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Fiber Bragg grating sensor for measurement of impact absorption capability of mouthguards

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Abstract – *Background*: There is no standard technique to monitor impact absorption capability of mouthguards. Earlier investigations have established that strain transferred to the teeth through mouthguard is a good indication of their efficiency. In the present study, a unique experimental scheme utilizing fiber Bragg gratings (FBGs) as distributed strain sensors is proposed and investigated to estimate impact absorption capability of custom-made mouthguard. The proposed methodology is useful due to advantages such as, very small size and flexibility for ease of bonding, self-referencing, and multiplexing capability of using FBG sensors. *Material and methods*: Finite-element analysis was performed to simulate the stress distribution due to impact on the mouthguard. The FBGs were fabricated by exposing the core of photosensitive fiber to intense Ultra-Violet light through a 'phase mask'. One FBG sensor was bonded on the jaw model and another on the mouthguard surface at similar positions, so that both gratings are simultaneously affected by impact. Two different sets of the sensors were used, one for the anterior region and another for posterior region. The impact was produced using customized pendulum device with interchangeable impact objects i.e. cricket ball, hockey ball, and steel ball. Response of gratings was monitored using optical spectrum analyzer and strain induced due to each impact was determined from the Bragg wavelength shifts for each grating. *Results and conclusions*: Strain induced due to impact was calculated from the Bragg wavelength shifts. Difference in the strain values for the two gratings is interpreted as impact energy absorbed by the mouthguard. The Bragg wavelength shifts (induced strain) for FBG bonded on the jaw model was much lower than the shift for FBG bonded on the mouthguard, indicating that most of the impact energy is absorbed by the mouthguard.

Participation in contact sports or even some individual sports like riding and skating puts a person at risk for injuries caused by impact of sport object, blow, kick, or fall. Such injuries may cause damage to dental or facial structures that might have lifelong repercussions and undermine the benefits such activities offer (1, 2). In view of this, now-a-days, the use of protective mouthguards as preventive measures for persons participating in sports activities is being encouraged. There is published evidence to indicate that mouthguards reduce the likelihood of dental trauma or facial and brain injury from the impact force (3). Since their inception more than a century ago, a lot of improvement has been made to make mouthguards more efficient to prevent transmission of excessive force to the teeth and jaw by absorbing high-impact energy. Of the three main types of mouthguards i.e. stock, boil-and-bite, and custom made, the last one had been reported to show superior properties in terms of comfort, adaptability, stability, ability to talk and breathe along with better protection (4, 5). As no licensing is needed to manufacture these mouthguards and no rigid quality control parameters exist till date, there are considerable variations in the properties of mouthguards manufactured by different sources. To evaluate the performance characteristics of such custom-made mouthguards, no standard technique has been defined and various groups have reported different approaches to the same. It has been recommended in these reports that a measure of strain transferred to the teeth through mouthguard is a better indication of their efficiency in terms of design and injury-preventing capability (6, 7). To assess the strain transfer, tests under controlled conditions are conducted to simulate the effect of actual sports-related impacts.

Several research groups have studied this assessment issue involving (i) different impact devices, drop ball, or pendulum-based being the most common, (ii) different impact objects (8) like balls of different materials or actual sport objects e.g. flat-ended (boxing, impacts with ground and floors), hemispherical (cricket ball, hockey ball) and rounded-cone (hockey stick, racket, cricket bat) and (iii) different sensing techniques (9) such as accelerometer, electrical strain gage (6, 9) or load cell (8, 9). Electrical strain gages, considered gold standard for strain measurements have various problems associated with their implementation for this application. These gages need to be mounted on flat areas with no or very small curvatures and therefore it is difficult to mount them on study models simulating normal occlusion and becomes more complicated for models with malocclusions. Very small size strain gages (< 2 mm grid size) are needed, and there is no space for soldering the lead wires or routing them. Moreover, they require electric voltage for excitation and carboxylate adhesive, a poor conductor, to fix them on the study models. Another problem associated with voltage is that a very low excitation has to be used to avoid self-heating of the strain gage, which results in significant reduction in Signal to Noise ratio.

