

Biomechanical Possibilities of Modelling the Jaws. A Biomechanical and Clinical Study of the Shape and Loading of Oral Implants.

Doctoral Theses

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1. INTRODUCTION

Biomechanics is present in all the fields of everyday dentistry, without the dentist paying any attention to it.

This is equally true for the field of oral surgery, too. Mechanical or biomechanical questions arise quite often in connection to the load bearing capacity of the jaws in case of dental and surgical treatment. Various impacts on the jaws, surgical interventions, injuries, developmental anomalies of the jaws, pathologies causing bone destruction may all modify the structure and physiological load bearing capacity of the jaws. Biomechanical investigations may help in analysing these processes and at the same time in planning surgery on the jaws. Upon certain surgical interventions the jaws may be weakened in a critical manner. Loading and biomechanical properties may gain utmost importance in cases of reconstructing a jaw damaged due to trauma or ablative surgery.

Biomechanics plays a special role in implant dentistry. Forces conveyed by implants and implant-born prosthetic devices differ from those conveyed by natural teeth, thus they require adaptation from the jaw bones. Osseointegration is a key term in implant dentistry (and the present study). Osseointegration is the basis of success of oral implants. It is of double importance: from a clinical point of view to judge whether the implant can be loaded, and how it will function on the long run, from a scientific point of view in designing implants, in evaluating implant morphology, the efficacy of implant surface morphology and loading protocols. The degree of osseointegration can be determined with a histological examination, as the ratio of direct bone-implant contact. In everyday clinical practice mostly indirect signs are used to infer upon the formation of osseointegration, or the lack of it. A biomechanical examination seems to be the most usable method to evaluate implant stability as it is relatively easy to perform and, taking into consideration certain conditions, based on the degree of stability one can infer on the degree of osseointegration.

Implant geometry plays an important role in the development and persistence of osseointegration. Implant geometry defines the transmission of masticatory forces to the jaw and thus it basically influences mechanical stress that occurs in the bone and

therefore it is important to design an implant geometry that provides a favourable transmission of stress.

Various technical problems might occur in connection with implants: fatigue phenomena might occur in certain parts of the implant or prosthetic parts as a result of loading. Cracks may also occur. Biomechanical studies may help in preventing such complications.

2. AIMS

The present studies were directed at the biomechanical study of dental implants and jaws. The basic aim was to gain as much information as possible on the osseointegration of implants, therefore several study methods were applied. Clinical studies were performed as well as various model studies that provided multifaceted information on the phenomenon in question.

2.1. Having examined implant stability with the Periotest® method the study goal was to investigate the typical temporal changes in implant stability, a quantitative evaluation of osseointegration. The effects of immediate loading were also studied. One piece implants placed with a one phase technique were compared to two piece implants placed with a two phase technique.

2.2. A model study was performed with a finite element analysis method. The aim was to learn how the various characteristics of implant shape influence mechanical stress occurring around the implant. It was also the aim to determine what implant design is ideal to keep mechanical stress in the physiological range without evoking peak stresses.

2.3.1. The next aim was to import the dataset of cone beam computer tomography scans into finite element networks and to develop a new method that makes creating a finite element model based on individual anatomical situations easier. The load bearing capacity of jaws was studied with this method. Special attention was paid to the changes of the mechanical properties of the jaw in accordance to ageing.

2.3.2. To present the practical uses of the model and to prove that surgery performed on the jaws can be planned based on biomechanical principles, the effects of the surgical

removal of an unerupted third molar were simulated with reference to the solidity of the jaw.

2.4. Laboratory model experiments were conducted to study the force transmission properties of implants, as well as the statical study of the individual parts of the implant.

2.4.1. In the case of plastic stress absorbent elements built into implants the changes in the mechanical properties of the various plastic materials as a result of repeated loading were studied. It was attempted to determine which plastic material seems to be the most suitable for this purpose.

