Eur. J. Prosthodont. Rest. Dent., Vol.17, No. 2, pp 50-57
Printed in Great Britain

Biomechanical Methods Applied in Dentistry: A Comparative Overview of Photoelastic Examinations, Strain Gauge Measurements, Finite Element Analysis and Three-dimensional Deformation Analysis

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Abstract - *The aim of this article is to illustrate and discuss current methods applied in the analysis of biomechanical components in dental applications. For illustration purposes, the strain development of a non-passively fitting implant supported fixed restoration was evaluated using the four techniques: photoelastic examination, strain gauge measurements, finite element analysis, and three-dimensional deformation analysis. Photoelastic analysis only allowed for a raw estimation of the strains evoked by superstructure fixation. Quantitative results could be derived from both strain gauge measurements and three-dimensional deformation analysis which could then be used to simulate the loading situation around the supporting implants.*

KEY WORDS: Photoelastic examination, Strain gauge, Finite element analysis, Three-dimensional deformation analysis, Biomechanics

INTRODUCTION

The study of biomechanics is critical to medical material sciences. Understanding how living tissue reacts to and interacts with external forces or artificial devices requires particular scientific research techniques. This requisite is a considerable challenge for existing measurement technologies.

Today various techniques are applied in biomechanical research both, for *in vitro* and *in vivo* investigations. No single technique meets all the requirements for displaying the extensive physiological interactions involved. The availability of high-capacity computer systems has enabled complex analytical methods in biomechanics such as photogrammetry and finite element analysis (FEA)[1-3]. However, numerous investigations can still be found in the literature using more traditional techniques such as photoelastic analysis and strain gauge (SG) measurements[4-7]. To be able to judge the significance of biomechanical measurements reported in the literature, it is necessary to understand the strengths and shortcomings of each technique.

The purpose of this paper is to discuss four applications applied in the analysis of biomechanical components in dentistry; photoelastic examination, strain gauge measurements, finite element analysis, and three-dimensional deformation analysis. In addition to information derived from the literature, all of the techniques were applied to analyse the strain situation around dental implants as evoked by the fixation of a non-passively fitting superstructure. Prior investigations had shown that it is impossible to fabricate implant superstructures exhibiting a passive fit on the supporting implants without any deformations being caused during fixation[7,8]. The lack of passive fit is still considered as a possibly detrimental factor for long term implant success, both from a technical and biological perspective[9].

A plain model consisting of photoelastic resin with two dental implants embedded was fabricated. According to standard clinical protocol a three-unit cement-retained restoration was manufactured to fit the model situation. It was expected that the fixation of the restoration causes a certain level of misfit stress in the model material surrounding both implants which could be analysed using all of the above techniques.

Photoelastic analysis

Photoelastic analysis is an inexpensive and easy-to-use visual technique that produces contours of principal stress differences. A polariscope is employed to view an object consisting of photoelastic resin under a certain load (Fig 1). The emerging isochromatic fringe patterns in the material are photographed and interpreted (Fig 2, Fig 3). In addition to the stress locations, stress intensity and stress concentrations can be interpreted based on colour, number, and closeness of the emerging fringes[6,10].

Photoelastic analysis has been extensively used in different fields of biomechanics and several reviews dealing with the technique can be found in the literature[11-13]. This traditional method of analysis has been applied for the evaluation of osteosynthesis devices[14], the fit of artificial legs[10] and forces acting on knee joints[15]. In dentistry, this technique has been

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Table 1. *Advantages and disadvantages of biomechanical methods.*

	Photoelastic analysis	*Strain gauge measurement s*	*Finite element modeling*	*Photogrammetric analysis*
Advantages	• Easy to use and inexpensive • Provides a general idea of a mechanical problem • Displays loading conditions within an object	• Quantitative assessment • Data can be used for mathematical procedures • Can be used for *in vivo* applications	• High level of accuracy • Different stress states can be displayed • Objects with different mechanical parameters can be investigated • Catastrophic events and unethical experiments can be simulated	• Non-contact and full-field • Independent of rigid body movement • Visualize strain gradients and 3D details • Test non-homogeneous and anisotropic materials • Study tissues and organs, *in vitro* or *in vivo* • Verify and iterate finite element models
Disadvantages	• Can not be applied *in vivo* • Requires the use of photoelastic resin • Internal residual stresses may falsify measurement results • Quantitative measurements can hardly be conducted	• Size of the gauges limits application on small objects • Different forces may lead to similar readings of unidirectional strain gauges	• Geometry of objects has to be transferred to a mathematical model • High amount of computer memory is needed • Assumptions regarding material parameters (isotropy, Young's modulus) have to be made	• Application of surface pattern • Surface measurement only • Region of interest must be located in view of cameras

used to investigate splinting techniques for traumatized teeth[5], rotary files for root canal preparation[16], endodontic post systems[17,18] and stress development in composite restorations[19,20]. Several studies related to implant dentistry have used photoelastic anaylsis to investigate the effect of implant abutment angulation[21], implant-abutment interface design[4], retention mechanisms[8] and the performance of implant-tooth supported fixed partial dentures upon load transfer[6].

When applying photoelastic analysis, the specific disadvantages of the technique have to be considered. The need for photoelastic resin limits its application to *in vitro* investigations of plain models. Small objects like dental implants or the anatomy of a root canal cannot easily be reproduced with a sufficient degree of accuracy. Furthermore, internal stresses inside photoelastic replications often lead to fringe patterns (Fig 2).

