Three-Dimensional Force Measurements With Mandibular Overdentures Connected to Implants by Ball-Shaped Retentive Anchors. A Clinical Study

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The purpose of this in vivo study was to determine maximum and functional forces simultaneously in three dimensions on mandibular implants supporting overdentures. The anchorage system for overdenture connection was the ball-shaped retentive anchor. Five edentulous patients, each with two mandibular ITI implants, were selected as test subjects. A novel miniaturized piezo-electric force transducer was developed for specific use with ITI implants. Force magnitudes and directions were registered under various test conditions by means of electrostatic plotter records. The test modalities were maximum biting in centric occlusion, maximum biting on a bite plate, grinding, and chewing bread. Maximum forces measured in centric occlusion and on the ipsilateral implant when using a bite plate were slightly increased in vertical and backward-forward dimension (z-, y-axis) compared to the lateral-medial direction (x-axis). On the contralateral implant, equally low values were found in all three dimensions. This may be the effect of a nonsplinted anchorage device. With the use of a bite plate, force magnitudes on the ipsilateral implant were significantly higher on the z- and y-axis than mean maximum forces in centric occlusion ($P < .001$). Chewing and grinding resulted in lower forces compared to maximum biting, particularly in the vertical direction. The transverse force component in backward-forward direction, however, reached magnitudes that exceeded the vertical component by 100% to 300% during chewing function. This chewing pattern had not been observed in previous investigations with bars and telescopes, and therefore appears to be specific for retentive ball anchors. The prevalent or exclusive force direction registered on both implants in the vertical direction was downward under all test conditions. In the transverse direction during maximum biting the forward direction was more frequently registered, while no obvious prevalence of transverse force direction was observed during chewing and grinding.
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Key words: mandibular implants, overdentures, retentive ball anchors, three-dimensional force measurements

Success and patient satisfaction with mandibular overdentures supported by various implant systems have been reported in recent studies.[1–6] For the mandible, the rate of success was slightly higher than that reported for fixed prostheses.[7] Although overdentures connected to a few mandibular implants have proved to be a reliable alternative to fixed prostheses,[8] the use of only two implants[9,10] has not yet become standard clinical procedure. Discussion continues about the number of implants to be placed and the anchorage system to be used for overdenture support with regard to load transfer and stress distribution onto implants. Preliminary clinical results of retrospective and longitudinal surveys with mandibular implants did not reveal differences in peri-implant findings between bar splints and single anchors.[1,9] Investigations with a two-dimensional finite element analysis concluded that stress distribution was more uniform if two mandibular implants were unconnected.[11] The test condition was vertical loading. Another in vitro study sought to demonstrate that the most favorable anchorage system for overdenture connection was the egg-shaped Dolder bar.[12] Results from an experimental study that used the technique of holography indicate that conical telescopes lead to

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optimal force distribution on implants.[13] From such investigations, however, it remains unclear to what extent three-dimensional functional forces are transmitted in vivo onto the implants.

To contribute to the understanding of biomechanical forces on implants, a method was developed that allows for force measurements simultaneously in three dimensions on implants in vivo.[14] Recently,[15,16] force patterns and magnitudes were investigated with overdentures connected to two mandibular implants by means of different bar splints or telescopes. The use of ball-shaped retentive anchors is a simple way of connecting the dentures to mandibular implants in the edentulous jaw.[17] The retention mechanism has a stress-breaking function, and it is believed that under in vivo conditions it might protect the implants from overload. The aim of the present investigation was to qualify and quantify functional forces with mandibular overdentures connected to the implants by means of retentive ball anchors and to compare the results with previous findings.

Materials and Methods

Patients, Implants, and Dentures. Five completely edentulous patients, one woman and four men, each with two mandibular implants, were selected as test subjects. All five patients were volunteers and had signed a consent form to participate in the study. Because most edentulous patients with implant-supported overdentures are elderly, the average age was 73.8 years. The implants, two-part ITI implants (Straumann AG, Waldenburg, Switzerland), were solid screws and had an intraosseous length ranging from 8 to 12 mm. They had all been placed in the period from 1987 to 1988. The implants were located in the area of the canines or slightly closer to the midline. The distance between the two implants varied from 19 to 29 mm. The parallelism of the two implant axes measured in the sagittal and in the frontal plane varied from 0 to 5 degrees. However, one patient was found with a disparallelism of 17 degrees in the sagittal plane and another patient a disparallelism of 18 degrees in the frontal plane. In the frontal plane, 9 of 10 implants showed an almost perpendicular implant axis in relation to the occlusal plane and a slight inclination to the left side of the jaw.

