fixed restorations after 5 years of function. These results coincide with biomechanical in vivo measurements by Richter,[13] who found that the vertical load level is almost the same on implants and teeth and that the amount of vertical mobility of these two different abutments is similar, at least during chewing. Therefore, the abutment stiffness in bone (quotient between load and amount of intrusion) is similar for implants, as well as for teeth, during normal oral functions such as chewing, clenching, and swallowing. Mandibular implants and teeth having the same load-bearing capacity were found by Rangert et al[14] in "hard-biting" patients. They tested five patients with three-unit fixed restorations using a 5-mm-high bite fork and maximum bite forces.

Even though some information about forces on implants has been gained in recent years (see publications cited in Richter[13]), there still is some uncertainty concerning load in general and the effects of load on bone loss.[14] For instance, implant failures often are presumed to be caused by "overload"; how-

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ever, the load level was not quantified in these particular patients.[15] The fact that chewing as well as maximum bite forces differ widely between individuals was not discussed.[5,16]

An underexplored subject is the load level in horizontal directions.[14] In 1974, Graf et al[17] reported transverse forces on teeth of 10 to 20 N on the working side and about 10 N on the nonworking side. Peters,[18] however, found peak loads of about 112 N and mean loads ranging between 12 and 22 N during mastication. Molars and premolars in the maxilla were bent to the lingual side, mandibular molars and premolars to the buccal side. Mean lateral forces to the buccal side in the maxilla and to the lingual side in the mandible varied only between 5 to 15 N, with a maximum of 60 N.

With regard to implants, models illustrating qualitative load configurations have been described widely (see publications cited in Olsson et al,[12] Rangert,[19] and others[20–23]). However, quantitative in vivo data rarely are available. Glantz et al[24] reported on load measurements in one patient with a mandibular five-implant Brånemark tissue-integrated prosthesis using a new type of strain-gauge abutment cylinder. The results differed from data from in vitro calculations. They revealed high bending moments in almost all experimental situations including chewing, clenching, and centric occlusion, with maximum bending moments of 160 Nmm. Rangert et al[14] reported mesial bending moments on five tooth-implant fixed restorations of 30 to 50 Nmm for the light-biting group, and 100 to 160 Nmm for the hard-biting group.

To date, it is generally accepted that freestanding implant-supported fixed restorations, as well as tooth-implant–connected prostheses, clinically perform without major problems. Nevertheless, the effects of load transfer into the bony bed, especially in a horizontal direction, are still unknown.

The purpose of this study was to quantify, on implants in the molar area, the in vivo load levels resulting from forces applied eccentrically to the implant axis. Stress levels in the implant-bone interface area caused by these loads were calculated using a finite element model.

Eccentric Loads

It is useful to distinguish between loads applied to implants in a transverse direction (perpendicular to the implant axis) and those parallel but eccentric to the implant axis (Fig 2). Loads in a transverse direction act on the inclined cusps, causing a bending moment on the suprastructure and on the implant in a buccolingual direction, as well as a transverse force

Fig 1a Tooth-implant fixed prosthesis, a standard type of therapy to complete a shortened dental arch.

Fig 1b Visible on the occlusal surface are two screw-heads that tighten the suprastructure to the implant and the tooth crown.

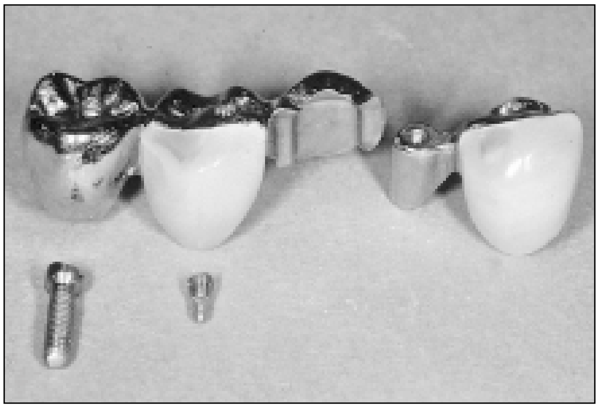

Fig 1c A channel-shoulder-pin attachment with an integrated female screw allows for a rigid connection of the fixed-detachable part of the prosthesis to the cemented crown part.

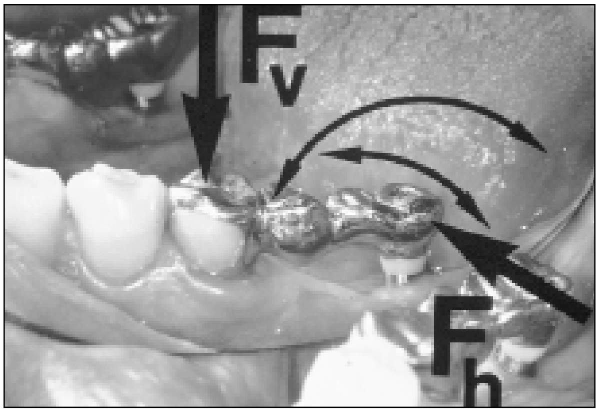

Fig 2 *(Above)* Vertical forces on the abutment tooth (F_v) cause a bending moment in the implant in a mesial or distal direction *(long curved arrow)*, transverse forces (F_h) in a buccolingual direction *(short curved arrow)*.

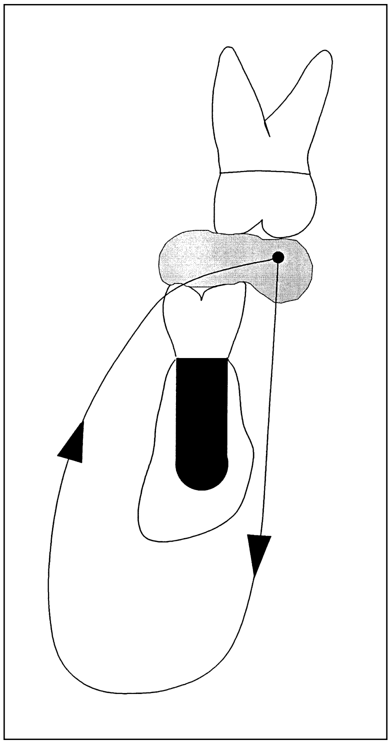

Fig 3 *(Right)* Typical movement of the mandible as seen from a frontoparallel plane: when grinding a piece of food, the mandibular molar moves into the centric occlusion position *(arrows* indicate opening and closing direction).