When the two-implant model fabricated for illustration purposes was placed in the polariscope, residual stresses in the model material could be observed around both implants (Fig 2). After fixation of the restoration on the implant abutments, significantly different fringe patterns were recorded (Fig 3).

Strain gauge measurements

Strain gauges consist of a meander of conducting material deposited on a plastic backing film. The gauge is attached to an object by means of an adhesive. The electrical resistance of the conductor depends on its cross-sectional area. Under tensile or compressive forces, this is altered, resulting in a different electric current that is measured using a Wheatstone bridge configuration which is integrated in a measurement amplifier (Fig 4).

Numerous applications of this technique can be found in the literature, including strain gauge venous occlusion plethysmography[22], biomechanical analysis of fracture fixation[23], studies on the constraint of the tibio-femoral joint

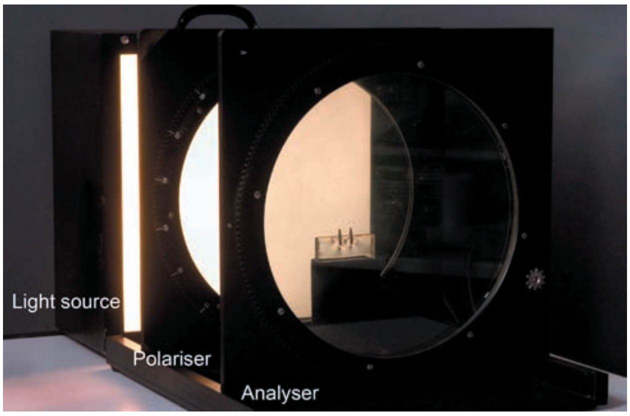


Figure 1. *View of a polariscope used for photoelastic investigations, with a model placed between polariser and analyser.*

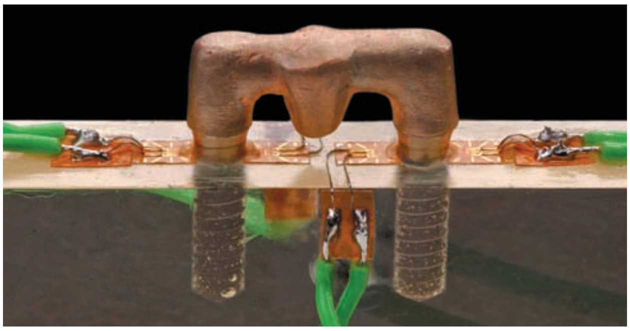


Figure 5. *Photoelastic model equipped with unidirectional strain gauges mesially and distally adjacent to the implants and cement-retained fixed partial denture seated on the implant abutments.*

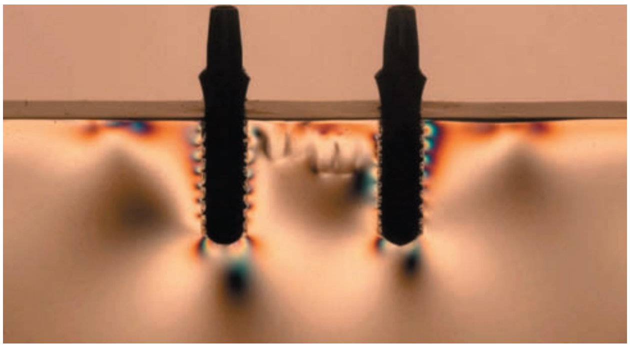


Figure 2. *Model situation with two dental implants embedded in a photoelastic resin. Internal residual stresses can be seen although the implants are not loaded.*

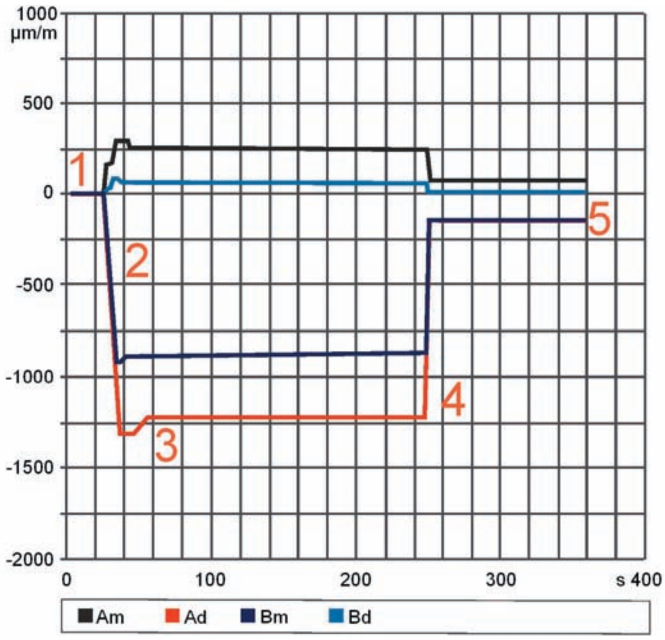


Figure 6. *Screenshot showing the strain gauge signals during the fixation of the implant supported restoration. First, the strain gauges are set to zero (1), then the restoration is seated (2) and loaded during cement setting (3). After a certain period of time, the restoration is relieved (4) and the cement is allowed to set for another few minutes before the experiment is finished (5).*