When this study began, all patients had worn their implant-supported dentures for over 7 years. All implants were stable and firmly osseointegrated and all patients were satisfied with the treatment outcome. For the in vivo registration of forces, the original mandibular denture was duplicated by a relining impression, ie, the original denture served as a custom impression tray. Master casts were molded with original implants in situ instead of brass analogs, and wax rims were fabricated. By means of an orientation index and by using a face-bow, tooth position and vertical dimension of occlusion of the original denture were transferred to the articulator. With this procedure of denture duplication, the occlusal concept with the original maxillary denture in situ was reestablished. The denture base was reinforced with a metal framework.

Force Transducers. For specific use with the ITI implants, miniaturized piezo-electric force transducers were fabricated (Kistler Instrumente AG, Winterthur, Switzerland) to allow for simultaneous force registration in three dimensions. They were mounted directly on the implants beneath the retention device. Engineering details of the piezo-electric transducers and calibration measurements in vivo and in vitro have been reported in a separate paper.[14] Specifically designed to fit on the transducers and implants (Fig 1), the ball-shaped retentive anchors were mounted by means of a torque-controlling instrument at a preset moment of 15 Ncm. This resulted in a preload force of over 300 N. Correct tightening of the suprastructure is a prerequisite for reduction of stress transfer onto the implants and for correct measurements.[18] Preloads of less than 300 N were not accepted since this could result in incorrect force registrations, particularly in transverse dimensions.[14] The female retainers of the ball anchors were polymerized into the denture base directly in the patient's mouth to provide optimal fit of the dentures. When the dentures were fixed on the ball anchors, the transducers as well as the implants remained free of any direct contact with the denture base material, because during function this would introduce high transverse forces onto the implants. Contact of the denture with the implants was established through the female retainers on the ball anchors. Therefore, forces were directed from the dentures to the implants exclusively through the anchorage device, ie, the ball anchors.

Force Registrations. By means of plotter records, forces were recorded simultaneously in three dimensions on both implants of each patient under various test conditions. Two sessions with intervals of 2 to 4 days were necessary for registration of the forces of each patient. The first session provided for adjustments of the duplicated dentures and for calibration and test measurements. The female retainers were fixed to the dentures in the mouth of the patients. Following this, proper function of the technical equipment was checked by various test sequences. These tests have been described elsewhere.[14]

During the second session, force registrations were carried out. Force magnitudes and directions in all three dimensions were recorded on both implants

Fig 1 Clinical intraoral situation: the miniaturized piezo-electric force transducers and the ball-shaped retentive anchors are mounted on both mandibular implants.

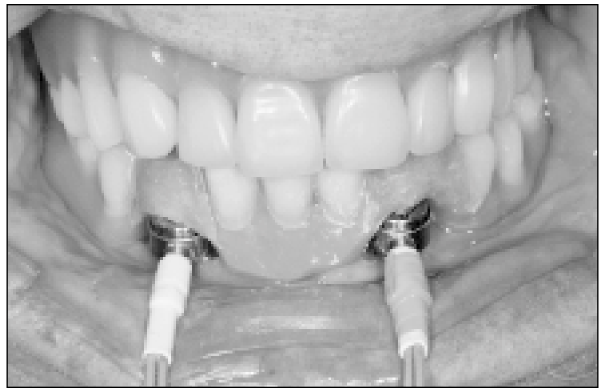

Fig 2 The denture is connected. Clinical situation when maximum force in centric occlusion (MOF) was measured.

