Received: 19 November 2023 | Revised: 2 April 2024 | Accepted: 22 April 2024
DOI: 10.1111/edt.12968

ORIGINAL ARTICLE

Dental Traumatology WILEY

Comparison of shock absorption capacities of three types of mouthguards: A comparative in vitro study

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Funding information
SEGULA Technologies

Abstract

Background/Aim: 3D printing processes can be used to manufacture custom-made mouthguards for sports activities. Few studies have compared the impact performance of industrial-created mouthguards with that of custom-made mouthguards manufactured by thermoforming or 3D printing. The objective of this in vitro study was to compare the shock absorption capacities of custom-made mouthguards manufactured by 3D printing with industrial mouthguards and thermoformed ethylene vinyl acetate (EVA) mouthguards.

Materials and Methods: For each type of mouthguard, eight samples were produced. 3D-printed mouthguards were manufactured using digital light processing technology. Each mouthguard was subjected to an impact performance test defined by the standard AFNOR XP S72-427, which evaluate maximum deceleration and force transmitted during impact. The thickness of each mouthguard before and after a series of five impacts was measured at the impacted inter-incisal area.

Results: The mean maximum decelerations during impact ranged from 129 to 189 g for industrial mouthguards, 287 to 425 g for thermoformed EVA mouthguards, and 277 to 302 g for 3D-printed mouthguards. The mean reduction in mouthguard thickness at the impact zone after five tests was 1.2 mm for industrial mouthguards, 0.6 mm for 3D-printed mouthguards, and 2.2 mm for thermoformed EVA mouthguards.

Conclusions: Custom-made 3D printed mouthguards showed slightly better shock absorption ability than thermoformed mouthguards with respect to the indicator proposed in XP S72-427. They seemed to combine the practical advantages of thermoformed mouthguards in sports with better shock absorption capacity and lower cost. Furthermore, they had the least thickness variation during the test, and their shock absorption capacity was the least affected by repeated mechanical tests. Other types of 3D-printing resin materials that will become available must continue to be tested for shock absorption to provide the best protection to users at low cost.

KEYWORDS
digital light processing, drop mass impact, mechanical tests, mouth protectors, printing three dimensional

1 | INTRODUCTION

A mouth protector, mouthguard, or intraoral protection is a medical device that covers the teeth and surrounding mucosa to prevent or reduce trauma to the teeth, gingival tissue, lips, and jaws.[1] Numerous studies have demonstrated the benefit of mouthguards during sports activities with a high risk of oro-facial injuries.[1–4] Stable occlusion and maximum contact with the anterior teeth help reduce mouth protector displacement during impacts.[5]

Different varieties of mouthguards have been described,[6–8] they are classified into three categories by the American Society for Testing and Materials: standardized type I mouthguards, adaptable in-mouth type II mouthguards, and custom-made type III mouthguards.[9,10] Moreover, the materials most used in their manufacture are polyvinyl acetate derivatives, ethylene vinyl acetate (EVA), and polyvinyl chloride.[11]

Type I mouthguards are industrially manufactured, typically composed of elastomeric materials, polyvinyl chloride, or EVA,[4] and are not modifiable. Type II industrial mouthguards are made of thermoplastic polymer and are shaped directly in the mouth by the user. They are the most used.[11–13] Type III mouthguards are custom-made intraoral protective devices. They are manufactured by collaboration between a dentist and a prosthesis laboratory, incurring higher costs than industrial-created mouth protectors. They are considered the most effective devices and are shaped by thermoforming on a personalized dental arch model.[14–17] However, the thermoforming process for these type II (boil and bite) and type III (thermoformed shell) mouthguards leads to a reduction in the initial thickness of the mouthguard.[11,12] The effectiveness of protection appears to be associated with the thickness of the mouthguard within acceptable limits for facial soft tissue but with no significant difference between 3 and 4 mm in thickness.[18–20]

Additive manufacturing using digital light processing and 3D printing technology is gaining prominence in the dental field and represents a promising alternative to traditional processes.[21] This technology could replace thermoforming in the production of type III mouthguards. It offers the advantage of streamlining the production process, depositing multiple layers of materials successively, and varying material composition during fabrication.[22,23] Furthermore, 3D printing CAD/CAM technology ensures consistency in the thickness of manufactured mouthguards. Unfortunately, little is available in the literature about the properties of a specific printable material for mouthguards. The most-examined physical properties of a mouthguard are energy dissipation, hardness, Young's modulus, tear resistance, and water absorption.[24]

To be marketed, industrial type I and II mouthguards must comply with standard AFNOR XP S72-427, which specifies their mechanical behavior during impact.[25] During standardized impact tests, deceleration of the impactor and force transmitted to the mouthguard are measured during five consecutive tests. Type III mouthguards provided by dentists are custom-made Class IIa medical devices not subject to this specification. However, several comparative studies of mouthguards have tested custom type III mouthguards according to this specification.[26–29] Mechanical impact tests described in the standard, called "impact performance," use a drop tower.[30–32] Recent studies of mouthguards have focused on materials or mouthguard shape,[21,32,33] but there are no studies on the impact performance of 3D-printed mouthguards.[33] Furthermore, no study has analyzed the degradation of the mouthguard following an impact or a series of impacts. Measuring the difference in thickness of the mouthguard before and after an impact seems important in assessing the degradation of mouthguards due to successive impacts and the preservation of their protective function for the athlete.

