

On the protectiveness of additively manufactured mouthguards

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ABSTRACT

A mouthguard is a piece of equipment worn in sports worldwide to greatly reduce the chance of orodental injuries. This work uses a newly developed method for testing and analysing mouthguards subjected to high impact energies of up to 100 J. This method allows investigation and comparison between the use of additive manufacturing, and current best mouthguard manufacturing technology of thermoforming with Ethylene-vinyl acetate (EVA). The impact experiments are conducted using a drop tower and high-speed images are captured for the further analysis. Important physical parameters such as peak force, impulse and dissipated energy in the mouthguard are determined. The results revealed that the additively manufactured mouthguards made from Arnitel® ID 2045 lead to a peak force and impulse of impact that is on average 10% and 25% lower, respectively, than that experienced when using the EVA mouthguard. A lower peak force and impulse is preferred as it reduces the chance of an orodental injury occurring. The research shows that previously mouthguards have been tested at impact energies far lower than those experienced in impact prone sports such as field hockey. When using impacts with higher energies, the findings show that additive manufacturing provides a viable technology for manufacturing mouthguards, which offers many new benefits.

1. Introduction

Orofacial injuries are common in physical activities and account for 18% of sports traumas [1]. Sports such as rugby, field hockey, boxing, and basketball expose athletes to a variety of impact scenarios, making the use of protective devices like mouthguards crucial in reducing the risk of dental injuries [2].

Different organizations recommend the use of mouthguards in sports to address the risk of orofacial injuries. The American Dental Association (ADA) [3,4], the FDI World Dental Federation [5,6], and the International Olympic Committee (IOC) [7] recommend mouthguards in various sports, while the National Collegiate Athletic Association (NCAA) mandates them for certain sports. Generally, however, enforcement of mouthguard usage in contact sports is still lacking.

Although guidelines and recommendations exist for mouthguard usage, there is a distinction between professional sports and amateur sports in terms of requirements and enforcement. Professional sports leagues and organizations, such as the National Hockey League (NHL) and professional boxing associations, have more comprehensive regulations and stricter enforcement when it comes to mouthguard usage.

They make it mandatory for players to wear mouthguards during games to protect against dental and orofacial injuries. In amateur sports, the requirements for mouthguard usage can be more variable, with some associations enforcing mandatory usage in certain sports or age groups, while others leave the decision to wear a mouthguard up to individual athletes or their coaches [8–10].

Regardless of the level of play, wearing properly fitted mouthguards is important for athletes to prevent orofacial injuries during sports activities. Mouthguards are designed to fit over the maxillary arch (upper teeth) and aim to reduce the impact forces transmitted to the teeth and surrounding structures [11]. They distribute the energy of impacts over a larger area, thus decreasing the risk of orofacial injury and mouthguard failure. An ideal mouthguard should offer a high level of wearing comfort without impairing the athlete's performance [12,13]. The material used should be biocompatible, non-toxic, and capable of absorbing and dissipating a significant amount of energy [14].

There are three main types of mouthguards commonly used in sports according to the ASTM F697-16 standard: (1) prefabricated mouthguards, (2) mouth-formed mouthguards and (3) custom-made mouthguards. Prefabricated mouthguards are ready to wear but often provide

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Nomenclature

E	Young's modulus	c_{mg}	Damping coefficient mouthguard
E^*	Young's modulus mixed	c_b	Damping coefficient impactor
E_b	Young's modulus impactor	x	Displacement
E_{mg}	Young's modulus mouthguard	\dot{x}	Velocity (potential)
σ_y	Yield stress	ΔT	Total contact time of impact
σ_{hy}	Hyperelastic stress component	CR	Coefficient of restitution
σ_{vis}	Viscoelastic stress component	I	Impulse
σ_{max}	Maximum stress	W	Energy
s_{hy}	Network ratio hyperelastic	W_{diss}	Dissipated energy
s_{vis}	Network ratio viscoelastic	W_{mg}	Energy mouthguard
η	Viscosity	W_b	Energy impactor
α	Crystallinity	W_{total}	Total energy
F	Force	W_{kin}	Kinetic energy
F_{mg}	Force mouthguard	W_{pot}	Potential energy
F_b	Force impactor	v	Velocity (kinetic)
M	Mass	ν	Poisson ratio
M_{mg}	Mass mouthguard	λ	Stretch ratio
M_b	Mass impactor	ϵ	Strain
A	Material model constant	L	Thickness
m	Material model constant	L_0	Initial thickness
n	Material model constant	$\dot{\epsilon}$	Strain rate
C_1	Material model constant	r^*	Radius mixed
\ddot{x}	Acceleration	r_b	Radius impactor
k	Spring stiffness	d	Width mouthguard
k_{mg}	Spring stiffness mouthguard	δ_b	Contact stiffness constant of the impactor
k_b	Spring stiffness impactor	δ_{pl}	Contact stiffness constant of the elastic barrier
c	Damping coefficient		

poor fit, comfort, and protection. They are usually made from rubber or polyvinyl and are inexpensive [15,16]. Mouth-formed mouthguards, such as boil-and-bite mouthguards, are individually fitted to the user's mouth. These mouthguards are made of a thermoplastic resin that softens in boiling water, allowing it to adapt to the shape of the user's teeth [17]. While they offer better comfort and protection than prefabricated mouthguards, they can be bulky. Custom-made mouthguards are manufactured in a dental laboratory based on a detailed model of the athlete's teeth [18]. They provide the best fit, comfort, and protection but are more expensive to produce. The most common manufacturing method involves thermoforming a sheet of polyethylene vinyl acetate (EVA) over the teeth model, creating a tight fit.

While custom-made mouthguards offer superior protection compared to other types, the commonly used EVA material has limitations. One of these limitations is the uneven thinning of the material due to its high swelling capacity and low stiffness [19]. This thinning can reduce the protective effect of the mouthguard as the impact energy is not adequately dissipated. To address this issue, more material can be used, but this can lead to excess material in other areas of the mouthguard, reducing wearing comfort [20].

To overcome these challenges and to maintain the protective performance of the mouthguard, additive manufacturing (AM) techniques can be employed [14]. AM allows for precise control of the shape and thickness of the mouthguard at every point, enabling an optimized design with areas of increased material for better protection and thinner areas for improved breathability and comfort. Additionally, AM opens up possibilities for incorporating features such as air cells or electronic components like sensors, which can further enhance the functionality of the mouthguard.

There are few studies investigating the suitability of AM for mouthguards. Unkovsky et al. conducted a proof-of-concept study for 3D printing of mouthguards [21]. This involved performing and evaluating a digital workflow, including tooth impression. In addition, Sousa et al. investigated different 3D-printed polymer candidates and their physical properties to replace the commonly used EVA material [22]. Here,

tensile tests were performed to qualify the mechanical performance of each material as a function of the printing parameters. They observed a decrease in impact strength with increasing thickness. Furthermore, Pinho et al. investigated the effect of ageing on the impact and flexural strength of 3D-printed multi-material sandwich polymers [23]. For this purpose, three-point bending tests at quasi-static loads and Charpy impact tests at 5 J were performed. It was found that ageing of the sandwich structures resulted in an insignificant decrease in mechanical performance.

