Dental Traumatology 2004; 20: 12–20
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DENTAL TRAUMATOLOGY

The influence of impact object characteristics on impact force and force absorption by mouthguard material

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. © Blackwell Munksgaard, 2004.

Abstract – Most impact force and impact energy absorption tests for mouthguards have used a steel ball in a drop-ball or the pendulum device. However, in reality most sports-related trauma is caused by objects other than the steel ball, e.g. various sized balls, hockey puck, or bat or stick. Also, the elasticity, the velocity and the mass of the object could change the degree and the extent of injuries. In this study, we attempted to measure the impact force from actual sports equipment in order to clarify the exact mechanism of dental-related sports injuries and the protective effects of mouthguards. The present study was conducted using the pendulum impact device and load cell. Impact objects were removable. Seven mobile impact objects were selected for testing: a steel ball, baseball, softball, field hockey ball, ice hockey puck, cricket ball, and wooden baseball bat. The mouthguard material used in this study was a 3-mm-thick Drufosoft (Dreve-Dentamid GmbH, Unna, Germany), and test samples were made of the one-layer type. The peak transmitted forces without mouthguard ranged from the smallest (ice hockey stick, 46.9 kgf) to the biggest (steel ball, 481.6 kgf). The peak transmitted forces were smaller when the mouthguard was attached than without it for all impact materials but the effect was significantly influenced by the object type. The steel ball showed the biggest (62.1%) absorption ability while the wooden bat showed the second biggest (38.3%). The other balls or the puck showed from 0.6 to 6.0% absorbency. These results show that it is important to test the effectiveness of mouthguards on specific types of sports equipment. In future, we may select different materials and mouthguard designs suitable for specific sports.

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Key words: mouthguard; impact absorption ability; impact object

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Accepted 14 May, 2003

Factors such as specific elasticity, velocities, and varying amounts of mass that impact objects possess determine the extent and the types of injuries that can be sustained in real-life trauma (1). It is commonly noted that the cause of dental-related sports injuries are one of three groups. These groups can be easily categorized in relation to the impact of different objects or surface areas: (i) another player, (ii) the ground or floor, (iii) the playing instrument being used for sports (e.g. balls, bats, rackets, and so on) (2).

In sports injuries, it is said that there is a common pattern of movement which is particular to each sport and that the object or equipment used, the playing surface and the amount of the impact power to an opponent player, are similar at every sports event and level. Therefore, to some degree, the type of sport will

Table 1. Previous studies for shock reduction ability with mouthguards materials

First author	Reference	Target	Method	Impactor	Result
Going RE	(4)	Material	Pendulum	Steel head	45.0–57.4%↓
Bishop BM	(5)	Material	Drop ball	Steel ball	28.9–31.6%↓
Yamamoto T	(6)	Material	Drop ball	Steel ball	90%↓
Ishijima TC	(7)	Material	Drop ball	Steel ball	333–33.3%↓
Maeda M	(8)	Material	Drop ball	Steel ball	2.11%↓
Park JB	(9)	Material	Drop ball	Steel ball	50.4%↓
Auroy P	(10)	Material	Pendulum	Steel stud	7.7–19.7%↓ 13.5–16.6%↓
Jagger R	(11)	Material	Tensile machine		○
Westerman B	(12)	Material	Pendulum	Steel striker	Hard insert↓
Bulsara YR	(13)	Material	Free-falling	Steel ram	30%↓ Sorbothane↓
Westerman B	(14)	Material	Pendulum	Steel striker	Thinning results in reduction↓
Westerman B	(15)	Material	Pendulum	Steel striker	32%↓ air inclusions↓
Westerman B	(16)	Material	Pendulum	Steel striker	Optimal thickness = 4 mm↓
Craig RG	(17)	Material	Pendulum	Steel head	80.6–90.6%↓
Low D	(18)	Material	Ultra micro-indentation system	–	10–24%↓

○: MG is protective without numerical data.

determine the type of injuries sustained, following a consistent pattern for each sport (3). Therefore, by understanding these patterns, it is possible to prevent many sports trauma using appropriate protection.