The main objective of this study was to compare the mechanical impact behaviors of type II industrial mouthguards (IMGs), three-layer type III mouthguards manufactured by thermoforming (TMGs), and type III mouthguards manufactured by 3D printing (3DMGs), to determine whether 3D printing can produce an effective protective mouthguard solution for users.[24,33,34] The secondary objective was to compare the thickness of the different types of mouthguards before and after the standard impact test. The null hypothesis was that all three types of mouthguards comply with the mechanical impact performance defined in the standard AFNOR XP S72-427.[25]

2 | MATERIALS AND METHODS

2.1 | Design and fabrication of 3D printing mouthguards (3DMG)

Eight individualized single-layer maxillary 3DMGs were fabricated (Figure 1A). The 3DMGs were designed to fit the Frasaco ANA-4 dental study model (GmbH, Tettnang, Germany), as recommended in standard XP S72-427.[25] The shape of this model was digitized by using the 3Shape digital scanner (D1000; 3Shape, Copenhagen, Denmark). Then, replicas of the maxillary and mandibular models were manufactured in Cobalt-Chrome. The maxillary 3DMG shape was designed using Computer-Aided Design (CAD) software (Splint module, Blender for Dental, Australia) to fit the Frasaco ANA-4 model. The digital model of 3DMG was designed with a constant thickness of 4 mm, and the occlusal surface was indented at 2 mm by mandibular cusps.[18–20,35–38] The maxillary 3DMG covered all teeth up to the second molars.[36–38] It extended into the buccal vestibule up to 1 mm from the depth of the buccal vestibule while following the contours of frenula and flanges. In the palatal area, it covered the neck of the teeth and stopped at the marginal gingiva, 7 mm from the cervical area.[38]

The 3DMGs were manufactured using indirect bonding resin (IDB) resin (IDB Sprintray, Sprintray, USA) with a 3D printer based on the principles of tank photopolymerization using digital light processing (Sprintray Pro 95S, Sprintray, USA) technology. This multipurpose photo-polymerizable resin for dental orthodontic splints essentially consists of methyl acrylate (30%–70%), urethane acrylate oligomer (20%–50%), 1,2-ethanediol bisacrylate (5%–30%), and 3,3,5-trimethylcyclohexyl acrylate (5%–30%). This resin is biocompatible and CE-marked (Tables 1 and 2).

(A) (B) (C)

FIGURE 1 Views of tested mouthguards: (A) custom-made 3D-printed mouthguard (3DMG), (B) custom-made thermoformed mouthguard (TMG), and (C) industrial mouthguard (IMG).

TABLE 1 Mechanical properties of IDB resin.

Mechanical properties	Method	IDB resin
Tear strength	ASTM D624-00	5.2 MPa
Hardness	ASTM D2240-00	<90 A
Flexural modulus	ASTM D2240-00	18 MPa
Tensile modulus	ASTM D412	8 MPa
Tensile Strenght	ASTM D412	7.2 MPa
Water absorption	ASTM D570	5.0%
Elongation at break (strain)	ASTM D638	130%

The printing layer thickness was 100 μm. Subsequently, the 3DMGs were placed in a postprocessing (print washing process and postcuring) following the manufacturer's protocol. They were cleaned in an isopropyl alcohol bath for 30 min (Form Wash, Sprintray, USA) and then placed in a UV chamber for 60 min (Form Cure, Sprintray, USA). The 3DMGs were then placed on plaster models and stored in a room protected from light and humidity at 19°C.[25] The occlusal thickness of the 3DMG was 2.1 ± 0.1 mm.

2.2 | Design and fabrication of thermoformed mouthguards (TMG)

Maxilla and mandible plaster duplicate models (Fujirock, GC Co., Tokyo, Japan) were obtained from molds of the Frasaco ANA-4 models to be used for TMG fabrication and the preservation and storage of mouthguards. Eight custom-made TMGs (Figure 1B) were fabricated in a prosthesis laboratory (Dental Vannes, Vannes, France) using Erkodent (Erkodent Erich Kopp GmbH, Pfalzgrafenweiler, Germany)-certified equipment, based on plaster duplicate models of the Frasaco ANA-4 models. Each TMG was made from a triple-layer disk with thickness 4.1 mm, consisting of 2 layers of EVA, 1.5 mm (outer layer) and 2 mm (inner layer), and an intermediate layer of cyclic olefin copolymer (COC) with thickness 0.6 mm (Playsafe triple light 4.1 × 125 mm, Erkodent Erich Kopp GmbH, Pfalzgrafenweiler, Germany).

Each TMG was fabricated according to the manufacturer's recommended protocol by using the recommended thermoforming machine (Erkoform 3 D Motion, Erkodent Erich Kopp GmbH, Pfalzgrafenweiler, Germany). Indentations of mandibular cusps on the occlusal surface of the maxillary TMG were created using a device integrated into the specific thermoforming unit (Occluform 3, Erkodent Erich Kopp GmbH, Pfalzgrafenweiler, Germany). Occlusal indentation depth was 2 ± 0.5 mm on the first mandibular molar and uniformized on the 8 TMG. During TMG fabrication, the triple-layer disk was placed on the thermoforming device's plate holder, heated to 120°C, and then applied with a vacuum pressure of 6 bars onto the plaster model. The overall shape and vestibular and palatal limits of the TMG were similar to those of the 3DMGs. The average occlusal thickness of the TMG at the first molar was 1.2 ± 0.11 mm.

