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Review

Finite element contact analysis as a critical technique in dental biomechanics: A review

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ARTICLE INFO

Article history:
Received 27 February 2014
Accepted 10 March 2014
Available online 4 April 2014

Keywords:
Finite element analysis
Stress
Dental
Implant
Nonlinear

ABSTRACT

Purpose: Nonlinear finite element contact analysis is used to mathematically estimate stress and strain in a time- and status-dependent mechanical model. However, the benefits and limitations of this method have not been thoroughly examined.
Study selection: The current review summarizes the utility of contact analysis in characterizing individual stressors: (1) tooth-to-tooth contact, (2) restorative interface, and (3) bone–implant integration.
Results: Opposing tooth contact, friction, and sliding phenomena were simulated to estimate stress distribution and assess the failure risk for tooth enamel, composite, and ceramic restorations. Mechanical tests such as the flexural tests were simulated with the contact analysis to determine the rationale underlying experimental findings. The tooth–restoration complex was modeled with interface contact elements that simulate imperfect bonding, and the normal and tangential stresses were calculated to predict failure progression. Previous studies have used a friction coefficient to represent osseointegration adjacent to dental implants, but the relationship between interface friction and the bone quality is unknown. An understanding of the local stress and strain may better predict loss of osseointegration, however, the effective stress as a critical contributor to bone degradation and formation has not been established.
Conclusions: Contact analysis provides numerous benefits for dental and oral health sciences, however, a fundamental understanding and improved methodology are necessary.

Contents

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http://dx.doi.org/10.1016/j.jpor.2014.03.001
1883-1958/

1. Introduction

The finite element (FE) method features a series of computational procedures that calculate the stress and strain within a structural model caused by external force, pressure, thermal change, magnetic field power, and other factors. The method is extremely useful in estimating the biomechanical characteristics of dental prostheses and supporting oral tissues that are difficult to measure *in vivo*. The stress and strain estimated through model structures can be analyzed using visualization software within the FE environment to evaluate a variety of physical parameters.

Until recently, linear static models have been employed primarily in dental biomechanics. A constant elastic modulus representing the linear stress–strain relationship of each material or oral tissue may be entered into a FE program. Linear analyses are valid in model structures with a linear stress–strain relationship up to a stress level known as the proportional limit and a within a bonded single unit volume. However, most oral physical phenomena are not adequately simulated by linear static structures; oral tissues and biomaterials exhibit time-dependent and status-dependent characteristics under mechanical stress. A more realistic simulation generates nonlinearities especially in principal categories such as changing status. This structural behavior is commonly observed in intra-oral contacts such as between occluding antagonistic teeth, adjacent teeth, and frictional contact between the denture and supporting tissues. Stress and strain may change dramatically with the changing status of each contact. Therefore, accurate calculation of the mechanical output from model simulations is essential.

Finite element contact analysis has recently appeared in numerous dental and prosthodontic studies. The method has become an increasingly powerful predictor of the realistic structural stress and strain that cannot be estimated in a linear static model. However, the benefits and limitations have not been thoroughly examined, particularly for data interpretation. The key elements required for the design and appropriate utilization of this method should be fully discussed. The present review describes the recent developments in the application of contact analysis to prosthodontics research of tooth-to-tooth contact, restorative interface, and bone–implant integration.

2. Tooth-to-tooth contact

The fracture risk of the enamel and ceramic restorations is determined by calculating the stress and strain distributions associated with tooth-to-tooth contact under occlusal loading. To estimate occlusal surface stresses using a linear elastic model, force is applied onto a node or an element, or the pressure upon an area of the occlusal surface is estimated to simulate occlusal loading. The resultant stress may be erroneous because this assumed loading condition is likely to excessively concentrate stress peripherally around the loading site, which is far from the reality.

These problems can be partially resolved by using contact analysis, which estimates sliding and friction phenomena during mastication using contact elements to simulate the contacting maxillary and mandibular teeth. However, the method is highly nonlinear and difficult to solve due to several limitations. First, the contact regions are unknown until a sequence of the problem has been solved. Depending upon the load, material, and environmental factors, the surfaces can move in and out of contact with each other unpredictably. Secondly, friction should be considered in most contact analyses. The frictional responses can be chaotic and make solution convergence difficult. In addition, contact simulations often require significant computer resources to perform.

Contact analyses enhance the estimated accuracy of the Hertzian damage experienced by the enamel and dental ceramics. Fig. 1 demonstrates the stress distributions created by a simple point loading on the occlusal surface of a linear static model (left) and a nonlinear contact simulation using the opposing tooth cusp (right). The linear analysis predicted an unrealistically high stress concentration and a tensile area surrounding the loaded point that does not reflect a real condition. The contact analysis by contrast predicted a compressive area from the contact cusp.

Contact analyses of tooth surfaces appeared within a two-dimensional model devised by Magne and Belser [1]. They demonstrated the stress distribution in maxillary and mandibular molar teeth during working, non-working, and vertical closure of the jaw. The same group later comprised computerized tomography (CT)-based FE models using standard triangle language (STL) and Boolean operations (volume addition, intersection, or subtraction) [2–4]. The method recently estimated the fracture risk of ultra-thin composite resin occlusal veneers [5].

The forces acting upon the molar teeth during mastication constantly change direction, magnitude, and location, depending on the specific contact between opposing tooth surfaces. Dejak et al. conducted a nonlinear contact simulation of the interface between molar occlusal surfaces and morsels, then analyzed the induced stresses on a mandibular molar during clenching and chewing of morsels of various elastic moduli [6]. The same group later assessed the mechanism underlying cervical lesion formation [7]. Damaged elements were removed from the computer tooth model based on the Tsai–Wu criterion. In addition, the strength of mandibular molars restored with composite resin inlays was compared to those restored with ceramic inlays, according to the Mohr–Coulomb failure criterion [8]. Recently, the strength of thin-walled molar crowns comprising various materials was analyzed under simulated mastication [9].