Many recent research studies (4–30) have provided the necessary data to show that there is an effective way to prevent tooth or maxillofacial trauma using a mouthguard (MG) (Tables 1 and 2). However, there are various types of mouthguards including the boil & bite, mass-produced and marketed to precision-manufactured, custom-made types. Thus, the attributes of mouthguards are not easy to identify, especially, the effectiveness of preventing trauma, which is influenced not only by the impact absorption ability of the material but also by the occlusal relationship and the conformability of the mouthguards' construction. Appropriate control of these factors could ultimately make the manufacturing of mouthguards that suits each possible sports. According to Cummins, the shock absorbency of mouthguards was affected by the stiffness of the object with which it collided (27).

Therefore, to develop and evaluate new optimal mouthguard material(s) and manufacture mouthguards suited for each sport (i) the impact power of mobile sports object, (ii) the surfaces used at various sports events and (iii) the impact absorption ability of mouthguards in relation to them (1, 2) must be fully understood.

To this point and with few exceptions (10, 28–30), mouthguards have been tested for impact energy absorption using drop-ball and/or pendulum devices with steel spheres as the common material of choice (4–9, 11–27). A better choice of impact materials would consist of the actual material used in different sports like sports balls, pucks, wooden bats. However, the impact materials would consist of various types of sports balls, pucks, wooden bats and the like, which normally account for actual trauma incidents. Studies have (30) found that there is always an impact absorption effect with the mouthguards but the degree of impact absorption was different depending on the materials tested. The purpose of this study was to

Table 2. Previous studies for shock reduction ability with mouthguards

First author	Reference	Target	Impact method	Impactor	Result
Godwin WC	(19)	Acrylic casts	Pendulum	Steel ball	50–92%↓
Watermeyer GJJ	(20)	Plaster cast	Pendulum	–	○
Johnston T	(21)	Sheep mand. segments	Servohydraulic machine	–	○
Morii H	(22)	Bovine tooth	Pendulum	Steel ball	8.1–30%↓
Morikawa M	(23)	Human dry skull	Electrodynamic shaker	–	○
de Wet FA	(24)	Artificial skull	Pendulum	Impact hammer	23–55%↓
Hoffmann J	(25)	Model Jaw	Pendulum	Steel head	7.5–58%↓
Bemelmanns P	(26)	Simulated maxilla	Pendulum	Steel ram	25.7–33.3%↓
Cummins NK	(27)	–	Finite element	–	△
Hickey JC	(28)	Cadaver	Impact machine	Plastic strike	○
Oikarinen KS	(29)	Plaster model	Dropping object	Stimulate ice hockey pack	○
Warnet L	(30)	Stimulated maxilla	Drop weight impact testor chamber	Hardwood impactor	○

○: MG is protective without numerical data; △: MG is protective only for hard object collisions.

investigate the damping effect of various types of mouthguard materials based on the impact of actual sports equipment.

Materials and methods

A pendulum device apparatus was constructed similar to that of a Charpy or Izod impact machine with the impact object being interchangeable (Fig. 1). Seven types of mobile impact objects were selected for testing: a steel ball, baseball, softball, field hockey ball, ice hockey puck, cricket ball, and wooden baseball bat (Fig. 2). Weight and Durometer hardness (except for steel ball) of the impact object are shown in Table 3. The axis length of the pendulum was about 50 cm and the apparatus was adjusted to hit the center of a surface of the acrylic resin (attached two layer of plate) fixed onto a load cell (LUR-A-KNSAI: Kyowa Electronic Instruments Co. Ltd, Tokyo, Japan) and was hung perpendicularly. Forces transmitted through the acrylic resin plate itself or when protected by EVA mouthguards were measured with the load cell. The mouthguard blanks used were Drufosoft (Dreve-Dentamid GmbH, Unna, Germany) with a 3-mm thickness. Three one-layer test samples of the same type 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 mould (it is of the same size as that of the resin plate attached to the load cell). To get a uniform thickness of around 2.7 mm, the same operating steps were conducted. For each sample, the impact test was repeated thrice. The electromagnet was used to control the release of the impact ram in order to concentrate the force over a smaller area and ensure a correct distance (50 cm) with the target (Fig. 1). All tests were conducted in an air-conditioned room at 25°C.

