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Short communication

Design and construction of a transducer for bite force registration

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ABSTRACT

This study describes the development of a system for quantification of human biting forces by (1) determining the mechanical properties of an epoxy resin reinforced with carbon fiber, (2) establishing the transducer's optimal dimensions to accommodate teeth of various widths while minimizing transducer thickness, and (3) determining the optimal location of strain gages using a series of mechanical resistance and finite element (FE) analyses. The optimal strain gage location was defined as the position that produced the least difference in strain pattern when the load was applied by teeth with two different surface areas. The result is a 7.3-mm-thick transducer with a maximum load capacity beyond any expected maximum bite force (1500 N). This system includes a graphic interface that easily allows acquisition and registration of bite force by any health-sciences or engineering professional.

1. Introduction

In spite of the predominant role occlusal force plays in the basic functions of the human masticatory system (Granger et al., 1999; Houston et al., 1994; Julien et al., 1996; Paphangkorakit and Osborn, 1997; Proffit et al., 1983; Throckmorton et al., 1996; Throckmorton and Ellis 3rd., 2000; Van Eijden et al., 1988; Vardimon et al., 1994), occlusal force transducers have previously only been developed as research prototypes, and few are commercially (Nishigawa et al., 2001; Van Eijden et al., 1988). In addition, these bite force transducers were developed without careful analysis to optimize their design. Design parameters should ensure: (1) sufficient strength in the appliance to withstand the highest estimated loads, (2) that the transducer fits in the mouth, and (3) that biting on the transducer is not painful or uncomfortable. Little attempt has been made to optimize transducer design to match the material properties and thickness of the transducer, or to optimize the location of the sensing elements for greatest reliability and sensitivity. Here we report on the development of a system for measuring static occlusal force according to the international metrology and bioinstrumentation regulations (Norman, 1988) and that meet the design parameters listed above. The system can evaluate occlusal force as a physiological variable related to craniofacial deformities, malocclusions and treatment effects.

2. Methods

The first step was to find an optimal structural model for evaluating the boundary conditions and the dimensions of the device. An analysis of elastic curves (Beer and Johnston, 1993) was performed on three basic configurations of single beams under flexion stress (Fig. 1), looking for a high mechanical resistance and low deflection. The model with the smallest deflection allows the thinnest transducer while guaranteeing that the transducer's two beams would not touch at maximum load (Shigley and Mischke, 1989).

Once the model was chosen, its flexion stress was calculated from normal flexion stresses in beams of rectangular cross section. We selected an epoxy resin, reinforced with longitudinally oriented carbon fiber, for two reasons (Chung, 1994): (1) the mechanical properties under tension (provided by the manufacturer; the fiber's Young's modulus ranges from 380 to 640 GPa) are higher than those of other materials, such as structural steel (approximately 200 GPa) or titanium (approximately 116 GPa) (Baral et al., 2008) and (2) the electric extensiometry technique can be applied with this material.

The mechanical properties of the model's material were determined by performing a flexion test (load vs. strain) that showed the maximal resistance and strain on the proportional limit for a beam fixed on its two ends with a central load (Pendleton and Tuttle, 1989). This experiment was performed in the EAFIT University's materials' laboratory using a UPM 120 Universal Testing Machine (SCHENCK TREBEL GmBH, Ratingen, Germany) that has a capacity of 120 kN. In accordance with the ASTM D790 regulation, 5 test specimens were built to obtain the mean maximal flexion stress and maximal strain on the proportional limit, as well as the standard deviation of the test, from the stress vs. strain curve.

After the mechanical properties of the material were determined its dimensions were calculated by fixing values such as load (P) and thickness (d), and varying the length of the support span (L) and width (b) in the following equation for flexion stress (Eq. (1)):

$$\sigma = \frac{3}{2}\frac{PL}{bd^3} \tag{1}$$

The value of σ could not be greater than that obtained from the mechanical properties test, neither b nor L could be less than 11 mm, (i.e., the average diameter of a molar) and L had to be greater than b to provide enough versatility for locating the transducer inside the patient's mouth.