Although there have been some studies exploring the use of AM for mouthguards, more research is needed to understand the strain rate-dependent performance of materials used in mouthguards subjected to different velocities. One study found that an additively manufactured material called Arnitel® ID 2045 exhibited better mechanical performance, in terms of dissipated energy, compared to EVA samples, indicating its potential as a suitable material for 3D printing mouthguards [24]. However, further investigations are necessary to comprehensively evaluate the impact behaviour and protective capabilities of 3D-printed mouthguards in comparison to traditionally manufactured EVA mouthguards.

While guidelines and material requirements exist, there is a significant gap in standardization for testing mouthguards. This gap affects the consistency and comparability of mouthguard performance evaluation across different manufacturers and models. Without a standardized testing protocol, it becomes challenging to accurately assess the protective capabilities of mouthguards and ensure quality control within the industry. Establishing a standardized testing protocol for mouthguards is crucial to ensure reliable and objective evaluation of their protective performance.

Currently, the regulation governing sports mouthguards is the Personal Protective Equipment (PPE) legislation. The PPE Directive 89/686/EEC became European Law in 1995 and was superseded in 2018 by Regulation (EU) 2016/425 on PPE. This legislation categorizes PPE into three categories: simple, neither simple nor complex, and complex [27]. Sports mouthguards fall under the category of neither simple

Table 1
Material properties of Arnitel®-3D and EVA.

Property	Arnitel®	EVA
Density (kg/m ³)	1100	945
Shore D hardness (-)	34	37
Melting point (°C)	158	87
Maximum tensile stress (MPa)	8	13

nor complex PPE equipment. To be certified and placed on the market, mouthguards must be tested and certified by an independent European notified body, which then allows the manufacturer to use the CE mark on their product. However, there is no standard testing protocol for prototype mouthguards, so the independent European notified body must ensure their tests cover the necessary requirements of the PPE legislation, including impact tests, minimum thickness, fluid absorption, and ergonomics.

The aim of this work is, therefore, to investigate the impact behaviour of 3D-printed mouthguards in comparison with the impact behaviour of mouthguards manufactured from EVA, the material which is used in current mouthguards on the market that have been certified. Firstly, tests are conducted according to the mechanical testing method newly established in Goldberg et al. [25]. Second, the suitability of the 3D-printed mouthguard compared to the traditionally used EVA mouthguard for different impact energies is investigated. Third, 3D-printed and traditionally manufactured mouthguards are assessed on their durability to understand their performance after multiple impacts. Finally, the experimental observations of the material influence on the protective effect of the mouthguard as a function of impact energy are discussed.

2. Methods

The impact tests follow the test program described in Goldberg et al. [25], in which mouthguards made of EVA material were investigated. In the present work, a 3D-printed mouthguard sample is used for each impact energy. In addition, repeated impact tests are carried out to one sample made of the 3D-printed material and one made of EVA material. This is to mimic the conditions mouthguards experience during actual use in sports such as field hockey or boxing where repeated impacts are present. Moreover, to assess the protectiveness of the mouthguards, tests are performed in which the impactor hits the mouthguard fixture with no mouthguard present. This represents the worst-case scenario test case in which no protection is considered.

2.1. Materials

The 3D-printed mouthguards investigated are made of Arnitel® ID 2045 Natural (DSM, Netherlands). This is a polyester-based thermoplastic copolymer (TPC) with a Shore D hardness of 34. This Shore hardness is equivalent to the Shore A hardness of EVA material of 83 according to ASTM D2240. It is important to find a material that is comparable to the best material currently in use, as there are no standards for mouthguard materials. In particular, Arnitel® ID 2045, and from now on referred to as Arnitel®-3D, is a multi-block copolymer comprised of polybutylene terephthalate (PBT) hard blocks and >50% renewable rapeseed-oil soft blocks [26]. As investigated in [26], Arnitel®-3D provides a suitable material for 3D-printing while also providing high elasticity necessary for the application in mouthguards to dissipate large amounts of energy to decrease the risk of injury. The main characteristics which supports this suitability are an adequate stiffness ($E = 58 \text{ MPa}$), high strength ($\sigma_y = 8 \text{ MPa}$), a low melt viscosity ($\eta_{100\text{rad}/s, 240^\circ\text{C}} = 102 \text{ Pa}\cdot\text{s}$), a low crystallinity ($\alpha_{cr} = 12\%$), and a high melt temperature with a melting onset above 100°C [26]. Table 1 summarises the main comparable material properties of Arnitel®-3D and EVA respectively.

2.2. Specimen design and manufacturing

Several test specimens are fabricated to investigate the impact behaviour of 3D-printed mouthguards as well as the repeated impact behaviour of 3D-printed and traditionally fabricated mouthguards. Fig. 1(a) illustrates the specimen dimensions.

The Arnitel®-3D mouthguards are made using the AM technology of Fused Filament Fabrication (FFF). According to the mouthguard design in Goldberg et al. [25], the Arnitel®-3D samples are a simplification of a real mouth scan of a healthy adult. This is to obtain a sufficiently representative set of teeth. The design is built layer by layer using the Creality CR10, which has a direct-drive extruder with the following settings: Nozzle diameter 0.4 mm, extrusion multiplier 90%, layer thickness 0.1 mm, fill 100%, overlap between contour and fill 5%, nozzle temperature 230°C , bed temperature 60°C , cooling fan 20%, and overall print speed 20 mm/s. As suggested by the supplier, best adhesion with Arnitel®-3D can be achieved by using an adhesive promoter such as painters tape. This is to prevent the first layer as well as possibly corners to lift and detach from the platform.

The mouthguard specimen made of EVA material for the durability tests is manufactured using a thermoforming process. Here, the EVA material is purchased as 3.0 mm thick discs from Keystone Industries. One 3.0 mm raw disc material results in roughly 1.0 mm thick sheets after the heating and thermoforming process. Five layers of the purchased sheets are heated and placed on top of each other, fusing them to the layer below. The layers were applied layer by layer, allowing the top layer to cool and cure before another sheet was applied.

Mouthguards made of the two different materials are manufactured with a thickness of 5.0 mm. Despite the fact that a study by Westerman et al. concluded that 4.0 mm is an optimal thickness, since the improvement in transmitted force decreases with increasing thickness [28]. However, as described in Goldberg et al. to ensure a more comprehensive evaluation of the mouthguards' performance under these higher impact energies it is believed that a slightly larger thickness is more appropriate for tests with impact energies up to 100 J rather than the 4.4 J used in the Westerman study [25]. The average thickness of the mouthguards is 4.84 mm.