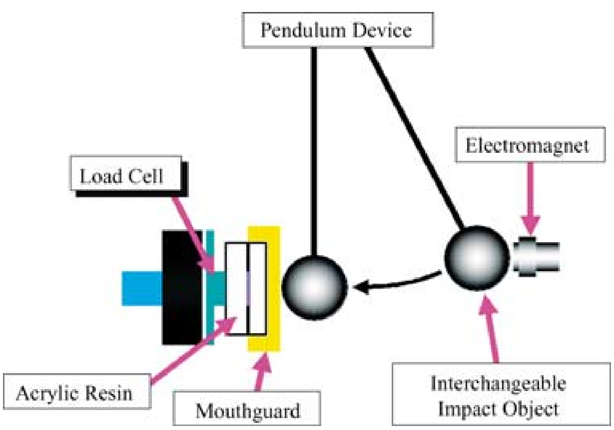

Fig. 1. A pendulum device apparatus was constructed similar to that of a Charpy or Izod impact machine and the impact object can be interchangeable.

Measured mechanical forces were amplified with a Strain Amplifier (Kyowa DPM-712B) and then converted into an electric output voltage and stored as data in an Oscillographic Recorder (Kyowa RDM-200 A, Kyowa Electronic Instruments Co. Ltd, Tokyo, Japan), 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). Figure 3 illustrates the measured heights of an impact response of the first wave as a peak transmitted force (or a maximum impact power). Means and standard deviations were calculated for each variable evaluated. Statistical comparisons were made using Student's *t*-test and a one-way analysis of variance (ANOVA) test followed by Tukey multiple comparison tests for further comparisons between sensors and impact objects ($P < 0.05$) using SPSS® (SPSS Japan Inc., Tokyo).

Results

Impact object differences and peak transmitted force without mouthguard

The waveform

The waveforms of the forces transmitted from various objects are illustrated in Fig. 4(A–G). The waveforms for the steel ball and wooden bat were sharp and strong compared with those of the other tested objects.

Peak transmitted force

Peak transmitted force of the seven different impact objects without mouthguard protection are shown in Fig. 5 (the left white column) with the results for the ANOVA and Tukey multiple comparison in Table 4.

The peak transmitted forces ranged from the smallest ice hockey (46.9 kgf) to the biggest steel ball (481.6 kgf). The maximum energy transmitted from the steel ball and wooden bat were similar and were very different from all the other objects tested.

Statistical analysis (ANOVA) showed significant differences between the seven impact objects ($P < 0.01$; Table 4). A significant difference was found with all the combinations. (Tukey test; Table 4). Thus, the difference of impact object influenced the peak transmitted force.

The effect of the impact object on mouthguard shock absorption

The waveform

The waveforms of the transmitted force of each impact object with mouthguards are illustrated in Fig. 6(A–G). The waveform for a steel ball and wooden bat with a mouthguard was sharper and stronger with a longer duration and lower value compared to testing without a mouthgurard (Fig. 4). On the other hand, the tendencies seen for the steel ball and wooden bat were not as clear for the other balls and puck. Thus, the type of impact object used influenced shock absorption ability of the mouthguard.

The peak transmitted force

The peak transmitted forces of seven different impact objects with mouthguard are shown in Fig. 5 (gray column) with the results for the *t*-test indicated by asterisks.

The peak transmitted force was significantly smaller when a mouthguard was attached than when it was removed for all impact materials. However, the tendency was stronger when the steel ball and the wooden bat were tested.

The impact absorption rate (%)

The impact absorption ability by wearing the mouthguard is shown in Fig. 7 with the results for the ANOVA and Tukey multiple comparisons in Table 5.