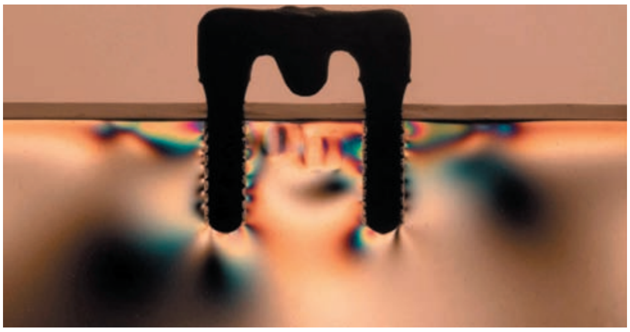
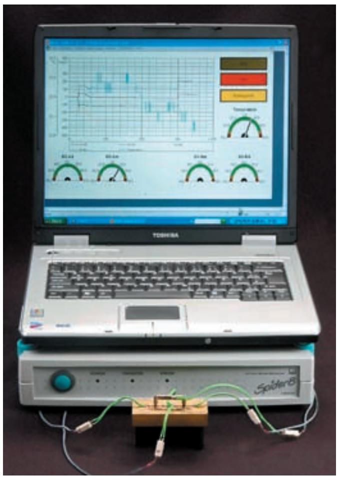


Figure 3. *Non-passively-fitting fixed partial denture placed on the implants. The alterations regarding the stress state compared to the unloaded situation are obvious.*

Figure 4. *Measurement amplifier used for strain gauge measurements and portable computer with analysing software.*



in dynamic movement[24], calculation of tibial loading[25], and measurement of the shear forces on the heel[26].

In the dental field, strain gauge measurements have been utilized to evaluate the effect of air-particle abrasion[27] and relining[28] on the performance of dentures, to investigate preloads of screws [29,30], to study polymerization shrinkage of composites [31], to record root deformation during endodontic treatment[32], to observe bone loading around dental implants under different conditions (Fig 5) [4,7,9,21,33], and to compare the accuracy of different impression techniques[34].

In comparison to photoelastic measurements, the numerical data gained from strain gauge signals (Fig 6) can be used for quantitative comparisons and as a basis for finite element calculations [35,36]. However, the size of the strain gauges makes them difficult to install in small-scale dental applications. For this reason, a common source of error is the limited area over which the strains are measured, which may not be located in the precise region of interest e.g. the implant-bone interface [21]. Additionally, unidirectional gauges are often used instead of strain gauge rosettes, which do not allow differentiation between the various forces acting on the sensor[21]. Several authors have found a good correlation between strain gauge measurements and photoelastic examinations[21]. Nevertheless, the classification of the isochromatic fringes in photoelastic measurements appears to be questionable, although the use of digital cameras may have brought some improvements[5]. Therefore, photoelastic analysis merely allows for qualitative assessments[6]. For the *in vivo* application of strain gauges, care has to be taken to avoid artefacts caused by mechanical disturbances or saliva[35,36]. Additionally, the temperature sequence should be recorded in order to be able to compensate for changes in strain gauge signals due to temperature changes.

In the model situation presented, unidirectional strain gauges were attached on the model material mesially and distally adjacent to the implants in order to analyse the strain developed following the fixation of the implant-supported restoration (Fig 5). During the cementing procedure, the strain developed was recorded using a measurement amplifier (Fig 4) and analysing software. The strain could be monitored throughout the cementing procedure (Fig 6).

Finite Element Analysis (FEA)

Finite element analysis was developed in the 1960s to solve structural problems in the aerospace industry. Subsequently, it has been used extensively for medical and dental applications[37,38]. Various authors have summarized the basic principles of FEA[2,39]. Cardot et al. applied this method to analyse lower limb response in car-bicycle accidents[40]. It has also been used to describe the mechanics of the normal heart[41], to model impact and shaking of a child's head[42] and to optimize the fit of artificial extremities[43].

In the dental field, FEA was mainly used to study load transfer between dental implants and prostheses with respect to their supporting tissues[2,39,44,45], to investigate vertical root fractures[46], and to study strains in proximal enamel of mandibular premolars[47].

The principle of this numerical method is to divide the system of interest; involving complicated geometries for which no simple analytical solutions can be found, into smaller and simpler domains. Mathematical functions for each finite element are set up and combined in order to obtain a description of the whole body[39]. For this numerical approach a number of assumptions must be made, which in itself can compromise the reliability of this method.

To utilize the FEA method, the geometry of the object to be studied must first be transferred into a numerical model, a process requiring both time and skill. Additionally, element downsizing for the creation of models with increased validity requires computer memory and calculation time[1]. To achieve FE models which most accurately duplicate reality computed tomography (CT) images can be constructed to assist in the finite element modelling [3,48].

The material properties of modelled structures, including inner architecture, Young's modulus, and shear moduli and the boundary conditions of the virtual objects may greatly influence the stress and strain distribution[2,39,49]. However, for cortical and trabecular bone reliable and uniform material parameters are missing[2].

Different studies evaluating the comparability of strain gauge measurements and finite element analysis have been conducted with antithetic results. Good correlations between numerical and strain gauge analysis have been reported for displacement measurements on dental implants[50], deformation analysis of the mandible[49], and in the evaluation of stresses occurring in teeth under dynamic loading[47]. On the other hand, Akca et al. found differences between both methods in the quantification of strains on a dental implant[45], and Lertchirakarn et al. detected noncompliance for the evaluation of root surface stresses[46]. A partial agreement between FEA and strain gauge analysis was found for predicting strains in an implant-abutment complex[51].

In order to analyse the strains occurring at the implant-bone interface as a consequence of superstructure fixation, a three-dimensional FE-model was set up resembling the master model made out of photoelastic resin. One implant was cut out free for the application of vertical loads (Fig 7). Bone was considered as an isotropic material with cortical and trabecular layers differing in Youngs modulus (Trabecular bone: 3 GPa, Cortical bone: 17 GPa, Implant: 100 GPa, Restoration: 160 GPa). By altering the load magnitudes it was possible to simulate the strain values measured in the strain gauge experiment. Von Mises equivalent stress was chosen to display the loading situation around the supporting implants (Fig 8).