2.3 | Fabrication of industrial mouthguards (IMG)

Eight identical IMGs (L500, Decathlon, France) were used after shaping according to the manufacturer's recommendations (Figure 1C). Type IV plaster duplicates of the Frasaco ANA-4 models were fabricated (Fujirock, GC Co., Tokyo, Japan) and mounted on a semi-adaptable articulator (Fag Quick Master, Fag, France). The operator immersed the IMG in water at 100°C for 40 s and then in water at 10°C for 3 s. After placement on the articulator, the maxillary IMG was molded on its occlusal and buccal aspects. The articulator was closed in occlusion on the maxillary IMG, and manual pressure was applied to create indentations of 2 ± 0.5 mm on the occlusal surface of the eight maxillary IMG. The average occlusal thickness of the IMG at the first molar was 4.2 ± 0.1 mm.

2.4 | Drop mass impact testing device

All mouthguards were then stored and preserved on plaster models, protected from light, at room temperature for 1 month as mentioned in the standard.[25] The impactor device included a drop tower system on top of the mouthguard. The mouthguard was secured on an adjustable "maxillary" jaw and a mobile "mandibular" jaw (Figure 2). The "maxillary" jaw consisted of the maxillary model made of Co–Cr alloy and a set of three adjusting supports that positioned the central inter-incisal area in line with the impactor, as specified in standard

TABLE 2 Abbreviations, manufacturers, batch numbers, and composition of the materials used (for 3DMG).

Materials	Manufacturer	Batch number	Posttreatment	Composition/characteristic
IDB Resin	Sprintray, Los Angeles, USA	XH431N01	IPA: 5 min Postcuring time: 10 min Postcuring Temperature: not specified	• (5-éthyl-1,3-dioxanne-5-yl) méthyl (30%–70%) • Oligomer urethane acrylate (20%–50%) • 1,2-éthanediyl diacrylate (5%–30%) • 3,3,5-triméthylcyclohexyl acrylate (5%–30%)
Dima Print Mouthguard	Kulzer Japan Co., Osaka, Japan	66094489	IPA: 3 min Post curing time: 10 min Post curing Temperature: 40°C	• 2-hydroxyethyl acrylate (25%–50%) • Oxyde de diphenyl (2,4,6-trimethylbenzoyl) phosphine (1%–2.5%) • 3-phenoxybenzyl alcohol (0.25%–1%)
Keyguard	Keyprint, Gibbstostown, USA	NL3631	IPA: 3 min Postcuring time: 10 min Postcuring Temperature: 40°C	• 2-hydroxyethyl methacrylate (25%–50%) • Trimethylbenzoyl) phosphine (<3%) • Titanium dioxide (<0.3%) • Trimethylolpropane triacrylate (<0.3%)

Abbreviation: 3DMG, 3D-printed mouthguard.

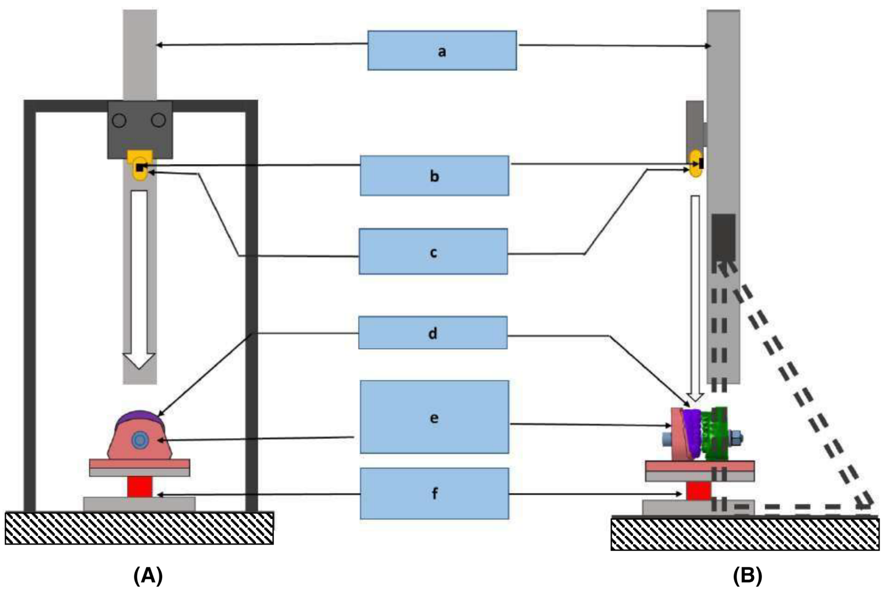


FIGURE 2 Diagram of the shock absorption test experimental setup. (a) Drop tower, (b) accelerometer, (c) impactor device, (d) mouthguard, (e) locked steel model on machined plate, (f) force sensor. Two different views such as (A) front view of the device and (B) side view of the device.