Fig 3 Unilateral biting on the bite plate (miniature bite plate) and simultaneous registration of forces on the ipsilateral (MF-ipsi) and contralateral (MF-contra) implant.

of each test subject during maximum biting, parafunction, and chewing function. Maximum biting was recorded with two different test setups: (*1*) maximum occlusal force (MOF) was registered when biting in centric occlusion (Fig 2), and (*2*) maximum force was measured simultaneously on the ipsilateral and contralateral implant (MF-ipsi and MF-contra) during unilateral biting on a miniature bite plate.[19] This miniature force transducer was placed consecutively between the occluding pair of second premolars on each side of the jaw (Fig 3). The biting tasks were performed by the patients three times during each test situation. The patients were asked to apply their maximum muscle strength. The means of the maximum force magnitudes were calculated from all registered test sequences. Further, the two directions of forces of each axis were analyzed during the test sequences, ie, the frequency of each force direction was counted and expressed in percentage from all plotted signals. If one force direction was found in over 50% of all plotted signals, this force direction was regarded as prevalent for the corresponding axis. Further, the relationship between maximum forces recorded on the miniature bite plate itself and forces transmitted simultaneously to the ipsilateral and contralateral implants was analyzed.

The recorded functional and parafunctional forces were grinding during 30 seconds and chewing pieces of hard crusted bread of standardized size without any special instructions. The force magnitudes reached during chewing and grinding were obtained from repeated chewing tasks and were expressed in ranges. The prevalence of force direction again was determined in all three axes for both functions. At the end of the clinical tests, calibration measurements were repeated. The axes and directions of registered forces are schematically illustrated in Fig 4.

Statistical Analysis. Means of maximum forces were calculated from all registered trials with both test setups. Comparison of means was done by parametrical testing using the *t* test, adjusted by the equation of Bonferroni. Furthermore, Pearson's correlation coefficient was calculated to describe the correlation between maximum biting forces on the bite plate and measured force magnitudes on the implants.

Results

The mean maximum force values recorded in centric occlusion (MOF) and with the bite plate in situ (MF-ipsi, MF-contra) for all three dimensions are given in Table 1. On the z and y axes, similar force magnitudes were found. The vertical and backward-forward force component (z-axis and y-axis, respectively) of maximum force measured on the ipsilateral

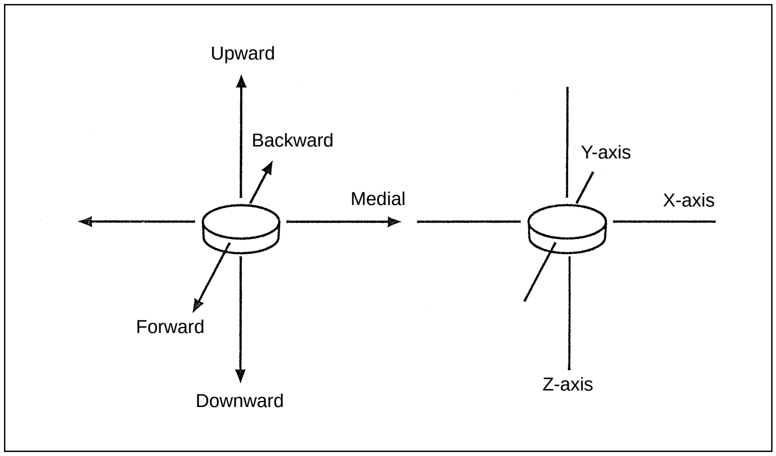

Fig 4 The three force axes (X, Y, Z) with their respective force directions.

was dominant, being significantly higher compared to the contralateral implant. No significant differences were found for the x-axis. On the x-axis (lateral-medial direction), the force magnitudes were consistently low, ie, forces never exceeded 28 N and did not show differences with regard to both test setups. On the z- and y-axis, the overall range of measured forces was from 2 to 40 N. Biting on the bite plate led to an increase in the range of up to 100 N on the ipsilateral implant. Therefore, in vertical and forward-backward direction, force magnitudes of the ipsilateral implant exceeded maximum force measured in centric occlusion by a factor of two to three. Table 2 shows the percentage frequency of both force directions of each axis during maximum biting. In the vertical dimension, only downward force directions were found when MOF was measured, while tensile forces (ie, upward direction) were registered as well with the use of the bite plate in 23% of all trials. Tensile forces were specific for the contralateral implant.

The scattergrams in Fig 5 show measured force magnitudes on both ipsilateral and contralateral implants plotted against force magnitudes recorded on the bite plate itself. The mean maximum force registered on the bite plate was 159.6 N + 47.9 N. The correlation between the force magnitudes recorded on the bite plate and forces measured on the implants was generally low, particularly for the contralateral implant. *R* values and statistical significances are given in Table 3.

