Comparison of Non-linear Finite Element Stress Analysis with In Vitro Strain Gauge Measurements on a Morse Taper Implant

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Purpose: *To understand the mechanical and biomechanical behavior of dental implants, validation of stress and strain measurements is required. The objective of this study was to compare a non-linear finite element stress analysis with in vitro strain gauge measurements on strains in an implant-abutment complex.* ***Materials and Methods:*** *Strain gauges were bonded to an implant-abutment complex and embedded in polymethylmethacrylate resin. A force of 75 N was applied vertically and laterally in separate load cases, and strains were recorded with a strain indicator. Then, a finite element model of the strain gauge model was constructed. Contact analysis with normal contact detection and separation behavior was performed between the implant and the abutment. The same loading protocol was followed, and strains were recorded at regions where gauges were bonded.* ***Results:*** *Under vertical loading, the qualification and quantification of strains were similar in both methods. Under lateral loading, the measurement of strains on the abutment and in the resin were similar in both methods. However, strains on the implant collar as measured by non-linear finite element analysis were higher.* ***Discussion and Conclusion:*** *There is a compatibility between non-linear finite element stress analysis and in vitro strain gauge analysis on the measurement of strains under vertical loading. However, there are differences between the methods in the quantification of strains on the collar of implants under lateral loading.* (INT J ORAL MAXILLOFAC IMPLANTS 2003;18:258–265)

Key words: *biomechanics, dental implants, finite element analysis, strain gauge analysis*

Dental implants have been used extensively for the rehabilitation of completely and partially edentulous jaws with either fixed or removable prostheses.[1–6] Despite the high success rates reported to date, implant failures do occur. While late implant failures are mainly related to biomechanical complications,[7] the major factor leading to such failures may be the lack of comprehensive understanding of biomechanical factors.[8]

Prudent control of functional loads on implants is essential to achieve long-term implant survival.[9] In this respect, correct qualification and quantification of forces on implants is crucial to understand their biomechanical characterization. Precise measurement and evaluation of these forces, however, is a perplexing problem and a challenge to resolve. In essence, the contribution of several biomechanical factors, such as bone density,[10] number of supporting implants,[11–15] angulation of implants in bone,[16,17] direction and amplitude of forces,[11,12] type of prosthesis,[18–20] and superstructure fit,[21,22] affect their in vivo isolation and make scientific proof virtually impossible. The information obtained under differing experimental conditions can also lead to uncertainty in clinical interpretation and prediction.

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There are contradictions among the results of different engineering methods used to evaluate the biomechanics of implants.[23–27] Although 3-dimensional finite element stress analysis (3D FEA) and strain gauge analysis (SGA) have provided mutual compatibility and agreement on the detection of forces on implants,[28,29] these studies have not included comprehensive finite element modeling, and strain gauges were bonded to solid-like structures. Hence, it is unclear whether the experimental setup might have affected measured strains. In spite of the claims reported,[28,29] it is doubtful that any significant conclusions can be drawn before further evidence is presented on the compatibility of SGA and 3D FEA.

Accordingly, the purpose of the present study was to gain more insight into the phenomenon by comparing the strains obtained from an in vitro SGA of an implant with its comprehensive 3D finite element model solved by non-linear FEA (NL-FEA).

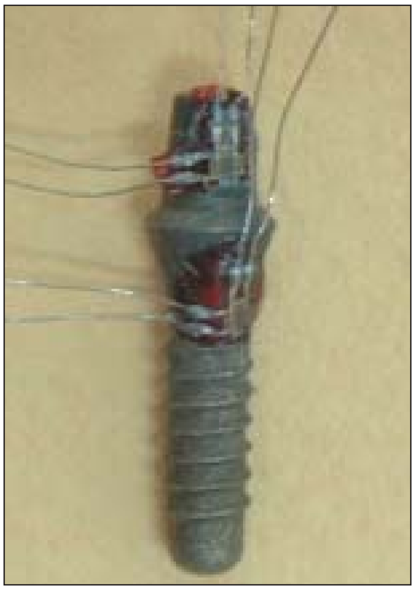

Fig 1 Two-element, 90-degree strain gauges bonded on the implant-abutment complex.