Three-dimensional deformation analysis

Full-field three-dimensional (FF3D) optical inspection systems combine increased computer power with high-resolution digital cameras to provide the measurement of strain for industrial and biomedical applications[52,53]. A single-point gauge cannot demonstrate strain gradients, and may miss critical details, particularly with the non-homogeneous and anisotropic materials used in biomechanics. The two-dimensional results of moiré patterns, electronic speckle pattern interferometry, and digital image correlation can only provide simple in-plane deformation measurements and are very sensitive to movement of an object[54]. Whereas three-dimensional (3D) image correlation provides the

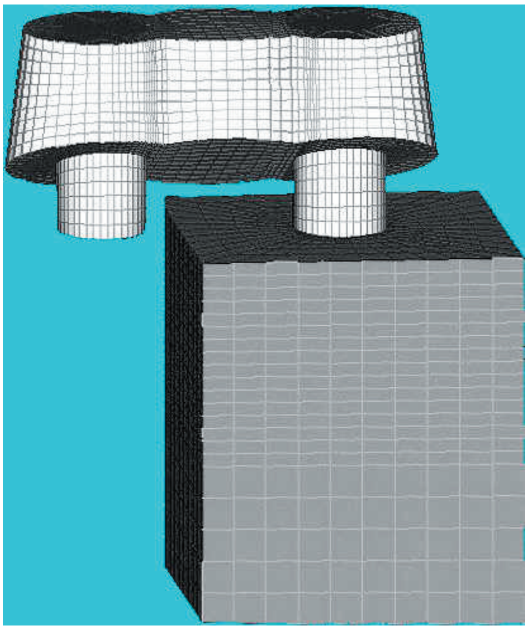


Figure 7. *Finite element model displaying a three-unit implant-supported restoration. The left implant is cut free, allowing for the introduction of inner preloads by a vertical force acting on the respective implant. In doing so, it is possible to simulate the measured strains caused by superstructure fixation.*

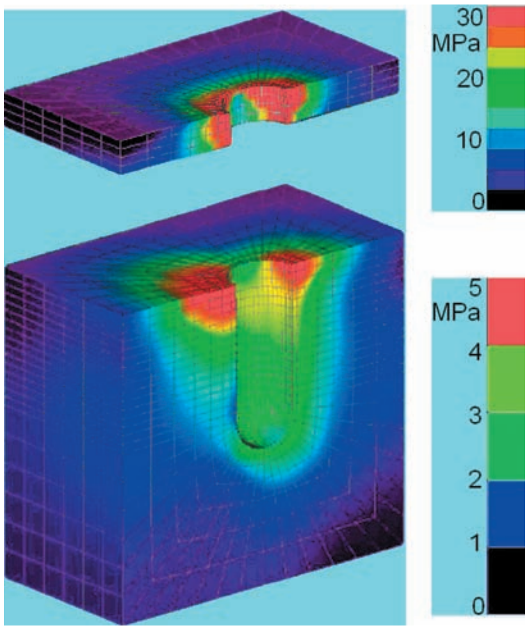


Figure 8. *Specific loading situation around a supporting implant shown as von Mises equivalent stress. In the cortical layer, stress values of up to 30 MPa are reached, whereas in the trabecular layer, stress values of up to 5 MPa were recorded.*

strain measurements in all dimensions, which are critical for accurate strain and loading response measurements in objects. The results of these optical measurements are compatible with finite element analysis software, and facilitate verification and iteration of models.

In FF3D strain analysis, a pair of synchronized high-resolution digital charge coupled device (CCD) cameras, which measure the sample's 3D coordinates and 3D deformations, image the sample. The key to 3D image correlation is that it tracks changes in an applied micro-pattern (stochastic pattern), rather than a projected pattern. This surface pattern changes when the object deforms under an applied load. The pattern is recorded by the CCD cameras and then evaluated. The initial image processing defines unique correlation areas known as macro-image facets (approximately 5-20 pixels square) across the entire imaging area. Each facet center is a measurement point that can be thought of as an extensometer point and strain rosette. These facets are tracked in each successive image with sub-pixel accuracy. Then, using photogrammetric principles, the 3D coordinates of the entire surface of the specimen are precisely calculated[52,53,55]. The results are the 3D shape of the component, the 3D displacements, and the plane strain tensor of every point on the surface of the object. The motion of the rigid body has no effect on the measurements but can also be calculated from the original pixel registration. In fact, as long as the surface pattern is unaltered, measurements can be continued after a component has been removed, processed, and replaced within the camera viewing zone[53,56].

Full-field 3D strain analysis has been applied in medical applications from measuring the effect of an axial pre-torque on facet capsular strains and estimating the risk for subcatastrophic capsular injury[57], to evaluation of the mechanical behaviour of arterial tissue[58] and the mechanical properties of chordae tendineae under physiologic loading conditions[59]. In dentistry, photogrammetry has been used predominantly for digital surface analysis of the human face[60,61], *in vitro* model based 3D measurements of the jaws[62,63], and display of movement in implant impressions[56]. Initial attempts have also been made to establish photogrammetry as an alternative for conventional implant impression techniques[64,65].

While comparison and verification of FE models and calculations via optical three-dimensional inspection systems is standard procedure in industrial applications, such studies are currently lacking in the field of dental biomechanics.

