INTRODUCTION

Be it contact or non-contact sports, mouthguards play an important role in preventing oral injuries and preserving the oral structures of athletes during sports. The American Society for Testing and Materials (ASTM) has classified mouthguards into three basic types: stock, mouth-formed or boil-and-bite, and custom-made. Custom-made mouthguards are the preferred choice for players and recommended by FDI (Fédération Dentaire Internationale) World Dental Federation. Besides preventing orofacial injuries, custom-made mouthguards provide athletes with better comfort and wearability and can be processed for end-use applications.

Ethylene vinyl acetate (EVA) is the most commonly used material for commercial and custom mouthguards because of these attractive features: widespread availability, can be easily molded, and yet has adequate physical and mechanical properties. Polyolefin is also another popular mouthguard material in terms of tensile and tear strength, hardness, contact angle to water, shock-absorbing capability, and good bonding durability like EVA when stored in water under pressure.

In vitro studies on the shock absorption capability of mouthguards quantify the direct impact on the latter by measuring force using load cells, accelerometers, fiber Bragg grating sensors and strain gages. Force is applied by using a free-falling object, drop-ball, pendulum, piston, or impact rig. Although these methods are useful in measuring the shock-absorbing capability, they do not measure the changes in actual intensity and distribution of stress under the mouthguard. Three-dimensional finite element analysis (FEA) is another comprehensive method which uses a virtual dynamic force to examine the shock absorption capability of a mouthguard by visualizing the dispersion of force three-dimensionally. However, this method has numerous limitations. The overall design is rendered by a computer-aided design (CAD) software, and the cushioning or supporting effect of mouthguard can be processed for end-use applications.

Keywords: Mouthguard material, Impact object, Load cell sensor, Film sensor

Combined analysis of shock absorption capability and force dispersion effect of mouthguard materials with different impact objects

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The aims of the present study were to investigate the shock absorption capability and force dispersion effect of mouthguard (MG) materials using load cell and film sensors. Two kinds of MG materials, ethylene vinyl acetate and polyolefin, were chosen for this study. When impact forces of approximately 5,000 N were applied on the MG materials using a round flat-nosed rod and a bluntly pointed rod, peak intensities were measured using the load cell sensor while peak stresses and impressed stress distribution areas were measured using the film sensor. Combined analysis using both load cell and film sensors clearly showed the shock absorption properties and force dispersion effects of different MG materials with different impact object shapes. Therefore, impact analysis involving a combined use of these sensor systems was useful and reliable in assessing the shock absorption capability and force dispersion effect of MG materials.

Keywords: Mouthguard material, Impact object, Load cell sensor, Film sensor
mouthguard material was investigated and most impact objects used were of a round shape.

Many orofacial injuries were sustained during team sports such as ice hockey (2.2–5.0%) which involved the use of sticks, hockey pucks, or by collision\(^{21,22}\), and shinty (4.8%)\(^{23}\). In non-contact sports like field hockey, the second major cause of dentoalveolar injuries was by hockey sticks (38.2%)\(^{24}\). In other words, many injuries were inflicted by impact objects which were not always spherical or round like a ball. Therefore, it is necessary to assess the shock absorption capability of a mouthguard material according to different types of impact objects.

The purpose of the present study was to observe the changes in shock absorption capability and behaviour of two conventional mouthguard materials as a function of the impact object’s shape. Findings of the present study would also show that compared with data independently obtained using each measurement system, combined analysis using both load cell and film sensors provided superior reliability in impact analysis.

**MATERIALS AND METHODS**

**Specimen preparation**

Two commercially available mouthguard sheets were used in this study. One was 4-mm-thick EVA sheet (Erkoflex\(^{\circledR}\), Erkodent Erich Kopp, Germany; Lot No. 1214004; coded as ERK), which was cut into 20 circular specimens of 5 cm diameter each. Another was 4-mm-thick Polyolefin sheet (MG21™, CGK Corp., Hiroshima, Japan; Lot No. 581240; coded as Ole), which was cut into 20 circular specimens of 5 cm diameter each.

**Shock absorption test**

Specimen was placed on the stainless steel platform of an impact test machine (modified IM-201, Tester Sangyo Co. Ltd., Saitama, Japan). Free-fall drop test was carried out using a free-falling metal object (500 g) at a vertical height of 25 cm onto the top end of two different types of metal rods: one had a round flat-nosed (Fl) tip of 12.7 mm diameter, and the other had a bluntly pointed (Pn) tip of 3.2 mm diameter (Fig. 1).

Two measuring systems were used for the shock absorption test: load cell sensor and film sensor (Figs. 2 and 3).