2.3. Experimental setup

The Arnitel®-3D specimens are tested at five different impact energies ranging from 20 J to 100 J, with the lowest impact energy of 20 J being further used for the subsequent impact test repeats on one mouthguard sample of each material. The energy levels from 20 J to 100 J were chosen following the field study of Goldberg et al. [25] for field hockey. This allows the investigation and development of improved mouthguards using real-world data. Additionally, one Arnitel®-3D specimen and one EVA specimen are used to investigate the durability of the mouthguard at an impact energy of 20 J. For that, the mouthguard of the two different materials is impacted five times. Between each impact, the mouthguard is left to relax until no significant change in thickness measurement is observed. This is to understand the mouthguards ability to withstand repeated impacts without experiencing degradation or failure. In order to realise the different impact energies and to allow comparison of the experimental results of the Arnitel®-3D material with the EVA material, the experimental setup described in Goldberg et al. [25] is employed: a drop tower is used together with an impactor consisting of a field hockey ball and a ball holder. The impactor is connected to the drop tower by a screw. The mouthguards are mounted on a mouthguard holder positioned so that the field hockey ball is aligned with the center of the width of the specimen. A Photron high-speed camera with a frame rate of 20,000 frames per second and an image resolution of 704x520 pixels was used to record the deformation of the mouthguard and the impactor. Fig. 1(b) shows the experimental setup. For more detailed information about the setup, the reader is referred to the paper by Goldberg et al. [25].

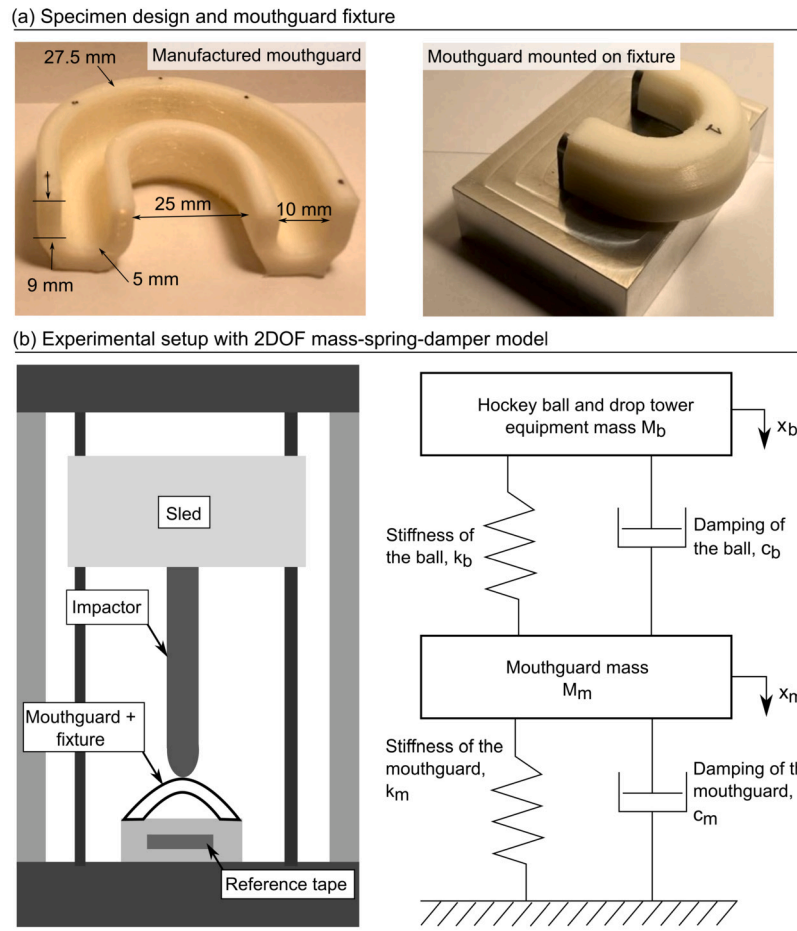


Fig. 1. Graphical illustration of (a) the specimen dimension and (b) the experimental setup together with the 2DOF mass-spring-damper model.

2.4. Data acquisition method

The data analysis is based solely on high-speed images as shown in Fig. 2. The impactor and each specimen were marked with a black point prior to each impact test. This point was used as a reference point in each frame to determine the compression of the mouthguard throughout the test. This allowed the calculation of the deformation history of the impactor and mouthguard using a MATLAB script. This script gave the automatic determination of the position of the marker for each frame. Considering the length of the reference tape (Fig. 1(b)), which is 0.018 m, this resulted in a pixel length of 0.000046 m, which was used to convert the pixel displacement into displacements. Ultimately, each impact test results in a displacement-time graph for the duration of the impact for the mouthguard and the impactor.

The impact tests with the mouthguard can be represented with a spring-damper system. This allows the calculation of acceleration, force, impulse and energy according to Goodwill et al. [29]. These physical quantities are important for understanding the impact performance and protectiveness of sports equipment such as mouthguards. As described in Goldberg et al. [25], the impact is represented by a spring-mass damper system with two degrees of freedom. The impactor and the mouthguard are each modelled with a spring and a damper, in parallel. The mouthguard holder, on the other hand, is rigid. This system allows the physical parameters considered to be determined as follows:

Considering the equation of motion the force F which acts on the mouthguard can be calculated following Goodwill et al. [29] and Nagurka et al. [30] as

$$F = F_{mg} = M_{mg} \ddot{x}_{mg} = k_b(x_{mg} - x_b) + c_b(\dot{x}_{mg} - \dot{x}_b) - k_m x_{mg} - c_m \dot{x}_{mg} \quad (1)$$

where k_i is the stiffness of the spring component and is calculated with

$$k_i = M_i \left(\frac{\pi}{\Delta T} \right)^2 \left[1 + \left(\frac{\ln(CR_i)}{\pi} \right)^2 \right] \quad (2)$$

and c_i represents the damping coefficient obtained through

$$c_i = -\frac{2M_i}{(\Delta T)} \ln(CR_i) \quad (3)$$

where $i = b, mg$ are the indices which stand for the impactor and the mouthguard, respectively and M_i is the mass of the relevant object.

The coefficient of restitution, CR_i is utilised within the equations and is obtained with the velocity at the end and at the beginning of the impact with

$$CR_i = \frac{|\dot{x}_i(\Delta T)|}{|\dot{x}_i(0)|} \quad (4)$$

where ΔT is the total contact time of the impact. The constants k and c are calculated for each impact test individually using the velocity-time data.