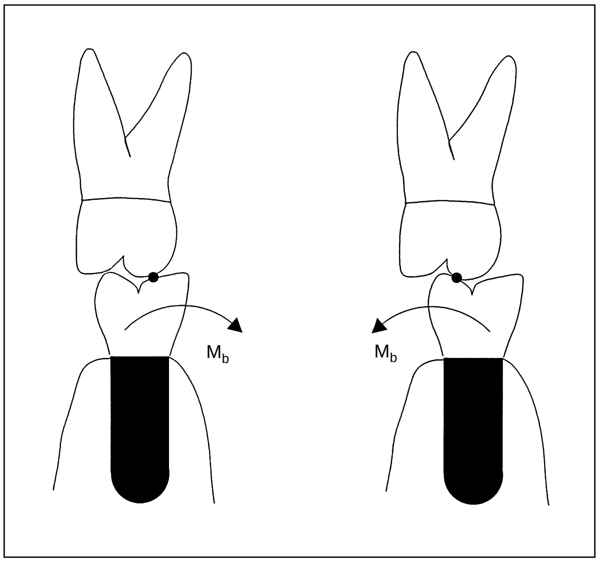

Fig 4 In centric occlusion, the implant-fixed suprastructure may be bent to the lingual or to the buccal side, depending on the contact point pattern on the cusp inclination.

at the crest of the alveolar bone. Forces applied eccentrically to the occlusal plane of the suprastructure but parallel to the implant axis cause a bending of the implant in the mesial or distal direction. During chewing, both types of loads are applied to a tooth-implant fixed prosthesis. The first is created by the sliding movement of the mandible from lateral into centric occlusion when grinding a food bolus (Fig 3); the second arises from the vertical approach of the mandible into centric occlusion. It is obvious that the implant load level during this phase of chewing (with some distance from centric occlusion) primarily depends on the kinetics of the mandible itself.

In contrast, load transfer during clenching and swallowing may be different. Bending of the implant is especially influenced by the occlusal relief of the suprastructure in centric occlusion. Depending on the contact point pattern and the accuracy of occlusal equilibration, a bending of the suprastructure to the buccal or to the lingual side is predominant (Fig 4).

Forces applied vertically along the implant axis are usually quantified in newtons (N).[13] However, in the horizontal plane, chewing forces act on the implant and surrounding bone via a lever arm. This cantilever (the height of the restoration [for transverse loads] and the length of a tooth-implant–supported fixed prosthesis [for eccentric, vertical forces]) increases loading of the implant. Therefore, a description of the load levels in bending moments in newton millimeters (Nmm) is appropriate. These measurements may help to calculate tension and compression in the bony tissue around the implant. Figure 5 illustrates equivalent systems according to Newton's mechanical principle that "action (a force on an implant) equals

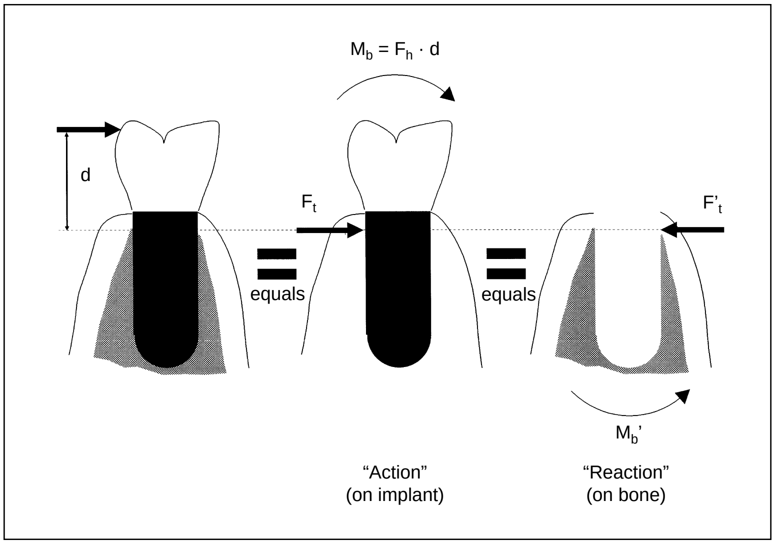

Fig 5 A horizontal (chewing) force component (F_h) at the occlusal surface is equivalent mechanically to a bending moment (M_b) and transverse force (F_t) at the crestal bone. According to Newton’s law, the bone has to withstand the same type and magnitude of loading, ie, the bone carries a bending moment (M_b’) and a force (F_t’) mainly at the rim.

reaction (corresponding force and a bending moment in bone around the implant).”

Materials and Methods

Bending moments on the molar implants were measured using a specially designed appliance instead of the intramobile element (IME) of a 3.3-mm-diameter IMZ implant (Interpore International, Irvine, CA). This appliance, which has the same height as the IME, consists of a double T-shaped bending bar with the typical conical top for attaching the suprastructure, and a separate screw component for connecting it to the implant (Fig 6), so that the bar can be aligned either along the tooth row (to measure the transverse bending moments on the implant) or perpendicular to the tooth row (to measure a bending of the implant in the mesial or distal direction) (Figs 7a and 7b). This design of the load cell permits separate measure of either one or the other type of load with the same type of appliance. With the bending bar along the tooth row, only transverse bending moments created by force components in the buccolingual direction were registered. In a second step, with the bending bar of the load cell perpendicular to the tooth row, only implant bending to the mesial or distal direction was measured. This type of stress is caused by eccentric vertical, implant-axis parallel forces on the prosthesis.

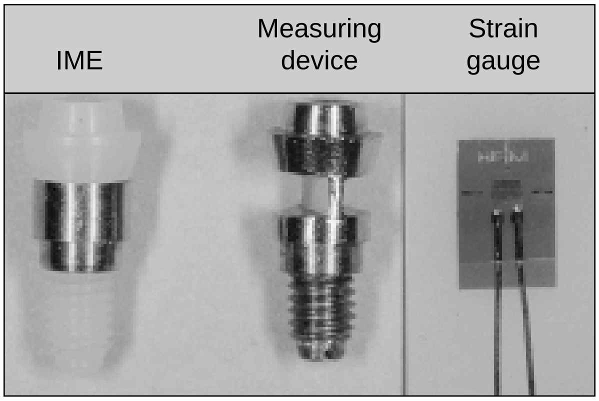

Fig 6 The IME of the IMZ implant *(left)* was replaced by a titanium-made measuring device *(center)*. At the bottom is a separate screw part, which is fixed by a screw from the apical end to permit attaching the device in different rotational orientations. Strain gauges *(right)* were cut to the minimum size and glued onto the two surfaces of the bending bar section of the appliance.