1. **Load cell sensor**

Three dynamic compression load cells (LMB-A-2KN, Kyowa Electronic Instruments Co., Tokyo, Japan) were placed 120° apart below a 10-mm-thick stainless
steel platform of the impact testing machine. Changes in load during and after impact load application, by dropping the free-falling object on both types of rods (with and without mouthguard material specimen), were recorded via a sensor interface (EDX-100A, Kyowa Electronic Instruments Co., Tokyo, Japan) in a personal computer. Sum of loads recorded by the three load cells was calculated, and the maximum sum of loads after impact load application was registered as the first peak intensity. Data were interpreted and analyzed using software (DCS-100A, Kyowa Electronics Instruments Co., Tokyo, Japan) at a sampling rate of 20 kHz. Load applied without mouthguard material was taken as control to compare against the load applied with the material.

2. Film sensor

A precut piece of film sensor sheet (Prescale Film, Fujifilm Business Supply Co., Tokyo, Japan) was used for the film sensor system. Seven types of Prescale films were available to measure different pressure levels. An appropriate film was selected for each pressure range condition and placed under the specimen. Low pressure two-sheet type (LW) and medium pressure mono-sheet type (MS) Prescale films were used to measure peak stresses ranging from 2.5 to 10 MPa and 10 to 50 MPa respectively. MS sheet (mono-sheet type) was composed of a polyester base coated with a color-developing material, with a layer of micro-encapsulated color-forming material on top. LW sheet was composed of two polyester bases (A-film and C-film). A-film was coated with a layer of micro-encapsulated color-forming material, and C-film was coated with a layer of color-developing material. Film thicknesses are given as follows: MS sheet at 105±10 µm; LW sheet A-film at 95±10 µm; LW sheet C-film at 90±10 µm.

Impact load was applied on mouthguard material specimen using two different rod tips. After load application, each induced red patch at load impact point (with and without specimen) was recorded by a camera (Data Shot FPD-100, Fujifilm Business Supply Co., Tokyo, Japan). Peak stress and impressed stress distribution area (Da) were analyzed using software (Data Shot FPD-100S, Fujifilm Business Supply Co., Tokyo, Japan) (Fig. 4). Da was defined when stress level was at least 2.5 MPa. For each mouthguard material, five measurements were performed with each type of rod tip at room temperature.

Statistical analysis

Data were statistically analyzed using two-way analysis of variance (ANOVA), followed by post hoc analysis using Tukey’s multiple HSD test ($p<0.05$). Statistical software SPSS 10.0 J for Windows (SPSS Inc., Chicago, IL, USA) was used to perform all analyses.

RESULTS

Without the mouthguard material, center of film sensor became perforated because of heavy force. As peak stress of control without mouthguard material exceeded 50 MPa, it could not be measured. Impressed stress distribution areas (Da) of Fl and Pn controls were successfully recorded. A schematic drawing of Da is shown in Fig. 5.

Two-way ANOVA for peak intensity and peak

![Fig. 4 Film sensor system used in this study: (a) Red patch on Prescale sheet, which is induced at load impact point; (b) A record of pressure-impressed area from the software.](image)

![Fig. 5 Schematic drawings of impressed stress distribution areas (Da) for different combinations of mouthguard material and impact object shape. Da was defined when stress level was at least 2.5 MPa.](image)
stress revealed significant interaction between mouthguard material and impact object shape \((p<0.001\) and \(p=0.026\) respectively).

For \(Da\), significant difference existed between mouthguard materials and impact object shapes \((p<0.001\) and \(p<0.001\) respectively).

From the load cell sensor system, first peak intensities without any mouthguard material with flat-nosed and pointed rods were \(5,036\pm176\) N (Ctrl-Fl) and \(4,852\pm149\) N (Ctrl-Pn) respectively. First peak intensities decreased when mouthguard materials were inserted. First peak intensities with ERK-Fl and Ole-Fl were significantly greater than those of pointed rod on both types of materials (ERK-Pn and Ole-Pn) (Fig. 6).

Peak stress of Ole-Fl was \(7.6\pm0.7\) MPa, which was significantly lower than ERK-Fl, ERK-Pn, and Ole-Pn (Fig. 7).

For controls without any mouthguard material, \(Da\) values with flat-nosed and pointed rods were \(17.9\pm3.4\) mm² (Ctrl-Fl) and \(14.9\pm2.4\) mm² (Ctrl-Pn) respectively. The \(Da\) value of Ctrl-Fl was significantly greater than that of Ctrl-Pn. \(Da\) values of ERK-Fl and Ole-Fl were significantly greater than those of ERK-Pn and Ole-Pn (Fig. 8).