Optical fibers, on the other hand, offer many advantages for biomedical applications due to their well-known intrinsic properties such as small size (thickness less than that of standard surgical suture), biocompatibility, non-toxicity, immunity to electromagnetic and radio frequency radiations as well as chemical inertness (10). Fiber Bragg gratings (FBGs) are a class of optical fiber sensor elements that have attracted a great deal of attention recently because they offer all the features of optical fibers with some added advantages unique to them such as self-referencing and multiplexing capability. The potential of FBGs as strain and temperature sensors array in various concrete and composite structures for structural health monitoring had been established much earlier (11–15). However, the use of this technology in biomedical arena is in early stage of research and development (16–19).

The first application of FBG sensors in dental science was reported by Tjin et al. (20) to monitor the force and temperature as a function of time in dental splints used by patients with obstructive sleep apnea. The small dimensions of the sensor allowed it to be embedded within the splint without diluting its effectiveness. These sensors are on a single fiber, working independently of the other, are unobtrusive and inherently safe as compared with conventional thermistor and piezo-electric pressure sensor. In another study, an FBG sensor was employed by Silva et al. (21) on a dried cadaveric mandible to measure strain at the mandible surface caused by impact loads on dental implants. A standard dental implant was embedded on a dry human cadaveric mandible and FBG fixed on its outer surface near canine tooth position. The impact was produced by dropping a steel mass of 52 g and Bragg wavelength shift was recorded to observe dynamic strain. The results matched with those obtained with strain gages confirming the feasibility of using FBG to monitor dynamic strain in a complex biomechanical system. Another research group in Portugal has applied FBG sensors to assess the performance of dental implant system by measuring static and dynamic bone strains around a dental implant (22).

The objective of this study was to assess the efficiency of mouthguard through impact test by using FBG sensors in place of the electrical strain gages. The impact was simulated using a customized pendulum device, and its response was observed using pairs of FBGs bonded on similar positions on custom-made mouthguard and a typhodontic jaw model, which is first of its kind arrangement. Use of FBG provided a unique advantage in terms of distributed sensing; two sensors were used simultaneously at mouthguard and jaw model. Response of both the sensors was monitored in single impact simulating real case scenario. The strain was calculated by the wavelength shift of the FBGs, and difference in strain at both the grating locations provides an indication of impact absorption capability of the mouthguard.

Working principle

In a FBG, there are no ‘grooves’ etched on the outer fiber surface. Instead, they are uniformly spaced narrow regions in a fiber core, where the refractive index has been raised from that of the rest of the core by illuminating it with Ultra-Violet (UV) light. Such a periodic variation of refractive index is created mostly by exposing the fiber to UV radiation through a phase mask. When a light wave enters a medium with varying refractive indices, it undergoes minute reflections from every interface. If all the individual reflections are in phase, constructive interference will take place between reflected waves leading to a strong reflection at a particular wavelength given by the Bragg equation,

$$\lambda_B = 2n\Lambda$$

where λ_B is the reflected Bragg wavelength, n is the effective refractive index of the core and Λ is the pitch of the grating. Therefore, when light from a broadband source is launched in an FBG, the spectral component defined by above equation is missing from the transmitted spectrum. Bragg wavelength is shifted if the effective refractive index or the grating periodicity is changed due to some perturbation; in fact, both these parameters are directly influenced by strain and ambient temperature with the associated wavelength shift given as,

$$\Delta\lambda_B = 2\left[\Lambda\frac{\partial n}{\partial l} + n\frac{\partial \Lambda}{\partial l}\right]\Delta l + 2\left[\Lambda\frac{\partial n}{\partial T} + n\frac{\partial \Lambda}{\partial T}\right]\Delta T$$