MATERIALS AND METHODS

In Vitro Strain Gauge Analysis

A 3.3×10-mm ITI solid-screw implant (Straumann, Waldenburg, Switzerland) connected to a 6-degree solid abutment 4 mm in height (Straumann) was used in this study. The solid abutment was torque-tightened into the implant with 35 Ncm using a torque control device for rachet (Straumann), as recommended by the manufacturer. The surface of the abutment and the collar of the implant were sandblasted with 50-µm aluminum oxide particles (S-U-Alustral, Schuler Dental, Ulm, Germany) to improve the bonding of strain gauges. Two-element, 90-degree rosette gauges (FCA-1-11, Tokyo Sokki Kenkyujo, Tokyo, Japan) were bonded to the flat surface of the abutment and on the collar of the implant with an adhesive (P2, Tokyo Sokki Kenkyujo) (Fig 1). Because of the size of the polyimide backing, the measuring grids of the gauges were located at the level of the abutment screw on the implant and approximately at the middle of the abutment. The location of the measuring grid on the implant thus allowed determination of possible separation behavior in the implant-abutment complex at the abutment screw level.

Using a surveyor, the implant was oriented centrally in the 1.5×1.5-cm cylindric space of a machined stainless steel container. Another 2-element, 90-degree rosette gauge was placed parallel to the cervical part of the implant at the first thread region and 1 mm away from the implant body. Then the implant and the strain gauge were embedded in autopolymerizing polymethylmethacrylate resin.[11,30,31]

Before strain gauge measurements were made, a cyclic load ranging from 20 to 200 N was applied 100 times on the implant to “age” the gauges. The purpose of “aging” was to minimize hysteresis, a lagging or retardation of the effect when forces acting upon a body are changed. Each gauge was wired separately into a Wheatstone bridge, and the excitation voltage used during the experiments was 10 V. The implant was loaded by a round-end loading probe of a static loading device. The following loading schedule was applied: 75-N static vertical force application centrally on the top of the abutment; then 75-N static 90-degree lateral load application on the inclined surface of the abutment.

During lateral loading of the implant, the stainless steel container, which had a flat surface on the strain gauge side of the implant, was secured to a rectangular metal platform with a custom-made metal clamp. The platform was then secured on the base of the loading device. This application allowed complete immobilization of the system during loading.

Strains were recorded by a strain indicator (Model 350 AZ, Vishay Instruments, Malvern, PA) and a switch and balancing unit (Vishay Instruments) 1 second after load application. Since strains immediately reached a plateau 1 second following load application, any change in strain amplitude was not detected by the measuring device after this period. The test was repeated 5 times for each loading type, allowing the strain indicator to recover to

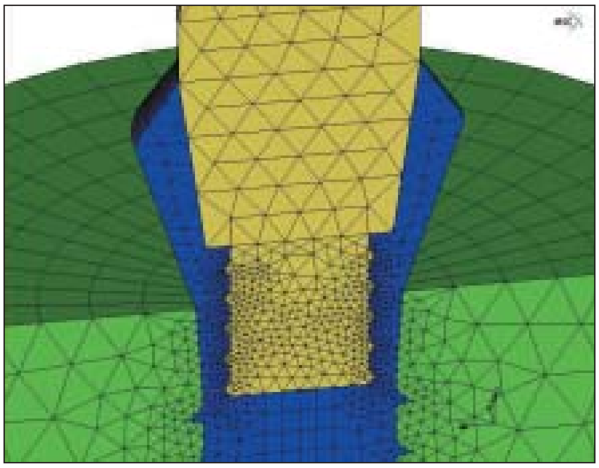

Fig 2 Close view of the implant-abutment complex embedded in resin.

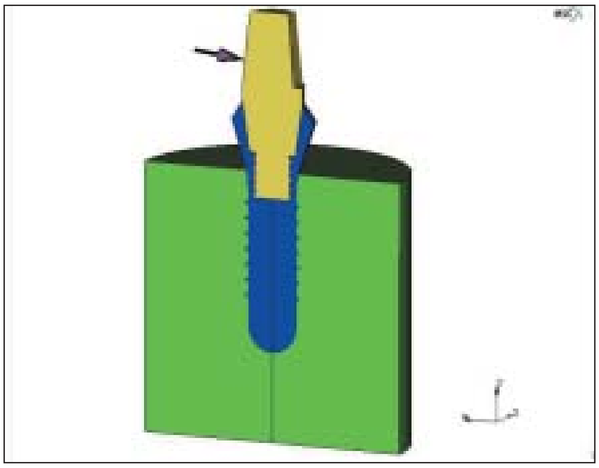

Fig 3 Lateral load application at the middle of the solid abutment.