**DISCUSSION**

A wide range of materials are potentially suitable for making mouthguards: natural rubber, silicone rubber, urethane rubber, polyvinylacetate-polyethylene copolymer, EVA, and polyvinyl chloride\(^{15,26}\). EVA is commonly used as a mouthguard material because of its widespread availability coupled with good mechanical and physical properties\(^8\). Polyolefin is a recent-emerging mouthguard material which has been popularly used during the past decades. It exhibits good shock absorption capability with lower water absorption and higher adhesive strength than EVA\(^9,10\). Therefore, EVA and polyolefin were two mouthguard materials selected for investigation in the present study.

*In vitro* studies which investigated the shock absorption capabilities of mouthguard materials had been carried out using different measurement methods such as load cells, accelerometers, and strain gages. However, it is not possible to observe the distribution of absorbed force with these methods.

With CAD technology and FEA systems, it is possible to observe the distribution of absorbed force. This phenomenon is gaining popularity with researchers in their quest to understand how and where the force is distributed upon impact in response to different impact objects. For example, in a study by Cummins and Spears\(^{27}\) on the effect of mouthguard design on stresses in the tooth-bone complex, FEA was used to observe the protective capabilities of mouthguards and stress distributions in the tooth-bone complex during collision. However, FEA investigations were not performed using real mouthguard materials; instead, simulations of CAD-generated structures were carried out in a virtual world. This limitation can be overcome by scanning the real mouthguard or mouthguard material, and then perform FEA to observe stress distribution in the material or tooth-bone complex. However, automatic
Table 1  Confirmation of the transmission of shock wave to the load cell sensor with or without film sensor

<table>
<thead>
<tr>
<th>ERK-Fl</th>
<th>ERK-Pn</th>
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<tbody>
<tr>
<td>Load cell</td>
<td>Load cell</td>
</tr>
<tr>
<td>+ Load cell</td>
<td>+ Load cell</td>
</tr>
<tr>
<td>Film</td>
<td>Film</td>
</tr>
<tr>
<td>1198 ± 46 N</td>
<td>1212 ± 22 N</td>
</tr>
<tr>
<td>718 ± 11 N</td>
<td>715 ± 19 N</td>
</tr>
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</table>

The obtained data were statistically analyzed by unpaired- \( t \)-test (\( p<0.05 \)). There were no significant differences between the first peak intensities with film sensor and without film sensor (ERK-Fl; \( p=0.563 \), ERK-Pn; \( p=0.725 \))

meshing of geometrically complex objects—such as the mouthguard—could pose the problem of poor aspect ratios, which would significantly reduce the accuracy of the solution.

Alongside the load cell sensor, a film sensor was also used in this study to precisely record the impact area, whose color was changed to red to indicate the impressed stress distribution area\(^{29}\). The reliability and superiority of such a combined measurement system was already well documented in previous studies\(^{29,30}\). Low pressure two-sheet type (LW) and medium pressure mono-sheet type (MS) Prescale films were used to measure peak stress levels ranging from 2.5 to 10 MPa and 10 to 50 MPa respectively.

Another reason of choosing the load cell sensor and film sensor for a free-falling object was because of their easy operation and data interpretation. A free-falling object of 500 g dropped from a height of 25 cm onto the top of a rod without mouthguard material served as the control to generate a force more than the punching force of an Olympic boxer (3,427±811 N). It was then compared against the force delivered on the mouthguard material. It was also found that impact objects’ shapes and that these changes varied depending on the mouthguard material to assess the effectiveness of a mouthguard material\(^{11}\). Results of the present study agreed with the aforementioned claims of Takeda et al.\(^{11,20}\).

Sports that involve the use of sticks like ice hockey, field hockey, shinty, bandy, and hurling are good examples where impact objects are different from round types such as the hockey puck or ball. In this study, the rods were used to simulate different types of impact objects and with a view to obtaining more realistic insights into choosing the appropriate mouthguard material by the clinicians. For instance, a flat-nosed rod resembled impact objects with a spherical end or surface like the baseball, cricket ball, sliotar, or bat. A bluntly pointed rod resembled impact objects with a thin-edged, pointed end like the hockey stick, toe or heel of the hurling stick, bandy stick blade and edge, or shinty stick. Results of this study showed that both EVA and polyolefin materials exhibited shock absorption capability in different ways depending on the type of impact object. Further research should be carried out to improve the existing EVA and polyolefin materials or develop new mouthguard materials which can show widely versatile shock absorption abilities in response to impact forces from different impact object shapes.

**CONCLUSIONS**

Within the limitations of this *in vitro* study, it was concluded that the shock absorption properties of mouthguard materials varied according to impact objects’ shapes and that these changes varied depending on the mouthguard material. It was also found that a combined use of load sensor system and film sensor system was a useful, reliable, and superior method in understanding the shock absorption ability and force dispersion effect of mouthguard materials.

**REFERENCES**