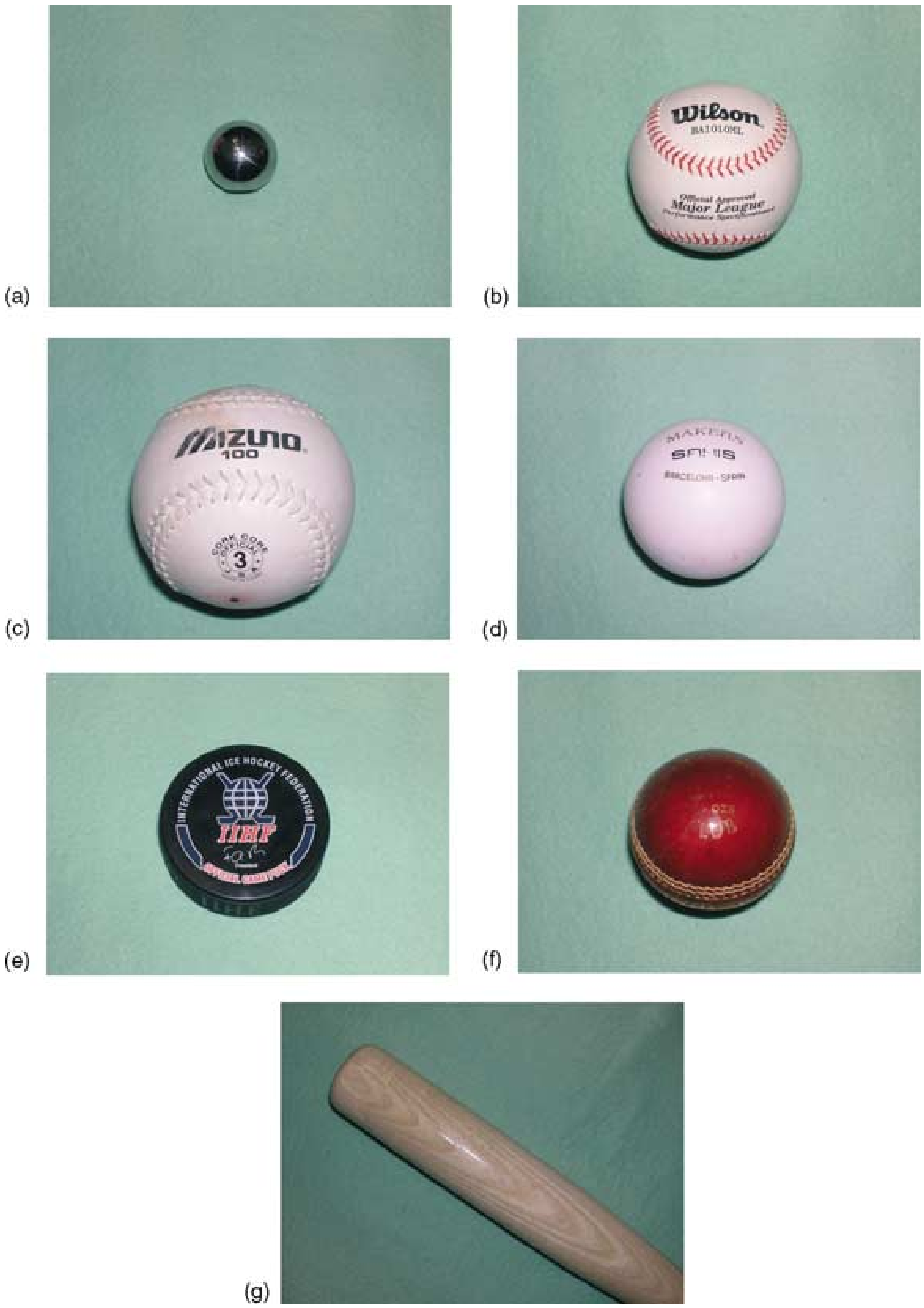

Fig. 2. Seven types of mobile impact objects were selected for testing: (a) steel ball, (b) baseball, (c) softball, (d) field hockey ball, (e) ice hockey puck, (f) cricket ball, and (g) wooden bat.