The bending strain was registered during a chewing sequence by two strain gauges (LY 11, Hottinger Baldwin Meßtechnik, Darmstadt, Germany) glued to the bending bar. The electrical signals of the load level were amplified (KWS 3078, Hottinger Baldwin Meßtechnik) and analog-digitally transformed. The anatomy of each of the tested patients—namely the design of their suprastructures related to lever arms (distances between occlusal plane and location of the strain gauges and between strain gauges and crestal bone margin, and prosthesis length)—was measured clinically or radiographically. The prostheses were three- or (seldom) four-unit, retrievable prostheses[10] that were fixed to the crown of the tooth by a screwed channel-shoulder-pin attachment (Fig 1c). The length of the prosthesis ranged from 9 to 13 mm.

The mechanical stiffness and the electrical sensitivity of the load-cell device was tested extraorally. Vertical forces central to the implant axis and/or bending

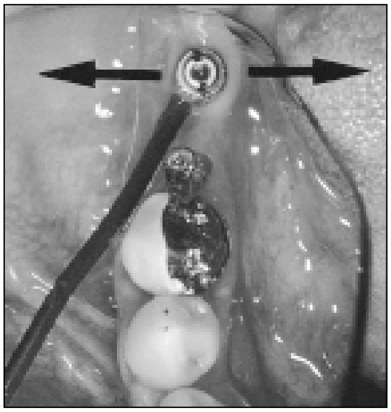

Fig 7a *(Left)* The direction of the bending bar was marked on top of the measuring device *(black spots)* to allow special placement of the device in relation to the tooth row and selected load measurements. In this case, only transverse loads were registered.

Fig 7b *(Right)* The alignment of the bar perpendicular to the tooth row allows for only mesiodistal implant-bending registration.

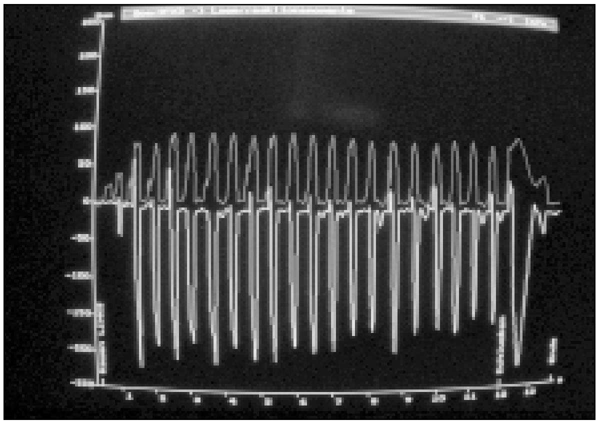

Fig 8 A typical tracing illustrating a chewing sequence with changes of the bending moments, photographed from the computer monitor. The horizontal axis is the time scale in seconds, and the vertical axis is the bending moment to the oral (above zero) and to the lingual side (below zero) in Nmm. This is one of the registrations of the only patient with a tooth-implant fixed restoration on each side. The top line indicates the bending moments of the right (chewing) side, the bottom line indicates the loading of the left side. The steep increase and decrease of the signal denotes a high load speed.[13]

around an axis perpendicular to the length of the bar barely influenced the measurements, because in these directions the device was approximately 4 to 10 times stiffer than for bending forces around the length of the bar.[5] Calibration of the appliances was done intraorally after placing the suprastructure, so as to prevent prestress by fixing the restoration. For measurements in the transverse direction, a small cavity was prepared on the lingual aspect of the prosthesis near the occlusal plane above the implant. After placing the pointed end of a metal bow into the cavity, horizontal forces were applied step-by-step to the restoration with a spring balance (see Richter,[13] Figs 8b and 8c). With the help of the distance between crestal bone margin and "spring balance cavity," the bending moments were calculated. The bending calibration in the mesiodistal direction was made by placing a vertical, axial load on the mesial abutment tooth of the prosthesis (see Richter,[13] Fig 8a). The relationships between load, strain, voltage, and digit scale were linear. Special software[25] was provided for tracing the registration on the monitor (Fig 8) and for data analysis, as follows (for details see Richter[13]):

- Maximum force (the highest peak of each chewing cycle)
- Mean maximum force (the mean peak value of a chewing cycle)
- Mean load level (the mean value of each *integrated* peak signal divided through the signal's duration for each chewing cycle. This value quantifies a rectangular constant load level)

Chewing of four types of food (rubbery confection, pieces of sausage, carrots, and crackers) was examined three times in continuous sequences. Patients then clenched in centric occlusion three times with full strength.

To verify the influence of high loads on the mesial abutment tooth, up to two 100-µm-thick tin foils were placed on the occlusal surface on the tooth-side of the prosthesis. For this test, patients were asked to clench with maximum muscle force. In another test, performed to quantify the load distribution between implant and tooth, vertical loads of 5 N and 10 N were applied along the tooth axis.

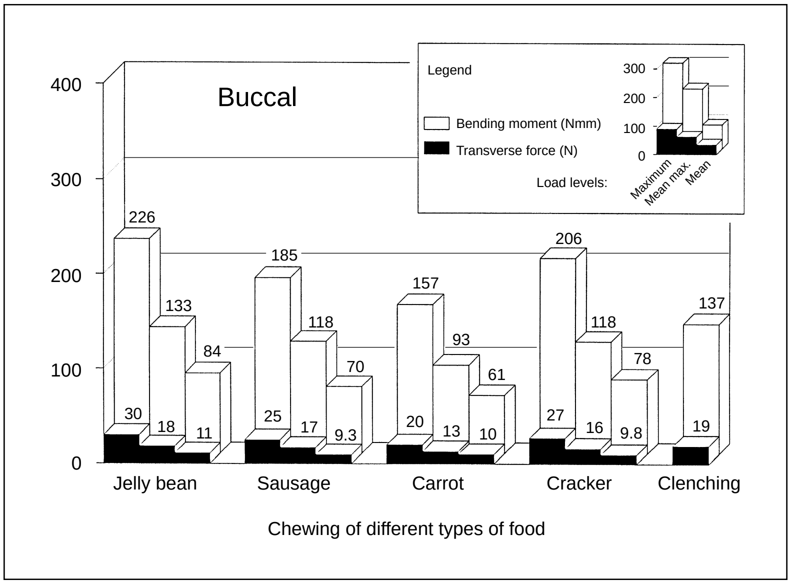

Fig 9 Bending moments and corresponding transverse forces on the implant to the *buccal* during chewing, calculated for the three different load levels and various food types, and for maximum loads during clenching.