± 0.0000 µє between trials. The recovery time for strains on the abutment and the implant was only a few seconds. However, 2 to 3 minutes were required to observe full recovery of strains induced in the resin. Because recovery to 0 ± 0.1 µє was not achieved before the last 2 strain measurements in the resin, balancing the measuring device at zero was required before load application. Finally, the mean of the data measured from each gauge was calculated.

Finite Element Model

The computer-assisted design (CAD) model of the 3.3-mm-diameter ITI implant and the solid abutment (4 mm in height) was constructed by I-DEAS Artisan Series 3.0 (Structural Dynamics Research Corporation, Milford, OH) separately. The geometry and dimensions of the CAD model of the implant and the abutment were identical to the actual implant. However, to simplify the modeling, the threads of the implant and the abutment were not represented in their spiral characteristics, but as symmetric rings.[30] The CAD models were transferred to the preprocessor, MSC.Marc Mentat 2000 (MSC.Software, Los Angeles, CA), for finite element model conversion. The implant-abutment complex was embedded vertically in the center of an acrylic cylinder. The finite element model was constructed by using 8-node isoparametric brick and 4-node isoparametric tetrahedral elements, resulting in 13,296 elements in the implant, 12,931 elements in the abutment, 12,288 elements in the acrylic resin cylinder, and a total of 17,922 nodes in the entire model (Fig 2). The following values were assumed for Young's modulus and Poisson ratios, respectively: implant and abutment 114,000 MPa and 0.369; acrylic resin 3,000 MPa and 0.3.[30] A value of 0.5 was assumed for the friction between titanium abutment and implant surfaces for the contact analysis, as reported by Abkowitz and coworkers.[32]

Load Conditions and Constraints

Vertical and lateral load conditions in the SGA were simulated. The vertical load was applied as a point load on the top of the abutment. For lateral loading, the load was applied on the 6-degree inclined surface of the abutment (Fig 3). Boundary conditions were established by constraining the acrylic cylinder circumferentially and from its bottom.

Finite Element Analysis

Contact area was defined between the implant and the abutment. For contact checking, the node-to-segment contact mechanism was used. Contact analysis with normal contact detection and separation behavior was performed between the implant and the abutment. A NL-FEA solver MSC.Marc 2000 (MSC.Software) was used for processing the situations. The analyses were performed using 3 incremental solutions. Strains induced on regions corresponding to strain gauges (an area of 0.7 mm [width] by 1 mm [length] for each element), consisting of 35 nodes on the implant, 1 node on the abutment, and 20 nodes in the resin, were recorded and the mean strain values were calculated. The area corresponding to the measuring grid of the gauge on the abutment consisted of 8 elements in the finite element model. The node selected for strain measurements on the abutment was located at the center of these elements. Considering that this node was also in contact with a number of elements beneath

Table 1 Strains Measured by In Vitro SGA and Non-Linear FEA on the Implant and the Abutment and in the Resin Under 75 N Force Application

Load type/ location	In vitro SGA			Non-Linear FEA		
	Implant	Abutment	Resin	Implant	Abutment	Resin
Vertical load						
y-axis	48 (6)	78 (24)	103 (52)	43.1	89.05	84
z-axis	–200 (21)	–230 (45)	–204 (86)	–200.1	–242.5	–104.3
Lateral load						
y-axis	545 (75)	114 (27)	1,700 (322)	1,048.8	131.7	2,000.6
z-axis	–1,496 (123)	–210 (42)	–1,525 (415)	–3,395.1	–216.1	–1,433.7

Values are mean (SD), $\times 10^{-6}$.

the surface of the abutment, an overall detection of strain gradient was performed in this region.

RESULTS

Mean microstrains on the implant and the abutment and in the resin are presented in Table 1. Compressive strains were measured parallel to the long axis of the implant (y-axis) for all regions analyzed by both methods. Tensile strains were recorded in the z-axis for all regions under both loading conditions. Under 75-N vertical loading, the quantification of strains with both techniques was very similar. As a sequel of lateral loading, the strain levels on the abutment measured by both techniques were similar. Under both loading conditions, the strain distribution on the abutment was similar (Figs 4a and 4b). Strains on the implant collar as measured by NL-FEA were almost two-fold higher than the comparable data obtained by in vitro SGA. A remarkable bending of the implant was observed under lateral loading (Figs 5a and 5b). Differences were observed between the 2 techniques; the quantification of strains in resin and the distribution of strains in resin were significantly affected by the mode of loading (Figs 6a and 6b).

