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Fiber Bragg Grating based bite force measurement

Sharath Umesh [a], Srivani Padma [a,b], Sundarrajan Asokan [a,*], Talabattula Srinivas [b]

[a] Department of Instrumentation and Applied Physics, Indian Institute of Science, Bangalore, India
[b] Department of Electrical Communication Engineering, Indian Institute of Science, Bangalore, India

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ABSTRACT

The present study reports an *in vivo*, novel methodology for the dynamic measurement of the bite force generated by individual tooth using a Fiber Bragg Grating Bite Force Recorder (FBGBFR). Bite force is considered as one of the major indicators of the functional state of the masticatory system, which is dependent on the craniomandibular structure comprising functional components such as muscles of mastication, joints and teeth. The proposed FBGBFR is an intra-oral device, developed for the transduction of the bite force exerted at the occlusal surface, into strain variations on a base plate, which in turn is sensed by the FBG sensor bonded over it. The FBGBFR is calibrated against a Micro Universal Testing Machine (UTM) for 0–900 N range and the resolution of the developed FBGBFR is found to be 0.54 N. 36 volunteers (20 males and 16 females) performed the bite force measurement test at molar, premolar and incisor tooth on either side of the dental arch and the obtained results show clinically relevant bite forces varying from 176 N to 635 N. The bite forces obtained from the current study for a substantial sample size, show that the bite forces increases along the dental arch from the incisors towards the molars and are found to be higher in male than in female. The FBG sensor element utilized in FBGBFR is electrically passive, which makes it a safe *in vivo* intra-oral device. Hence the FBGBFR is viable to be employed in clinical studies on biomechanics of oral function.

1. Introduction

The masticatory system comprises of jaw muscles, teeth and temporomandibular joints which play an important role in every individual's oral health. Bite force is an established indicator of the functional state of the masticatory system (Bakke, 2006; Ahlgren and Owall, 1970), which is the resultant force generated by the craniomandibular structure comprising functional components such as muscles of mastication, joints and teeth. Bite force is defined as the force applied between the maxillary and mandibular teeth by the masticatory system in dental occlusion. The evaluation of the individual bite force has been widely utilized in dentistry, mostly in understanding the mechanics of mastication to provide vital information for prosthetic device therapy assessment (Fernandes et al., 2003; Koc et al., 2010). Further, the bite force aids in various applications of maxillofacial surgery and odontology, along with providing suggestive standards on the biomechanical properties of prosthetic devices (Lantada et al., 2012). Some of the factors that influence the generated bite force are the positional offset of teeth and mandible, elastic deformation of the jaw bone, load applied on the periodontal soft tissue, lever effect and masticatory muscle activities (Ando et al., 2009).

As bite force plays a predominant role in dentistry, several studies are carried out on bite force measurement, among which a large number of these intraoral apparatus are based on electrical sensors (Fernandes et al., 2003; Bates et al., 1975; Hagberg, 1987; Waltimo and Könönen, 1993). These electrical sensors mainly work on the basis of either resistance strain gauge, piezoresistive, inductive, capacitive or thermo-electrical principles, which are known to have their own drawbacks (Bakke et al., 1992; Williams et al., 1984; Glantz and Stafford, 1985; Steenberghe and De Vries, 1978). Bite force measurements are further influenced by the mechanics of the force recording system, together with the placement of the sensor along the occlusal surface, degree of mouth opening and unilateral or bilateral type bite force measurement methodology employed (Koc et al., 2010).

Bite force measurement has been realized with different methodologies with varying resolution and range of measurements (Mora et al., 2014; Yoda et al., 2013; 2015; Lin et al., 2011; Isaza et al., 2009). Majorly these sensors utilize electrical power for bite force measurement, which is not desirable for *in vivo* studies. Bite force measurement methodologies employing fiber optics have also been proposed, but are limited by the resolution of measurement being 10 N (Roriz et al. 2014; Kopola et al., 1995).