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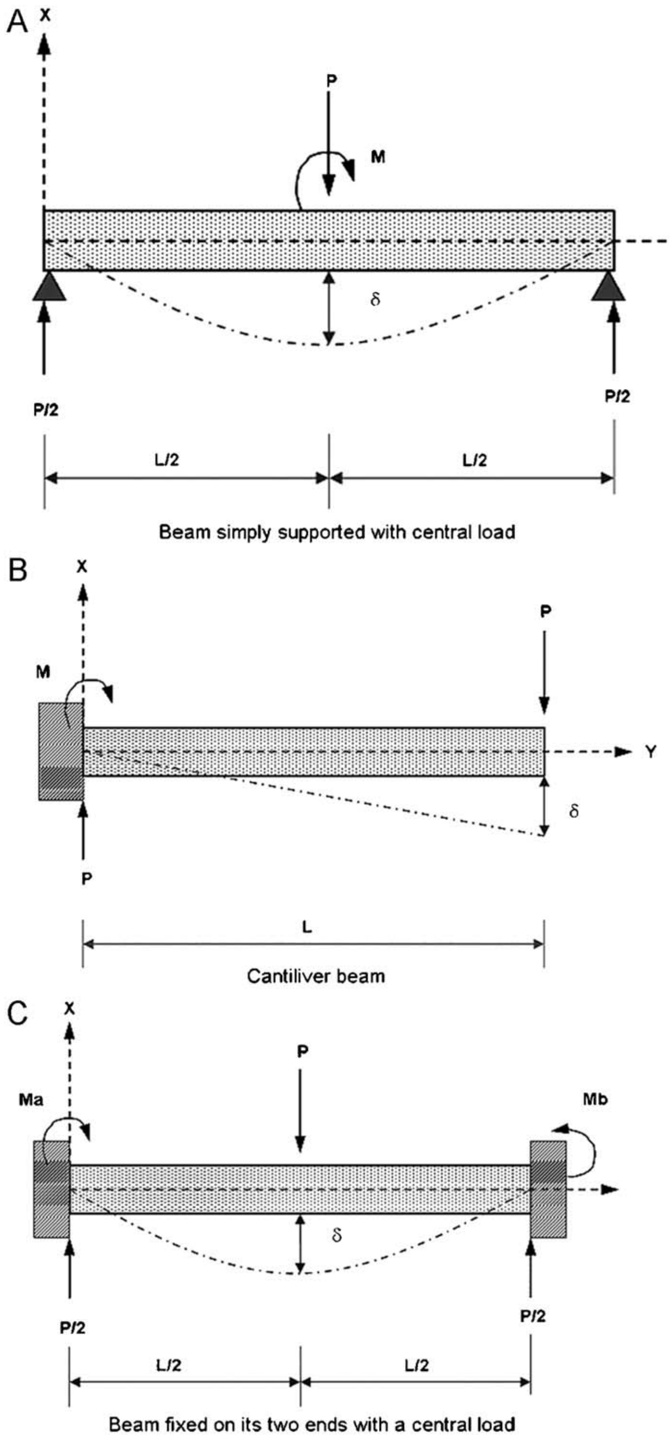

Fig. 1. Three configurations of single beams under flexions stress. (A) Beam simply supported with a central load; (B) cantilever beam; (C) beam fixed on its two ends with a central load.

Once the transducer's dimensions were defined, an orthotropic numeric three-dimensional model was built by means of the finite elements method (FEM) in order to determine the optimal location for the strain gages (Zienkiewicz and Taylor, 1989). This method located the positions on the transducer where strains were similar for (1) a concentrated load model, simulating the one produced by incisors; and (2) a distributed load model simulating the one produced by the first molars.

The geometry was drawn in standard CAD software (Pro/ENGINEERWILDFIRE; Parametric Technology Corporation, Needham, MA), and then exported as a part to numeric analysis software that uses FEM (ANSYS 8.1; Technology Drive Canonsburg, PA). We used tetrahedric elements of ten nodes incorporating the mechanical properties obtained from the previously described flexion test and two more tests performed according to the ASTM D 3039/D 3039M and D 3518/D 3518M standards (ASTM, 2000, 2001). These provided the five elastic constants necessary to build an anisotropic model of the transducer's structure.

Table 1
Mechanical properties of the reinforced epoxy resin.

Property	Value
Elastic modulus (E_X)	186 GPa
Elastic modulus (E_Y)	10 GPa
Elastic modulus (E_Z)	10 GPa
(G_{XY})	6 GPa
(G_{YX})	5 GPa
(V_{XY})	0.3
Tension strength	2.8 GPa
Density	1.5 g/cm^3
Fiber content (vol.)	68%

Table 2
Results of the flexion test on a beam fixed on its two ends.

