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The influence of the sensor type on the measured impact absorption of mouthguard material

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Abstract – Mouthguards have been tested for impact energy absorption using drop-ball and/or pendulum devices. While all reports show efficiency of the mouthguard, the impact absorption abilities reported differ considerably. This difference has been attributed to differences of mouthguard material, design, and the impact force used. However, it is also possibly because of the difference in the sensors used in the experiments. The purpose of this study was to test three types of sensors and to assess which type was most appropriate for measurement of the impact absorption ability of mouthguards. A pendulum-type testing equipment and steel ball, wooden bat, baseball, field-hockey ball were used as the impact object. For all sensors or impact objects, the mouthguard decreased the impact forces. However, the absorption ability of the mouthguard varied according to the sensor or impact object. The absorbency values became smaller with the strain gauge, the accelerometer, and the load cell, respectively. With the steel ball as the impact object, 80.3% of impact absorption was measured with the strain gauge and the accelerometer but, only 62.1% with the load cell sensor. With the wooden bat, impact absorption was 76.3% with the strain gauge and 38.8% for the load cell. For the baseball ball, the absorption measurement decreased from 46.3% with the strain gauge to 4.36 with the load cell and for the field-hockey ball, the decrease in measurement values were similar (23.6% with the strain gauge and 2.43% with the load cell). It is clear that the sensor plays an important role in the measurement values reported for absorbency of mouthguard materials and a standard sensor should be used for all experiments.

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Key words: mouthguard; impact absorption ability; difference of sensor

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It has been estimated that during a single season, athletes have a 1/10 chance of suffering a facial or dental injury. Lifetime risk of such an injury is estimated at 45%. An athlete is 60 times more likely to sustain a dental injury while not wearing a mouthguard (1). Thus, mouthguards have been used for the purpose of reducing sports related orofacial injuries. Soft-tissue injuries, broken teeth, teeth displacement, bone fractures, temporomandibular joint injuries and concussions may be prevented to some degree by the use of mouthguards while the athlete participates in sports activities (1–21).

However, even with the potential benefits of mouthguard use their use is the exception rather than the rule. As the beneficial effects of mouthguards has not been communicated efficiently to the public, many improper mouthguards are used, which further limits their use. It is essential that the mouthguard is made so that it fits accurately, and that it is designed for the specific sport for which it is being used.

Most studies on mouthguards impact energy absorption have used drop-ball and/or pendulum devices and all have reported the efficiency of mouthguards (6–21). However, the impact energy absorption values have varied considerably for most studies (6–20). The differences of reported absorption values have been attributed to the type of mouthguard material or impact object being tested. However, there is also the possibility that the type of measuring sensor used is an important factor explaining these differences.

The purpose of this study was to evaluate the effect of three different sensors on the measured impact absorption of mouthguard.

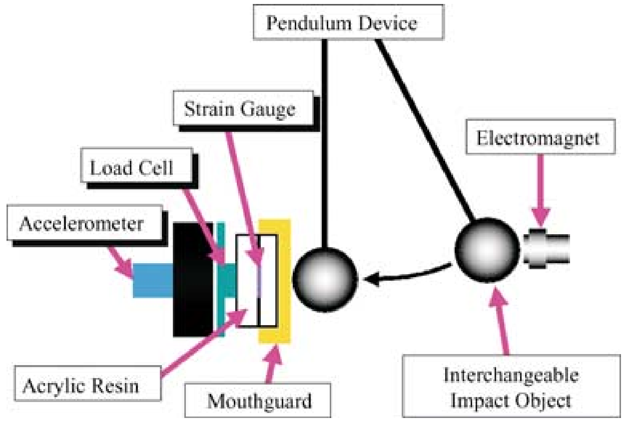

Fig. 1. Specially designed device to measure the shock absorption ability of mouthguard material with 3 different sensors.