* Corresponding author. Fax: +91 80 23608686.
E-mail addresses: sundarrajan.asokan@gmail.com, sasokan@iap.iisc.ernet.in (S. Asokan).

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Therefore, an optical fiber sensor approach for bite force measurement with a better resolution would benefit greatly for clinical dentistry.

In the present study, a novel *in vivo* methodology for intraoral measurement of maximum individual bite force based on Fiber Bragg Grating (FBG) sensor is proposed. The developed Fiber Bragg Grating Bite Force Recorder (FBGBFR) converts the bite force exerted at the occlusal surface region into strain variations over a metal plate, which in turn is dynamically sensed by the FBG sensor bonded over it. One of the major advantages of the FBGBFR developed over its conventional counterparts is that it is an semi active device, with no electric power supplied to the sensing element, making it a safe *in vivo* intra-oral device. The bite forces measured in the present study on a substantial sample size, will prove the efficacy of the developed FBGBFR and further the bite force variation may be compared between different tooth positions along the dental arch and also comparison may be carried out with respect to gender. The inherent advantages of a FBG sensor, such as insensitivity to electromagnetic interference, high sensitivity, compact dimensions, low fatigue and ultra-fast response, makes the present FBGBFR an effective means for measurement of individual bite force (Othonos, 1997).

2. Materials and methods

2.1. Theory of Fiber Bragg Grating

FBG is a periodic modulation of the refractive index of the core of a single-mode photosensitive optical fiber, along its axis (Morey et al., 1989). When a broadband light is launched into an FBG, a single wavelength which satisfies the Bragg condition is reflected back while the rest of the spectrum is transmitted (Othonos, 1997). This reflected Bragg wavelength λ_B of the FBG is given by

$$\lambda_B = 2\, n_{eff} \Lambda \qquad (1)$$

Here, Λ is the periodicity of the grating and n_{eff} is the effective refractive index of the fiber core. In the present work, FBG sensors with a gauge length of 3 mm are fabricated in photo sensitive germania doped silica fiber, using the phase mask grating inscription method (Hill et al., 1993).

Any external perturbation such as strain, temperature, *etc.* at the grating site of the FBG sensor, will alter the periodicity of the grating and in turn the reflected Bragg wavelength. By interrogating the shift in Bragg wavelength, the parametric external perturbation can be quantified (Kersey et al., 1997; Othonos and Kalli, 1999). The strain effect on an FBG sensor is expressed as,

$$\Delta\lambda_B = \lambda_B \left[1 - \frac{n_{eff}^2}{2} [P_{12} - \nu (P_{11} - P_{12})] \right] \epsilon \qquad (2)$$

Where, P_{11} and P_{12} are components of the strain-optic tensor, ν is the Poisson's ratio and ε is the axial strain change (Kashyap, 1999; Tahir et al., 2006). The strain sensitivity of a FBG inscribed in a germania-doped silica fiber, is approximately 1.20 pm/$\mu\varepsilon$ (Melle et al., 1993).

2.2. FBGBFR design and fabrication

The FBGBFR consists of an aluminum base plate of length 120 mm, width 10 mm and thickness 2 mm. An FBG sensor of 3 mm gauge length is bonded over the base plate, such that sensor resides at one of its ends. A hollow box structure of length 10 mm, width 10 mm and height 10 mm is constructed with the same aluminum plate material, ensuring that the FBG sensor is positioned inside the box, by taking care that the FBG sensor is at the center of the box structure over the base aluminum plate. Also, a provision is made in one of the side plates of the box structure, for pig-tailing the fiber along the length of the base plate. A synthetic rubber material of length 10 mm, width 10 mm and thickness 2 mm is adhered on both the top and bottom surface of the box structure, which provides the required cushioning and serving as the biting platform (Fig. 1). The FBGBFR is designed such that the distance between the biting platforms is maintained to be 14 mm, since the maximum individual biting force may be recorded with the jaw opening of 14–20 mm, as indicated in the earlier studies (Koc et al., 2010; Mackenna and Türker, 1983; Cosme et al., 2005; Kogawa et al., 2006). The extended length of the aluminum base plate acts as the handle for precise positioning of FBGBFR to measure the individual bite force at the occlusal surface.