Table 3. Impact object

	Weight (g)	Hardness
Steel ball	172.5	*
Baseball	147.3	82.5
Softball	197.4	79.5
G. hockey	176.6	91.5
Ice hockey	164.9	83.5
Cricket	160.9	91.9
Wooden bat	199.8	98.5

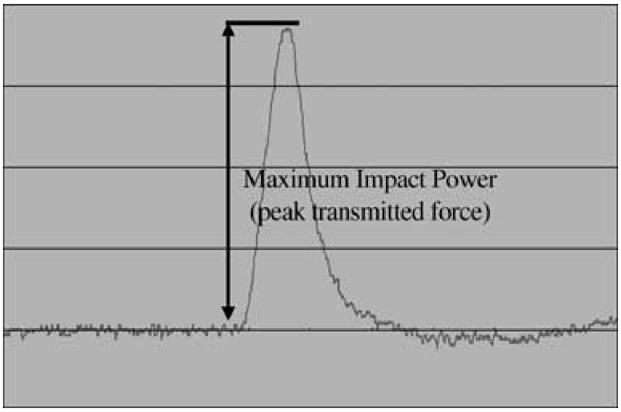

Fig. 3. It measured that a height of an impact response of the first wave as a peak transmitted force (or a maximum impact power).

The steel ball showed 61.3% of absorption compared to 0.7–6.0% with the other balls or puck (Fig. 7). Statistical analysis (ANOVA) showed significant differences between the seven impact objects ($P < 0.01$; Table 5). No significant difference was found between field hockey and cricket (Tukey test; Table 5). Thus, the absorption ability appeared to be the highest with the steel ball and wooden bat compared to the others.

Discussion

When an impact force is applied to a human body, there are two possible results. If the energy (momentum) is not big enough to damage the body, it is consumed as heat energy by the body. However, if the energy is large, it changes to a destructive energy which causes damage to the soft tissue, dislocations and the fracture of teeth, bone, etc. (3). In sports, trauma occurs when the impact power exceeds the

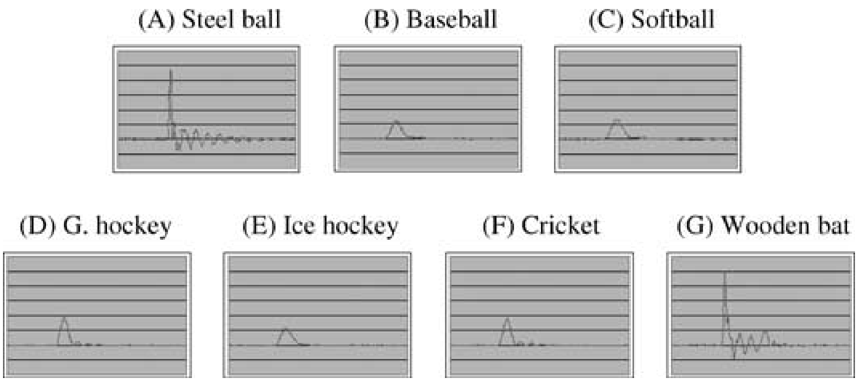

Fig. 4. As for the steel ball and wooden bat, the waveforms without mouthguard were sharp and strong compared with that of the other impact objects.