XP S72-427 (Figure 3). The mobile jaw consisted of the mandibular model made of Co–Cr alloy and a fixation system that held the mandibular model in occlusion on the mouthguard placed on the maxillary model.

The clamping device maintained the mandibular model in occlusion on the maxillary mouthguard with a preconditioning bite force of 400 N on the tested mouthguard (Figure 3).[29,31,32] The mouthguard holding device consisted of the two Co–Cr alloy models with the tested mouthguard, with the clamping device fixed on the metal base plate of this fixation system.

The Frasaco maxillary model was positioned on the drop tower so that the 16-mm diameter hemispherical head of the impactor struck the central interincisal area (between teeth 11 and 21) of each tested mouthguard on the buccal aspect, in line with the interincisal midline.

A one-axis force sensor (SCAIME type K-1250, sensitivity 1.021 mV/V) with a maximum measurable force of 20 kN was placed below the mouthguard holding device's base plate (Figure 2). A one-axis accelerometer (PCB Piezotronics model 352A21, Sensitivity 10.29 mV/g) was glued on the superior surface of the moving mass, vertically aligned with the gravity and the impact direction.

2.5 | Impact tests

For each type of mouthguard, eight mouthguards were tested. The mouthguards were stored at room temperature (25°C) for at least 4 h before the test. A 1 kg impactor was dropped from a height of 0.4 m relative to the mouthguards and guided along the vertical axis to produce an impact of 4 J at the maxillary central incisors (teeth 11–21), on the buccal aspect, in line with the interincisal midline.[25,39] Five impacts were performed on each mouthguard as specified by the standard.

For each impact on the tested mouthguards, the impactor's deceleration at impact and the transmitted force to the mouthguard

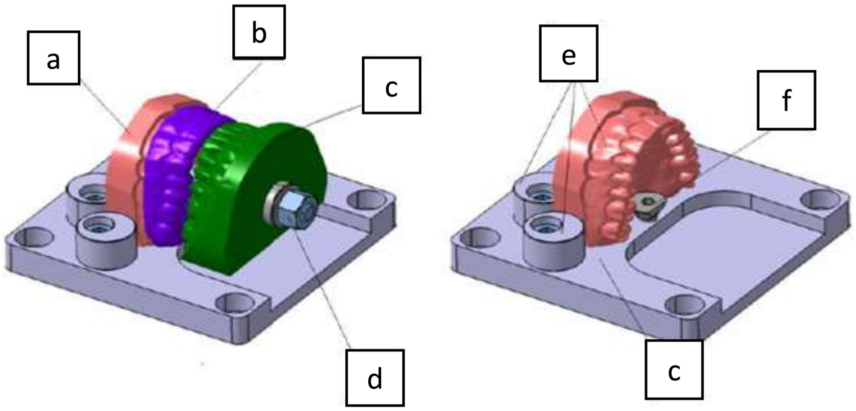


FIGURE 3 Diagram of the fixation system for Co-Cr models at the drop tower. (a) Maxillary adjustable jaw; (b) mouthguard; (c) mandibular mobile jaw; (d) clamping system (screw + nut + hemispherical washers); (e) adjustable positioning pin (×3); (f) eccentric holding screw; (g) base interface with drop tower structure.

were measured. This force corresponds to the force transmitted to the osteo-mucosal or dental support during a simulated impact in a sports injury.[25] The higher the value of the transmitted force, the lower the shock absorption capacity of the mouthguard.

Following the recommendations of standard XP-S72-427, force and acceleration were measured at 50 kHz, then filtered using a Butterworth low-pass filter with a cutoff frequency of 600 Hz for maximum deceleration peak measurement.

The maximum deceleration and maximum force were calculated as the averages of the first five maximum deceleration and maximum force measurements, respectively. To comply with standard XP S72-427, these averages must not exceed 230 g, and no individual impact should exceed 250 g ($g = 9.81\,m/s^2$).

2.6 | Thickness measurements

The thickness of each mouthguard was measured at the maxillary interincisal impact point (11–21), located 2 mm from the free edge between the inner surface and outer surface of the mouthguard. Thickness measurements were taken before and after the five impacts by using an Iwanson thickness caliper with a reading accuracy of 0.1 mm (Reference 4447, GACD, France).

2.7 | Data processing and statistical analysis

Maximum decelerations and maximum forces transmitted were compared between the three mouthguard types (3DMG, TMG, IMG). The data were analyzed by Kruskal–Wallis test followed by Dunn's multiple comparison test with GraphPad Prism software (GraphPad Prism, GraphPad Software, Boston, MA, USA). Statistical significance was set at $p < .05$.

3 | RESULTS

The mean maximum decelerations measured during impact ranged from 129 to 189 g for IMGs, 287 to 425 g for custom TMGs, and 277

TABLE 3 Mean maximum decelerations for each mouthguard by mouthguard type (in *g*).