The bite force applied on the biting platform imparts a load on the box structure of the FBGBFR, which in turn is transferred to the aluminum base plate.

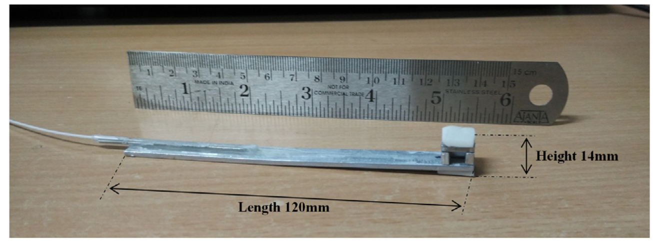

Fig. 1. Picture of FBGBFR.

The segment of aluminum base plate included in the box structure experiences tensile strain as a result and these strain variations are sensed by the FBG sensor bonded over it. The transduction of bite force into strain variations on the aluminum plate, which is dynamically sensed by the FBG sensor bonded over it, constitutes the principle of the FBGBFR, explained schematically in Fig. 2.

2.3. Experimental methodology

The present study has been approved by the Institutional Human Ethics Committee (IHEC), Indian Institute of Science. The experiments carried out in the present study are within the guidelines of the IHEC for human studies and are carried out under the strict supervision of a registered dental practitioner. Also, the subjects have been detailed fully about the experimental procedure and their consent is obtained prior to the experiments. The present study involved 36 volunteers (20 males and 16 females) aged between 24 and 35 years. Subjects are chosen such that they have good dentition history with no craniofacial trauma, no cast restorations, no cuspal coverage, no surgery, and no signs or symptoms of temporomandibular or cranio-cervical disorders, along with a minimum of 28 teeth. Prior to the onset of the test, the subjects are made to sit comfortably on a chair with a back rest, and are allowed to acclimatize with the surroundings for about 10 min. Two molars, two premolars and two incisors are chosen for individual bite force measurement in the present study for each subject, on either side of the dental arch as shown in Fig. 3. Further, the FBGBFR is wrapped with a thin disposable latex cover (which is replaced for individual subjects' hygienic purposes) and is positioned between the maxillary and mandibular jaws exactly between the selected tooth as shown in Fig. 4. The subjects are instructed to clench the FBGBFR thrice in each position, whose individual unilateral bite force is obtained *via* strain variations over the aluminum base plate, using the FBG sensor bonded over it. The maximum individual bite force for a subject, at a specific position by the FBGBFR is the highest peak force recorded among the three repeated bites performed at that position.

3. Results

3.1. Calibration test

The calibration test for the FBGBFR is conducted in the laboratory under a controlled environment. Fig. 5 shows the experimental set up used for the validation and calibration of the FBGBFR. A micro Universal Testing Machine (UTM) with a loading resolution of 1 N is employed for loading the FBGBFR. The biting platforms are loaded from 0 N to 900 N, at a constant displacement rate of 1 mm/min and the simultaneous response of the FBGBFR is recorded.

It is found that the response from both the Micro UTM and FBGBFR are in good accordance throughout the duration of the experiment as shown in Fig. 6. Further, the data obtained from FBGBFR is compared against the data obtained from the micro UTM, which provides a correlation coefficient of 0.99, indicating a linear response of the FBGBFR with force applied by the micro UTM, as shown in Fig. 7. A slope of 1.51 is obtained which denotes the sensitivity of the developed FBGBFR, namely 1.51 $\mu\varepsilon$ for 1 N of force applied. It can be noted here that the response of FBGSS is acquired with a Micron Optics Interrogator (SM 130-700) which has the ability to measure the Bragg wavelength with resolution of 1 pm corresponding to 0.83 $\mu\varepsilon$. Consequently the resolution of the proposed FBGBFR in the present work is computed to be 0.54 N.