Figures 6 and 7 represent ranges of parafunctional and functional forces in all dimensions of the left and right implants for all five patients. Grinding resulted in rhythmic alternation of the force direction in the x-axis, and a prevalence of vertical force direction was identified in the z-axis. When chewing, a prevalent transverse force direction (on x- and y-axis) was rarely found. On the z-axis, minimal upward force

Table 1 Maximum Occlusal Force (MOF) and Maximum Force (MF) Measured With the Bite Plate

Setup	Axis	Forces (N) measured on implants			
MOF	Z	*	26.9 ± 12.7		xx
MF, bite plate	Z	Ipsilateral	58.9 ± 20.0	xxx	
MF, bite plate	Z	Contralateral	3.5 ± 2.8		xxx
MOF	Y	*	14.2 ± 9.2		xxx
MF, bite plate	Y	Ipsilateral	47.8 ± 22.9	ns	
MF, bite plate	Y	Contralateral	9.9 ± 5.4		xxx
MOF	X	*	9.8 ± 5.8		ns
MF, bite plate	X	Ipsilateral	12.3 ± 6.8	ns	
MF, bite plate	X	Contralateral	9.2 ± 8.5		ns

t test: x = $P < .05$; xx = $P < .01$; xxx = $P < .001$.
*MOF: left and right implants pooled.

Table 2 Direction of Maximum Force of the X-, Y-, and Z-Axis

Setup	Axis	Force direction (%)	
		Downward	Upward
MOF	Z	100	—
MF, bite plate	Z*	77	23
		Forward	Backward
MOF	Y	73	27
MF, bite plate	Y	63	37
		Medial	Lateral
MOF	X	50	50
MF, bite plate	X	37	63

Direction of forces calculated from plotted signals.
*Exclusively on contralateral implant.