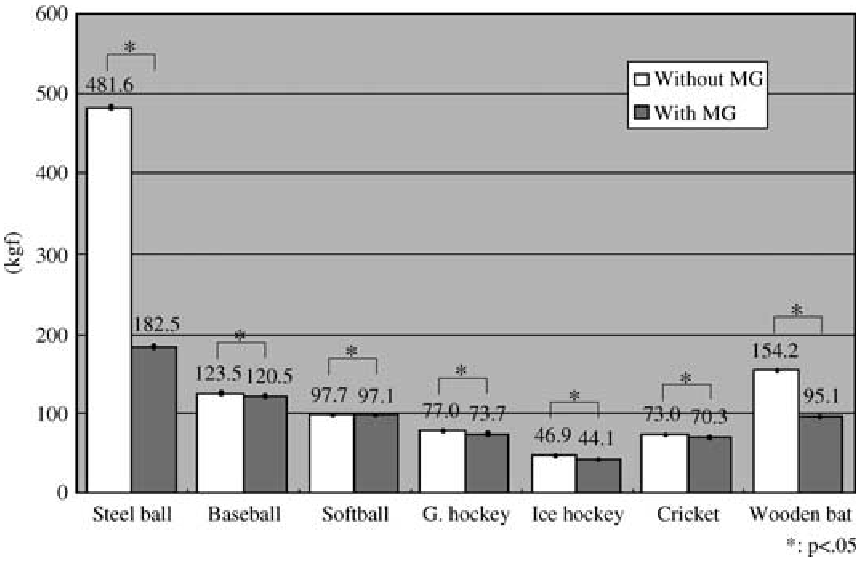

Fig. 5. The peak transmitted forces were ranged from smallest ice hockey (46.9 kgf) to the biggest steel ball (481.6 kgf) impact objects. The peak transmitted forces were smaller when the mouthguard was attached than when it was removed for all impact materials. But the tendency was strong at the steel ball and at the wooden bat. Thus, the mouthguard showed the shock absorption capacity regardless of impact object, and the impact equipment influence the shock absorption ability strongly.

Table 4. ANOVA and Tukey multiple comparison (maximum impact power of seven different impact object without MG)

	Sum of squares	df	Mean square	*F*	Significance
Between groups	1488372.0	6	248062.0	171590.6	0.000
Within groups	101.19636	56	1.445662		
Total	1488473.2	62			

Tukey HSD

	Steel ball	Baseball	Softball	G. hockey	Ice hockey	Cricket	Wooden bat
Steel ball							
Baseball	*						
Softball	*	*					
G. hockey	*	*	*				
Ice hockey	*	*	*	*			
Cricket	*	*	*	*	*		
Wooden bat	*	*	*	*	*	*	

*:$P < 0.01$.

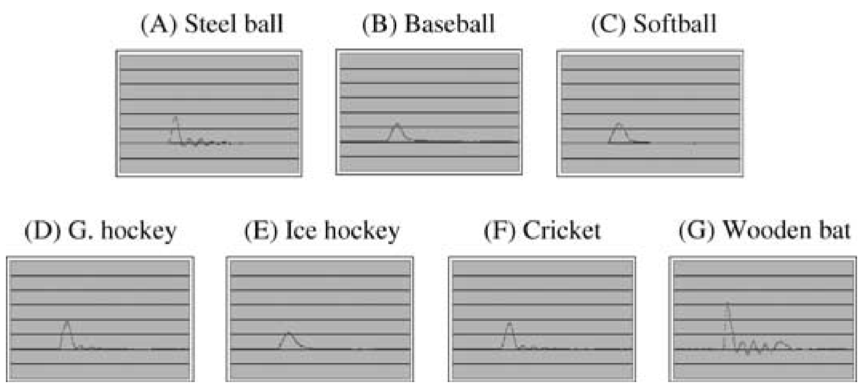

Fig. 6. When looking at the effect of mouthguard, waveform of the steel ball with mouthguard was flatter, weaker, and duration is longer compared to that without mouthguard (Fig. 4); and the wooden bat showed the approximately same tendency as steel ball, even though the mouthguard's effect was small. On the other hand, the other objects, the effects were not so clear as the steel ball and wooden bat.