Specimen	Load, P (N)	Flexion stress on the proportional limit (MPa)
1	1488	484.375
2	1488	484.375
3	1492	485.677
4	1490	485.026
5	1491	485.351
Mean (MPa)	Standard deviation	
484.96	0.582	

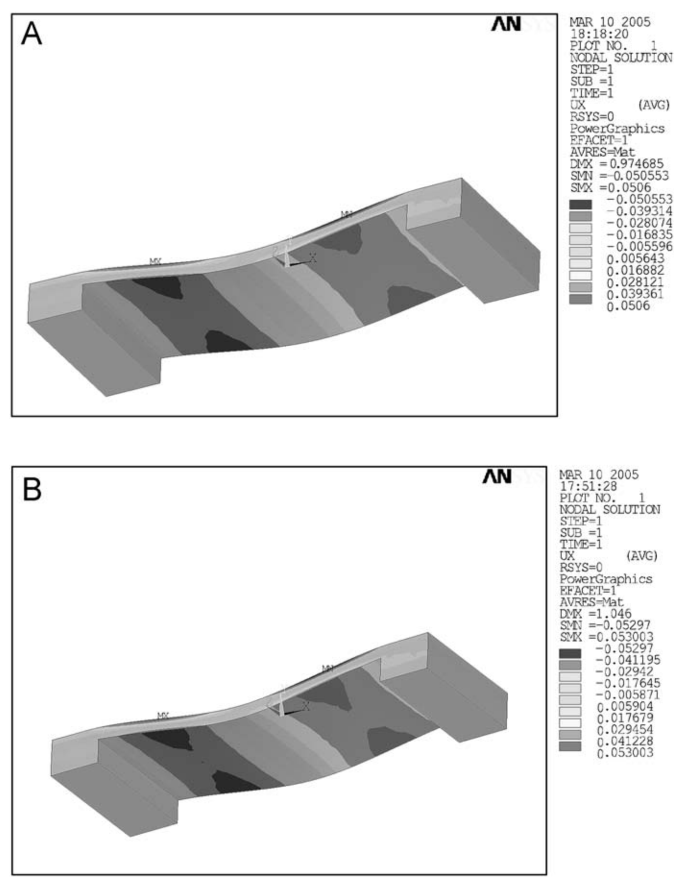

Fig. 2. *X*-axis displacements when models with concentrated loads for the incisors (A) and more distributed loads for the molars (B); note the close similarity of the displacement patterns between the two loads.

We analyzed the displacements in the nodes throughout the *X*-axis (along the carbon fibers) for two FEM models under both incisor- and molar-simulated loads. The displacements at the supported end of each model were compared, and the zones where the displacements were similar determined the ideal position for strain gages so that measurements in molars and incisors could be done without calibrating for each biting position.

The strain gages (Measurements Group, Raleigh, NC) were placed at the optimal locations according to the company's recommendations (Measurements Group Inc., 1983), and the transducer was sealed and connected to the acquisition system. Finally, two polyethylene covers (0.3 mm thick each) were attached to the transducer with surgical tape to protect the teeth and provide a more comfortable bite. The transducer was then calibrated (Norman, 1988) using a universal machine (EAFIT University) according to NTC regulation #3761. For the acquisition, visualization and registration of the data, we used a data acquisition device (DAQ 6024E; National Instruments, Texas) with a differential input range of $\pm$50 mV and a total gain of 100, with the graphic display provided by LabView 6.1 (National Instruments, Austin, Texas).

3. Results

A beam fixed at its two ends with a central load produced the lowest deflection. The results of the flexion test performed on this material are shown in Table 1 and other specific characteristics of the material are shown in Table 2. The *X*-axis displacements for the models of concentrated (incisors) and distributed loads (molars) are shown in Fig. 2. Both load models presented a great similarity of displacements over the entire surface, especially in the zones near the supports. These zones are the optimum positions for strain gage installation. Three data sets of equally spaced (every 150 N) loads from 0 to 1500 N resulted in a linear regression with an $R^2 = 0.999$.

For visualization, the graphic interface in LabView 6.1 (National Instruments, Texas) has two separate graphs; the top one displays the real-time condition of the transducer, the bottom one remains empty until data collection ends and then displays transducer output for the entire duration. The display has a number of buttons: the "personal data" button saves the patient's data, the "observations" button saves any special observations prior to or after the study, the "acquire" and "stop" buttons are used to start and finish data acquisition, and the "save curve" button saves the occlusal force data acquired from the transducer as a .dat file.