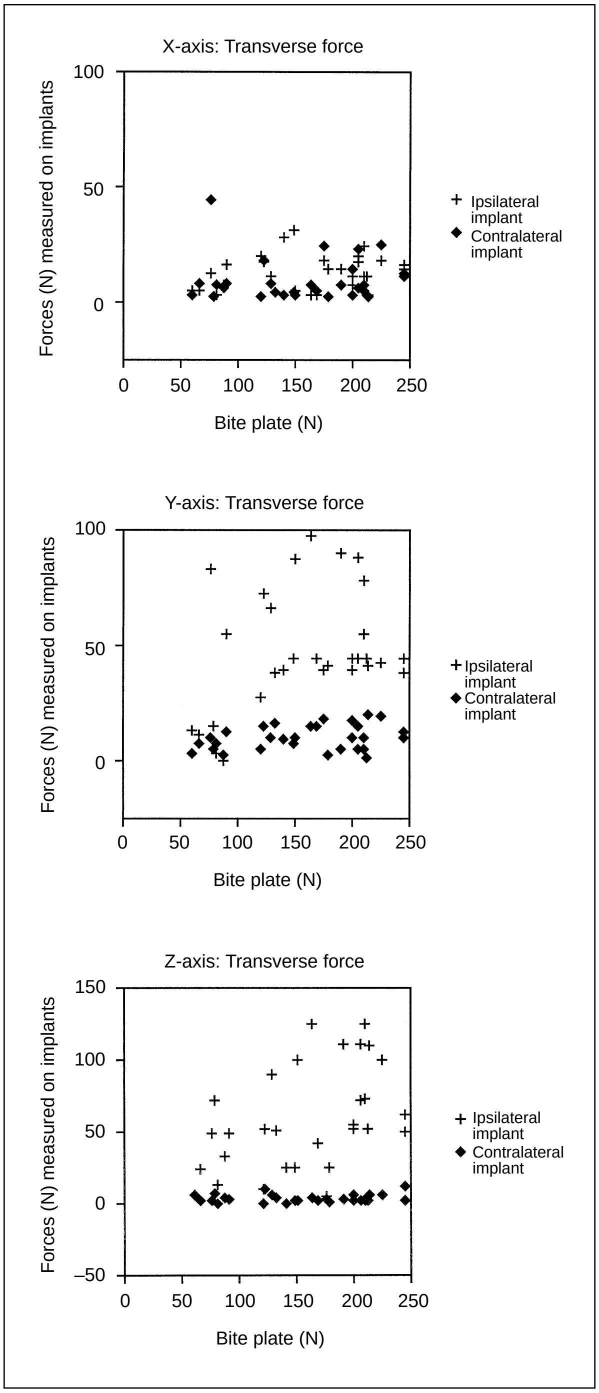

Fig 5 The three scattergrams show forces recorded on the bite plate plotted against forces measured simultaneously on the contralateral and ipsilateral implant. Each patient performed three biting tasks consecutively on both sides of the mandible. Note that the scale of the vertical axis of the scattergrams is different.

Table 3 Correlation Between Recorded Forces on the Bite Plate and on the Implants

Axis	Implant	Pearson's correlation coefficient	
Z	Ipsilateral	.471	*P* < .05
	Contralateral	.096	ns
Y	Ipsilateral	.346	ns
	Contralateral	.303	ns
X	Ipsilateral	.285	ns
	Contralateral	.004	ns

directions were observed in two patients only. Figure 6 (grinding) shows ranges of equal force magnitudes in all three dimensions, with a slight tendency to higher forces in backward-forward direction (y-axis). Figure 7 (chewing) demonstrates that the ranges of forces in anterior-posterior direction were distinctly increased by a factor of two to five compared to the z- and x-axis.

Discussion

Questions associated with loading and overloading of implants are widely disputed. The assumption that unfavorable loading of implants may lead to bone resorption has been neither confirmed nor rejected. Therefore, it is necessary to learn more about naturally occurring forces in vivo. Because of technical difficulties, in vivo measurements of forces with the transducers mounted directly on the implants are rare.[20,21] In the present study, it was possible to measure forces on implants that support overdentures by means of retentive ball anchors. Comparison of the present results with those of previous studies[15,16] provides further information on the influence of anchorage devices (splinted versus nonsplinted, ie, bars versus single attachments) and the retention mechanism (rigid versus stress-breaking, ie, telescopes or U-shaped bars versus ball anchors or simple round bars) for overdenture connection. A stress-breaking retention mechanism allows some movement of the dentures (eg, rotational) that presumably directs more forces to the denture-bearing tissue than does a rigid mechanism that probably directs higher forces to the implants.

The results of the present study varied inter- and intraindividually. Nevertheless, some fundamental principles of stress distribution in vivo can be established for mandibular overdentures connected by means of retentive ball anchors. In general, low forces, particularly in the vertical dimension, were found that resembled results seen with complete