To display the applicability of the technique in the current model situation, a black and white stochastic pattern was applied to both the resin block and the restoration (Fig 9). Digital photographs were taken prior to and after seating of the restoration on the implants. From the data set obtained, the major strain, minor strain and comparable total strains, X,Y,Z displacements and the component shape could be analyzed and displayed or exported as full-field data (Fig 10).

CONCLUSION

Experimental analysis of biological specimens has already led to valuable findings that have improved medical and dental devices and techniques. Nevertheless, the complexities inherent in materials like bone, and demanding test settings such as multi-axial loading experiments preclude the use of only one technique. Additionally, the structures of biomechanical samples are often quite complex so that solely theoretical models cannot regard all aspects of a sample. Only by combining results from different analytical

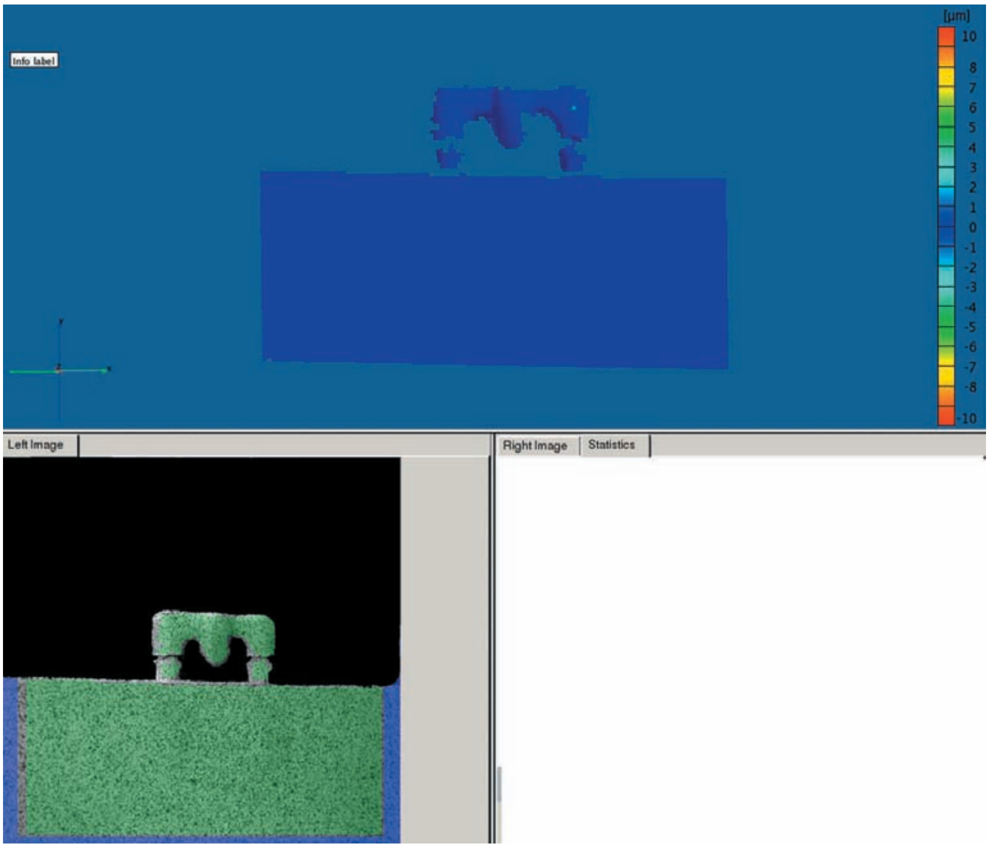


Figure 9. *Three-dimensional image correlation camera pair, ready for measuring of the test object. The resin block is prepared with a stochastic pattern of black and white areas sprayed onto the model surface.*