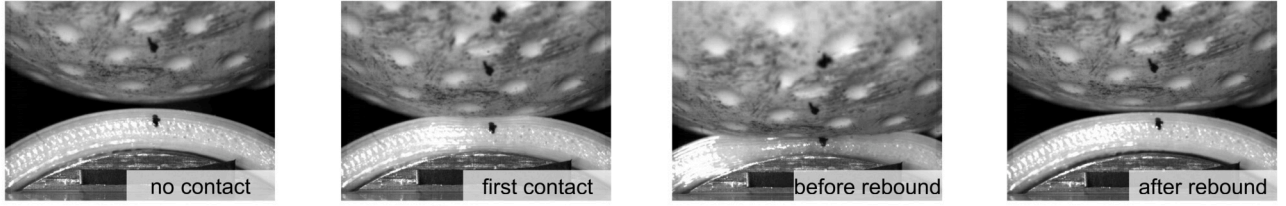
With the calculation of the force which the impactor exerts on the mouthguard using Eq. (1), it is possible to determine the impulse I during the impact time t with

$$I = \int F dt \quad (5)$$

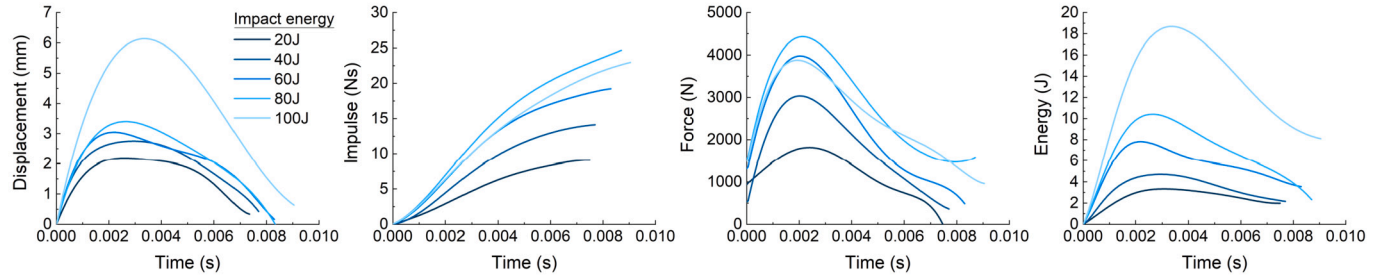
Ultimately, the energy (W) which the mouthguard experienced is obtained using force and displacement (x) using

$$W = \int F dx \quad (6)$$

(a) Image sequence of ball impact



(b) Impact energy dependent responses of Arnitel®-3D mouthguards



(c) Repeated fatigue results for Arnitel®-3D and EVA mouthguards

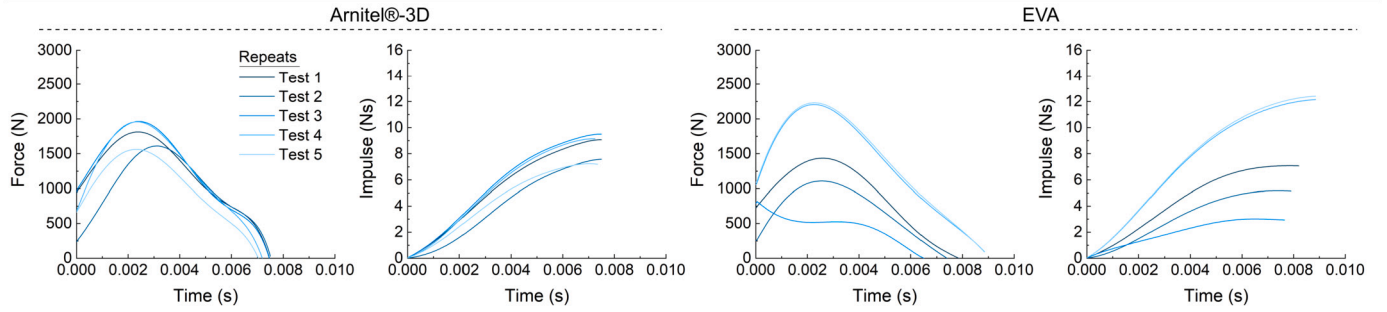


Fig. 2. Experimental results showing (a) the impact dependent displacement, impulse, force and dissipated energy histories for Arnitel®-3D and (b) the durability results for force and impulse histories for Arnitel®-3D and EVA.

Using the conservation of energy, the correctness of the aforementioned equations and their results is verified. For that, the following equation is used

$$W_{total}(0) = W_{mg}(\Delta T) + W_b(\Delta T) + W_{diss}(\Delta T) \quad (7)$$

where W_{total} is the targeted energy which was set up and calculated at the start of the impact at time $t=0$ considering the drop mass and drop height. The calculated energies for the mouthguard and the impactor are represented by W_{mg} and W_b , respectively at the end of the impact $t=\Delta T$. The energy which is dissipated in the system during the impact due to e.g. heat, is presented by W_{diss} . It is highlighted that the whole impact scenario involves the loading and unloading – impact and rebound stage.

Since the mass-spring-damper model enables the calculation of the different energies individually, it is possible to obtain the energy dissipated in the system with

$$W_{diss} = c_i \int \dot{x}_i dt \quad (8)$$

In addition to the verification method using the conservation of energy approach, experimental results from Ranga et al. [31] and Lißner et al. [33] are considered to further provide validity of the proposed technique.

For that, the results of Ranga et al. [31] are used to be compared with the experimental results of the impact tests without mouthguard. This is possible since D. Ranga et al. investigated the same hockey ball as used in this research. Using the impact velocity-coefficient of restitution (COR) relationship for the polyurethane (PU) hollow hockey ball, it is possible to obtain the impact velocity-impact energy relationship

by using the known mass of the hockey ball $m=0.1579\text{ kg}$ as measured in Goldberg et al. [25]. In addition to this, the work-energy theorem of the hockey ball-to-steel plate impact allows the calculation of the maximum force at impact. The impact scenario can be modelled and calculated using a single degree of freedom mass-spring-damper system as follows:

The maximum force is found when the kinetic energy W_{kin} of the impact is equal to the potential energy W_{pot} of the hockey ball represented by a spring as

$$W_{kin} = W_{pot} \quad (9)$$

$$\frac{1}{2}mv^2 = \frac{1}{2}k_b x^2 \quad (10)$$

where k_b is the contact stiffness and can be calculated by considering the Hertz-contact theory of an elastic spherical shell impacted with an elastic barrier as demonstrated in Mansoor et al. [32] using

$$k_b = \frac{4}{3\pi} \frac{\sqrt{r_b}}{(\delta_b + \delta_{pl})} \quad (11)$$

where δ_b and δ_{pl} are calculated as follows

$$\delta_i = \frac{1 - \nu_i^2}{\pi E_i} \quad \text{with } i = b, pl \quad (12)$$

and where ν_i and E_i are the Poisson ratio and the Young's modulus, respectively, for the hockey ball ($i = b$) and the elastic barrier ($i = pl$) and which are $E_b = 34.8\text{ MPa}$, $E_{pl} = 200,000\text{ MPa}$, $\nu_b = 0.42$ and $\nu_{pl} = 0.31$.