where Δl is change in grating length due to strain and ΔT is change in ambient temperature. The first term on the RHS gives strain dependence, while the second term gives temperature dependence of the Bragg wavelength. A standard FBG with Bragg wavelength ~1550 nm has a strain sensitivity of 1.2 pm/$\mu\varepsilon^{-1}$ at constant temperature and temperature sensitivity of 12 pm °C^{-1} at zero strain (11, 12). At constant temperature, a Bragg wavelength shift $\Delta\lambda_B$ is due to strain induced at the grating as a result of impact and thus strain can be calculated by this wavelength shift using the calibration factor of 1.2 pm $\mu\varepsilon^{-1}$.

Materials and methods

A typhodontal or jaw model i.e. Nissin Typhodont Model D1-01BN representing normal occlusion was selected for the study. The mouthguards were custom-made according to this jaw model by Buy-Dent Agencies, Hyderabad, India.

Two sets of parallel locations were chosen on the mouthguard and the jaw model to bond FBGs in a manner so that they coincide with possible points where the impact object may hit. Impact was made using pendulum device with interchangeable round impact objects. A set of FBG sensors was used for each location to measure the effect of respective impacts on the mouthguard and the jaw model. The FBGs were fabricated by exposing the core of a hydrogenated photosensitive fiber to intense UV light from a KrF excimer laser at 248 nm using standard 'phase mask technique' (11, 12, 23). All the FBGs had their Bragg wavelengths λ_B between 1545 and 1550 nm with grating lengths of $\sim$10 mm and similar reflectivities. These FBGs were recoated for strength and thermally annealed at 150°C for 24 h to stabilize their properties.

The stress distribution due to impact was simulated through finite-element analysis (FEA) using COSMOS-Works design analysis software and is shown in Fig. 1. A non-linear FEA analysis was performed on the 3D model of the mouthguard with a load of 40 N applied at two impact points on anterior and posterior region of its outer surface. These points were selected to coincide with the labial and buccal regions of the jaw model. One set of FBGs was used for the anterior region; one bonded on the labial area of properly cleaned outer surface of the mouthguard and the other on the most prominent tooth of the jaw model using standard EA-2A epoxy. Similarly, another set of FBGs were used in the posterior or buccal region; one on the mouthguard and other on the molar tooth. Both the FBGs were bonded parallel to each other so that they are affected simultaneously when hit by an impact object. The spectrum of all the FBGs was monitored using an optical spectrum analyzer (Yokogawa AQ 6319).

A custom-made simple pendulum-based device with interchangeable impact objects was procured by Pyrodynamics with the arrangement to fix jaw model. Figure 2 shows photograph of the jaw model, mouthguard, and the pendulum setup. A pendulum rod was designed so that it can hold different round objects and can impart impact with varying intensity by releasing it from different angles. Three impact objects namely, cricket ball, hockey ball and steel ball were used for this study. This choice was made because cricket and hockey are the most popular sports in our country, steel ball can simulate very hard impact and these balls could be replaced easily by removing the nut.

The axis length of the pendulum was about 50 cm and the apparatus was adjusted to hit the surface of the jaw model with mouthguard at a point coinciding with the position of the FBG sensors. The jaw model was fixed rigidly on the pendulum base plate using set of screws to avoid any displacement because of the impact. The pendulum rod is first fixed horizontally by a handle and then released to hit the jaw model and mouthguard combination. Intensity of the impact can be varied by changing the angle of release; in the present investigation, the object was released from 30°, 45°, and 60° angles. The impact energy estimated for each ball and each angle has been shown in Table 1. In the first set of experiment, the jaw model with mouthguard on it was mounted on the pendulum set up in such a way that when the object ball is released, it hits at labial surface of the most prominent tooth affecting the FBGs at mouthguard and that at the jaw model (center impact) simultaneously. Bragg wavelength shifts of both these FBGs were recorded for three release angles with each impact object one after another. In another set of experiment, the jaw model was fixed in a different position so that the impact affects posterior region (side impact) and the same procedure was repeated for each angle and with each impact object.