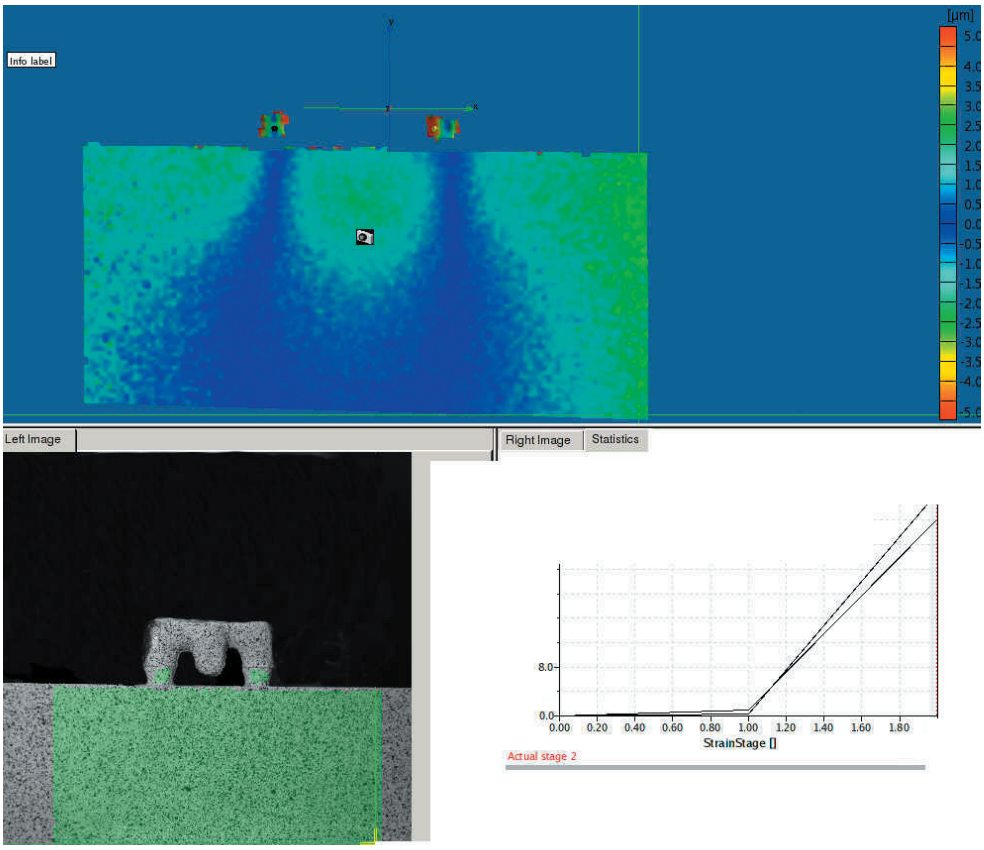


Figure 10. *Camera view of the test object during the actual data collection (left). The inspection area is overlaid with the measurement grid, where each point represents the center of a macro-image facet (top). This grid correlates well with the FEM (finite element model) mesh of the computer models.*

methods can statistical material properties be established, local effects analyzed, and resultant models verified. The combination of techniques (Photoelastic analysis, Strain gauges, Finite element analysis and Full-field three-dimensional optical inspection) will, in the future provide a much more reliable basis for interpretation of results and for application in vivo.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Dr. W. Winter, Institute of Applied Mechanics, Friedrich-Alexander-University Erlangen-Nuremberg for his invaluable support and suggestions.

MANUFACTURERS´ DETAILS

- Photoelastic resin: Araldit, Ciba-Geigy, Wehr, Germany
- Dental implants: Straumann solid screw implants 4.1mm diameter, 12mm bone sink depth, Institut Straumann AG, Basel, Switzerland
- Strain gauges: LY11/120, Hottinger Baldwin Messtechnik, Darmstadt, Germany
- Measurement amplifier: Spider 8, Hottinger Baldwin Messtechnik, Darmstadt, Germany
- Analysing software: BEAM for Spider, AMS GmbH, Flöha, Germany
- FE program: MSC Nastran, MSC Software Corporation, Santa Ana, CA, USA
- Photogrammetric system: ARAMIS, GOM Gesellschaft für optische Messtechnik, Braunschweig, Germany