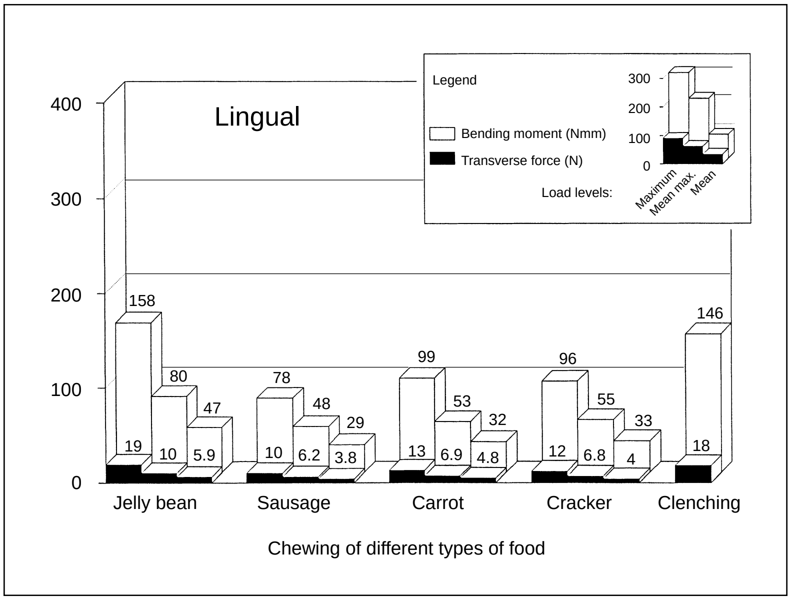

Fig 10 Bending moments and corresponding transverse forces on the implant to the *lingual* during chewing, calculated for the three different load levels and various food types, and for maximum loads during clenching.

Patients participating in these two test sequences were free of temporomandibular joint malfunctions and received one implant in a molar position between 1986 and 1990. The implant was connected to the most distal premolar by a retrievable prosthesis. All patients had a natural maxillary dentition or fixed tooth-supported maxillary restorations, except one (who had a fixed-removable partial prosthesis). One patient was restored bilaterally by tooth-implant fixed mandibular restorations. The groups consisted of 10 and 11 patients, respectively (mesiodistal bending test). Nine of the patients participated in both tests.

Statistical analysis was performed using STSC (v.4.0, Rockville, Maryland) using the Mann-Whitney-Wilcoxon test or the Friedman test, for multiple samples. The Figures show data without standard deviation; details are listed in Tables.

Results

Transverse Bending. Bending moments and corresponding transverse forces were significantly ($P <$ .05) higher on the buccal (Fig 9) than on the lingual side (Fig 10). Chewing of rubbery confection was associated with the highest bending moments (Table

Table 1 Implant Load Levels in a Transverse Direction (Mean ± SD)

Type of food	Maximum (Nmm)	Mean maximum (Nmm)	Mean (Nmm)
Bending moment in a buccal direction:			
Cracker	206.1 ± 93.5	118.1 ± 62.2	73.7 ± 43.3
Carrot	157.3 ± 95.4	92.6 ± 52.0	60.8 ± 33.7
Sausage	185.1 ± 128.8	117.9 ± 92.0	69.6 ± 56.6
Rubbery confection	226.3 ± 133.4	133.3 ± 92.8	84.3 ± 58.5
Clenching	137.0 ± 87.2		
Bending moment in an oral direction:			
Cracker	96.3 ± 70.3	55.4 ± 32.7	32.5 ± 23.4
Carrot	99.2 ± 78.0	53.3 ± 35.0	31.6 ± 28.9
Sausage	77.6 ± 36.7	47.7 ± 22.7	29.3 ± 19.0
Rubbery confection	157.7 ± 81.4	80.0 ± 45.6	46.5 ± 34.3
Clenching	145.8 ± 73.9		
	Maximum (N)	Mean maximum (N)	Mean (N)
Transverse force in a buccal direction:			
Cracker	27.11 ± 17.22	15.53 ± 10.92	9.79 ± 8.15
Carrot	20.4 ± 13.86	12.82 ± 8.99	10.0 ± 7.98
Sausage	25.28 ± 20.29	16.83 ± 14.26	9.32 ± 7.91
Rubbery confection	29.57 ± 20.34	18.01 ± 15.83	11.33 ± 10.11
Clenching	18.82 ± 10.61		
Transverse force in an oral direction:			
Cracker	11.9 ± 7.95	6.83 ± 3.5	4.04 ± 2.61
Carrot	12.96 ± 9.38	6.85 ± 4.13	4.33 ± 3.44
Sausage	10.18 ± 5.46	6.19 ± 3.02	3.8 ± 2.37
Rubbery confection	18.65 ± 9.99	10.09 ± 5.64	5.92 ± 4.2
Clenching	17.57 ± 8.35		

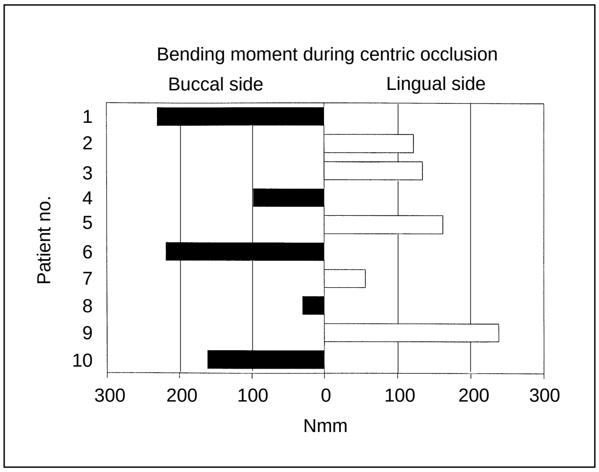

Fig 11 Bending moments during clenching in *centric occlusion* for each patient.

1), although the type of food had no influence on the particular load level (*P* > .05). The load levels (maximum, mean maximum, and mean) differed significantly (*P* < .05). The duration of loading was longer on the buccal (0.23 ± 0.09 seconds) than on the lingual (0.09 ± 0.04 seconds; *P* > .05).

Clenching in centric occlusion, however, caused a relatively low maximum bending moment of about 140 Nmm to the buccal, as well as to the lingual (*P* > .05) (Figs 9 and 10). The restoration was bent either to the lingual or to the buccal, depending on the location of occlusal stops and their equilibration (Fig 11). Therefore, the mean values in Figs 9 and 10 are based on the measurements of five patients for each side (Fig 11).