The maximum deformation x can be expressed using the force applied on a spring with a stiffness of k_b as

$$x = \frac{F_b}{k_b} \quad (13)$$

This allows the calculation of the maximum force depending on the impact velocity by substituting Eq. (13) in Eq. (10) which results in

$$F_b = v\sqrt{m_b k_b} \quad (14)$$

On the other hand, the maximum force acting on the Arnitel[®]-3D mouthguards at each impact can be approximated using the material model calibrated in Lißner et al. [33]. This material model is calibrated using strain-rate dependent compression test samples of Arnitel[®]-3D material tested in Saunders et al. [24]. Using the maximum displacements measured at each mouthguard impact it is possible to calculate the maximum stress using the hyper-viscoelastic material model considering the parallel rheological framework. For that, the hyperelastic stress representation follows

$$\sigma_{hy} = 2C_1(\lambda - \lambda^{-2}) \quad (15)$$

where C_1 is a material model constant and amounts to 2.1636, and where λ is the stretch calculated using the strain ϵ and maximum deformation x definition using

$$\epsilon = \frac{\Delta L}{L_0}, \quad \Delta L = x - L_0, \quad \lambda = \epsilon + 1 \quad (16)$$

where L_0 is the initial thickness of the mouthguard.

And the viscoelastic part is calculated using the equation as follows

$$\sigma_{vis} = \left\{ \frac{\dot{\epsilon}^{m+1}}{A[(m+1)\epsilon]^m} \right\}^{\frac{1}{n}} \quad (17)$$

with the material model constants $A = 0.4245$, $n = 0.9964$, $m = -0.5$ as published in Lißner et al. [33], and where the strain rate $\dot{\epsilon}$ is calculated using the maximum impact velocity and the initial mouthguard thickness.

The total maximum stress can then be obtained as follows

$$\sigma_{max} = s_{hy}\sigma_{hy} + s_{vis}\sigma_{vis} \quad (18)$$

where s_{hy} and s_{vis} are the network ratios which amount to 0.9 and 0.1, respectively.

The maximum force of Arnitel[®]-3D material can then be calculated considering the Hertz-Contact relationship of two elastic spheres using

$$F_{mg} = 2\pi r^* d(1 - v^2) \frac{\sigma^2}{E^*} \quad (19)$$

where r^* and E^* are the mixed relationship of radii and Young's modulus for the impactor (b) and mouthguard (mg) material and are calculated as

$$r^* = \frac{r_b r_{mg}}{r_b + r_{mg}} \quad \text{and} \quad E^* = 2 \frac{E_b E_{mg}}{E_b + E_{mg}} \quad (20)$$

3. Results

The experiments for the different impact energies and durability tests are analysed using the aforementioned method. Fig. 2(a) shows the displacement, force, impulse and energy history graphs for Arnitel[®]-3D mouthguards for the five different target impact energies 20 J, 40 J, 60 J, 80 J and 100 J. Table 2 summarises the maximum impact results for both, the Arnitel[®]-3D experiments as well as the impact tests without a mouthguard present. Fig. 2(b) shows the repeated impact tests at 20 J on one mouthguard sample each for Arnitel[®]-3D and EVA. In addition, the dissipated energy in the mouthguard is presented in Table 3 for the impact and repetition tests.

The results show for the Arnitel[®]-3D mouthguards a clear dependence of displacement, force, impulse and dissipated energy on the

Table 2

Overview of the obtained maximum displacement, force, impulse and energy depending on the impact energy for the Arnitel[®]-3D mouthguard tests and the obtained maximum force and coefficient of restitution (COR) for the experiments with no mouthguard present.

Parameter	Test 20 J	Test 40 J	Test 60 J	Test 80 J	Test 100 J
Arnitel [®] -3D					
Displacement (mm)	2.3	2.7	2.8	3.3	4.9
Peak force (N)	1815	3040	3981	4438	3880
Impulse (Ns)	9.1	14.0	19.2	24.6	22.9
Energy in mouthguard (J)	3.3	4.7	7.8	10.4	18.7
No mouthguard present - impactor only					
Peak force (N)	4436	5166	6007	6530	7260
COR (-)	0.45	0.44	0.39	0.32	0.34

impact energies. The physical parameters are increasing with increasing impact energy. Furthermore, the 20 J-repetition experiments show a higher variation for mouthguards made from EVA material when compared to Arnitel[®]-3D. In the following section, the differences and possible explanations for this is addressed.

4. Discussion

The results show the displacement, force, impulse and dissipated energy histories for the whole impact scenario which includes the impact and rebound stage (loading and unloading of the mouthguard). Fig. 3 suggests, that with increasing impact energy the force, the impulse and dissipated energy increase. Furthermore, it appears that the mouthguards made from EVA are more prone to a loss in material behaviour due to repeated impacts than the ones made from Arnitel[®], as seen in Fig. 4. The results will be investigated and discussed in more detail in this section, and a comparison between the two different mouthguard materials will be made. For that, the impact results for EVA mouthguards investigated in Goldberg et al. [25] are considered. Ultimately, the results will also be used to quantify the safety of the mouthguards.

Due to the absence of a standard for mouthguard testing, the impact tests in this study investigate the performance of Arnitel[®]-3D mouthguards compared to current EVA mouthguards which, although not being certified by an independent European notified body themselves, are manufactured in the same way with the same material and thickness to current mouthguards on the market that have been certified. It is not possible to quantify the protection of the Arnitel[®]-3D mouthguard models against any government set tests.

The discussion is split into five sections: First, for completeness, the impact tests for the Arnitel[®]-3D mouthguards are verified using conservation of energy as demonstrated in Goldberg et al. [25]. Second, the impact experiments without a mouthguard are compared with the observations made in Ranga et al. [31]. Third, the Arnitel[®]-3D impact experiments are compared to analytical representation using the material model calibrated in Lißner et al. [33]. Fourth, the impact performance of the mouthguards made from Arnitel[®] is compared to the one reported in Goldberg et al. [25] for the commercially used EVA material. Fifth, the effect of repetition on each type of material will be examined. The ability of the mouthguard to withstand multiple impacts without a significant risk to the safety of the user is a key attribute of this device.

4.1. Test verification using conservation of energy theorem

To verify that the results obtained are correct, the concept of energy conservation is used. It is known that, at the start of the impact, all the energy is contained in the kinetic energy of the drop mass. At the end of the impact, this energy has been transferred into deforming the mouthguard, deforming the ball and the kinetic energy of the drop mass as it rebounds.

Fig. 5(a) illustrates the initial energy and the final energy of each impact. There are differences between the initial and final energy present

Table 3

Experimental results for the five test repeats on one mouthguard made of each material – Arnitel® (3D printed) and EVA (thermoformed) – at a low impact energy of 20 J.