DISCUSSION

Contact and friction have important roles in the mechanical behavior of 2 parts of a complex, such as dental implants. In conventional FEAs of implants,[12,13,33] linear solutions are undertaken, where the friction and torque between implant components are underestimated. The solution of such finite element models is simple, cost effective, and not time-consuming. However, perfect bonding or connection between an implant and an abutment is not the actual scenario for dental implants. For specific loading conditions such as lateral or oblique loading, specific parts can separate, or new parts that were initially not in contact can come into contact. Consequently, more deformation may be expected. In this regard, the pattern and magnitude of deformation will be influenced by the implant design.[30] Hence, for correct emulation of an implant-abutment complex, contact was defined between the implant and the abutment in this study.

The contact phenomenon is non-linear, even if elastic behavior is assumed. In otherwise linear problems, the contact problem is relatively simple. The location of the potential contact is known, and contact elements can easily be specified. In large displacement and large strain problems, it is generally not known where contact will occur, although contact is often the main driving factor for the deformation. Accordingly, a reduced-diameter implant was used in this study, and one of the gauges was bonded at the implant collar to detect high strains induced under lateral loading.

In the present study, the rationale for bonding a gauge on the implant collar was to compare the detection of strains by 2 engineering techniques on non-solid structures. Further, the reason for bonding gauges on the abutment and embedding the model in resin[31] was to compare both techniques on the measurement of strains on and in solid structures, respectively. In previous comparative studies, strain gauges were bonded on solid-like structures (human femur and implant abutment),[28,29] and a mutual agreement and compatibility was found between SGA and FEA. In a recent study, the authors found that in vitro strain measurements at the neck of internal-hex implants were higher than those obtained from a linear finite element solution.[34] In the present study, comparable results

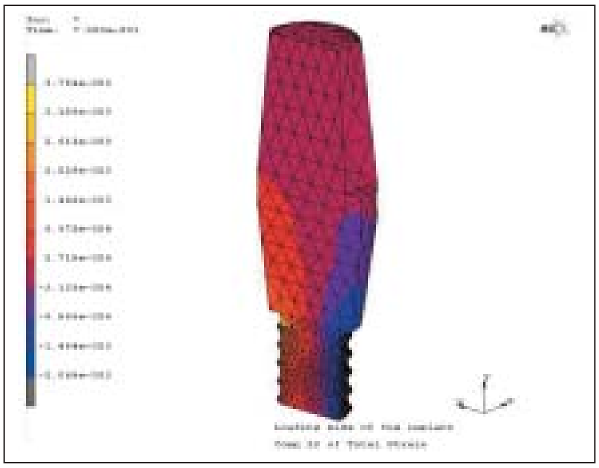

Fig 4a Distribution of strains in y-axis in the abutment under a 75-N lateral load.

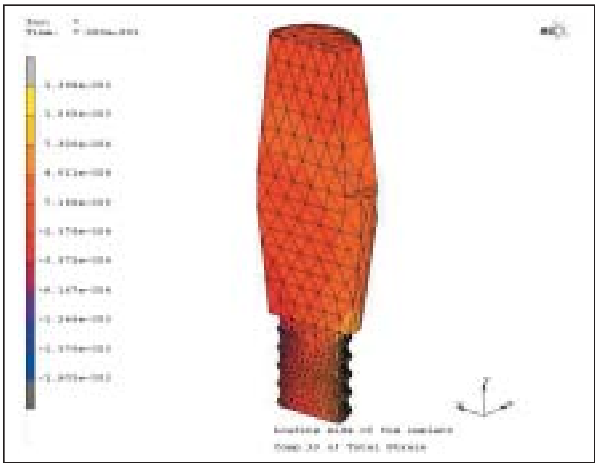

Fig 4b Distribution of strains in z-axis in the abutment under a 75-N lateral load.

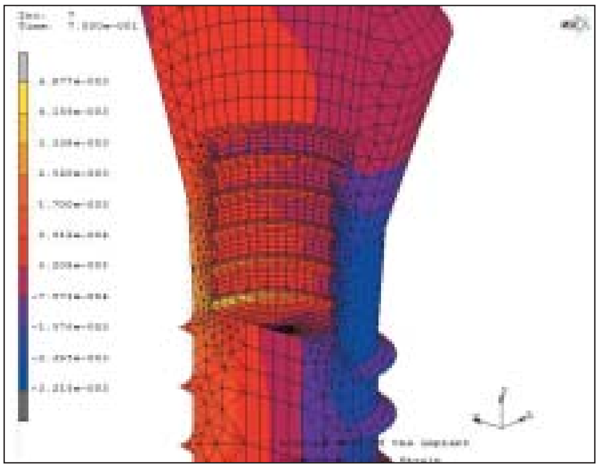

Fig 5a Distribution of strains in y-axis in the implant under a 75-N lateral load.