Mesiodistal Bending. Implant bending moments in the mesial direction during chewing did not exceed 57 Nmm (Fig 12). Normal values were about 40 Nmm for maximum mesial bending (Fig 12) and about 30 Nmm for the distal direction (Fig 13), but the standard deviation was high (Table 2). The load levels (maximum, mean maximum, and mean) differed significantly (*P* < .05), but for each level no difference between mesial and distal bending was found (*P* > .05). Distal implant bending lasted significantly longer (0.22 ± 0.1 seconds; *P* < .05) than mesial bending (0.15 ± 0.05 seconds).

In 7 of the 11 patients, an anterior implant bending of about 45 Nmm in centric occlusion was found (Fig 12). A slightly higher distal bending (50 Nmm) was found for the remaining 4 patients (Fig 13).

Load Distribution. An interposition of tin foil between a pair of occluding surfaces led to a concentration of loads in this area, because the rest of the dentition was less able to transmit loads.[13] But

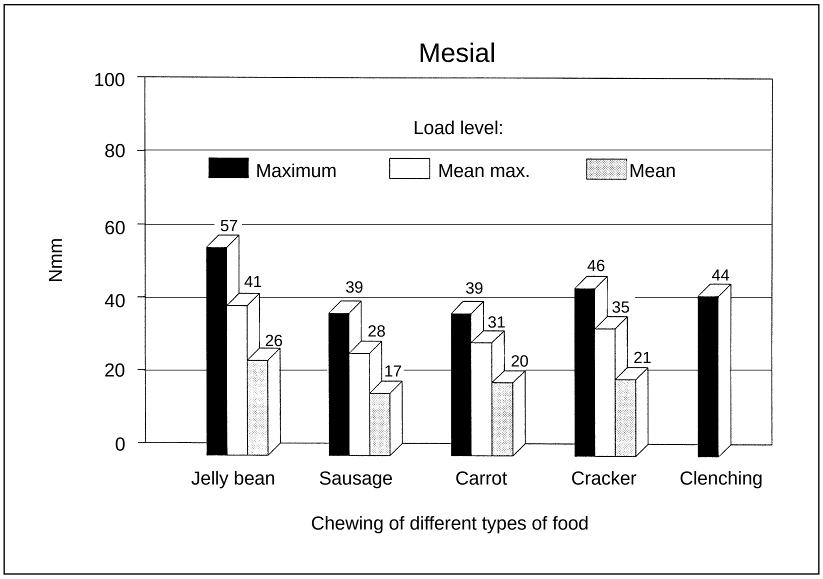

Fig 12 Implant bending moments to the *mesial* during chewing calculated for the three different load levels and various food types, and for maximum loads during clenching.

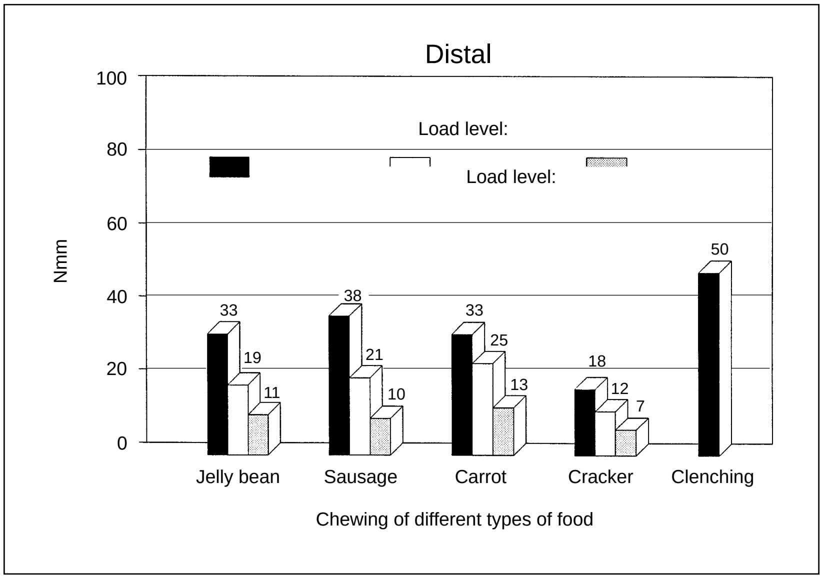

Fig 13 Implant bending moments to the *distal* during chewing, calculated for the three different load levels and various food types, and for maximum loads during clenching.

Table 2 Implant Load Levels in a Mesiodistal Direction (Mean ± SD)

Type of food	Maximum (Nmm)	Mean maximum (Nmm)	Mean (Nmm)
Bending moment in a mesial direction:			
Cracker	46.2 ± 40.2	34.9 ± 32.6	21.1 ± 19.3
Carrot	39.1 ± 33.8	30.9 ± 29.6	20.2 ± 19.5
Sausage	39.4 ± 36.6	28.3 ± 28.5	16.5 ± 16.0
Rubbery confection	56.5 ± 44.7	41.3 ± 38.3	26.2 ± 22.8
Clenching	44.1 ± 33.0		
Bending moment in a distal direction:			
Cracker	17.7 ± 22.3	11.9 ± 16.0	7.2 ± 10.0
Carrot	32.9 ± 38.1	24.5 ± 31.9	12.5 ± 14.1
Sausage	37.5 ± 50.7	20.5 ± 27.7	10.0 ± 11.4
Rubbery confection	32.5 ± 51.0	18.6 ± 31.1	11.2 ± 19.5
Clenching	49.5 ± 39.0		

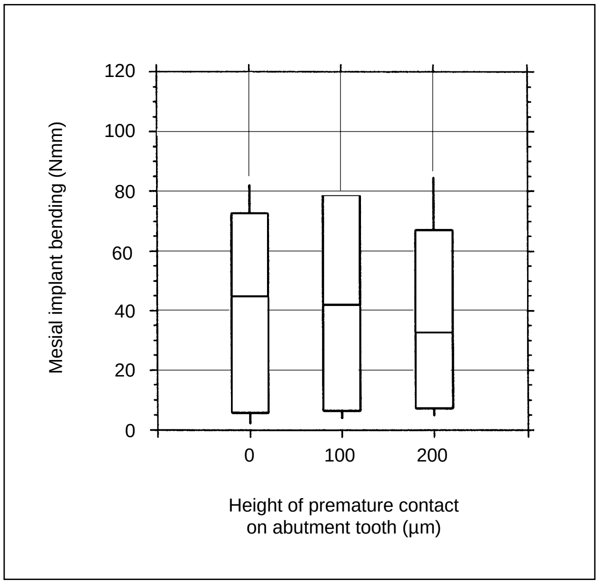

Fig 14 Increasing the number of 100-µm-thick tin foils on the mesial abutment tooth (thereby increasing the vertical force on that tooth during clenching in centric occlusion) did not result in a higher mesial implant bending moment.