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5
Arnitel®-3D					
Peak force (N) (\pm Stdv)	1815 (\pm 22)	1610 (\pm 123)	1967 (\pm 129)	1961 (\pm 125)	1565 (\pm 155)
Impulse (Ns) (\pm Stdv)	9.1 (\pm 0.4)	7.6 (\pm 0.6)	9.5 (\pm 0.7)	9.1 (\pm 0.4)	7.2 (\pm 0.9)
Energy in mouthguard (J) (\pm Stdv)	3.3 (\pm 0.4)	1.8 (\pm 0.7)	3.3 (\pm 0.4)	3.1 (\pm 0.2)	2.3 (\pm 0.3)
EVA					
Peak force (N) (\pm Stdv)	1443 (\pm 43)	1113 (\pm 276)	529 (\pm 356)	2206 (\pm 496)	2227 (\pm 511)
Impulse (Ns) (\pm Stdv)	7.1 (\pm 0.6)	5.1 (\pm 1.9)	3.0 (\pm 3.5)	12.1 (\pm 2.9)	12.4 (\pm 3.1)
Energy in mouthguard (J) (\pm Stdv)	1.5 (\pm 0.3)	1.0 (\pm 0.7)	1.4 (\pm 0.4)	3.0 (\pm 0.7)	2.9 (\pm 0.6)

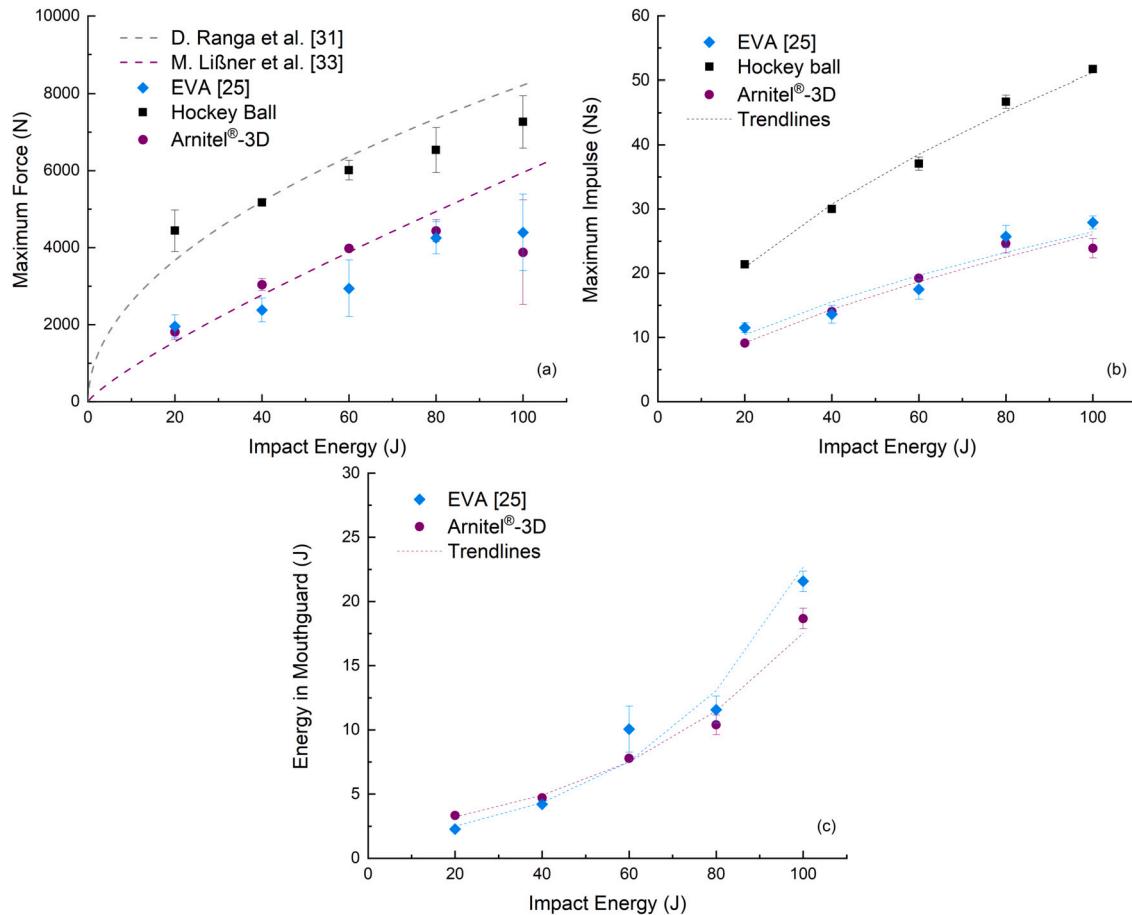


Fig. 3. Experimental results showing (a) the maximum force, (b) the maximum impulse and (c) the dissipated energy in the mouthguard dependent on the different impact energies for Arnitel®-3D, EVA, no mouthguard and from the references [31,33,25] where applicable.

in each test which may be due to inefficiencies in the impact test, leading to imperfect energy transfer between the impactor, the deformation of the ball and mouthguard. In particular, energy is likely to be lost through friction between the impactor and mouthguard, and in the test rig. In some tests, the final energy calculated is higher than the initial energy, which is likely to be a result of errors introduced during the data analysis, such as the calculation of the constants of the mass-spring-damper system. Nevertheless, the differences amount to less than 8% which suggest a strong agreement between the values. The error was obtained by using the target energies as a reference.

4.2. Test verification using impact results without mouthguard in literature

Another way the method is verified is by using the COR-impact velocity experiments published in [31]. By applying equation (14) it is possible to obtain the force-impact energy representation from Ranga

et al. [31]. This allows a direct comparison with the experiments performed in this research.

As Fig. 5(b) demonstrates the average deviation of the COR values for the hockey ball experiments with no mouthguard present amounts to 10%. Similar trend is observed for the peak force-impact energy relationship as demonstrated in Fig. 3(a). This is believed to provide a good verification of the experimental setup.