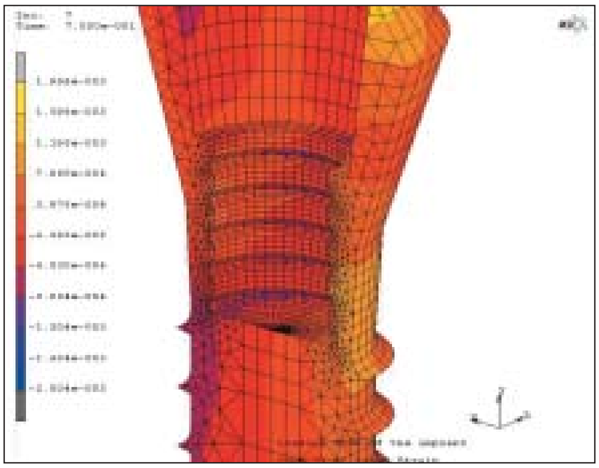

Fig 5b Distribution of strains in z-axis in the implant under a 75-N lateral load.

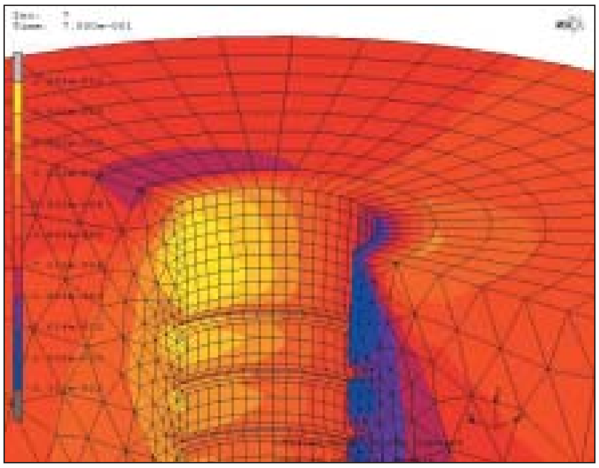

Fig 6a Distribution of strains in y-axis in the resin under a 75-N lateral load.

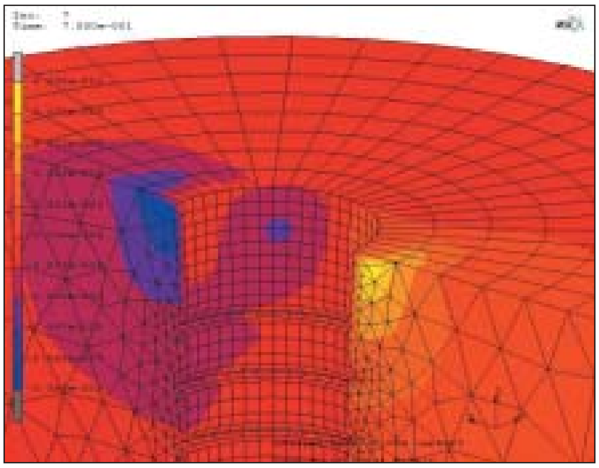

Fig 6b Distribution of strains in z-axis in the resin under a 75-N lateral load.

were found between in vitro SGA and NL-FEA on the qualification and quantification of strains, except for measurements on the implant collar under a 75-N lateral force. Thus, the present data on solid abutment and resin appear to be in agreement with previous studies.

In addition, the type and the magnitude of strains on the implant collar were compatible between both methods for vertical loading. This result was not surprising, since no separation occurred in the NL-FEA, leading to more deformation of the implant neck. For lateral loading, strains on the implant collar were of the same quality. However, NL-FEA showed approximately double the strain of in vitro SGA. Therefore, it seems that there are fundamental differences between the 2 techniques as to the detection of bending moments on non-solid structures, such as the collar of an implant-abutment complex.