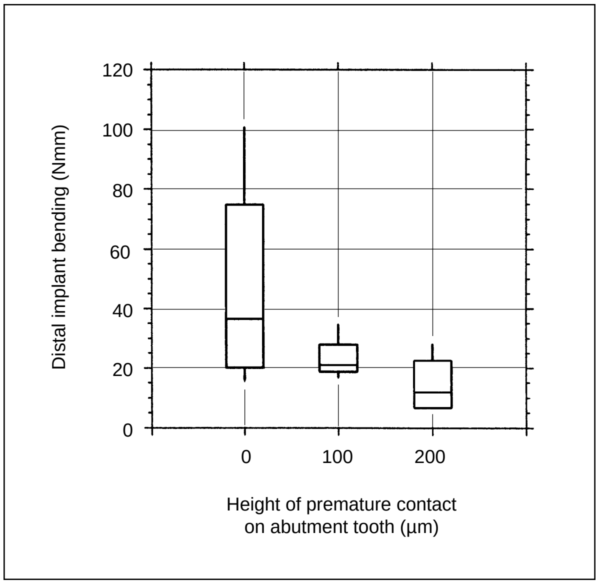

Fig 15 In those four patients who showed a distal implant bending moment, increasing the number of 100-µm-thick tin foils on the mesial abutment tooth (thereby increasing the vertical force on that tooth during clenching in centric occlusion) resulted in a lower distal implant bending moment.

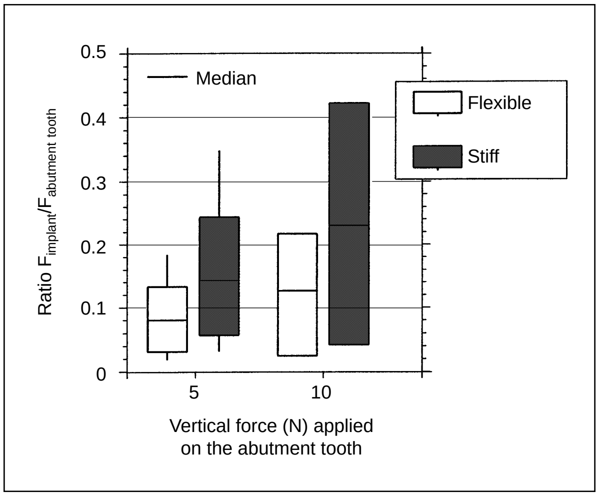

Fig 16 Load distribution between tooth and implant: for a vertical force of 5 N and 10 N, respectively, applied on the abutment tooth, a maximum of 22% of this load created the implant bending moment.

increasing the force on the mesial abutment tooth did not result in a higher mesial implant bending moment (Fig 14). On the other side, those four patients with a distal implant bending in centric occlusion showed a decreasing moment with an increasing number of interposed tin foils on the tooth (Fig 15).

Based on in vitro measurements of the bending characteristics of the load cell,[5] that part of the vertical tooth load that created a bending of the implant could be quantified (Fig 16). For forces up to 10 N and for a "stiff" implant, only about 22% of the load was directed to the implant; however, the tooth's periodontal anchorage withstood 78% of the load.

Discussion

Shortcomings and major issues concerning the interpretation of this investigation have been mentioned previously.[13] The most important result of this study was that chewing loads in the transverse direction caused the highest bending moments in the implant and in the surrounding bone. These were 4 to 5 times greater than the bending moments in a mesiodistal direction. Unfortunately, there is no easy method for comparing these moments with loading of the implant by axial forces.

There may be objection to the fact that the measuring device allows a certain degree of flexibility and that the elastic deformation may significantly alter the results. Of course, chewing forces create some deflection or it would not be possible to measure forces with strain gauges. But these elastic deformations are very small, and they do not influence the load level of forces in the transverse direction. In any case, for equilibration, Newton's law of "action =

Fig 17a *(Left)* A different type of tooth-implant fixed prosthesis that (in contrast to Fig 1) takes into consideration esthetic relevancy: two molar implants support a fixed-detachable suprastructure that is connected mesially to a tooth crown by a screwed attachment. The screw access is from the lingual side slightly below the occlusal plane.

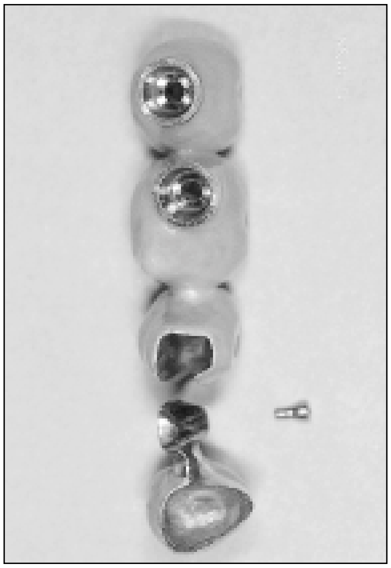

Fig 17b *(Right)* The prosthesis from underneath: inside the second premolar, an individually shaped, square-type pin attachment houses a female mini-screw.

reaction" is valid. For vertical but eccentric loads to the implant, however, the implant's bending is influenced by the stiffness of the bone-anchored implant, its abutments, and the load distribution between tooth and implant. Therefore, results for the implant's mesiodistal bending are so far only valid according to the load cell's flexibility. A "stiff" implant with "stiff" abutments would require higher loads to obtain the same deflection as with a flexible abutment. In this situation, in vitro measurements related to the bending characteristics of different IMZ implant inserts, including the load cell used, were helpful.[5]

It was found that the strain-gauge device behaved in a similar manner to the IME of the IMZ implant system, and proved to be more flexible by a factor of 5/3 compared to an implant with stiff abutments. The result of this test was used to calculate the moments for "stiff" implant bending in a mesiodistal direction; the in vivo measurements must be multiplied by the factor 5/3. Table 3 summarizes all the results as median loads on a molar implant. To simplify the data, loads for the different food types have been averaged, and the vertical loads have been added.[13]

These calculations show that the moment applied to the implant in the buccal direction during chewing was more than 3 times greater than the bending moment in the mesial direction. Table 3 shows the average load values for only the highest peaks of all the chewing cycles (based on four different food types, three chewing sequences, and 10 and 11 patients, respectively, or 120 and 132 measurements, respectively). The mean maximum load level, however, included all peaks of any chewing sequence, and therefore was lower. This load level decreased to about two thirds of the maximum values. The mean load level considers the duration of a peak signal and only reaches approximately one third of the maximum values.

