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Digital photoelastic analysis applied to implant dentistry

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ABSTRACT

Development of improved designs of implant systems in dentistry have necessitated the study of stress fields in the implant regions of the mandible/maxilla for better understanding of the biomechanics involved. Photoelasticity has been used for various studies related to dental implants in view of whole field visualization of maximum shear stress in the form of isochromatic contours. The potential of digital photoelasticity has not been fully exploited in the field of implant dentistry. In this paper, the fringe field in the vicinity of the connected implants (All-On-Four® concept) is analyzed using recent advances in digital photoelasticity. Initially, a novel 3-D photoelastic model making procedure, to closely mimic all the anatomical features of the human mandible is proposed. By choosing appropriate orientation of the model with respect to the light path, the essential region of interest were sought to be analysed while keeping the model under live loading conditions. Need for a sophisticated software module to carefully identify the model domain has been brought out. For data extraction, five-step method is used and isochromatics are evaluated by twelve fringe photoelasticity. In addition to the isochromatic fringe field, whole field isoclinic data is also obtained for the first time in implant dentistry, which could throw important information in improving the structural stability of the implant systems. Analysis is carried out for the implant in the molar as well as the incisor region. In addition, the interaction effects of loaded molar implant on the incisor area are also studied.

1. Introduction

Use of dental implants to replace missing natural dentition in edentulous arch is common in clinical dentistry. Extensive research done on artificial implants has resulted in newer designs and concepts. Recent advancements in connected implant systems such as All-On-Four® [1] treatment procedure has revolutionised the concepts of total rehabilitation in cases of complete edentulism. Edentulism refers to a toothless condition which can be due to various situations. In All-On-Four® concept, only four implants are used for supporting the prosthetic arch where the entire teeth are replaced by prosthetics. The position and orientation of the implants have a great influence on the structural integrity between the bone and implants, as higher stresses around the implants can adversely affect the osseointegration process. Osseointegration is the process by which the implant becomes a part of the living bone/tissue over a period of time [2]. Understanding such complex systems demand better knowledge of the bio-mechanics involved in such implant placements. As analytical solutions are not possible for such configurations, it is necessary to go for an experimental or a numerical procedure. Photoelasticity directly provides stress field information in the form of $(\sigma_1-\sigma_2)$ contours and hence photoelasticity is chosen for analysing the stress distribution in such implant designs.

Even though photoelastic analysis is capable of providing whole field information regarding the principal stress difference (isochromatics) and the orientation of the principal stresses (isoclinics), several researchers in the field of implant dentistry have applied it merely as a visualization tool based only on isochromatics [3–13]. Till date, in implant dentistry, photoelasticity is used as a point by point technique rather than a whole field experimental technique [14–16]. To simplify experimentation, some of the early studies adopted 2-D analysis by placing the implants on commercially available rectangular blocks made of photoelastic material [11,14,17,18]. In order to improve the accuracy of the model, curved blocks made of photoelastic material have also been attempted [3–7,12,13,16]. Although, in many of these studies [5–7] fringe visualisation is improved by immersing the model in a liquid bath having the same refractive index, the immersion tank used is cylindrical which does not ensure normal incidence. This has serious implications on data reduction. With advancements in image processing techniques, modern digital photoelasticity [19,20] is capable of providing rich whole field data even for problems with complex specimen shapes. The potential of digital

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photoelastic techniques have not been fully exploited so far in implant dentistry.

One of the challenges in photoelastic experiments, in implant dentistry is to develop a model which is realistic and closely reflects the geometric complexities of the mandible/maxilla as the case may be. Mandible refers to the lower jaw region containing teeth and maxilla is the corresponding upper jaw region. This paper proposes a new 3-D model making approach that results in photoelastic model almost free of residual stress, making it suitable to study different regions of the mandible with implants. By modifying the direction of the light incident on the model, the relevant region of interest are sought to be obtained by keeping the model in live load conditions.

Use of coloured isochromatics has already been studied in the dental literature using conventional photoelasticity. Great strides have been made in the last decade on quantitative use of colour information in digital photoelasticity. So the natural choice in digital photoelasticity is to use TFP (Twelve Fringe Photoelasticity) [21] to extract isochromatic fringe orders using colour information. Hitherto the isoclinic field in implant dentistry has not been reported. Knowledge of this can help in improved prosthetic designs. The nature of the isoclinic fields in the mandible is reported for the first time in this paper. To record the isoclinic fields as well as isochromatics, five-step method is used [20,22]. For completeness, essential details of these methodologies and also certain basic information related to implant dentistry are briefly described wherever necessary.