2.4.2. Fatigue phenomena were investigated in the area of the implant-bone interface. Model implants were subjected to cyclical loading and differences between the effect of various thread designs were detected in a direct model experiment as a continuation of the previous computer simulations.

2.4.3. The studies of the chances of fracture of the neck of temporary titanium implants were aimed at examining the cervical part of the implants most prone to fracture at the same time looking for the geometric solution most suitable to prevent these fractures.

3. METHODS

3.1. A study of implant stability and osseointegration with the Periotest® method.

A study of the immediate loading of implants.

One and two piece implants were placed in the study, a total of 59. In the case of complete edentulous jaws 4, 5 or 6 implants were placed, whereas in the case of partially edentulous jaws a minimum of 2 implants were placed. Insertion torque was measured to characterise primary stability and the implant was also examined with a Periotest device. Periotest testing was performed according to protocol upon every control visit. Screw retained prosthetic devices were fabricated and the implants were splinted. A part of the implants were immediately loaded, in other cases delayed loading was performed. Immediate loading was applied in completely edentulous lower jaws after placing 5 implants in the interforaminal region if appropriate primary stability was achieved. The previously fabricated full denture was converted for immediate loading.

Screw retained cantilever bridges or bridge prostheses were fabricated as a definitive solution.

3.2.1. A photoelastic study of the mechanical stress transmission of implants with various geometric design to the jaws.

In the first series the stress transmission properties of DIAKOR® implants were compared. Four implant types were of a step design and two were screw implants. The implants were fixed between two linear polarizers. Loading was performed in the form of axial static forces and the fringe pattern was photographed in a MEOPTA photoelastic analyzer.

In the second series the effect of plastic stress absorbent elements on the load transmission properties of titanium screw implants were studied. The implants were placed between two linear polarizers. Some samples were fixed with adhesives, others were placed without fixation. Loading was performed in the form of axial static forces.

3.2.2. A finite element study of the mechanical stress transmission of implants with various geometric design to the jaws.

The effect of the shape and various parameters of the thread of screw implants on stress transmission was modelled with a computerized finite element analytic method. In the first series the geometric properties of commercially available screw implants were studied with two and three dimensional finite element methods as well as the effect of these properties and loading conditions on the mechanical stresses arising in the bone surrounding the implants. The stress transmission of two various implants with three various thread designs were compared with a 2D finite element method. In the continuation of the study a 3D finite element method was used to investigate the effect of implant length, diameter and way of loading on mechanical stress modelling axial and paraxial static loading. The place of load transmission from the prosthetic abutment to the implant was also varied. In the second series the stress transmission properties of various further implant shapes were compared to find the optimal geometry for stress transmission. Three various thread designs were studied. A computer programme was developed to facilitate and speed up the creation of the finite element network. Axial and lateral, static and dynamic loading was also simulated. As a further development of the model the spongy structure of bone was modelled with the introduction of ‘porosity’.

3.3.1. Creating finite element jaw models using the dataset of volume tomography scans to judge the load-bearing capacity of the jaws considering individual anatomical features.

The CBCT datasets of three patients of various ages (12, 20 and 67 years olds) were selected for the study and computer modelling. A surface (outer) and a volume (inner) network was created. Individual mechanical properties were linked to each node of the volume network: a Young modulus value was determined for each node based on the density value measured individually in the CBCT dataset based on a new algorithm. The models were then subjected to ‘masticatory loading’. The masticatory loading was directed at the first molar tooth. The forces exerted by the masticatory muscles were modelled based on their anatomical insertion point. The occurring forces, stresses, complete deformation and the first and third primary stress values, as well as the von Mises stresses were determined.

3.3.2. Surgical and loading simulation based on the finite element model: the effect of surgical removal of lower third molars on the stresses arising upon masticatory loading.