Results

The relative Bragg wavelength shift with respect to each impact load determines strain at the point of impact and the difference in the strain values for both the FBGs can be interpreted as impact energy absorbed by the mouthguard. Figures 3 and 4 (a and b) indicate changes in spectra of FBGs bonded on the mouthguard and that on the jaw model (denture) due to cricket ball and hockey ball impact in that order. Strain induced at the mouthguard and at the denture surfaces due to impact was calculated from the Bragg wavelength shifts and plotted in Fig. 5a,b.

Discussion

It was observed that the induced strain in the mouthguard was directly proportional to the angle from which

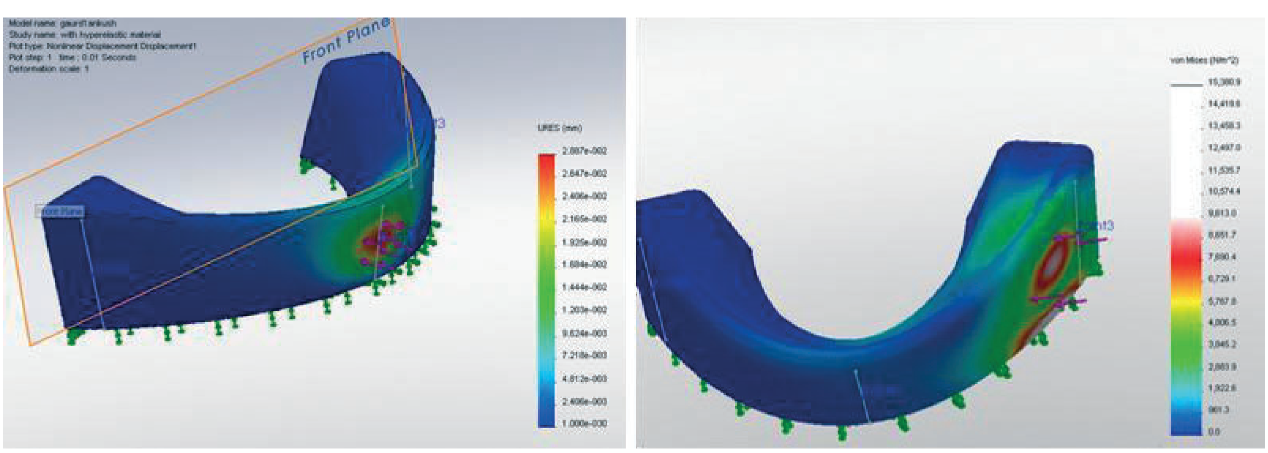

Fig. 1. Finite element analysis simulation of stress distribution in mouthguard due to impact (Center and Side); Pink arrows show impact point and colour gradient represent stress distribution.

Fig. 2. Photograph of Jaw Model and mouthguard with sensors bonded on them and pendulum-based device used for Impact Study.

Table 1. Impact energy for different balls dropped from three different angles

Angle (°)	Hockey ball (120 g) (joules)	Cricket ball (130 g) (joules)	Steel ball (210 g) (joules)
30	0.2822	0.3058	0.4939
45	0.4234	0.4586	0.7409
60	0.5645	0.6115	0.9878

the impact balls were released and also for the same angle, it was the highest for steel ball as expected from the impact energy values (Table 1).

For FBGs bonded on the mouthguard, significant changes in their spectrum and hence in Bragg wavelength were observed for various impacts, while spectrum or Bragg wavelength for the FBGs bonded on the jaw model had shown negligible or no changes for the same (Fig. 3 and 4). Comparison of strain induced due to impact (Fig. 5) ascertains that the center impact produced one order more strain than side impact under the same conditions indicating that the most prominent tooth is more prone to damage as compared with teeth at posterior regions. For the same impact, the difference in strain produced in the FBG fixed on the mouthguard and that on the denture is because of impact absorption capability of the mouthguard. The impact absorption capability thus calculated for cricket ball, hockey ball, and steel ball was found to be more than 90% for the center impact and between 50% and 100% for side impact simulation decreasing with higher impact energies as shown in Table 2. Thus, although the center impact produced larger strain, the mouthguard used for this study was able to absorb a major part of impact energy. However, for side impact, the design needs to be modified to improve its efficiency.