	Mean deceleration (*g*)		
Mouthguards	IMG ($n = 5$)	TMG ($n < 5$)	3DMG ($n = 5$)
1	159.5 ± 3.7	287.1 ± 21.0 ($n = 4$)	287.6 ± 2.5
2	129.3 ± 8.2	317.3 ± 50.0 ($n = 2$)	297.8 ± 6.9
3	137.0 ± 8.6	425.2 ± 25.8 ($n = 3$)	281.7 ± 2.9
4	147.8 ± 10.8	387.4 ± 52.7 ($n = 3$)	276.7 ± 7.6
5	137.0 ± 7.1	312.3 ± 68.1 ($n = 2$)	302.2 ± 11.0
6	140.3 ± 7.2	333.1 ± 95.6 ($n = 2$)	277.1 ± 5.2
7	136.3 ± 8.9	330.3 ± 82.3 ($n = 2$)	280.5 ± 7.3
8	189.2 ± 6.6	369.9 ± 57.8 ($n = 2$)	296.6 ± 6.1

Abbreviations: 3DMG, 3D-printed mouthguard; IMG, industrial mouthguard; TMG, thermoformed mouthguard.

to 302 g for 3DMGs (Table 3). Not all measurements could be taken for TMGs because of their failure before the fifth trial.

Only the IMGs met the standard with a maximum transmitted deceleration of <250 g ($2453\,m/s^2$). The mean maximum decelerations for 3DMGs and TMGs reached 230 g ($2256\,m/s^2$) with maximum values >250 g. Impact decelerations significantly differed between industrial and custom-made mouthguards ($p < .05$) (Figure 4).

The mean values for maximum forces transmitted on impact ranged from 1347 to 1943 N for IMGs, 3117 to 4695 N for TMGs, and 3099 to 3389 N for 3DMGs (Table 4).

For 3DMGs, both maximum deceleration and maximum transmitted force slightly decreased with the number of impacts (Figures 5 and 6), in contrast to IMGs, which showed an opposite trend (Figures 7 and 8).

The mean thickness of mouthguards before impact was 2.6 mm (*SD* 0.18) for TMGs, 3.9 mm (*SD* 0.11) for 3DMGs, and 5.9 mm (*SD* 0.23) for IMGs. After the impact test, the thickness of all mouthguards had decreased (Table 5). The mean reduction in thickness was 1.2 mm for IMGs, 0.6 mm for 3DMGs, and 2.2 mm for TMGs. Furthermore, most TMGs exhibited substantial degradation at the impact point as early as the second trial, before completing all five impacts.

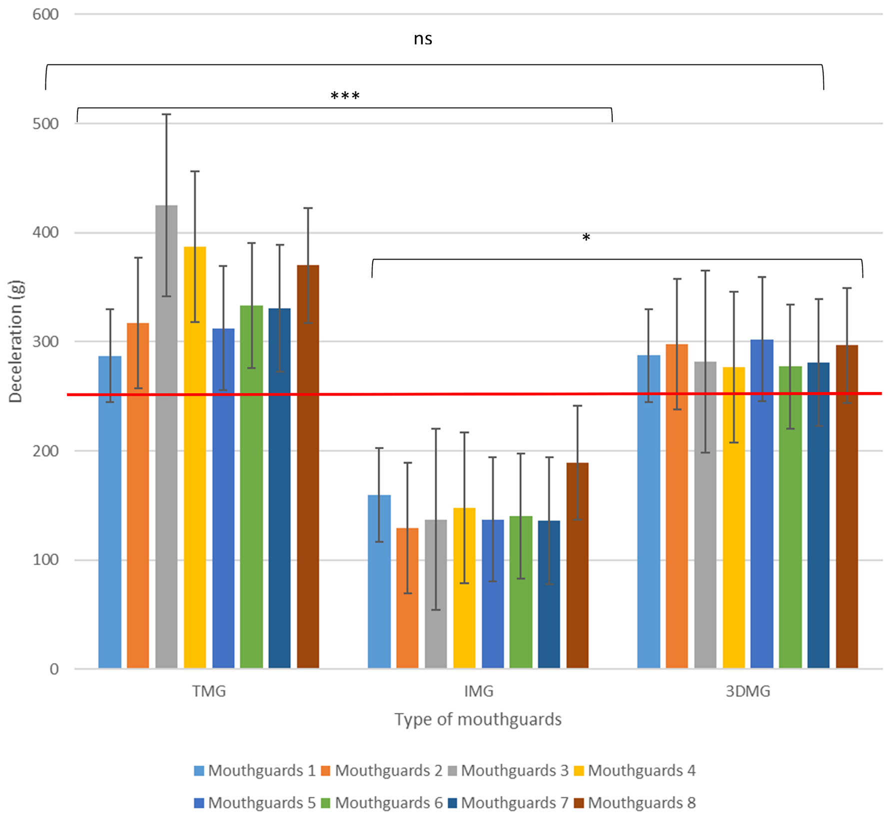


FIGURE 4 Comparative graph of shock absorption performance by mouthguard type. Measurements are expressed as mean ± *SD*. Threshold limit is defined by ISO standard XP S72-427 indicated by the red line. IMG, industrial mouthguard; TMG, thermoformed mouthguard; 3DMG, 3D-printed mouthguard. Kruskall–Wallis test with Dunn's multiple comparison, *$p > .05$; ***$p < .01$; ns, not significant.

TABLE 4 Mean maximum forces transmitted for each mouthguard by mouthguard type (in N).