The biomechanical modelling of the surgical removal of impacted third molars was chosen to test the possibilities and restrictions of the new finite element method and also to evaluate the possible practical uses of the method. The model made from the data of the 20 year-old female patient with unerupted wisdom teeth was chosen to further study the jaw. Two virtual surgical interventions were simulated. In one intervention the third molar in position 48 was removed without damaging the surrounding bone, whereas in the other one the tooth and a part of the cortical bone was removed on the buccal side of the crown of the tooth and in the area of the external oblique line. Masticatory forces were modelled as above adding that loading on the operated side was complemented by loading on the contralateral side.

3.4. Laboratory model studies to investigate the stability and force transmission properties of implants

3.4.1. Investigating the fatigue phenomena occurring in plastic stress absorbent elements modifying the stress transmission properties of implants.

The in vitro examination of the physical properties and deformation of various plastic materials was performed. A part of the tested materials was already in use in various

implant systems, another part of the materials included in the study had potentially good mechanical properties and were therefore candidates to be used as implant stress absorbents. The materials studied were: polyethylene (PE), polypropylene (PP), poly(oxy-metilene) (POM), poly(acryl-nitrilco-stirol)-block-polybutadiene (ABS), polyamide-6 (PA), polyimid (PI). The tests were done with an MTS mechanical test equipment with static and mechanical axial loading. The temporal changes in the deformation of the plastic materials were determined, the work produced during the individual cycles was calculated as well as the energy absorbed during deformation. Stress transmission was demonstrated using the photoelastic method.

3.4.2. Investigating fatigue phenomena in the area of the bone-implant interface as a result of cyclic loads.

Model implants were manufactured based on the shape determined in an earlier finite element study. To model the bone-implant interface implants were glued into cloth-based phenol cylinders, the elastic properties of which are close to those of bone. An Instron 8872 (Instron Corporation, Norwood, Massachusetts, USA) loading device was used. Similar to the numerical analysis implants were loaded with a dynamic force resulting from the superposition of the forces at a right angle with each other in 50000 cycles using constant preloading.

3.4.3. Investigating the fracture risk of the cervical portion of temporary titanium implants.

Titanium test objects and a loading device were designed and manufactured to model the cervical part of the implant, most prone to fracture based on the prototype of temporary implants. During the study the model implants were subjected to bending forces so that one end of the test objects were strongly fixed and a loading arm was fixed to the other end. Varied forces were applied to this latter end, so that the torque exerted on the on the cross section weakened by an incision remained constant, irrespective of the dimensional changes of the object. The loading forces and the bending angle characteristic of deformation were registered. Safe geometric parameters were determined by calculations based on these data.

4. RESULTS

4.1. A study of implant stability and osseointegration with the Periotest method. A study of the immediate loading of implants.

The success rate of implants involved in the study is currently 96.1%, all the implants in immediate loading are free of infection and function well.

Based on the statistical evaluation of the Periotest results the following statement could be made:

1. There is a significant difference between the stability of implants placed in the upper and lower jaws: implants in the lower jaw had significantly lower Periotest values and are therefore more stable. The mean of Periotest values (PTV) in the upper jaw: -0.5889, standard deviation: 1.772; n=11; in the lower jaw mean PTV: -4.2136, standard deviation: 2.279; n=48, significance level: p<0.0001.
2. In case of higher insertion torque values significantly lower Periotest values were seen, therefore implants were more stable. (p<0.0001) (Figure 1.).