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REFERENCES

1. Sato Y, Wadamoto M, Tsuga K, Teixeira ER. The effectiveness of element downsizing on a three-dimensional finite element model of bone trabeculae in implant biomechanics. *J Oral Rehabil* 1999 **26**: 288-291.
2. DeTolla DH, Andreana S, Patra A, Buhite R, Comella B. The role of the finite element model in dental implants. *J Oral Implantol* 2000 **26**: 77-81.
3. Shimizu Y, Usui K, Araki K, Kurosaki N, Takanobu H, Takanashi A. Study of finite element modeling from CT images. *Dent Mater J* 2005 **24**: 447-455.
4. Cehreli M, Duyck J, De Cooman M, Puers R, Naert I. Implant design and interface force transfer. A photoelastic and strain-gauge analysis. *Clin Oral Implants Res* 2004 **15**: 249-257.
5. Cengiz SB, Atac AS, Cehreli ZC. Biomechanical effects of splint types on traumatized tooth: a photoelastic stress analysis. *Dent Traumatol* 2006 **22**: 133-138.
6. Ochiai KT, Ozawa S, Caputo AA, Nishimura RD. Photoelastic stress analysis of implant-tooth connected prostheses with segmented and nonsegmented abutments. *J Prosthet Dent* 2003 **89**: 495-502.
7. Heckmann SM, Karl M, Wichmann MG, Winter W, Graef F, Taylor TD. Cement fixation and screw retention: parameters of passive fit – An in vitro study of three-unit implant-supported fixed partial dentures. *Clin Oral Implants Res* 2004 **15**: 466-473.
8. Guichet DL, Caputo AA, Choi H, Sorensen JA. Passivity of fit and marginal opening in screw- or cement-retained implant fixed partial denture designs. *Int J Oral Maxillofac Implants* 2000 15: 239-246.
9. Karl M, Winter W, Taylor TD, Heckmann SM. In vitro study on passive fit in Implant-supported five-unit fixed partial dentures. *Int J Oral Maxillofac Implants* 2004 **19**: 30-37.
10. Sewell P, Vinney J, Noroozi S, Amali R, Andrews S. A photoelastic clinical study of the static load distribution at the stump/socket interface of PTB sockets. *Prosthet Orthot Int* 2005 **29**: 291-302.
11. Orr JF, Humphreys PK, James WV, Bahrani AS. The application of photoelastic techniques in orthopaedic engineering. In: Hyde TH, Ollerton E (eds). Applied Stress Analysis. Barking: *Elsevier Applied Science*,1990: 111-120.
12. Orr JF. Photoelastic stress analysis. In: Workshop for strain measurement in biomechanics. The Canadian Medical and Biological Engineering Society Conference, Banff, Alberta 1991: 13-30.
13. Orr JF. Two- and three-dimensional photoelastic techniques. In: Miles AW, Tanner KE (eds). Strain Measurement in Biomechanics. London: Chapman and Hall,1992: 109-125.
14. Meyer C, Serhir L, Boutemi P. Experimental evaluation of three osteosynthesis devices used for stabilizing condylar fractures of the mandible. *J Craniomaxillofac Surg* 2006 **34**: 173-181.
15. Papachristou G. Photoelastic study of the internal and contact stresses on the knee joint before and after osteotomy. *Arch Orthop Trauma Surg* 2004 **124**: 288-297.
16. Anderson DN, Joyce AP, Roberts S, Runner R. A comparative photoelastic stress analysis of internal root stresses between RC Prep and saline when applied to the Profile/GT rotary instrumentation system. *J Endod* 2006 **32**: 222-224.
17. Cohen BI, Pagnillo M, Musikant BL, Deutsch AS. Comparison of the retentive and photoelastic properties of two prefabricated endodontic post systems. *J Oral Rehabil* 1999 **26**: 488-494.
18. Loney RW, Kotowicz WE, McDowell GC. Three-dimensional photoelastic stress analysis of the ferrule effect in cast post and cores. *J Prosthet Dent* 1990 **63**: 506-512.
19. Braga RR, Boaro LC, Kuroe T, Azevedo CL, Singer JM. Influence of cavity dimensions and their derivatives (volume and 'C' factor) on shrinkage stress development and microleakage of composite restorations. *Dent Mater* 2006 **22**: 818-823.
20. Tachibana K, Kuroe T, Tanino Y, Satoh N, Ohata N, Sano H, Caputo AA. Effects of incremental curing on contraction stresses associated with various resin composite buildups. *Quintessence Int* 2004 **35**: 299-306.
21. Clelland NL, Gilat A, McGlumphy EA, Brantley WA. A photoelastic and strain gauge analysis of angled abutments for an implant system. *Int J Oral Maxillofac Implants* 1993 **8**: 541-548.
22. Androne AS, Hryniewicz K, Hudaihed A, Dimayuga C, Yasskiy A, Qureshi G, Katz SD. Comparison of metabolic vasodilation in response to exercise and ischemia and endothelium-dependent flow-mediated dilation in African-American versus non-African-American patients with chronic heart failure. *Am J Cardiol* 2006 **97**: 685-689.
23. Ming JH, Zhou PH, Zhou JP. Biomechanical analysis of fracture fixation with external fixator in vivo. *Chin J Traumatol* 2006 **9**: 100-104.
24. Sobczak S, Gilbert B, Feipel V, Van Sint Jan S, Lefevre P, Salvia P, Rooze M. Development and use of the strain gauge for study the constraint of tibio-femoral joint in dynamic movement: Feasibility and first results. *Comput Methods Biomech Biomed Engin* 2005 **8**: 259-260.
25. Funk JR, Crandall JR. Calculation of tibial loading using strain gauges. *Biomed Sci Instrum* 2006 **42**: 160-165.
26. Nakagami G, Sanada H, Konya C, Kitagawa A, Tadaka E, Tabata K. Comparison of Two Pressure Ulcer Preventive Dressings for Reducing Shear Force on the Heel. *J Wound Ostomy Continence Nurs* 2006 **33**: 267-272.
27. Husham AM, Al-Bazirgan MH. Effect of air-particle abrasion on the retention and texture of the maxillary complete denture. *Am J Dent* 2006 **19**: 115-122.
28. Al-Ghannam NA, Fahmi FM. Effect of direct relining on stresses at the denture base and the metal frame of removable partial dentures. *J Contemp Dent Pract* 2005 **6**: 37-47.
29. Cehreli MC, Akca K, Tonuk E. Accuracy of a manual torque application device for morse-taper implants: a technical note. *Int J Oral Maxillofac Implants* 2004 **19**: 743-748.
30. Byrne D, Jacobs S, O'Connell B, Houston F, Claffey N. Preloads generated with repeated tightening in three types of screws used in dental implant assemblies. *J Prosthodont* 2006 **15**: 164-171.