Table 3 Maximum Loads During Chewing

Direction	Specification	Load level (Mean ± SD)
Vertical	Intrusion force	≈70 ± 15 N
Transverse	Buccal moment	≈170 ± 50 Nmm
	Oral moment	≈90 ± 12 Nmm
	Buccal transverse force at crestal bone margin	≈21 ± 6 N
	Oral transverse force at crestal bone margin	≈11 ± 1.5 N
Mesiodistal	Mesial moment	<52 ± 26 Nmm
	Distal moment	≈35 ± 17 Nmm

The in vivo results of this study, concerning the importance of the transverse implant bending as well as the load level, are in agreement with the measurements of Glantz et al[24]; the maximum bending moment was about 170 Nmm. This load level is below the critical loading that causes such problems as screw-joint opening and fracture or tooth mobility–induced "bending overloading" of the implant.[11]

It should be emphasized that, in contrast to theoretical considerations,[11,20,26] mesial implant bending is not critical. Therefore, implants and teeth may be connected rigidly (Figs 17a and 17b) rather than with a "semi-precision stress-breaking" attachment, which tends to develop an occlusal misalignment of the prosthesis components during function.[27]

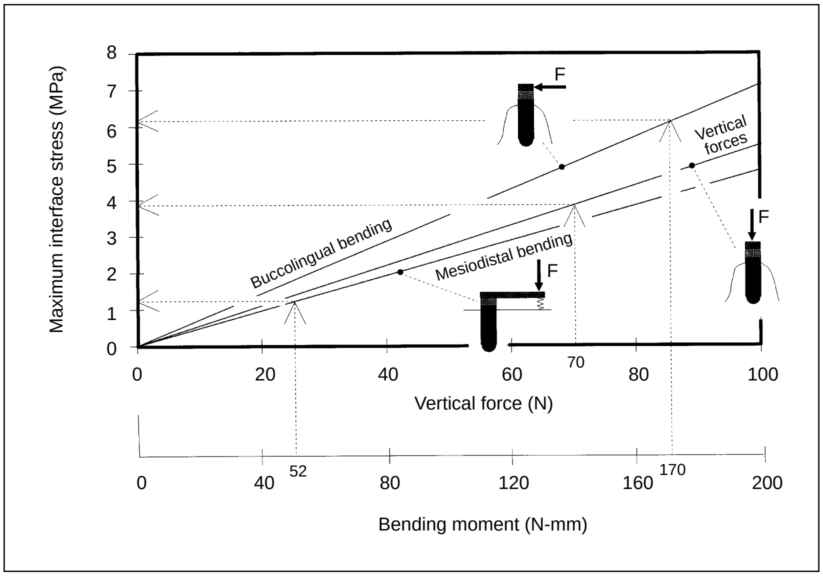

Fig 18 The maximum interface stress around an implant caused by a mean vertical force (70 Nmm) and the mean bending moments (170 Nmm and 52 Nmm; see Table 4), according to the finite element model from Siegele.[28]

Table 4 Maximum Pressure During Chewing

	Type of implant-bone anchorage	
Direction and load	With interface bonding	Without interface bonding
Vertical load, 70 N	$\sigma_{max} \approx 3.8$ MPa	$\sigma_{max} \approx 4.4$ MPa
Transverse bending, 170 Nmm	$\sigma_{max} \approx 6.2$ MPa	$\sigma_{max} \approx 6.8$ MPa
Mesiodistal bending, 52 Nmm	$\sigma_{max} \approx 1.3$ MPa	$\sigma_{max} \approx 1.0$ MPa

These results are definite with respect to the "critical load direction," but only one patient specified the implant-anchored side of the jaw to be the preferred chewing side. The other patients favored chewing on the opposite side, which, in general, had more teeth than the implant side when considering the total number of maxillary and mandibular premolars and molars. This minor aspect of the study seemed of interest because the patients had been successfully provided with a tooth-implant fixed restoration at least 3 years prior. Before this treatment, patients preferred chewing on the nonshortened side, but years later the reconstructed side was not fully integrated into the oral system.[13]

Stress in the Peri-implant Bone. An implant in the molar position that is connected to a mesial tooth with a prosthesis is loaded by vertical[13] and horizontal forces during any oral function. Vertical loads are directly transmitted into the bone around the implant; horizontal forces, however, are transmitted via a lever arm, creating bending moments. These facts cause two major problems in interpreting in vivo measurements: forces and bending moments cannot be compared to each other relative to their stress levels in the peri-implant area. Second, it is not possible to directly measure the stress level caused by these loads in the bone. Therefore, the only way to determine the different stress levels caused by the different forces is to use a theoretical model. The aim of this method was to quantify the stress (in MPa) in the area of interest (the peri-implant bone area) that permits comparing the different loads applied to the implant. Thus, it is possible to estimate the critical force direction that causes the highest stress level.

A standard procedure for calculating the stress around an implant is the numerical finite element method. Siegele[28] used this technique (ADINA[29]) to create a model of a two-dimensional tooth-implant fixed restoration. Design elements enabled him to calculate the three-dimensional clinical situation rather similar to reality. The procedure Siegele[28] used required the following simplifications and prerequisites:

- Model: length 30 mm; thickness 5 mm
- Aluminum oxide implant: length 12 mm; diameter 4 mm

- Prosthesis: height of implant crown 7.5 mm; length (from center of implant to center of tooth crown) 16 mm; thickness 4 mm; elasticity modulus 80 GPA (gold)
- Cortical bone: thickness 2 mm; elasticity modulus 20 GPA
- Spongy bone: elasticity modulus 2 GPA
- Stiffness of the tooth: initially 50 N/mm; after 20 µm intrusion, 4120 N/mm

The geometric parameters of the restoration in this model are very similar to the average values of the clinically examined prostheses of this study. Rather than an aluminum oxide implant, a titanium implant was used in the present study. Though there definitely is a difference in the elasticity modulus, the slightly higher flexibility of the titanium implant minimally influences the stress level and stress pattern around the implant.[30,31]

Figure 18 was drawn using the data presented in Siegele's study.[28] The results for the in vivo measurements for mean forces[13] and mean bending moments were added, so the maximum interface pressure around the implant is obvious (the implant's type of anchorage is assumed to be load-bearing for tension *and* pressure). The pictograms identify the type of load input. Table 4 summarizes the results, in comparison to results that are calculated when interface bonding is omitted. The latter model may be highly appreciated with nonmicroretentive implant surfaces (eg, the Brånemark implant).