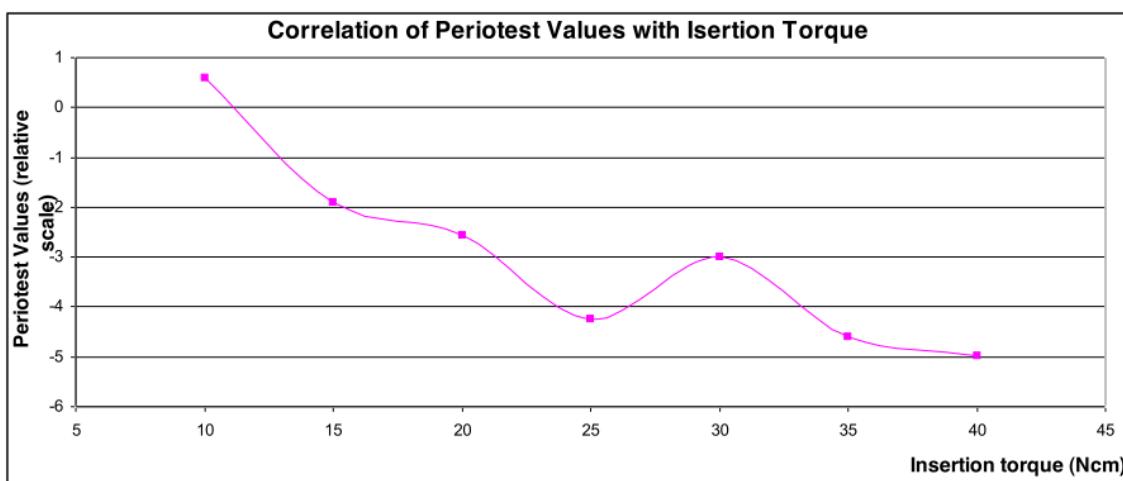


Figure 1. Correlation of implant insertion torque and Periotest values.

3. In cases of immediate loading the stability measured during surgery was significantly higher than in other cases: mean PTV of immediately loaded implants -5.480, standard deviation: 0.8654; n=15; mean PTV of implants with delayed loading: -2.755, standard deviation: 2.919; n=54, significance level: p<0.0001.

4. When examining the temporal changes in Periotest values it can be stated, that the curve had a statistically determined course in relation to time, the probability of a type I error: $p<0.0001$ (Figure 2.). There is a diminishing tendency for approximately 9-12 months and values remain statistically the same after this period. The number of implants with a longer follow-up period was lower, so further assertions can only be made based on the future continuation of the study.

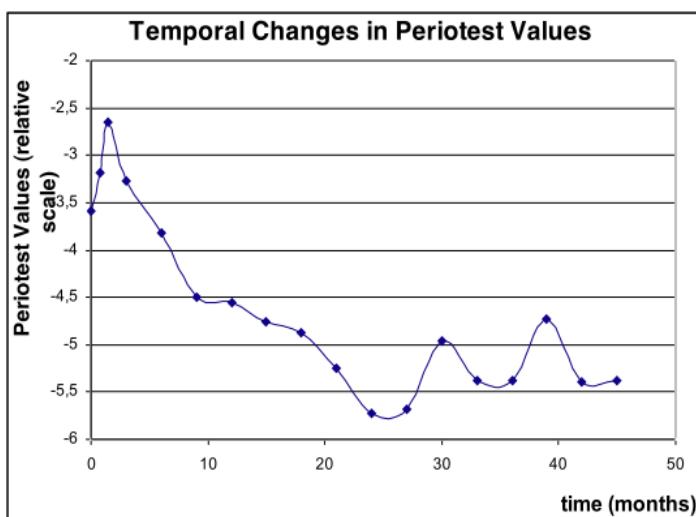


Figure 2. Temporal changes in Periotest values

5. No significant differences were seen on the following characteristics (in all cases: $p>0.5$):

- intraoperative stability of one and two piece implants
- the stability of implants placed on different sides in view of implant position
- the stability of implants in the various regions (frontal, premolar, molar) (very low number of implants),
- the size of implants (the number of implants in the individual groups was very low).

Proper primary stability is a very important but not the only condition of immediate loading. The Periotest method is a reliable indicator, according to the present study, of implant stability and is suitable to numerically characterise and document it. The detectability of minor changes in stability with the method is questionable, but it shows well any significant loss of stability that might require quick action. Due to the low number of cases it is not possible to evaluate the prosthetic method used in immediate

loading in the present study, but it was successful in all the cases and patient comfort was increased.