4. Discussion

The most important factor in occlusal force transducers is balance between thickness and load capacity. In general, devices that must register very high loads require a high vertical dimension (Hickman et al., 1993), and those with lower dimensions are not capable of supporting high loads. Our design overcomes this problem with a fixed beam at both ends, resulting in less deflection when applying central loads. This design can respond to very high loading of 1500 N with a transducer's thickness of only 7.3 mm, including the polyethylene tops (Fig. 3). Selecting an optimal position for the gages made possible the use of a single calibration chart for both molars and incisors.

No previous reports describe the use of composites such as reinforced plastics in the design of occlusal force transducers. The reinforced epoxy resin with carbon fiber used for this system presents better mechanical properties than stainless steel,

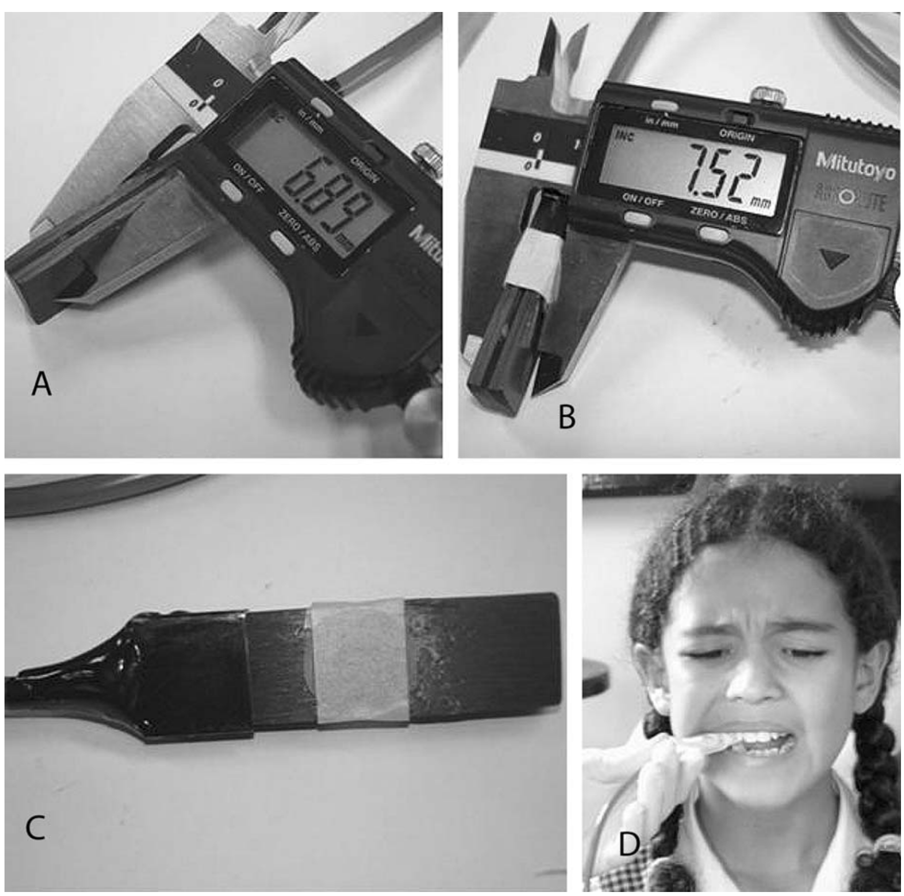

Fig. 3. Four views of the finished transducer. (A) Digital calipers showing the thickness of the transducer before covering with polyethylene tops. (B) Digital calibers showing the thickness of the transducer with the polyethylene tops. (C) Occlusal view of the finished transducer. (D) Subject biting on the transducer at the premolar position. Transducer was inserted into a latex sleeve to provide infection control.

allowing reduced thickness of the beams and, consequently, minimal vertical height. The high correlation coefficient demonstrated good stability of the reinforced epoxy resin with carbon fiber and confirms the applicability of the technique of electric extensiometry. Therefore, we recommend the use of this kind of material in the design of occlusal force transducers.

Conflict of interest statement

We declare that none of the authors have any financial or personal relationship with persons or organizations that might inappropriately influence the work presented here.

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