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Experimental and numerical estimations into the force distribution on an occlusal surface utilizing a flexible force sensor array

Keng-Ren Lin[a], Chih-Han Chang[a,**], Tzu-Hsuan Liu[a], Shi-Wei Lin[a], Che-Hsin Lin[b,*]

[a] Institute of Biomedical Engineering, National Cheng Kung University, No. 1 University Road, Tainan 701, Taiwan
[b] Department of Mechanical and Electro-Mechanical Engineering, National Sun Yat-sen University, No. 70 Lien Hai Road, Kaohsiung 804, Taiwan

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ABSTRACT

This study presents a novel flexible force sensor array for measuring the distribution of the force distribution over the first molar. The developed force sensor array is composed of a flexible polyimide electrode and barium-titanate-based multilayer ceramic capacitors (MLCCs). The piezoelectric and material properties of industrial-grade MLCCs are ideal for measuring large-force loadings. The sensors are cheap and easy to integrate with automated manufacturing processes. Prior to experimental measurements, the force responses for the MLCC sensor cells were systematically measured and evaluated, confirming their high fracture strength and good sensing properties. Finite element (FE) simulations were used to calculate the force distribution over the tooth crown from the measurement results of the 3×3 force sensor array. Results indicate that the sensor has great sensitivity and linearity under a high-speed cycle loading of 500 N/s conducted to simulate normal chewing. The total force measured using the developed sensor array within the artificial tooth had an error of less than 5%. In addition, the force distributions over the molar crown obtained using a numerical method of FE analysis agree well with those obtained from experiments. The developed flexible force sensor array thus has potential for in-situ bite force measurements that are low-cost and reliable.

1. Introduction

The measurement of occlusal force is still attracting a lot of attention for researcher in various fields as of today (Gibbs et al., 1981; Kohyama et al., 2004; Lundgren and Laurell, 1986; Varga et al., 2010). Generally speaking, chewing conditions including the magnitude, the direction and the distribution of the chewing forces are vital factors related to fracture of teeth and the failure of dental prostheses and other dental treatments (Kishen, 2006; Ozcan, 2003; Tanaka et al., 2003). In some aspects, the direction and position of occlusal forces within a single tooth may be more important than the force magnitude for estimating long-term success of most dental treatments (Holmgren et al., 1998; Watanabe et al., 2003). From a biomechanical point of view, information about occlusal force has been widely used in various researches including dental implant designs, endodontically treated teeth and dental prostheses (Ausiello et al., 2002; Kuo et al., 2010; Lin et al., 2010a; Lin et al., 2010b). Insufficient knowledge about the chewing conditions may cause damage risks in the dental treatment procedures (Gapski et al., 2003; Kishen, 2006). Hence, it is important to better understand the force loading and distribution over a chewing tooth. However, a complete study of the force loadings during mastication especially for the force concentration and the force direction on the dental crown is still lacking.

Finite element (FE) analysis is a commonly adopted tool for simulating bite force conditions and the stress distributions on the occlusal surface (Dejak et al., 2003; Lee et al., 2002). FE analysis has several distinct advantages in modeling a biomechanical system with complicated parameters and complex geometry without using delicate experimental procedures. Nevertheless, only prediction results have been obtained for these analyses. Direct in-vivo measurements of bite forces have been obtained using commercial multiple-point sheet sensors (Dan et al., 2005; Kubo et al., 2009). The average chewing force and the contact area of the denture were simultaneously measured using a force sensor during the chewing of food samples. However, the resolution for describing the force distribution on a single tooth is limited. Moreover, a sheet sensor may interfere with the normal chewing process. Implant-type sensors, which can be integrated with prosthetic teeth, have been developed to overcome this problem (Mericske-Stern et al., 1996). The sensors can reliably measure the bite force under normal chewing. Force vectors and

* Corresponding author. Tel.: +886 7 5252000x4240; fax: +886 7 5254299.
** Corresponding author. Tel.: +886 6 2757575x63427; fax: +886 6 2343270.
E-mail addresses: cchang@mail.bme.ncku.edu.tw (C.-H. Chang), chehsin@mail.nsysu.edu.tw (C.-H. Lin).

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