The accuracy of the results obtained in this study is limited by speed of data acquisition system used to record the spectrum. There is a finite time delay between the time of impact and the instant at which the spectrum was recorded. This time delay may result in Bragg wavelength shift not exactly representing true impact effect, but the wavelength shifts of two FBGs are recorded at the same instant always. This self-referencing is a unique advantage of the methodology used in the present investigation; both the FBGs will be influenced by the same impact and effect of any experimental error will also be the same for both so the relative wavelength

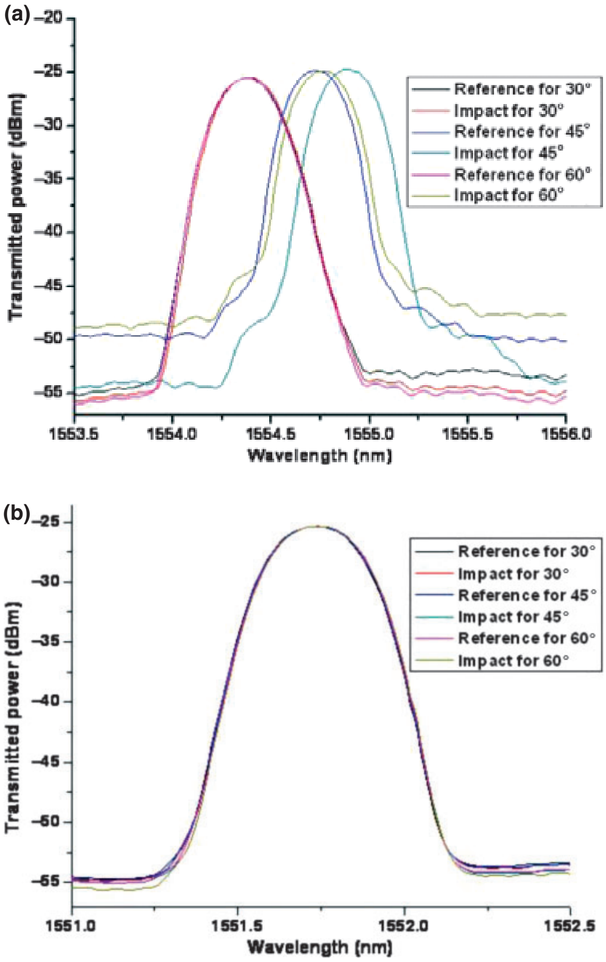

Fig. 3. (a) Fiber Bragg grating spectra with cricket ball impact for sensor bonded on mouthguard showing more shift for larger angle impact; (b) Fiber Bragg grating spectra with cricket ball impact for sensor bonded on Jaw model showing negligible shifts for each impact.

shift is largely error-free. High energy absorption level does not necessarily mean maximum protection, as some of the absorbed energy may be transmitted directly to the underlying structure (5). In the present case, this aspect has been taken care of due to self-referencing feature.