Materials and methods

A pendulum device apparatus (15) was constructed similar to that of a Charpy or Izod impact machine with interchangeable impact objects (Fig. 1). Four impact objects were used: a steel ball, wooden baseball bat, a baseball ball, and a field-hockey ball (Fig. 2). Weight and the Durometer hardness (except for steel ball) of the impact equipment are shown in Table 1. The weight varied from 147.3 g of the lightest baseball to 199.8 g of the heaviest wooden bat. The hardness varied from 82.5 g of the softest baseball to 98.5 g of the hardest wooden bat. The axis length of the pendulum was about 50 cm and the apparatus was adjusted to hit centrally a surface of the acrylic fixed onto a load cell (LUR-A-KNSAI: Kyowa Electronic Instruments Co. Ltd, Tokyo, Japan). A strain gauge (KFG-1–120-D171–11 N30C2: Kyowa, Tokyo, Japan) was applied to the intermediate layer of resin plate just below the

Table 1. Impact equipment

	Weight (g)	Durometer hardness
Steel ball	172.5	–
Baseball	147.3	82.5
F. hockey	176.6	91.5
Wooden bat	199.8	98.5

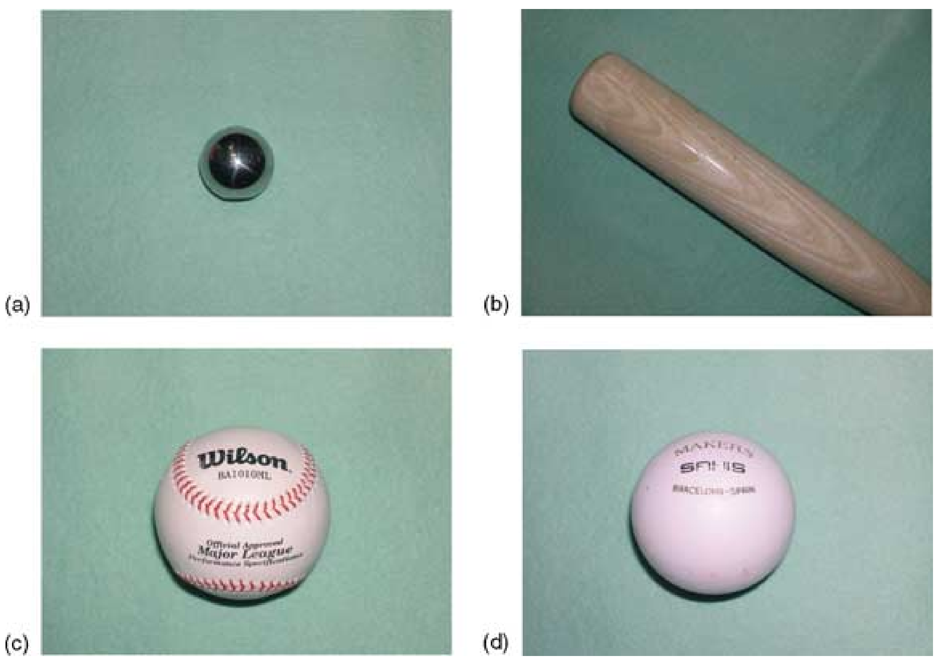

Fig. 2. Four impact objects were used: (a) steel ball, (b) wooden baseball bat, (c) field-hockey ball, and (d) baseball.

point of contact. Accelerometers (AS-A YG-2768 100G, Kyowa) were fitted on the back. Consequently, responses to the impacted forces with or without protection by EVA mouthguard material were measured with the three different sensors. An electromagnet was used to control the release of the impact ram in order to concentrate the force over a smaller area and make a distance (50 cm) with the target precise. (Fig. 1)

Measured mechanical forces were amplified with a Strain Amplifier (Kyowa DPM-712B) and then converted into an electric output voltage and the data were stored with Oscillographic Recorder (Kyowa RDM-200 A) and analyzed with a personal computer (PC-SJ145V: Sharp Co. Ltd, Tokyo, Japan). The data were processed with Tooth Piece: (Amisystem Co. Ltd, Tokyo, Japan). Fig. 3 illustrates the measured heights of an impact response of the first wave as a maximum impact force. Mean and standard deviations were calculated for each variable evaluated. Statistical comparisons were made using a Student T-test and a two-way analysis of variance (ANOVA) test followed by a Tukey multiple comparison tests for further comparisons between sensors and impact objects ($P < 0.05$), using SPSS® (SPSS Japan Inc., Tokyo).

All tests were conducted in an air-conditioned room at 25°C. The mouthguard blanks used were Drufosoft (Dreve-Dentamid GmbH, Unna, Germany) with a 3-mm thickness. Three one-layer test samples were made by means of a Dreve Drufomat (Type SO, Dreve-Dentamid, Unna, Germany) air pressure machine on a flat-topped round acrylic plate of 50 mm diameter and 30 mm height as a mold (It is a same size of the resin plate attached to the load cell). To get uniform thickness of around 2.7 mm, the same operating steps (including constant heating time: 150 s) were used. For each variable, the impact test was performed three times.