Summary

The results appear to show that the transverse forces creating the bending of the implant in a buccolingual direction cause the highest interface stress. These high-stress areas are located at the implant's neck,[28] which is usually located in the cortical shell of the bone.

The stress levels (Table 4) are estimated maximum values, but only for the named direction. However, stress in bone may be higher because of the oblique direction of the chewing forces. Therefore, the components of the three different directions in space have to be superimposed.

References

1. Adell R, Eriksson B, Lekholm U, Brånemark P-I, Jemt T. A long-term follow-up study of osseointegrated implants in the treatment of the totally edentulous jaw. Int J Oral Maxillofac Implants 1990;5:347–359.
2. Engquist B, Bergendal T, Kallus T, Lindén U. A retrospective multicenter evaluation of osseointegrated implants supporting overdentures. Int J Oral Maxillofac Implants 1988;3:129–134.
3. Quirynen M, Naert I, van Steenberghe D, Teerlinck J, Dekeyser C, Theuniers G. Periodontal aspects of ossseointegrated fixtures supporting an overdenture: A 4-Year retrospective study. J Clin Periodontol 1991;18:719–728.
4. Spiekermann H, Jansen VK, Richter E-J. Long-term follow-up study of IMZ- and TPS-implants in the edentulous lower jaw using bar retained overdentures. Int J Oral Maxillofac Implants 1995;10:231–243.
5. Richter E-J. Die Verbundbrücke zwischen Zahn und Implantat: Ergebnisse experimenteller und klinischer Untersuchungen. Med. Habil. [thesis]. Germany: Univ of Aachen, 1992.
6. Naert I, Quirynen M, van Steenberghe D, Darius P. An up to 6 years follow-up study on 509 consecutively installed Brånemark implants in partial edentulism: Prosthetic aspects. J Prosthet Dent 1992;67:236–245.
7. Jemt T, Lekholm U. Oral implant treatment in posterior partially edentulous jaws: A 5-year follow-up report. Int J Oral Maxillofac Implants 1993;8:635–640.
8. Zarb GA, Schmitt A. The longitudinal clinical effectiveness of osseointegrated dental implants in posterior partially edentulous patients. Int J Prosthodont 1993;6:189–196.
9. Lekholm U, van Steenberghe D, Herrmann I, Bolender C, Folmer T, Gunne J, et al. Osseointegrated implants in the treatment of partially edentulous jaws: A prospective 5-year multicenter study. Int J Oral Maxillofac Implants 1994;9:627–635.
10. Spiekermann H. Implantology. Stuttgart, New York: Thieme Medical Publishers, 1995.
11. Rangert B, Gunne J, Sullivan DY. Mechanical aspects of a Brånemark implant connected to a natural tooth: An in vitro study. Int J Oral Maxillofac Implants 1991;6:177–186.
12. Olsson M, Gunne J, Åstrand P, Borg K. Bridges supported by free-standing implants versus bridges supported by tooth and implant. Clin Oral Implants Res 1995;6:114–121.
13. Richter E-J. In vivo vertical forces on implants. Int J Oral Maxillofac Implants 1995;10:99–108.
14. Rangert B, Gunne J, Glantz P-O, Svensson A. Vertical load distribution on a three-unit prosthesis supported by a natural tooth and a single Brånemark implant. Clin Oral Implants Res 1995;6:40–46.
15. Current Issues Forum. Is nonaxial loading harmful to the bone-implant interface of osseointegrated implants? Int J Oral Maxillofac Implants 1995;10:621–625.
16. Quirynen M, Naert I, van Steenberghe D. Fixture design and overload influence marginal bone loss and fixture success in the Brånemark system. Clin Oral Implants Res 1992;3:104–111.
17. Graf A, Grassl H, Aeberhard H-J. A method for measurement of occlusal forces in three directions. Helv Odontol Acta 1974;13:7–11.
18. Peters A. Untersuchungen zur Kaubelastung natürlicher Seitenzähne. Med. Dis. [thesis]. Germany: Univ of Aachen, 1992.
19. Rangert B. Biomechanische Richtlinien für Implantate im Seitenzahnbereich. Phillip J 1995;6:277–282.
20. Weinberg LA. The biomechanics of force distribution in implant-supported prostheses. Int J Oral Maxillofac Implants 1993;8:19–31.
21. Kay HB. Free-standing versus implant-tooth-interconnected restorations: Understanding the prosthodontic perspective. Int J Periodont Rest Dent 1993;13:47–69.
22. Rangert B, Krogh PHJ, Langer B, van Roekel N. Bending overload and implant fracture: A retrospective clinical analysis. Int J Oral Maxillofac Implants 1995;10:326–334.

23. Patterson EA, Burguete RL, Thoi MH, Johns RB. Distribution of load in an oral prosthesis system: An in vitro study. Int J Oral Maxillofac Implants 1995;10:552–560.
24. Glantz PO, Rangert B, Svenson A, Stafford GD, Arnvidarson B, Randow K, et al. On clinical loading of osseointegrated implants. A methodological and clinical study. Clin Oral Implants Res 1993;4:99–105.
25. Robertz R. Aufbau einer rechnergestützen Datenerfassung zur Messung der an einem Zahnimplantat wirkenden Kaukräfte. Studienarbeit [thesis]. Lehrstuhl für Maschinenelemente und Maschinengestaltung. Aachen: RWTH Aachen, 1989.
26. Richter E-J, Spiekermann H, Jovanovic SA. Tooth-to-implant fixed prosthesis: Biomechanics based on in vitro and in vivo measurements. In: Laney WR, Tolman DE (eds). Tissue Integration in Oral, Orthopedic, and Maxillofacial Reconstruction. Chicago: Quintessence, 1992:133–139.
27. Rieder CE, Parel SM. A survey of natural tooth abutment intrusion with implant-connected fixed partial dentures. Int J Periodont Rest Dent 1993;13:335–347.
28. Siegele D. Numerische Untersuchungen zur Optimierung der durch Zahnimplantate bedingten Beanspruchung des Kieferknochens. Thesis. Fraunhofer-Institut für Werkstoffmechanik. Freiburg, Germany: W 8/89, 1989.
29. ADINA. Handbuch, User's Manual. Report AE 84-1, 1994.
30. Soltész U, Siegele D. Einfluß der Steifigkeit auf die im Knochen erzeugten Spannungen. Dtsch Zahnärztl Z 1984;39:183–198.
31. Röhrle H, Sollbach W. Kraftflußberechnungen von Zahn- und Wurzelimplantaten. BMFT-Forschungsbericht. Friedrichshafen, Germany: T 85–137, 1985.