These values cannot be compared with the values reported earlier (6–9) because we have used totally different experimental technique. In the earlier works, the impact was made twice, once on the mouthguard, the

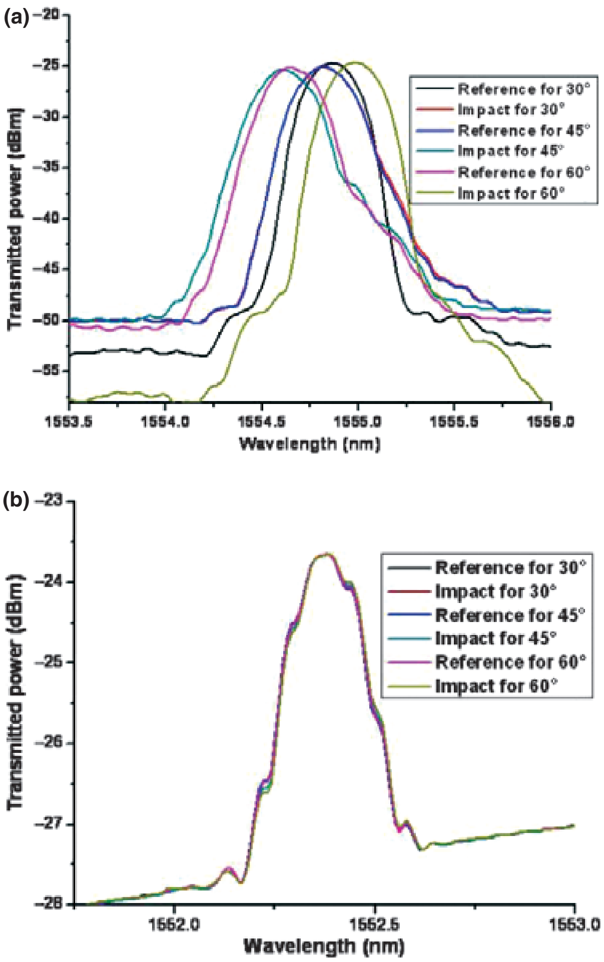

Fig. 4. (a) Fiber Bragg grating spectra with hockey ball impact for sensor bonded on mouthguard showing more shift for larger angle impact; (b) Fiber Bragg grating spectra with hockey ball impact for sensor bonded on Jaw model showing negligible shifts for each impact.

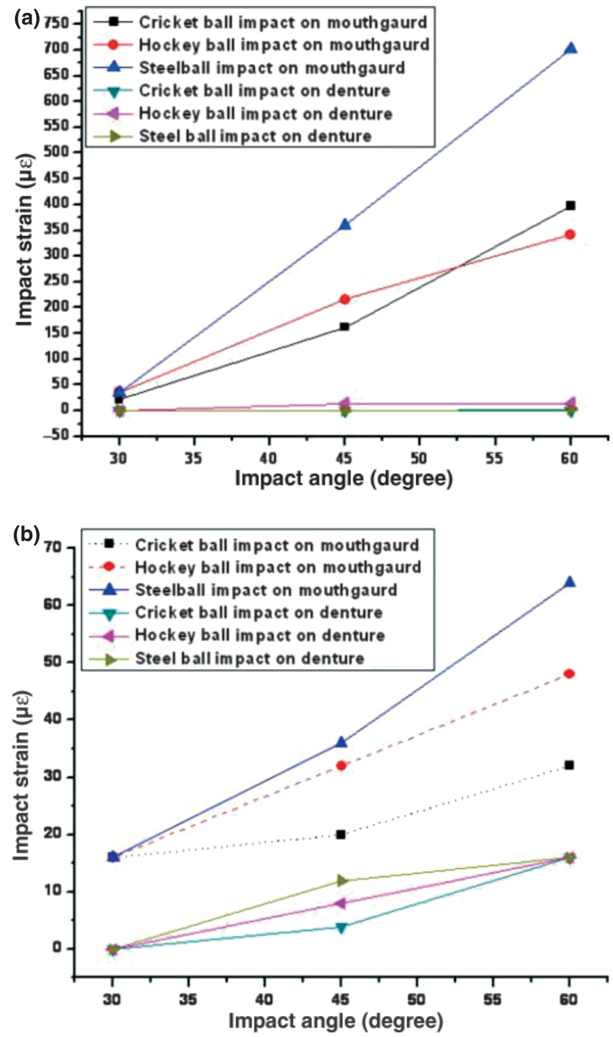

Fig. 5. (a) Strain induced at mouthguard (upper three curves: blue, red and black lines) and Jaw model (lower three curves: yellow, pink and green lines) due to center impact; upper curves represent larger induced strain while lower curves indicate less strain; (b) Strain induced at mouthguard and Jaw Model (denture) due to side impact. Upper curves represent larger induced strain while lower curves indicate less strain.