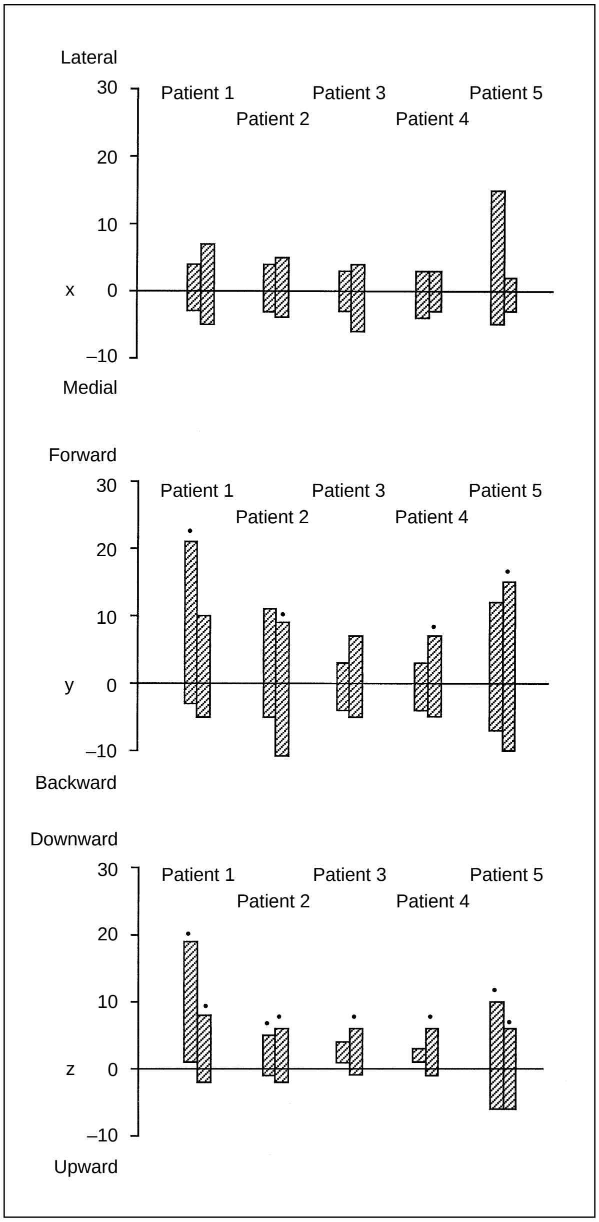

Fig 6 Ranges of forces during grinding for the right and left implant of all five patients. A small point above or underneath the columns indicates the prevalent force direction.

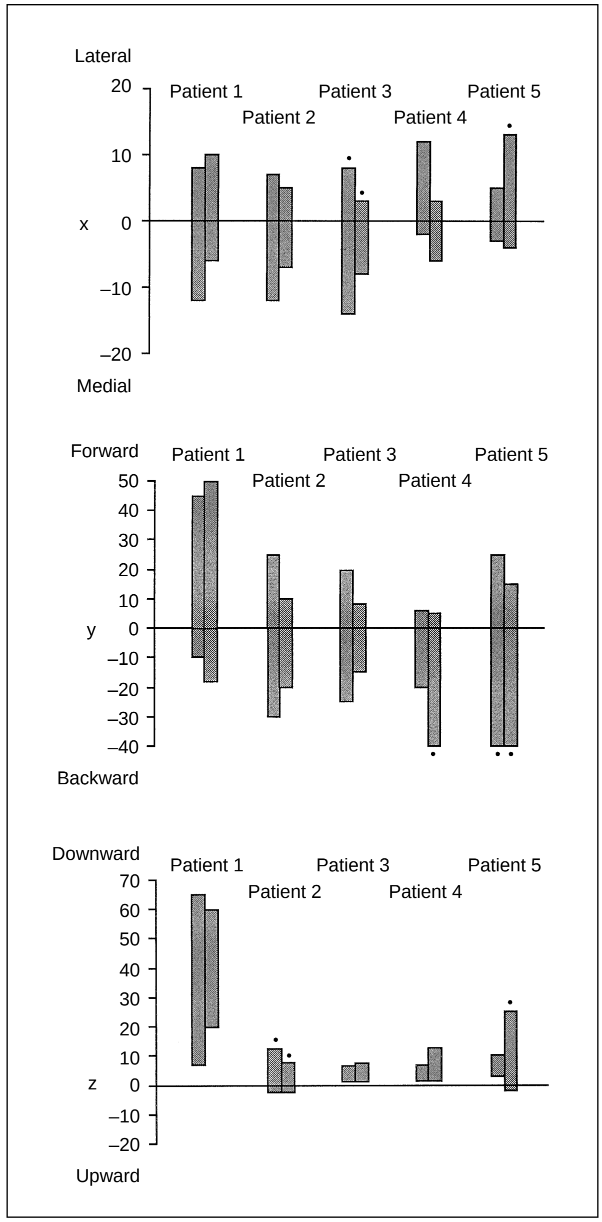

Fig 7 Ranges of force during chewing bread for the right and left implant of all five patients. A small point above or underneath the columns indicates the prevalent force direction. Note the different scales of the diagrams.

dentures.[22] On the x-axis, maximum forces were uniformly low, while the force magnitudes recorded on the y- and z-axis were increased, and comparable under both test conditions. In comparison with previous findings (bars and telescopes), it was observed that connecting the overdentures to retentive ball anchors resulted in a slight decrease of maximum forces in the vertical dimension. Because different measuring equipment was used in other studies by other authors, direct comparisons are not reliable. Nevertheless, maximum forces recorded in the present investigation were generally lower than forces measured with implant-supported fixed prostheses occluding with complete dentures.[23–25]

Lundgren et al[26] and Falk et al[27] measured local forces in the vertical dimension with 4- to 8-strain gauge transducers mounted in the implant-supported prostheses to calculate the total force acting on the prostheses. Interestingly, in the present study the values of maximum occlusal force in the vertical direction registered on the two implants resembled local maximum forces reported for the anterior part of the prostheses in these two studies. The percentage distribution of force directions showed a prevalence of vertical, forward, and laterally directed forces. This pattern of maximum force was not distinctly different from measurements with bars or telescopes.