	Mean F_{tmax} (N)		
Mouthguards	**IMG ($n = 5$)**	**TMG ($n < 5$)**	**3DMG ($n = 5$)**
1	1773.7 ± 32.4	3117.2 ± 432.0 ($n = 4$)	3173.7 ± 10.2
2	1411.8 ± 131.6	3587.7 ± 478.0 ($n = 2$)	3331.9 ± 69.6
3	1592.0 ± 103.2	4694.9 ± 281.6 ($n = 3$)	3112.1 ± 43.2
4	1655.9 ± 133.8	4264.9 ± 698.5 ($n = 3$)	3114.1 ± 87.4
5	1367.5 ± 62.3	3398.6 ± 806.9 ($n = 2$)	3388.8 ± 122.8
6	1413.6 ± 83.6	3607.0 ± 1143.6 ($n = 2$)	3171.1 ± 83.4
7	1347.2 ± 106.0	3587.8 ± 985.1 ($n = 2$)	3098.9 ± 66.0
8	1942.7 ± 69.0	4047.9 ± 675.8 ($n = 2$)	3270.9 ± 67.3

Abbreviations: 3DMG, 3D-printed mouthguard; IMG, industrial mouthguard; TMG, thermoformed mouthguard.

4 | DISCUSSION

Unlike 3DMGs and TMGs, IMGs complied with the standard for mechanical shock absorption tests. However, 3DMGs achieved values of transmitted force and deceleration close to the maximum permissible values of the standard. They demonstrated better shock absorption performance than TMGs. For 3DMGs, shock absorption was improved with subsequent impacts, but for IMGs, performance decreased with repeated shocks, and TMGs were destroyed at the impact point before the fifth trial.

This study compared the impact performance according to the XPS72-427 standard for type II and III mouthguards commonly available and used by the athlete. It also included mouthguards from the emerging 3D printing technology. The impact performances of three mouthguards were compared in this study. These type II and III mouthguards use different materials compatible with their specific manufacturing techniques. In addition, the mouthguard tested were of different shapes and thicknesses and prevented a direct comparison of the mechanical properties of the materials.

The material used, shape, and thickness are essential parameters in the shock-absorbing capacity of mouthguards.[30,31,40,41] The main materials used include EVA, methyl methacrylate acrylic, acrylic resin, latex, polyurethane, polyvinyl chloride, and silicone.[29,42] Currently, EVA is the material predominantly used in the composition of type II and type III mouthguards.[41,42] The resin used for 3DMGs was a multipurpose resin indicated for dental splints, not specifically for mouthguards, which can be considered a limitation of this study, although the mechanical properties of this printed resin are close

FIGURE 5 Graph of deceleration evolution as a function of number of impacts for each 3D-printed mouthguard.

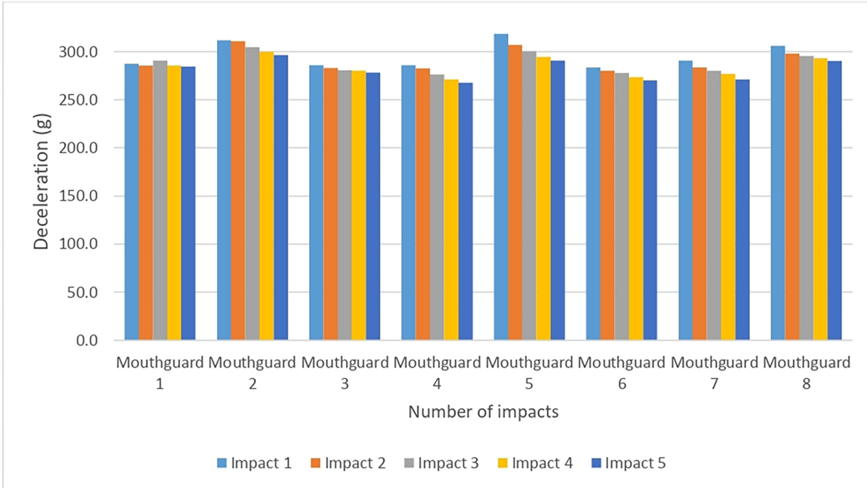
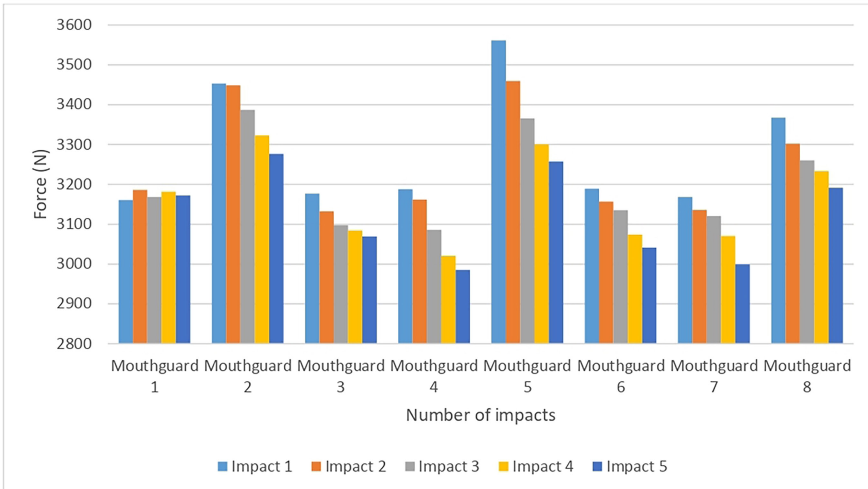