next on the jaw model itself, whereas in our case, there was no direct hit on the jaw model and the strain was monitored simultaneously for mouthguard and jaw model at each impact using two FBGs in series. This capability of multiple FBG sensors to work in series giving response independent of each other is another advantage our experimental scheme offers over other conventional strain sensors. It is worthwhile to mention here that in principle, it is possible to use all four FBGs or even more in series, but we had used two at a time which were simultaneously affected by each impact. This approach is justified for the regular typhodontic model with normal occlusion taken up in this case. According to FEA simulation results, no significant stress is transferred at points distant from the impact, so the indirect effect on other two FBGs can be considered as negligible. For denture models with different types of malocclusions, this stress distribution will be very different and hence it will be required to evaluate the effect of a single impact on different locations simultaneously. Application of several

Table 2. Impact absorption by mouthguard

	Hockey ball		Cricket ball		Steel ball	
Angle (°)	Side impact (%)	Center impact (%)	Side impact (%)	Center impact (%)	Side impact (%)	Center impact (%)
30	100	100	100	96.0	100	97.2
45	75.0	93.5	80.0	99.3	67.0	99.7
60	67.0	96.0	50.0	99.7	75.0	99.7

FBG sensors multiplexed in series with a single data acquisition system will be very functional in such cases. Impact tests on various locations can detect the vulnerable points where the mouthguard is less protective. Through further investigations with collaboration of scientists, dental clinicians, and mouthguard manufacturers, it will be possible to quantify the level of protection and hence to predict the required modifications in the mouthguard. All the previous studies on mouthguards had taken into account the impact with and without mouthguard, but in real life situations, the impact occurs simultaneously on the mouthguard as well as the teeth i.e. the denture, in our study. Therefore, by carrying out this study, we are able to simulate the real life impact situation as close as possible. It will help in better designing of custom-made mouthguard, especially for teeth with malocclusion.

Conclusion

In this investigation, a new experimental scheme utilizing FBG sensor was proposed and investigated to measure impact absorption capability of custom-made mouthguards. This technique is much better than other reported methods because (i) very small size and flexibility of fiber results in easier bonding and (ii) self-referencing and multiplexing capability of FBGs make possible simultaneous strain measurements at various points and (iii) the effect of impact on the mouthguard and jaw model was monitored at the same instant simulating real-life scenario. This study will be useful for better designing of custom-made mouthguards for different malocclusion, as the proposed method can give strain not only at the point of impact but at other vulnerable points also in a single hit. Thus, with a faster data acquisition scheme and improved experimental setup, this technology can be used for setting standard tests to design and evaluate absorption capability of custom-made mouthguards.