Result

Waveform of the three sensors and two impact objects

The waveforms for each sensor and impact object with or without mouthguards are illustrated in Fig. 4. With the mouthguard material, the impact forces decreased and also waveform smoothing was observed regardless of the sensors when using the steel ball. However, the effect of the mouthguard differed dependent on the sensors used. The effect is most obvious with the strain gauge and accelerometer for the steel ball. The waveform of wooden bat and steel ball were similar, as were the field hockey and baseball balls.

Impact forces with the three different sensors with or without mouthguard

Impact forces of three different sensors with or without mouthguard are shown in Table 2. For all the sensors, the attachment of the mouthguard resulted in a decrease in the recorded impact force. Statistical analysis (T-test) showed significant differences between with and without mouthguard for all sensors with any four impact objects except for the accelerator with the baseball ($P < 0.01$). However, the sensor and impact object used heavily influenced the recorded effects of the mouthguard.

Effect of sensor and mouthguard on impact absorption ability (%)

Shock absorption abilities by wearing the mouthguard are shown in Fig. 5. The absorbency values

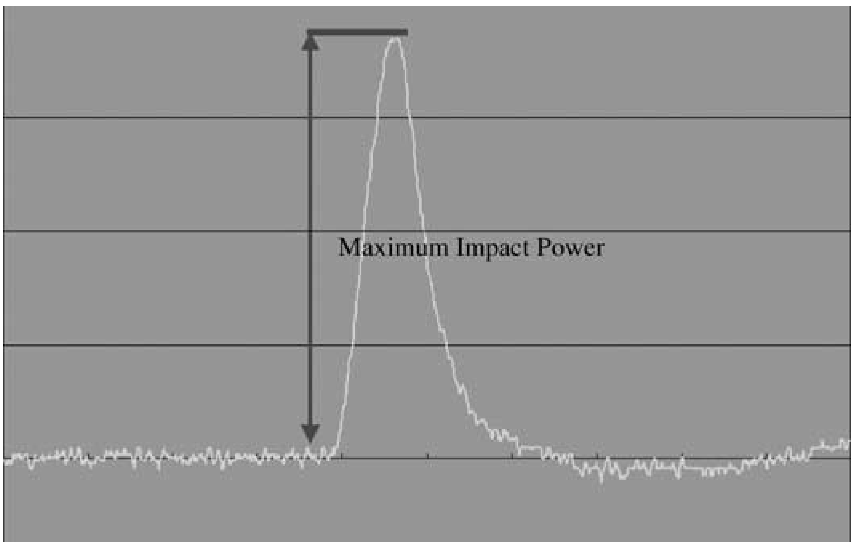

Fig. 3. Height of an impact response.

Table 2. Result of *T*-test

		Load cell (kgf)			Accelerometer (G)			Strain gauge (με)		
		MG	NO	*P*-value	MG	NO	*P*-value	MG	NO	*P*-value
Steel ball	Mean	182.5	481.6	*	100.2	513.6	*	1289.1	6594.5	*
	SD	1.1	2.4		3.2	20.8		29.5	300.6	
Baseball	Mean	120.5	123.5	*	24.5	25.3	*	19.7	25.8	*
	SD	2.0	2.0		1.2	2.3		0.9	5.1	
F. hockey	Mean	73.7	77.0	*	108.0	129.1	*	71.8	133.7	*
	SD	0.7	0.2		0.0	2.4		2.1	0.9	
Wooden bat	Mean	95.1	154.2	*	63.8	152.2	*	202.5	853.0	*
	SD	0.1	0.4		3.0	4.9		3.1	11.9	

*$P < 0.01$.

tended to became smaller in order of the strain gauge, the accelerometer, and the load cell. With the steel ball, it was 80.3% of impact absorption with the strain gauge and the accelerometer but in load cell, 62.1% absorption was recorded. For the wooden bat, it was 76.3% with the strain gauge and 38.8% (about half) with the load cell. The absorbency of baseball ball and a field-hockey ball was recorded at 46.3 and 23.6% with the strain gauge and 4.36 and 2.43% (about 1/10) with the load cell, respectively.