4.3. Test verification using material model from literature

To verify the validity of the experimental results of impact tests using the mouthguard, the analytical derived peak force using Eq. (19) for each impact energy is considered [33]. Fig. 3(a) shows that the peak force of Arnitel®-3D experiments can be represented well by the analytical approach up to 80 J. The average deviation from the Arnitel®-3D experiments to the analytical method amounts to 12%. This is indeed a

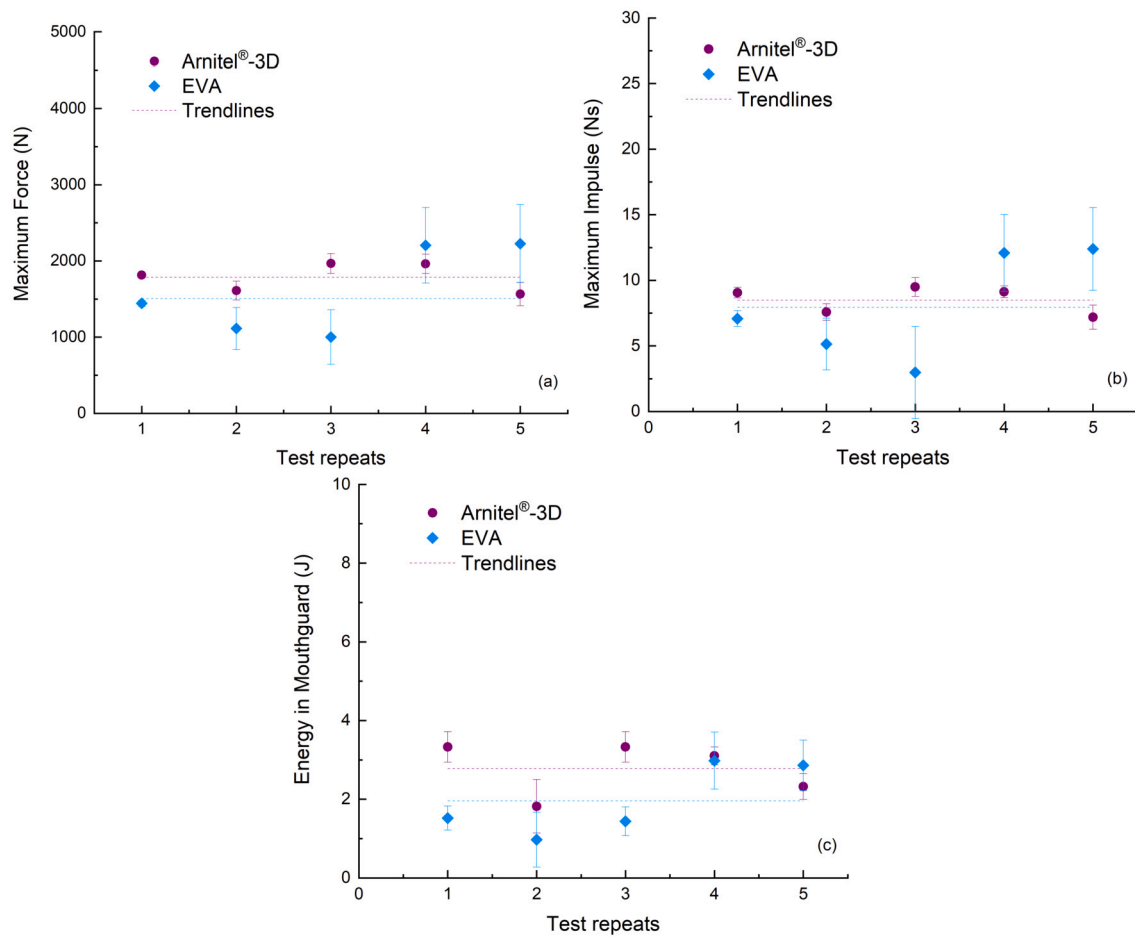


Fig. 4. Experimental results showing (a) the peak force, (b) the impulse histories and (c) the dissipated energy for five repeated impacts on the mouthguards made from Arnitel®-3D and EVA for an impact energy of 20 J.

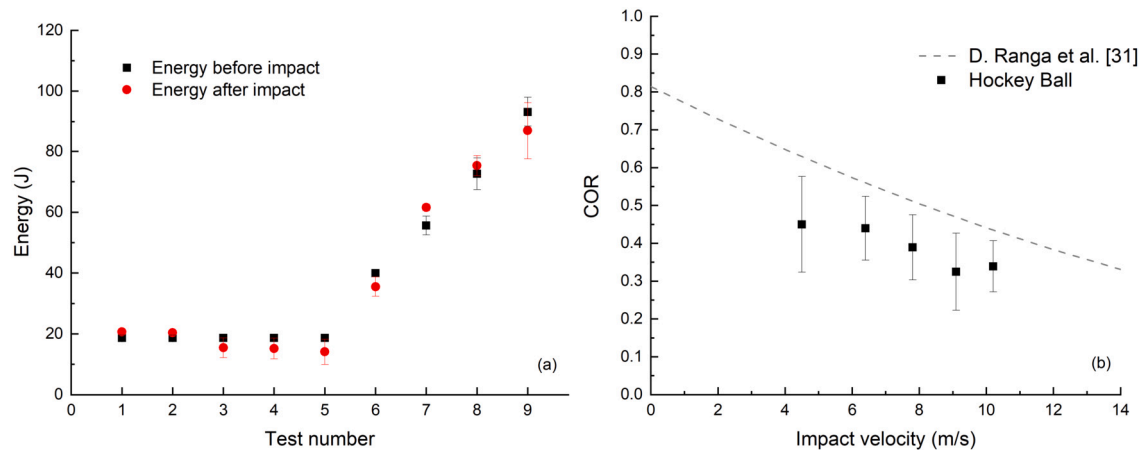


Fig. 5. Demonstration of the test setup's validity for the Arnitel®-3D mouthguards considering (a) the conservation of energy theorem and (b) the comparison with COR results presented in [31].

promising value which suggests that the test setup and data acquisition method is valid.

4.4. Effect of impact

Five impact energy tests are conducted at target energies of 20 J, 40 J, 60 J, 80 J and 100 J. To discuss the response of the mouthguards in each test, the peak force, impulse and energy dissipated in the mouthguard are plotted against the applied impact energies. This is done for

the impact tests of the Arnitel®-3D mouthguards investigated in this work and compared to the mouthguards made from EVA material investigated in Goldberg et al. [25]. In addition, the impact tests with the different mouthguard tests are compared to tests without mouthguards.

The peak force experienced during the impact increases linearly with impact energy between 20 J and 80 J for both mouthguard materials while it then increases small up to 100 J as shown in Fig. 3(a). The EVA and Arnitel®-3D mouthguards demonstrate very similar peak forces, with Arnitel®-3D resulting in generally slightly higher forces.

Both mouthguards reduce the peak force by more than a factor of 2.5 when compared to the situation with no mouthguard present; reducing the peak force from 6,553 N to 4,253 N and 4,438 N when using the EVA and Arnitel®-3D mouthguards respectively for an impact energy of 80 J. The results suggest that both mouthguards are very effective in reducing peak forces. In more detail, Arnitel® mouthguards result on average in peak forces 6% higher than EVA mouthguards over the tested impact energy ranges.

As Fig. 3(b) illustrates, the impulse increases more than the peak force indicating increase in impact duration with increasing impact energy. Both mouthguards reduce the impulse of an impact. However, the difference is not as significant as the reduction of the peak force. The impulse appears to follow a steady increase as it is suggested when following the trendline. In addition, the 3D printed mouthguards result in 7% less impulse than the mouthguards made from EVA material.