31. Feng L, Suh BI. The effect of curing modes on polymerization contraction stress of a dual cured composite. *J Biomed Mater Res B Appl Biomater* 2006 **76**: 196-202.
32. Lin CP, Chou HG, Chen RS, Lan WH, Hsieh CC. Root deformation during root-end preparation. *J Endod* 1999 **25**: 668-671.
33. Stegaroiu R, Khraisat A, Nomura S, Miyakawa O. Influence of superstructure materials on strain around an implant under 2 loading conditions: a technical investigation. *Int J Oral Maxillofac Implants* 2004 **19**: 735-742.
34. Naconecy MM, Teixeira ER, Shinkai RS, Frasca LC, Cervieri A. Evaluation of the accuracy of 3 transfer techniques for implant-supported prostheses with multiple abutments. *Int J Oral Maxillofac Implants* 2004 **19**: 192-198.
35. Heckmann SM, Karl M, Wichmann MG, Winter W, Graef F, Taylor TD. Loading of bone surrounding implants through three-unit fixed partial denture fixation: a finite-element analysis based on in vitro and in vivo strain measurements. *Clin Oral Implants Res* 2006 **17**: 345-350.
36. Karl M, Winter W, Taylor TD, Heckmann SM. Fixation of 5-Unit Implant-Supported Fixed Partial Dentures and Resulting Bone Loading: A Finite Element Assessment Based on In vivo Strain Measurements. *Int J Oral Maxillofac Implants* 2006 **21**: 756-762.
37. Merouheh KA, Watanabe F, Mentag PJ. Finite element analysis of partially edentulous mandible rehabilitated with an osteointegrated cylindrical implant. *J Oral Implantol* 1987 **12**: 215-238.
38. Siegele D, Soltesz U. Numerical investigations of the influence of implant shape on stress distribution in the jaw bone. *Int J Oral Maxillofac Implants* 1989 **4**: 333-340.
39. Geng JP, Tan KB, Liu GR. Application of finite element analysis in implant dentistry: a review of the literature. *J Prosthet Dent* 2001 **85**: 585-598.
40. Cardot J, Masson C, Arnoux PJ, Brunet C. Finite element analysis of cyclist lower limb response in car-bicycle accident. *Comput Methods Biomech Biomed Engin* 2005 **8**: 47-48.
41. Tendulkar AP, Harken AH. Mechanics of the normal heart. *J Card Surg* 2006 **21**: 615-620.
42. Roth S, Raul JS, Ludes B, Willinger R. Finite element analysis of impact and shaking inflicted to a child. *Int J Legal Med* 2007 **121**: 223-228.
43. Portnoy S, Yarnitzky G, Yizhar Z, Kristal A, Oppenheim U, Siev-Ner I, Gefen A. Real-Time Patient-Specific Finite Element Analysis of Internal Stresses in the Soft Tissues of a Residual Limb: A New Tool for Prosthetic Fitting. *Ann Biomed Eng* 2007 **35**: 120-135.
44. Williams KR, Watson CJ, Murphy WM, Scott J, Gregory M, Sinobad D. Finite element analysis of fixed prostheses attached to osseointegrated implants. *Quintessence Int* 1990 **21**: 563-570.
45. Akca K, Cehreli MC, Iplikcioglu H. A comparison of three-dimensional finite element stress analysis with in vitro strain gauge measurements on dental implants. *Int J Prosthodont* 2002 **15**: 115-121.
46. Lertchirakarn V, Palamara JE, Messer HH. Finite element analysis and strain-gauge studies of vertical root fracture. *J Endod* 2003 **29**: 529-534.
47. Palamara JE, Palamara D, Messer HH. Strains in the marginal ridge during occlusal loading. Aust Dent J 2002 47: 218-222.
48. Rüegsegger P, Koller B, Müller R. A microtomographic system for the nondestructive evaluation of bone architecture. *Calcif Tiss Int* 1996 **58**: 24-29.
49. Al-Sukhun J, Lindqvist C, Helenius M. Development of a three-dimensional finite element model of a human mandible containing endosseous dental implants. II. Variables affecting the predictive behavior of a finite element model of a human mandible. *J Biomed Mater Res* A 2007 **80**: 247-256.
50. Baiamonte T, Abbate MF, Pizzarello F, Lozada J, James R. The experimental verification of the efficacy of finite element modeling to dental implant systems. *J Oral Implantol* 1996 **22**: 104-110.
51. Iplikcioglu H, Akca K, Cehreli MC, Sahin S. Comparison of non-linear finite element stress analysis with in vitro strain gauge measurements on a Morse taper implant. *Int J Oral Maxillofac Implants* 2003 **18**: 258-265.
52. Mikhail EM, Bethel JS, McGlone CJ (eds). Introduction to modern photogrammetry. New York: John Wiley & Sons Inc,2001.
53. Luhmann T (ed.). Nahbereichsphotogrammetrie - Grundlagen, Methoden, Anwendungen. [Close Range photogrammetry – Basic Principles, Methods, Applications] 2nd ed. Heidelberg: Wichmann Verlag, 2003.
54. Tyson J. Noncontact full-field strain measurement with 3D ESPI. *Sensors* 2000 **17**: 62-70.
55. Tyson J, Schmidt T, Galanulis K. Biomechanics deformation and strain measurements with 3D image correlation photogrammetry. *Experimental Techniques* 2002 **26**: 39-42.
56. Holst S, Blatz MB, Goellner M, Bergler M, Wichmann M. Influence of impression material and time on the 3-dimensional accuracy of implant impressions. *Quintessence Int* 2007 **38**: 67-73.
57. Winkelstein BA, Nightingale RW, Richardson WJ, Myers BS. The cervical facet capsule and its role in whiplash injury: A biomechanical investigation. *Spine* 2000 **25**: 1238-1246.
58. Zhang D, Eggleton CD, Arola DD. Evaluating the mechanical behaviour of arterial tissue using digital image correlation. *Exp Mech* 2002 **42**: 409-416.
59. Ritchie J, Jiminez J, He Z, Sacks MS, Yoganathan AP. The material properties of the native porcine mitral valve chordae tendineae: An in vitro investigation. *J Biomech* 2006 **39**: 1129-1135.
60. Weinberg SM, Kolar JC. Three-dimensional surface imaging: limitations and considerations from the anthropometric perspective. *J Craniofac Surg* 2005 **16**: 847-851.
61. Fernandez-Riveiro P, Smyth-Chamosa E, Suarez-Quintanilla D, Suarez-Cunqueiro M. Angular photogrammetric analysis of the soft tissue facial profile. *Eur J Orthod* 2003 **25**: 393-399.
62. Smahel Z, Trefny P, Formanek P, Mullerova Z, Peterka M. Three-dimensional morphology of the palate in subjects with unilateral complete cleft lip and palate at the stage of permanent dentition. Cleft Palate Craniofac J 2004 41: 416-423.
63. Bell A, Ayoub AF, Siebert P. Assessment of the accuracy of a three-dimensional imaging system for archiving dental study models. J Orthod 2003 30: 219-223.
64. Ortorp A, Jemt T, Back T. Photogrammetry and conventional impressions for recording implant positions: a comparative laboratory study. Clin Implant Dent Relat Res 2005 7: 43-50.
65. Jemt T, Back T, Petersson A. Photogrammetry-an alternative to conventional impressions in implant dentistry? A clinical pilot study. Int J Prosthodont 1999 12: 363-368.