Statistical analysis (ANOVA) showed significant differences between three sensors and four impact objects also ($P < 0.01$) (Table 3). Additionally, there were significant differences between the load cell and accelerometer compared to the strain gauge. There were no significant difference between steel ball and wooden

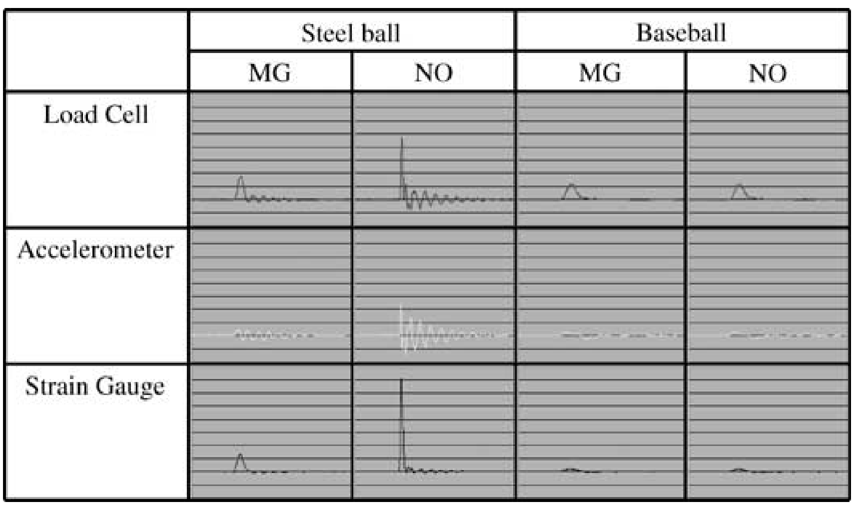

Fig. 4. Wave form of each of three sensors and two impact equipment.

Table 3. Stastical analysis (ANOVA)

Source	Type III sum of squares	df	Mean square	*F*	Significance	Noncent. parameter	Observed power
Corrected model	9951.9	5	1990.4	31.8	0.000	159.1	1.00
Intercept	20137.1	1	20137.1	321.9	0.000	321.9	1.00
Impact equipment	8155.7	3	2718.6	43.5	0.000	130.4	1.00
Sensor	1796.2	2	898.1	14.4	0.005	28.7	0.96
Error	375.3	6	62.6				
Total	30464.3	12					
Corrected total	10327.2	11					

Tests of between-subject effects.
Dependent variable: shock absorption abilities.
Computed using alpha = 0.05.
$R^2 = 0.964$ (adjusted $R^2 = 0.933$).

Table 4. Statistical analysis (Tukey's HSD)

	Load cell	Accelerometer	Strain gauge
Load cell			
Accelerometer	–		
Strain gauge	*	*	

	Steel ball	Baseball	F. hockey	Wooden bat
Steel ball				
Baseball	*			
F. hockey	*	–		
Wooden bat	–	*	*	

*: $P < 0.05$.

bat, baseball and field-hockey balls. (Tukey test) (Table 4).

Discussion

Many studies have investigated the shock absorption of mouthguard materials and many recommendations have been made in order to improve them based on these measurements (6–21). However, there is an enormous difference between 2 and 90% reported impact absorption ability of mouthguard material (Table 5) and thus a common opinion cannot be obtained as to what is the best material or fabrication method.

Previous studies are classified into one of three types: (i) testing the impact absorption ability of the mouthguard material itself; (ii) testing a direct blow to the dentition and the effect of a mouthguard; and (iii) testing the effect of a mouthguard from an indirect blow to the dentition via a traumatic episode to the oro-facial structures.

The limitations of these studies are: (i) the mouthguard material used was different in many tests; (ii) The mass, hardness and shape of the impact object varied from test to test; (iii) The sensors used for the experiment were often different; and (iv) It is the difficulty to simulate a 'real' and reproducible injury on an artificial tooth, jawbone or skull.

The aim of the present study was to evaluate the variation in measured impact absorption of mouthguards depending on the sensor used. As was seen from the results of the study, the type of sensor used results in a wide variation of recorded impact absorption. This was further complicated by the fact that the impact object also results in additional variations in measurements. However, all showed some absorption by use of mouthguard material. When the steel ball was used as the impact object the strain gauge