4.2.1. A photoelastic study of the mechanical stress transmission of implants with various geometric design to the jaws.

The stress distribution patterns of the tested stepped design DIAKOR® implants were similar to each other, stress values were at their highest in the apical region and peak stresses were observed at the top of the steps as well. Stresses are lower next to larger implants and their distribution is more even. Comparing stepped and screw design DIAKOR® implants of similar dimensions the stress transmission of the stepped version seemed to be more favourable. Peculiarities of the thread design might be the cause for this finding. DIAKOR® implants are not in use any more, but conclusions can be drawn concerning the stress transmission of stepped design implants from the present study.

In the second series of experiments the effect of osseointegration on stress transmission were demonstrated. It can be stated that the stress transmission properties of the glued implant, which is a model of the osseointegrated implant are more favourable, as higher stress values are present in the cervical region, where there is compact bone that has a higher stress bearing capacity, but at the same time there is force transmission along the threads as well. Stresses mostly occur around the apical part of the implant in the case of non-glued ‘non-osseointegrated’ implants. This might evoke overloading in the spongy bone that has weaker mechanical properties together with its consequences (microinjury, bone resorption).

4.2.2. A finite element study of the mechanical stress transmission of implants with various geometric design to the jaws.

In the first series in the 2D study a more even distribution of tensile and compressive stresses was found next to rounded thread profiles when comparing three different thread designs. Various loading methods significantly influenced the stresses that developed. Upon lateral loading the larger implant diameter and thread depth proved to be more favourable. Comparing implants with various thread designs it can be concluded that the stress distribution only differs significantly in the very near bony environment. The tensions are only characteristic of the thread design around the implant-bone interface within 0.5 mms, further away the stress peaks disappear. In the

three-dimensional experiments examining different thread profile implants, tensions were lower by 20-25 per cent in larger diameter implants with rounded profiles. Comparing different modes of loading when the load is only on the implant neck, higher tensions appeared only surrounding the implant neck closer to the alveolar ridge and around the apical part of the implant. In reality load is probably transferred in a shared way and in this case the present study showed a more even stress distribution. In the second test series a dynamic geometric model was created that can be parameterized easily whereby spongy bone can be modelled as well. Outstandingly high stresses were demonstrated at sharp thread profiles. The rounded square thread design appeared to be the most advantageous, stress distribution was the most even along all the surface in the case of the compression screw.

4.3.1. Creating finite element jaw models using the dataset of volume tomography scans to judge the load-bearing capacity of the jaws considering individual anatomical features.

The study shows that in the load bearing areas stress is mainly increased in the cortical bone. Stress values are indicative of fatigue, fracture, resorption and remodelling processes. The developed method is suitable to create a finite element network showing the individual geometry of the jaw for subjects of different ages based on CBCT images; to transmit muscular forces through the insertion of the masseter muscle and to determine the mechanical stress distribution in the jaw by simulating masticatory forces in the first molar area. Based on the CBCT data set, it was possible to analyse stress conditions based on properties unique to age groups and taking into consideration individual mechanical properties, too.

Based on the mechanical stresses induced by a masticatory force of 100 N it can be stated that stresses are usually within physiological limits. A dangerous level of mechanical stress (above 3000 microstrain) was only approached or reached in certain areas: the external oblique line on both sides at the ages of 12 and 20 years (2633-3197 microstrain), and the mandibular neck on the bite side on the jaw models of 12 and 67 years (3228 and 3498 microstrain). In the subcondylar area of the 12 year-old patient relatively high values of deformation occurred on both sides: on the opposite side of the bite, 3949, while on the bite side 2257 microstrain. The highest values of deformation were seen in the articular process of the 12 year-old boy's model: 18800 microstrain,

which is the border of fracture risk, but very high strain (8532 and 4031 microstrain) was also reported for the 67 and 20 year-old patients respectively. High tensions in the condylar process can be explained by the lack of modelling of the articular discus.