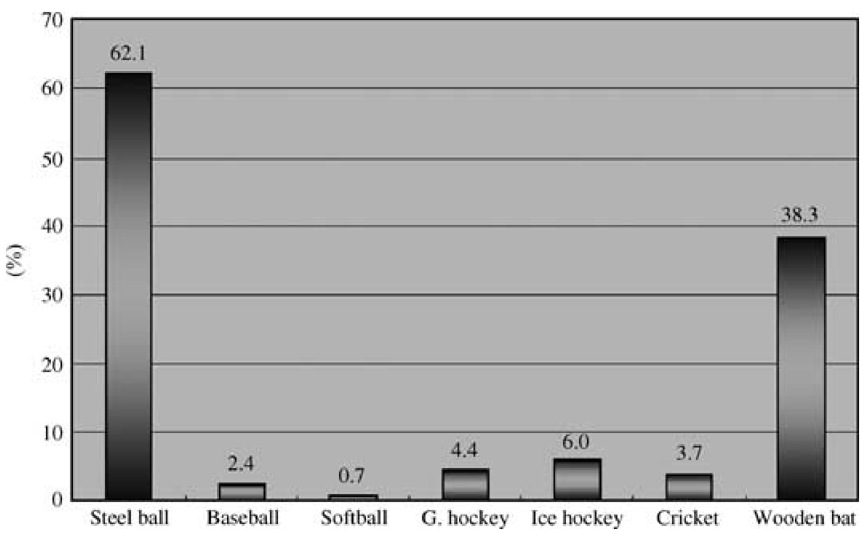

Fig. 7. Steel ball showed the biggest 62.1% of the absorption ability, wooden bat showed the second biggest 38.3%; on the other hand, it were from 0.7 to 6.0% at the other balls or the pack.

Table 5. ANOVA and Tukey multiple comparison (impact absorption rate of seven different impact object)

	Sum of squares	df	Mean square	F	Significance
Between groups	37694.10624	6	6282.3510	6795.68585	0.000
Within groups	64.71231636	56	0.92446166		
Total	37758.81855	62			

Tukey HSD

	Steel ball	Baseball	Softball	G. hockey	Ice hockey	Cricket	Wooden bat
Steel ball							
Baseball	*						
Softball	*	*					
G. hockey	*	*	*				
Ice hockey	*	*	*	*			
Cricket	*	*	*	–	*		
Wooden bat	*	*	*	*	*	*	

*: $P < 0.01$.

physical resistance of the player. Impact power is provided by collision with other players, the object used to play the sport, a fall on the floor, ground, or road, etc.

The most effective way of reducing orofacial injuries is to minimize the impact power on the athlete. Thus, in order to fabricate mouthguards suitable to each sport, the mouthguard must be designed to have enough impact absorption ability to limit the impact force unique to each sport. Most research into the damping effect of mouthguard material and mouthguards have used the drop-ball or the pendulum-testing methods with steel ball as the impact (4–30). Exceptions include piston devices with plastic strikers attached at the end (28) to simulate an ice hockey puck (29), or hardwood impact objects (30), or simulated boot studs used in field sports (10). However, mobile objects such as balls, pucks, and bats are more frequently associated with sports injuries than those stationary equipment made of steel. Therefore, the purpose of this study was to simulate the effect of different impact objects, as would be found in real sports situations involving real impact forces and to clarify the damping effect of mouthguards for each.

After reviewing the results, we see the influence of different impact objects on the impact energy. The waveforms recorded at the time of impact were sharp, high, and short in duration after the tests with a steel ball and wooden bat in contrast with various balls or pucks, where the waveform was not sharp and was rather low.

When viewing the waveform in relation to the effect of the mouthguards, it was noted that the height decreased when the steel ball and the wooden bat were tested. Moreover, the duration was extended and a flattening was observed and the height decreased with the steel ball and the wooden bat. Changes were not as dramatic as other types of balls or hockey puck.

Overall, mouthguards were effective in reducing the impact force of all impact objects; however, the effect depended enormously on the differences of each impact object. The impact absorption percentage of the steel ball (61.3%) and bat (38.3%) was vastly different compared to the other object tested (2.4–6.0%). Even though the method we used for the steel ball was slightly different, our results were comparable to those of Going et al. (4) (45.0–57.4%) and Park et al. (9) (50.4%) who used steel impact objects.