The energy dissipated by each mouthguard using Eq. (6) is plotted against the impact energy in Fig. 3(c). The Arnitel®-3D mouthguards follow a steady increase in energy dissipation with increasing impact energy, rising from 3.3 J at an impact of 20 J up to 18.7 J under an impact of 100 J. As mentioned before, due to the lack of a set of government standards, the results of the Arnitel®-3D mouthguards are compared to mouthguard tests made from the current best material used which is EVA. The comparison shows that the EVA mouthguards appear to dissipate 2% more energy than the Arnitel® mouthguards on average over all tested impact energies.

Ultimately, it is demonstrated that both mouthguard types provide significant improvement when compared to tests without mouthguards. Nevertheless, to discuss the safety of mouthguards accurately, information on the maximum physical loads of heads and necks of the athletes are required.

4.5. Durability assessment

The durability tests are performed five times at an impact energy of 20 J on the same specimen for EVA and Arnitel®-3D, respectively. Between each impact the mouthguards had time to recover and the thickness was remeasured. Fig. 4 summarises the results for peak force, impulse and energy dissipation in the mouthguards made from the two different materials under investigation. The standard deviations provided for each test represent the variability observed in the results obtained from the test result of the first impact. Including standard deviations helps to quantify the level of consistency or reproducibility of the test outcomes.

The peak force is plotted against the test number and displayed in Fig. 4(a). The graph suggests that the peak force in the Arnitel®-3D mouthguard is not affected significantly by repeated impacts at the same energy, as it is shown by the mean peak force and standard deviation of 1783 ± 170 N. In contrast, however, the EVA mouthguard has an increase in peak force from 1,443 N in the third test to 2,226 N in the fourth test, which is also shown by the deviation across all tests of 1504 ± 651 N. The trendline in 4(a) used to calculate the standard deviation illustrates this. This high deviation could be a substantial problem during impact prone sport, such as field hockey, as it suggests that the effect of repeated impacts could result in the peak force of an impact increasing by a factor of two. However, for the first three repeated impact tests, the EVA mouthguard outperformed the Arnitel®-3D mouthguard. This is very useful as it strongly suggests that multiple impacts have a little effect on the structural integrity and, hence, can continued to be worn during games. It is important to note that both mouthguard models significantly reduced the peak force of an impact compared to that without a mouthguard present, which was 4,436 N.

The impulse of the impact with the Arnitel®-3D mouthguard decreased steadily from 9.0 Ns in the first impact to 7.0 Ns in the fifth. However, the third impact gave the highest impulse of 9.5 Ns. In comparison, the impulse of the EVA mouthguard model follows a similar trend to the peak force, as it decreases in the first three impacts and

then drastically increases in the fourth and fifth impacts. It is likely that this is strongly correlated to the sharp increase in peak force for these tests. This is shown on the impulse graph, in Fig. 4(b). The impulse is comparable to the peak force analysis, which suggests that the EVA mouthguard outperformed the Arnitel®-3D for the first three impacts, but is more affected by the repetition which leads to a significant increase in impulse after the third test. This is likely to lead to important changes in the protection of the EVA mouthguard. This can be additionally demonstrated by the standard deviation which is for Arnitel®-3D much lower with 8.5 ± 0.9 Ns when compared to 8.0 ± 4.0 Ns for the EVA material.

Energy dissipation in the mouthguards is an important factor regarding the safety of the devices, as the energy that does not go into the deformation of the mouthguard or the impactor will be transferred to the teeth of the user. As a result, a higher energy dissipation in the mouthguard is desirable. Comparing the Arnitel®-3D and EVA mouthguards, using Fig. 4(c), the Arnitel®-3D mouthguard dissipates more energy in the first four impact tests, and the EVA mouthguard dissipates more energy in the final durability test. Similar to the peak force and the impulse, the energy dissipated in the EVA mouthguard increases sharply after the third impact test, suggesting that less energy is being transferred to the user's teeth. However, as it is correlated to the force applied, it is likely that the increase in energy dissipation is a result of the increase in peak force. The energy dissipated by the Arnitel®-3D mouthguard does not vary as much between impact tests, but Fig. 4(c) suggests that the energy dissipation is slightly affected by the repetition of the mouthguard as it decreases from 3.33 J in the first test to 2.32 J in the fifth test. The mean peak force and standard deviation for the dissipated energies across the different durability tests for Arnitel®-3D and EVA is 2.8 ± 0.6 N/mm and 2.0 ± 0.8 N/mm, respectively. This investigation provides a new insight into the influence of repeated impacts on mouthguards as to the best knowledge of the authors, no studies on the assessment of durability was found.

The thickness of the mouthguard models was measured before and after each of the impact tests to investigate whether the thickness is altered significantly by repeated impacts, and whether this is related to the results witnessed above. The thickness of each mouthguard for both materials reduces by less than 1%. While this may not be significant, if the impacts were repeated more times, it may lead to issues with the mouthguard which could be problematic for use during sports. The decrease in thickness might be one reason why the peak force, impulse and energy dissipated by the mouthguard decreases steadily throughout the durability tests. Interestingly, while the thickness decrease measured after each impact is very similar of Arnitel®-3D and EVA material, the mechanical performances of peak force and impulse varies a lot for the EVA material. This might be explained with EVA experiencing a more erratic deformation to the impacts than the Arnitel®-3D mouthguard, and this may be due to the dimensional inaccuracies of the thermoforming manufacturing process. The mouthguard contains five layers of EVA that may deform differently between tests, leading to a more random deformation. And yet, further investigations are necessary to fully appreciate this such as considering the influence of repositioning of the mouthguard after each test.

5. Conclusions

In general, the Arnitel®-3D and EVA mouthguards respond similarly in terms of peak force, impulse and energy dissipation at different impact energies. There appears to be an anomaly in the data for the test conducted at 60 J for the EVA mouthguard, thus, to better understand the responses, it is recommended that further impact tests are conducted at varying impact energies.

Both mouthguards reduce the peak force and impulse of the impact significantly when compared to the situation where no mouthguard is present, and the Arnitel®-3D mouthguard performs extremely well when compared to the EVA mouthguard.

The impact test results suggest that the EVA mouthguard model is more affected by material performance reduction due to repetition than the Arnitel®-3D mouthguard. However, further durability testing needs to be conducted to verify this. The changes in response of the EVA mouthguard may be due to the less accurate manufacturing process of the mouthguard, whereas, the Arnitel®-3D mouthguard is manufactured with more precision using a 3D printing technology, which leads to a more constant response to the durability tests.

This study has shown that the impact performance of the Arnitel®-3D mouthguard for a range of impact energies typically encountered during sporting events is at least as good as the established EVA mouthguard. Furthermore, there are no major problems witnessed in the Arnitel®-3D mouthguard with relation to repeated impacts. The Arnitel®-3D mouthguard is, therefore, a viable choice for use in high impact sports such as field hockey.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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