Use of the miniature bite plate enabled the registration of maximum forces between the posterior teeth, ie, forces acting onto the denture. The unilateral use of this bite plate leads to an increase in occlusal-vertical dimension and may evoke pain, discomfort, and instability of the maxillary complete denture during maximum biting. Therefore, such measurements probably will result in underregistration of the maximal muscle capacity. In spite of such objections, this measuring method, combined with the piezo-electric transducers mounted on the implants, may provide some information on load sharing between the denture-bearing tissue and the implants themselves if a force of known magnitude is acting on the denture. The force measured on the contralateral implant remained low in all three dimensions, ranging from 0 to 20 N. Force magnitudes up to and rarely exceeding 100 N were found on the ipsilateral implant in the z- and y-axis, while the force magnitudes recorded on the bite plate rarely reached up to 250 N. The correlation between forces measured on the implants and the records on the bite plate itself was low and mostly insignificant.

These results were partly in contrast to previous results with bars and telescopes, where a higher correlation was found, particularly for the ipsilateral implant on the y- and z-axis. The mean maximum force measured on the bite plate itself in the present study—about 158 N—was comparable to the mean values of previous findings, which were between 130 and 190 N.[15,16,28] Therefore, it appears that the pattern of force distribution found in this study was specific for a nonsplinted anchorage device with a stress-breaking retention mechanism such as the retentive ball anchor. In the presence of retentive ball anchor forces, it seems that with increasing forces acting on the denture, the residual ridge is increasingly loaded, and to a larger extent than the unilateral implant. Furthermore, the effect of nonsplinting was clearly recognized in the very low forces registered on the contralateral implant.

Grinding resulted in low forces, with similar values as were found in two previous studies with bars and telescopes. For the x-axis, no prevalent force direction was identified, whereas in the z-axis the downward direction was dominant. For the y-axis, a slight dominance of the forward direction was found. This force pattern of the y- and z-axis was in contrast to previous findings, where mostly rhythmic changes of the force directions were observed.

When chewing function was analyzed, low forces were observed in the x-axis and z-axis, except for one patient in vertical direction. Transverse forces on the y-axis reached from 100% to 300% of the vertical forces and therefore mostly exceeded the vertical force magnitudes. This leads to the assumption that vertical chewing forces acting on the denture were transmitted to a higher extent to the residual ridges than to the implants if overdentures were connected by means of retentive ball anchors. This obvious change of ratio of transverse and vertical forces (ie, a dominance of the transverse force in forward direction) had not been observed with bars and telescopes, where transverse forces reached 50% and rarely up to 100% of the vertical force magnitudes. It is generally assumed that horizontal forces directed to the implants should be avoided to prevent bone resorption or angular defects. One may speculate whether the pattern of chewing forces as observed in the present study must be regarded unfavorably and if an anchorage system that provides for more vertical loading would be more desirable. Comparative longitudinal surveys that investigated the success rate of implants with regard to the effect of the overdenture anchorage are not yet known.

Conclusions

From the present results and their comparison with previous findings, it may be concluded that with the use of retentive ball anchors, a tendency to record low forces on both implants in all three dimensions and under various test conditions was found. This may be a favorable factor regarding the long-term loading of implants. Chewing function resulted in a more pronounced transverse force component, particularly in anterior direction, that exceeded the vertical force magnitudes. This force pattern was specific for the retentive ball anchor and has not been observed with bars and telescopes. With regard to biomechanical considerations, final recommendation of the optimum use of overdenture anchorage systems cannot yet be given. The anchorage system, which connects the mandibular overdentures to two implants, may have a more minor influence than is generally believed, and other parameters may also determine loading characteristics of implants, such as anatomic morphologic conditions, fit of the suprastructures, and occlusion.

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