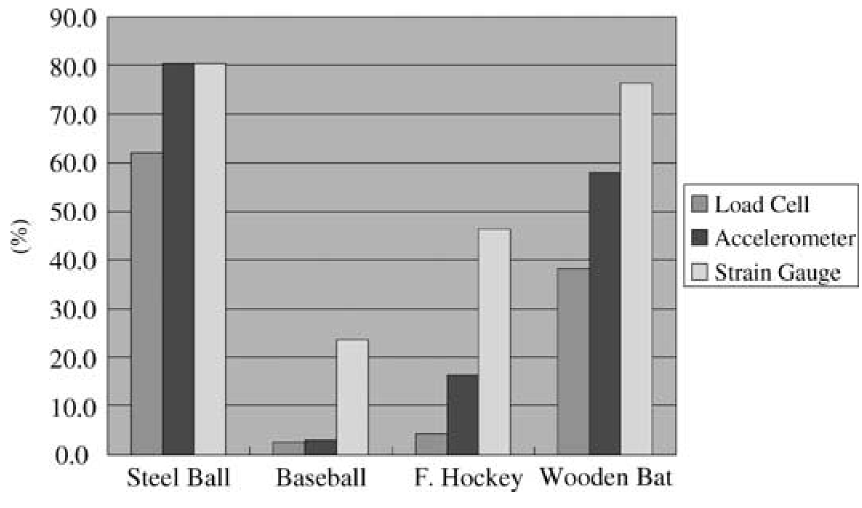

Fig. 5. Shock absorption abilities by wearing the mouthguard.

Table 5. Shock absorption ability by the mouthguard in previous studies

First author	Ref. no.	Target	Impact method	Impactor	MG	Gauge or method	Absorption (%)
Godwin WC	(7)	Acrylic casts	Pendulum	Steel ball	12 types MG	Rebound angle	50–92
Going RE	(8)	Material	Pendulum	Steel head	EVA	Rebound angle	45.0–57.4
Bishop BM	(9)	Material	Drop ball	Steel ball	9 types MG	Rebound angle	28.9–31.6
Yamamoto T	(10)	Material	Drop ball	Steel ball	Sorbosane	Accelerometer	90
Ishijima T	(11)	Material	Drop ball	Steel ball	14 types MG	Accelerometer	3.33–33.3
Maeda M	(12)	Material	Drop ball	Steel ball	7 types MG	Force transducer	2–11
Park JB	(13)	Material	Drop ball	Steel ball	EVA	Force transducer	50.40
Auroy P	(14)	Material	Pendulum	Steel stud	Silicon rubber MG; EVA	Pressure transducer	7.67–19.71; 13.5–16.6
Mori H	(15)	Bovine tooth	Pendulum	Steel ball	1.5–4.5 m	Stain gauges tooth back	8.1–30
de Wet FA	(16)	Artificial skull	Pendulum	Impact hammer	5 types MG	Load cell on hammer	23–55
Hoffmann J	(17)	Model jaw	Pendulum	Steel head	EVA	Integrated metal pin, a writing pad	7.5–58
Bemelmanns P	(18)	Simulated maxilla	Pendulum	Steel ram	Custom-made MG	Strain gauge; tooth back	25.7–33.3
Craig RG	(19)	Material	Pendulum	Steel head	EVA	Rebound angle	80.6–90.6
Low D	(20)	Material	Ultra micro-indentation system		4 types EVA; MG	/	10–24

and accelerometer recorded similar impact absorption. However, with all other impact objects, absorption from mouthguard material decreased with strain gauge, accelerometer and load cell, respectively.

With the use of the steel ball and EVA mouthguard material, the strain gauge and the accelerometer values (about 80%) and the value of the load cell (about 62%) were similar to the results of the Godwin (7) (50–92%) and Craig (19) (80.6–90.6%) but larger than the values reported by Going (8), Park (13) de Wet (16), and Hoffmann (17). However, other experiments, showed lower absorption percentage values compared to our results (see Table 5).

Even with the variation seen in impact absorption with the use of different sensors, the effectiveness of the mouthguard in absorbing an impact force was consistent. However, the damping effectiveness of the mouthguard was heavily dependent on the difference of the sensors used. This difference was particularly obvious when the impact object was soft. Therefore, when evaluating a mouthguard material or mouthguard design, it is necessary to understand that the sensor used will affect the measurements. In addition, some sensors are more suitable for specific measurement points on the mouthguard. The results of this study appear to indicate that the strain gauge is more suitable to measure absorbency at the impact point while the accelerometer is better suited for measurements at a distance from the impact point.

Conclusions

1 Mouthguards can reduce impact stress regardless of type of sensor and impact equipment.

2 The mouthguard's shock absorption abilities are varied significantly with different sensors and impact materials. The strain gauge is most sensitive to measure the shock absorption abilities. Especially, when the impact object is soft.

3 Ideally, one should select more than one sensor and impact object in order to get a more realistic view of the effectiveness of mouthguards and mouthguard material.

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