ATHLETIC MOUTHGUARDS

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Abstract

Indulging in sports and sports-related activities enhances physical and mental health. Sometimes, athletes are prone to injuries either during practice sessions or on-field events. Preventive measures in the form of personal protective equipment and proper training methods will contribute to minimizing the incidence of such unfortunate injuries. There is a reportedly significant number of injuries occurring among individuals of all age groups, not only due to sports but also other activities of daily living. A mouthguard is an intraoral device that protects the teeth and intraoral structures. It is a part of the protective equipment worn by athletes, especially in field and contact sports. With the advent of advanced materials and fabrication methods, mouthguards have come a long way from being a wad of cotton or wood molded around a boxer’s teeth to being custom-made to suit the morphology of an individual athlete’s dentoalveolar structures.

Keywords: Athletes, Injury, Mouthguards, Personal Protective Equipment, Sports, Three-dimensional printing, Sports, Trauma.

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I. INTRODUCTION

Traumatic dental injuries are a common occurrence globally. The chief etiologic factors for traumatic dental injuries in the permanent teeth are sports and sports-related activities. The World Health Organisation (WHO) estimates that approximately 900 million people aged 7 to 65 years have experienced such injuries at least once in their lifetime. So, about 20% of the primary or permanent dentition among such individuals have been affected by trauma. Using a mouthguard as part of the personal protective equipment by athletes during training or the main sporting events can reduce or prevent the incidence of traumatic dental injuries. Despite this, most athletes do not wear a mouthguard due to reasons like discomfort or forgetfulness. This chapter discusses the emergence, importance, and various types of mouthguards available along with recent advancements and possible futuristic concepts.

II. DEFINITIONS

1. **Dental Trauma:** An impact injury to the teeth and the mouth arising from any activity of daily living.

2. **Mouthguard:** A removable occlusal device that is useful in reducing mouth injuries and protecting the teeth and the surrounding structures from injury. It is also defined as ‘A resilient device or appliance placed inside the mouth to reduce oral injuries, particularly to teeth and the surrounding structures.’

3. **Athletic Exposure (AE):** Athlete participating in one practice, competition, or performance where he or she can be exposed to the possibility of athletic injury.

4. **Shock absorbance capacity:** The reduction in impact energy of force transmitted through the mouthguard.

5. **Reportable injury:** An injury that occurred as a result of participation in an organized high school competition or practice, required medical attention by a team athletic trainer or a physician, and resulted in restriction of high school athlete’s participation for one or more days beyond the day of injury or any fracture, concussion, heat illness/injury, or dental injury regardless of whether or not it resulted in restriction of the student-athlete’s participation.

6. **4D printing:** ‘3D-printing technology with the addition of the fourth dimension of time.’

Table 1: ADA’s list of sporting events warranting the use of mouthguards

Aerobatics	Handball	Skydiving
Basketball	Ice hockey	Soccer
Bicycling	Inline skating	Softball
Boxing	Lacrosse	Squash
Equestrian events	Martial arts	Surfing
Extreme	Racquet ball	Volley ball

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sports		
Field events	Rugby	Water polo
Field hockey	Short putting	Weight lifting
Football	Skateboarding	Wrestling
Gymnastics	Skiing	–

III. HISTORY AND EVOLUTION OF MOUTHGUARDS

The concept of a device to protect the teeth and the oral structures originated in the boxing community. The players used various available materials like wood, sponge, tape, and cotton to fabricate their own custom-made devices to protect their teeth from impact injuries during boxing matches. These were the first crude designs of mouthguards. Though the boxers made them to suit their individual jaw and tooth structures, these devices had no inherent self-retentive capacity to be retained in the mouth and had to be held in the mouth by clenching down on teeth.

Towards the end of the 19th century, Woolfe Krause fabricated a mouthguard for boxers using thermoplastic latex strips (gutta percha) that behaved like rubber. Unfortunately, during that time, most individuals supported the opinion that wearing a mouthguard violated the boxing sports rules. However, the subsequent increase in the number of injuries during boxing events led the New York State Athletic Commission to allow boxers to use a mouthguard during the sport from 1927 onwards.

Today, the American Dental Association (ADA) and the International Association of Sports Dentistry (IASD) recommend the use of mouthguards in a total of 29 sports and other activities [Table 1]. Additionally, ADA has designed posters depicting the importance of mouthguards for children and teenagers. (Figures 1a and 1b).