FIGURE 6 Graph of the evolution of transmitted Fmax as a function of the number of impacts for each 3D-printed mouthguard.



to those defined in the specifications of the ideal mouthguard. Our study revealed a reduction in thickness in the impact zone due to irreversible plastic deformation in this area for all mouthguards. After several successive impacts in the same location, IMGs or TMGs were damaged, whereas 3DMGs showed a slight improvement in shock-absorbing capabilities. The growth of 3D printing processes has led to the development of polymers with better mechanical properties tailored for mouthguard indications (KeyGuard, KeyPrint, Keystone Industries). The currently available information on the mechanical properties of these new 3D printing resins, such as the modulus of elasticity, is incomplete or even nonexistent. However, similar values for the tested IDB resin are provided for hardness, elongation at break, and water absorption (Table 1). Both the IDB resin and these new resins are primarily composed of ethyl acrylate.

Furthermore, shock absorption in mouthguards increases with the material's thickness.[43,44] In general, mouthguards need to have a minimum thickness of 3 mm.[41] Hence, during the thermoforming process, the initial thickness of the sheet on the final mouthguard is halved at the end of manufacturing, which constitutes a limitation of the study. Consequently, TMGs, IMGs, and 3DMGs do not have similar thicknesses once shaped.[34]

Finally, the shape of custom-made mouthguards can be considered similar in terms of tooth coverage, extension to the depth of the buccal vestibule, and occlusal surface with indentations. In contrast, the shape of IMGs varies depending on the operator's handling during thermoforming.[32] IMGs are also less enveloping mouthguards, with less extensive boundaries and less retentive.[45]

In professional sports, users favor custom-made devices over IMGs.[30,46] Indeed, custom-made mouthguards are more retentive, comfortable, better-fitted, less cumbersome, and less deformable; they provide overall support to the dento-alveolar block and offer better protection.[38,44,47] These criteria, not considered by standard XP S72-427, are nevertheless essential in protecting against sports-related injuries. Furthermore, standard XP S72-427 characterizes localized impact on mouthguards and does not allow for deducing the transmitted stresses on teeth or alveolar bone.

Standard XP S72-427 identifies a discriminative threshold value of 250 g for acceleration, but scientific studies have not determined the effective protection threshold. However, the standard, primarily based on mouthguard impact behavior, does not characterize the overall effectiveness of the mouthguard, which depends on many criteria

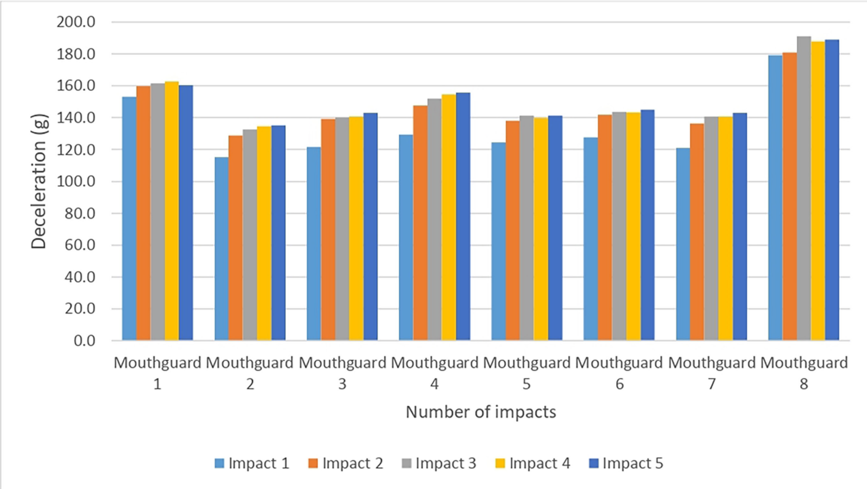


FIGURE 7 Graph of deceleration evolution as a function of the number of impacts for each industrial mouthguard.

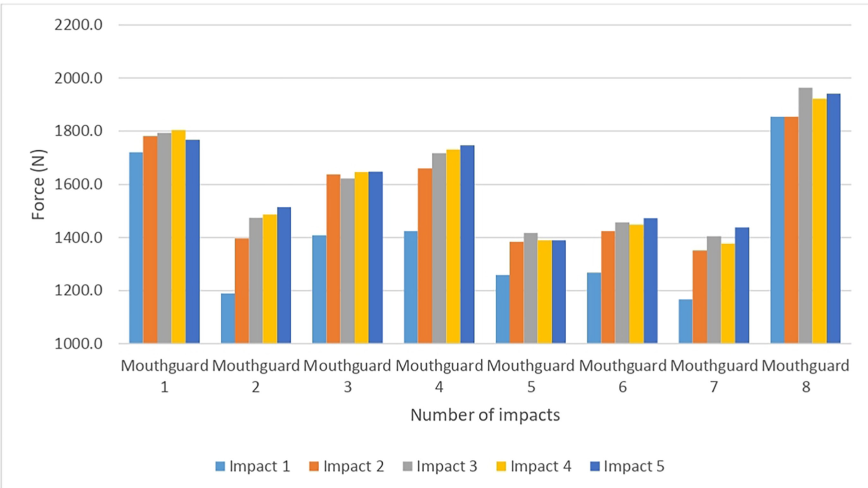


FIGURE 8 Graph of the evolution of transmitted Fmax as a function of the number of impacts for each industrial mouthguard.