The following statements can be made concerning the results of this study:

1. Our model indicates a more flexible structure in younger age, represented by a higher susceptibility to deformation and stretch values.
2. In case of loading in the first molar area the highest stress values are found in the contralateral mandibular neck and subcondylar areas.
3. Reactionary forces induced by the masticatory muscles become higher with the progression of age. The distribution of forces on the bite side shifts: forces in the condylar area rise, and those in the first molar area are diminishing.
4. At a bite force of 100 N the forces evoked on both condyles are higher than the masticatory force itself
5. The stress and deformation of the peaks in the model made of the 67 year-old patient are lower at the front edge of the articular surface indicating an increased bone density in this area.
6. The load bearing role of the symphysis area does not change with age, as in this area there is no change in the degree of stress and deformations.
7. The reduction in the cross-section of the mandibular corpus with age level of stresses and deformations on the bite side.

4.3.2. Surgical and loading simulation based on the finite element model: the effect of surgical removal of lower third molars on the stresses arising upon masticatory loading.

The external oblique line is the physiological stress transmission zone as seen in the pre-intervention model. The stresses are concentrated under the surface layer of the cortical plate. The cortical bone on the medial side of the third molar has no significant load bearing role in the usual masticatory process. Peak stress values arising during loading on the operated side can double if an extensive ostectomy is performed in the area of the. Peak stress values in the operated region can be triple of the pre-intervention values if loading is on the contralateral side. The latter observation is important in clinical practice. In critical cases, when large amounts of cortical bone are removed

from the buccal area, patients' attention has to be drawn to the fact that excessive loading of the contralateral area may convey an increased fracture risk.

4.4. Laboratory model studies to investigate the stability and force transmission properties of implants:

4.4.1. Investigating the fatigue phenomena occurring in plastic stress absorbent elements modifying the stress transmission properties of implants.

Thermoplastic polymers deform momentarily upon loading, and then, when the stress is over, permanent deformation is seen. During the course of repeated loading permanent deformations are additive. In mechanical terms the applicability of mechanical stress absorbents depends on two factors, the rate of deformation and the energy loss per cycle.

Polyethylene (PE) shows a very large deformation under stress. High deformation also means a high loss. Polypropylene (PP) is much less deformed and shows less loss, but even this loss is relatively high compared to other tested materials. Poly(oxy-methylene) (POM) and polyamide (PI) used in clinical practice behave almost identically. ABS shows the same degree of deformation, but the loss of approximately 20% higher. The deformation of polyimide is twice larger under the same conditions. It can be concluded that out of the materials used in practice, only polyethylene is not suitable for use as a stress absorbent based on its mechanical properties. The energy absorption of the material, although very high, the deformation is excessive and in part permanent. The prosthesis, therefore, becomes loose, which promotes plaque accumulation and might cause damage to the prosthesis. The other material used is poly(oxy-methylene), which has small deformation and small loss, its mechanical properties are appropriate. Out of the rest of the materials tested ABS, polyamide, and polyimide also seem to be suitable. The mechanical properties of ABS appear to be the most advantageous, however, its yellowish colour may be a disadvantage. The permanent deformation of polypropylene is excessive, but it can be positively influenced by additive and other materials.