This finding may be dependent on several factors in NL-FEA, including assumptions made during the construction of the mathematical model, the contact phenomenon, number and type of elements, and number of nodes used for measurement. Another reason for these differences may be lack of preload application in the present finite element model. In a recent NL-FEA study, Merz and collaborators[30] included a torque value of 53.2 N in the taper joint of a 4.1-mm-diameter ITI implant, which was determined by preload testing and calculations. In this study, a 3.3-mm-diameter ITI implant was used, and preload testing of reduced-diameter ITI implants was not included. The lack of preload did not have any effect during vertical loading, but resulted in more separation at the screw joint under lateral loading. Considering that this clamping force has a considerable effect on the maintenance of screw joint integrity, it is likely to observe a decreased amount of deformation (strain) and separation when preload is included in NL-FEA.

The actual mechanical characterization of the ITI implant-abutment connection also supports this idea, since form lock and friction are the basic principles of its screw joint. This mechanism, referred to as positive or geometric locking, is responsible for protecting the abutment threads from excessive functional load.[30] Functional forces are resisted mainly by the taper interface, and this property results in a mechanical behavior similar to that of a 1-part ITI implant under vertical load. Recent studies have proven the mechanical advantages of ITI Morse taper implants over butt-joint implants.[30,35,36] Indeed, the distinct mechanical advantages of the ITI Morse taper resulted in remarkably lower incidences of mechanical complications, specifically abutment screw loosening and fracture in comparison to those reported for butt-joint implants. However, when dealing with reduced-diameter ITI implants, it should be taken into account that the amount of alloy surrounding the abutment screw in this implant is thinner than that of the standard 4.1-mm-diameter implant, which leads to more deformation of the implant neck under oblique load. Yet, there have been no reported fractures of standard-diameter (4.1-mm) solid-screw implants, and only a small number of reduced-diameter (3.3-mm) solid-screw implant fractures.[36] The mechanical properties of the Morse taper joint, which result in a very stiff implant-abutment complex, also improve the biomechanical behavior of the implant. Accordingly, long-term studies of single-tooth ITI restorations indicate high survival rates and marginal bone levels that decline slightly after 5 to 10 years.[37–39]

Another reason for the disagreement of strain measurements at the implant neck may be a result of the nature of the SGA, since there is always a potential risk of random error in this method. In addition, before bonding on the abutment, the dimensions of the polyimide backing (carrier) of the strain gauges were modified to fit the flat surface, although these gauges were “miniature.” However, this procedure is believed to decrease the sensitivity of strain gauges. Perhaps more miniature devices should be developed for force measurements on implants. Overall, it is evident that there are numerous factors that affected the results of this study. Further studies are required to clarify these claims.

Small differences were found between the 2 techniques on the quantification of strains in resin. These differences are assumed to be dependent on the displacement of the gauge during the polymerization shrinkage of the resin and the influence of the region (selection of nodes, number of nodes, and plane assumed) in which strains were measured in NL-FEA. However, it is unknown whether these differences are within acceptable limits for the measurement of strains on/in bone for the prediction of bone tissue differentiation around dental implants.[40] Nevertheless, SGA in acrylic resin is probably not an accurate way to measure a strain field that is 3-dimensional. Performance of SGA in resin also results in a wider strain range compared with that obtained from implant components, as observed in the present study. The issue becomes more important in situations, for example, when strain gauges are embedded in resin around the neck of multiple implants. Because displacement of the gauge is likely to occur during the polymerization shrinkage of acrylic resins, and because it is almost impossible to locate the gauges in the same position around all implants, the reliability and reproducibility of the measurements will be questionable. Perhaps this technique should not be used for in vitro SGA of implants. Instead, bonding of the gauges around the neck of the implants, but on the resin surface, would be preferred.

In previous studies,[18,27] fundamental differences were found between in vitro and in vivo SGA. This finding has led to the understanding that valid biomechanical studies can only be made at the in vivo level. Thus, the results of the present study indicate the need for comparison between in vivo SGA and NL-FEA. The possible compatibility found between in vivo SGA and NL-FEA would facilitate evaluation of biomechanical factors.

CONCLUSIONS

Under the conditions of this study the aforementioned conclusions were drawn:

1. In vitro SGA and NL-FEA were comparable when measuring the strains on implant abutments and at the implant collar.
2. With both techniques, the quantification of strains was in agreement for vertical loading of the implant-abutment complex. However, higher strains were measured on the implant collar by NL-FEA in comparison to in vitro SGA under lateral load.
3. Further research is indicated to investigate acceptable limits of differences between quantification of strains in bone simulants, since differences in strain magnitudes were found between in vitro SGA and NL-FEA in resin.

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