TABLE 5 Comparison of interincisal thickness before and after impact by mouthguard before and after impact testing (in mm).

	TMG		3DMG		IMG	
Type of mouthguard	Before impact	After impact	Before impact	After impact	Before impact	After impact
Mean thickness (mm) (*SD*)	2.58 (0.18)	0.38 (0.34)	3.94 (0.11)	3.30 (0.20)	5.95 (0.23)	4.80 (0.21)
Minimal thickness (mm)	2.30	0.00	3.80	3.00	4.40	4.40
Maximal thickness (mm)	2.80	0.70	4.10	3.60	6.20	5.10

Abbreviations: 3DMG, 3D-printed mouthguard; IMG, industrial mouthguard; TMG, thermoformed mouthguard.

related to its performance during use (impact behavior, ease of insertion, comfort, effective protection of teeth and temporomandibular joints, sufficient retention, ability to speak for communication, etc.) as well as medical-economic aspects (cost, ease of implementation, etc.). These criteria depend on various parameters, including design choices with material and shaping processes; environmental usage conditions such as storage conditions; aging due to light, temperature, or saliva; and individual-related parameters such as growth or cleaning.

Furthermore, the degradation of the mouthguard with repeated impacts should be considered. In practice, athletes are advised to replace a damaged, torn, perforated, cracked, shredded, or locally crushed mouthguard because its protective functions are reduced.[38,48] Therefore, mouthguards should be inspected carefully by athletes after each use, during cleaning operations.

3DMGs were the least damaged in the interincisal zone after a series of five impacts, with an average reduction in thickness of

0.6 mm. Therefore, they may have a greater capacity to withstand successive impacts with minimal irreversible plastic deformation.

The development of new 3D printing resins[39] could contribute to the broader adoption of custom-made 3DMGs. Indeed, manufacturing costs and technological simplicity of design and production favor the proliferation of this protection tool, particularly among young people, for whom device replacement is rapid due to growth. Further studies are needed to analyze the effect of storage conditions and biofilm between each use and the potential consequences on mechanical performance over time.

5 | CONCLUSION

Unlike custom-made type III thermoformed mouthguards (Playsafe triple light, Erkodent) and type III 3D-printed mouthguards (IDB, Sprintray), the type II industrial mouthguards we tested (Decathlon) met the shock absorption capacity indicators specified by standard XP S72-427. However, the professional sports world favors custom-made type III thermoformed mouthguards, although they do not comply with this specification because they are more retentive, comfortable, and provide better support for the dento-alveolar block. Therefore, type III mouthguards seem to provide effective protection to users and are recommended for contact and combat sports. For type III mouthguards, adaptation, retention, and occlusal indentation are controlled by the dentist. Therefore, dentists play a central role in informing and educating athletes about protecting the player's integrity, providing information on the proper use of mouthguards, and encouraging appropriate behaviors in case of trauma or damage to the mouthguard recommended for contact and combat sports.

Custom-made 3D-printed mouthguards showed slightly better shock absorption ability than thermoformed mouthguards with respect to the indicator proposed in XP S72-427. They seemed to combine the practical advantages of thermoformed mouthguards in sports with better shock absorption capacity and lower cost. Furthermore, they had the least thickness variation during the test, and their shock absorption capacity was the least affected by repeated mechanical tests. Other types of 3D printing resin materials that will become available must continue to be tested for shock absorption to provide the best protection to users at low cost.

AUTHOR CONTRIBUTIONS

Arfi Yohan: Conceptualisation and study design, prototype design CAD, prototype manufacturing CAM, data analysis and interpretation, drafting manuscript and agreement for accountability. **Benoit Aurélie**: Data collection, critical revision of the manuscript, approval of the manuscript. **Tapie Laurent**: Data collection, critical revision of the manuscript, approval of the manuscript. **Sandoz Baptiste**: Data collection, critical revision of the manuscript, approval of the manuscript. **Persohn Sylvain**: Data collection, critical revision of the manuscript, approval of the manuscript. **Attal Jean-Pierre**: Critical revision of the manuscript, approval of the manuscript. **Rignon-Bret Christophe**: Conceptualisation and study design, data collection, drafting manuscript and agreement for accountability, critical revision of the manuscript, approval of the manuscript. All the authors made substantial contributions to the manuscript.

FUNDING INFORMATION

We would like to thank the industrial partner company SEGULA Technologies for the financial contribution made throughout this study.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ETHICAL STATEMENT

This experimentation does not include a human study.

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How to cite this article: Yohan A, Aurélie B, Laurent T, Baptiste S, Sylvain P, Jean-Pierre A, et al. Comparison of shock absorption capacities of three types of mouthguards: A comparative in vitro study. Dental Traumatology. 2024;00:1–10. https://doi.org/10.1111/edt.12968