4.4.2. Investigating fatigue phenomena in the area of the bone-implant interface as a result of cyclic loads.

Typical charts can be created from the displacement values of model implants during load cycles, which makes it possible to assess the various thread profiles from the point of view of loosening. Deformation of ‘decreasing thread depth’ implants (the implant neck area has virtually no threads) shows a continuously growing tendency right from the outset of loading. However, the displacement amplitude is only 0.011 to 0.017 mm. For the ‘saw thread’ design the displacement charts have a slope almost parallel with horizontal axis for almost all the time and a mild rise is only seen in the last third of the test, that suggest loosening in that phase. The amplitude of displacement is almost linear in the ‘near metric thread’ case thus there was no sign of loosening. It may be stated that the degree of absolute deformation detected in the present series of experiments was not significant in either of the cases. In the case of the ‘decreasing thread depth’ implants the reason for continuously increasing deformation might be that normally the most load is born by the first threads, which condition cannot be fulfilled in this case. The best results were obtained from the near-cylindrical implant in the present study. Based on the result concerning the cervical threads on implants it can be concluded that the area in connection with cortical bone is of prime importance in the stress transmission of implants.

4.4.3. Investigating the fracture risk of the cervical portion of temporary titanium implants.

Calculations were performed based on the applied loading force and the bending caused by it in the model implant. Evaluating the results it can be concluded that the test model, the maximum strain (ϵ_{max}) is greater than the shear strain ϵ_b stated in the material certificate and acquired by material testing, so there is a possibility of fracture, which occurred once during the tests. Based on the results of the investigation it was necessary to examine the effect of enlarging the groove: if the necessary angle of deflection is $\phi = 20^\circ$, then, if $s = 1.2$ mm then $\epsilon_{max} = 34.90\%$, while if $s^* = 2.2$ mm then there is a $\epsilon_{max} = 19.04\%$, i.e. maximum elongation does not reach the ϵ_B elongation value stated in the material certificate. It is suggested that the length of the groove be increased by 1 mm to reduce the risk of fracture. It can be stated that the test pin was not in balance: had the

test been continued for a longer period of time distortion would have continued until the destruction of the pin. Therefore pins should be bent carefully and, ‘overbending’ should be avoided.

5. CONCLUSIONS

1. The stability of dental implants was characterized quantitatively, to help assess the possibility of early loading, indicating the changes in osseointegration, the possible failure of technical components, thus facilitating the prevention of complications. The Periotest method may be a useful tool in daily patient care and scientific research as well.
2. Comparing implants with different geometry using finite element analysis and the photoelastic method conclusions were drawn concerning the geometric characteristics of a favourable stress transmission implant. A computer software was developed that is capable of modelling various thread designs and their bony surroundings, the concept of porosity was introduced to imitate spongy bone tissue. Correct implant geometry is fundamental in the success of implant prosthetics. Future research will certainly yield a lot of information in this field, resulting in improved design of implant shapes.
3. A method was developed to model the jaw that is capable of creating the 3D finite element model of the jaw based on CT data sets. Differences were found in the biomechanical characteristics of jaw models acquired from data of patients of different ages. The method can be the basis of versatile surgical simulation studies, thus the effect of trauma, mutilating surgery or developmental anomalies can be studied and various reconstruction devices can be modelled. It may become possible to plan surgery and treatment on an individual basis founded on the mechanical properties of the patient.
4. Finite element analysis was used to analyse the effect of removal of unerupted lower wisdom teeth on the stresses developing in the mandible and the possibility was developed to preoperatively scan patients with a higher fracture risk. The simulation confirms the practical usefulness of the finite element method.

5. The mechanical properties of stress absorbent plastic components, used in implants, were tested. The fatigue characteristics of potentially relevant materials were established, and a recommendation was made for more suitable plastic materials.

6. In laboratory fatigue testing during cyclic loading differences were shown between the various implant thread designs, also studied in the finite element series. Thread shapes, as part of implant geometry, are an important factor in the development of load-bearing properties and thus deserves special attention.

7. Bending of the neck area of temporary implants was studied in laboratory measurements. Based on the results recommendations were made to modify this area of geometric design and to prevent fractures. Apart from optimising the stress transmission of implants to the environment, the mechanical stability of the implant and parts is also of utmost importance. Data were provided for improvement in this field as well.

List of own publications

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