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References

1. Sane J, Ylipaavalnimei P. Dental trauma in contact team sports. Endod Dent Traumatol 1988;4:164–9.
2. Flanders R, Bhat M. The incidence of orofacial injuries in sports: a pilot study in Illinois. J Am Dent Assoc 1995;126:491–6.
3. Newsome PRH, Tran DC, Cooke MS. The role of the mouthguard in the prevention of sports-related dental injuries: a review. Int J Paediatr Dent 2001;11:396–404.
4. Duarte-Pereira DMV, Del Rey-Santamaria M, Javierre-Garcés C, Barbany-Cairó J, Paredes-Garcia J, Valmaseda-Castellón E et al. Wearability and physiological effects of custom-fitted vs. self-adapted mouthguards. Dent Traumatol 2008;24:439–42.
5. Patrick DG, Noort R van, Found MS. Scale of protection and the various types of sports mouthguard. Br J Sports Med 2005;39:278–81.
6. Found MS, Patrick DG, Pearson JR. The influence of strain measurement on the impact performance of sports mouthguards. Compos Part A 2006;37:2164–70.
7. Godwin WC, Craig RG. Stress transmitted through mouth protectors. J Am Dent Assoc 1968;77:1316–20.
8. Takeda T, Ishigami K, Shintaro K, Nakajima K, Shimada A, Regner CW. The influence of impact object characteristics on impact force and force absorption by mouthguard material. Dent Traumatol 2004;20:12–20.
9. Takeda T, Ishigami K, Handa J, Nakajima K, Shimada A, Ogawa T. The influence of the sensor type on measured impact absorption of mouthguard material. Dent Traumatol 2004;20:29–35.
10. Mishra V, Singh N, Kapur P. Fiber Optic Sensors Technology in Medicine. In: Rai DV, Raj Bahadur, editors. Trends in medical physics and bio medical instrumentation. Chandigarh, India: New Era International Imprint; 2009. p. 225–42.
11. Kashyap R. Fiber Bragg gratings. London, UK: Academic Press; 1999.
12. Othonos A, Kalli K. Fiber Bragg gratings, fundamentals and applications in telecommunications and sensing. Norwood, MA: Artech House INC; 1999.
13. Singh N, Jain SC, Mishra V, Poddar GC, Jindal VK, Bajpai RP et al. Multiplexing of Fiber Bragg grating sensors for strain and temperature measurements. Exp Techniques 2007;31:54–6.
14. Tiwari U, Mishra V, Poddar GC, Kesavan K, Jain SC, Ravisankar K et al. Health monitoring of steel and concrete structures using fiber Bragg grating sensors. Curr Sci 2009;97:1539–42.
15. Rao YJ. Recent progress in applications of in-fiber Bragg grating sensors. Opt Lasers Eng 1999;31:297–324.
16. Mohanty L, Tjin SC, Lie D, Panganiban SEC, Chow P. Fiber grating sensor for pressure mapping during total knee arthroplasty. Sens Actuators A Phys 2007;135:323–8.
17. Talaia PM, Ramos A, Abe I, Schiller MW, Lopes P, Nogueira RN et al. Plated and Intact Femur Strains in Fracture Fixation Using Fiber Bragg Gratings and Strain Gauges. Exp Mech 2007;47:355–63.
18. Fresvig T, Ludvigsen P, Steen H, Reikeras O. Fiber optic Bragg grating sensors: an alternative method to strain gauges for measuring deformation in bone. Med Eng Phys 2008;30:104–8.
19. Mishra V, Singh N, Rai DV, Tiwari U, Poddar GC, Jain SC et al. Fiber Bragg Grating Sensor for Monitoring Bone Decalcification. Orthop Traumatol Surg Res 2010;96:646–51.
20. Tjin SC, Tan YK, Yow M, Lam YZ, Hao J. Recording compliance of dental splint use in obstructive sleep apnoea patients by force and temperature modeling. Med Biol Eng Comput 2001;39:182–4.
21. Silva JCC, Carvalho L, Nogueira RN, Simões JA, Pinto JL, Kalinowski HJ. FBG applied in dynamic analysis of an implanted cadaveric mandible. Second European Workshop on Optical Fibre Sensors (Santander, Spain), Proc. SPIE 2004; 5502: p. 226–9.
22. Schiller MW, Abe I, Carvalho P, Lopes P, Carvalho L, Nogueira RN et al. On the use of FBG sensors to assess the performance of a dental implant system. Proceedings of the Optical Fiber Sensors Conference (OFS-2006); 2006 Oct. 23–27; Cancún, México, ThE77.
23. Singh N, Jain SC, Aggarwal AK, Bajpai RP. Fiber Bragg Grating Writing Using Phase Mask Technology. J Sci Ind Res 2005;64:108–15.