Thus, impact responses (impact power and impact absorption ability) are greatly influenced by the differences of the impact object used.

Weight appeared to play a minor role in impact energy, as we used and comparatively light steel ball of 168 kg and the wooden bat was not heavy. It appears that the impact energy and impact absorption ability is influenced by the hardness of the impact object explaining the high values resulting from the steel ball and wooden bat.

Our results are similar to Cummins & Spears (27), although our explanation of the results are different. Cummins & Spears (27) argued that low-stiffness guards (9 MPa) were representative of the common choices for materials used in mouthguard fabrication to absorb shock during hard object collisions (e.g. baseball), and may not protect the teeth or bones during soft object collisions (e.g. using boxing gloves) (32). However, a few problems exist in making the assumption that the baseball is representative of all types of sports equipment stiffness. A substantial impact absorption ability was shown compared to other tests performed using the steel ball and wooden bat. It is easily understood in this report that 'When the material in both the object and the target are hard and difficult to transform, the mouthguard or damping material is very effective' (32).

When the response of the impact is different from these results, the action (mechanism) to the body is also different. Therefore, mouthguards should be designed to control such forces (31). Satoh reported (31) that when a sharp impact force is being exerted, the power acts near the point of the impact. Destruction will then take place in the very region the impact has occurred. On the other hand, when the impact is slow acting (a blunt impact), the likely destruction will happen to weaker regions such as the angle of the mandible, the neck of the ramus or around the impacted third molar. When a slow acting, blunt impact is applied to a body the force is distributed over the surrounding impact area (such as the mandibular complex). As this occurs, destruction takes place at the weakest point unable to endure the pressure.

The research of others (1, 27) has suggested that hard object collisions are more likely to cause fractures in impact zones. In contrast, collisions with soft objects are more likely to cause fractures away from the impact zone. In short, the process of fracture initiation is likely to differ depending on the type collision. That is, it is expected that in collisions with stiff objects, tooth fractures and direct bone fractures might occur at the point of impact. On the other hand, in sports dislocation of a tooth, an indirect bone fracture and or cerebral concussions often seem to occur, where there is a possibility of colliding with the ground when a player falls (from horseback or bike) or tumbles or makes contact with another player using a comparatively soft ball.

When the mobile object is much softer than steel, the effect of the mouthguard is not generally seen. In other words, the effect the mouthguard has is minor. However, the impact absorption ability (Tables 1 and 2) shown in previous studies reveals different results. Therefore, impact absorption should not be judged solely by this study alone, as future studies using different objects used to test absorption, precision of impacts, and the improvements and differences of sensors available must continue to be examined.

The results of the present study suggest that the thickness and hardness of a mouthguard will depend on the various sports in which people participate. In other words, individualized mouthguards are required for each sport and each player.

It is acknowledged that in collisions with stiff objects, the effectiveness of present-day mouthguards is remarkable. In sports that use goalposts or pointed spikes with almost the same hardness of a steel ball such as in soccer or the use of sticks or rackets such as in ice/field hockey, tennis or lacrosse, all with the approximate hardness of a strong wooden bat, it is necessary to use a mouthguard with high impact absorption ability as in contact sports.

Conclusion

It was found that different impact materials gave different results. Not surprisingly, there was a great difference recorded when comparing the impact and hardness of the steel ball and the wooden bat in the hard object collision category. It was also found that mouthguards could reduce impact stress regardless of the impact object used. However, the mouthguards' shock absorption abilities varied depending on different impact materials. The impact absorption ability was the greatest in the steel ball and the wooden bat tests in the hard object collision category.

The results of this study indicate the need to select various impact objects for evaluation in conjunction with the shock absorption abilities of mouthguards in order to select appropriate materials for making mouthguards that are suitable for each sport. These results support the idea of establishing a set of standards for the manner, in which one needs to evaluate the impact absorption ability of mouthguard material.

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