2. Evolution of an appropriate photoelastic model for implant dentistry

Most of the photoelastic studies done in the field of prosthodontics and orthodontic dentistry are confined to 2-D qualitative approaches [11,14,18]. In such situations, model analysis is easier as standard photoelastic sheets are available commercially. However, a 2-D model does not even capture the essential anatomical structure of the mandible/maxilla. Further, in connected implant retained designs, the stresses induced by one implant can affect the stresses near the other implants. This demands a three dimensional (3-D) photoelastic model which has the essential anatomical feature of the real mandible.

Fig. 1 shows a typical human mandible with different regions indicated. The mesial and distal refer to the direction towards and away from the symmetric midline respectively. The coronel region refers the direction towards the crown of the teeth and apical refers to the region towards the root. What is required is to simulate the loads due to mastication and see what happens at the implant region in a concept like All-On-Four design®. The masticatory load depends upon several factors such as age, type of food, etc. Previous studies have shown that the masticatory forces in dentate patients vary from 175–350 N in normal situations [24,25].

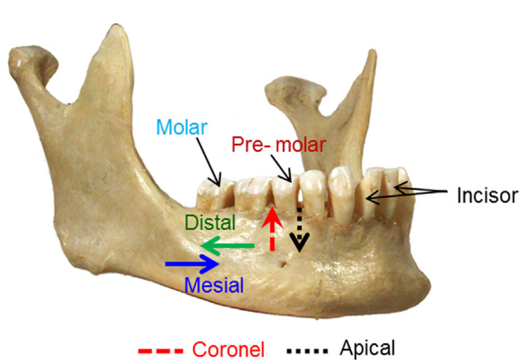

Fig. 1. Typical human mandible with the nomenclature and zones labelled (adapted from [23]).

In conventional 3-D photoelasticity, the 3-D model is stress frozen for a particular loading condition. In stress freezing, the loaded model is subjected to a thermal cycle and at the end of the thermal cycle, the loads are removed. In view of the special properties of the model material, the stresses are locked even after the loads are removed [26,27]. Any region of interest could be then studied by appropriately slicing the model. Interaction effects of loading in the molar region on implants at the incisor and vice-versa can also be studied by this approach. However, this approach would demand a new model for each study. An attempt is made in this work to utilize a live-loaded model to study specific region of interest by selecting suitable viewing orientations. A model of mandible to achieve this has been arrived at by trial and error.

Different ways of placing a mandible (photoelastic model) in a circular polariscope is shown in Fig. 2. In order to ensure normal incidence, the model is placed in a rectangular tank containing immersion liquid which has the same refractive index as that of the model. Implants placed in the incisor area can be evaluated using the configuration shown in Fig. 2(a). An angled view approach can be adopted to study the implants placed in the molar region (Fig. 2(b)). The model of the mandible is cast with desired configuration and the casting process is improvised such that the model obtained is free of residual stress or at least it is at the minimum level.

2.1. Strategies adopted in obtaining suitable photoelastic models

Different moulds for casting are explored for getting the models. The photoelastic models used in this study are made by a mixture of CY230 resin and HY951 hardener in 10:1 ratio by weight. Initially, a photoelastic model (Fig. 3(a)) is cast using the commercially available edentulous silicon mould which has a tongue space and soft tissue attachments with a supporting base. Fig. 3(b) shows the dark field isochromatics in the posterior region of the mandibular arch of the model obtained when viewed according to Fig. 2(b). Photoelastic fringes qualitatively indicate the presence of excessive residual stress in the model. In view of the tongue space and soft tissue attachments, under live load conditions, it was difficult to view the zones of interest by even altering the viewing directions.

The mould is then modified such that the limiting structure of edentulous mandible and soft tissue attachments, which are not relevant, are removed. The model obtained using the modified mould is shown in Fig. 3(c). This modification made the molar and incisor areas viewable in a polariscope under live loading conditions. Dark field isochromatics of the residual stress observed in the modified model when viewed according to Fig. 2(b) is shown in Fig. 3(d). Though the viewability has improved, the presence of residual stress is still prominent and there is further scope of improving the casting methodology.

As the focus of the study is to analyse the fringe field in the presence of implants, a fresh model is prepared with the implants installed by the following procedure. Initially, a human mandibular bone is reproduced without any limiting structure and soft tissue attachments using a wax pattern. On the wax model, the Adin [28] implant system is placed as in All-On-Four® concept, at the predetermined position. Using the wax model with implant, a mould made of silicon is then prepared. Duplication is done in such a way that, the silicon mould has a uniform thickness around the model. Following this, de-waxing is carried out by exposing the entire setup to elevated temperature ($T \approx 100$ °C) for removing the residual wax. Thus, the desired mould is obtained with the implant placed in the predetermined position inside the mould itself.