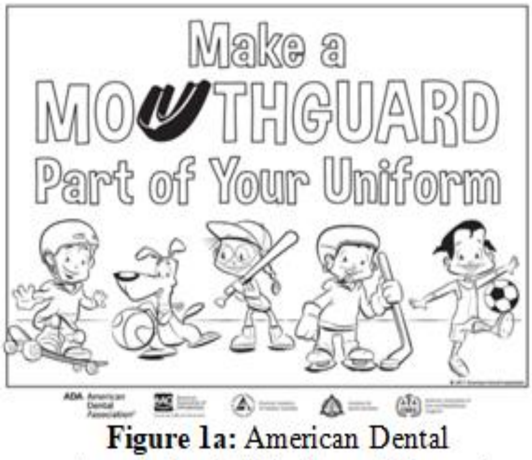

Figure 1a: American Dental Association's 'Mouthguard Poster'

Figure 1b: American Dental Association's 'Mouthguard Poster'

IV. ANATOMY OF DENTOFACIAL STRUCTURES

The dentofacial complex consists of various components like facial bones including the maxilla and mandible. The temporomandibular joint (TMJ) is a ginglymoarthrodial joint articulating the mandible to the skull. The surrounding muscles associated with the jaws and the facial region include the muscles of mastication and the muscles of facial expression. The oral cavity has two sets of teeth – deciduous/milk teeth and the permanent/succedaneous set of teeth. These teeth are arranged in the upper/maxillary arch and the lower/mandibular arch (Figures 2a and 2b). The types of teeth in the human dentition are the incisors, canines, premolars (absent in the deciduous dentition), and molars. Each tooth is embedded in an individual socket in the alveolar bone with the periodontal ligament interface between the tooth and the bone. The other supporting structures are gingiva and the cementum.

Figure 2a: Teeth in the oral cavity

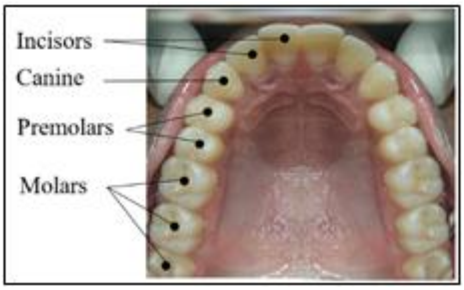

Figure 2b: Types permanent teeth

V. INJURIES DURING SPORTING EVENTS

Practicing sports and physical activities has positive physical, social, and psychological health benefits. Daily life activities, as well as sports/athletic activities, predispose an individual to injury due to trauma. Table 2 lists the common injuries to athletes during training and on-field sporting events.

Table 2: Common injuries during sporting events

1.	**General Injuries**	Concussion, contusion, lacerations, bruises, joint dislocations, bone fractures, sprains.
2.	**Dentofacial injuries**	Fractures of jaws and facial bones, TMJ fracture or dislocation, injury to teeth (avulsion, displacement, fracture), soft tissue lacerations (tongue, lip, cheeks, chin)

Consequences of Traumatic Dental Injuries: Dental trauma is defined as an impact injury to the teeth and the mouth arising from any activity of daily living. Approximately 1/3rd of injuries to the oral and craniofacial structures are caused due to sports accidents. Injuries during sporting events can cause damage to the brain, neck, facial bones, TMJ, as well as dentoalveolar structures (Figure 3). Dentoalveolar injuries may include injuries to teeth, oral and perioral soft tissues, and fractures of the upper and the lower jaws (the maxilla and the mandible respectively). Injuries to the teeth frequently result in subluxation of the tooth/ teeth, enamel-dentin fractures, followed by intrusion, extrusion, lateral luxation, concussion, or avulsion of the whole tooth/teeth. Individuals with protrusion of anterior teeth, mouth breathing, anterior open-bite, and Class II division 1 malocclusion have a greater chance of traumatic dental injuries. Individuals with inadequate lip coverage and increased overjet further predispose such individuals to the risk of trauma. The incidence of trauma occurring outdoors is more than the trauma occurring indoors.

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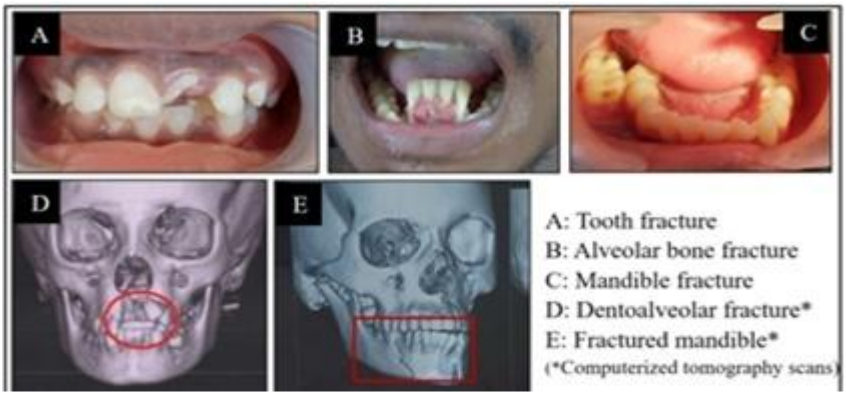

Figure 3: Consequences of Traumatic Dental Injuries

Long-term consequences of traumatic dental injuries range from tooth loss to necrosis of pulp and root resorption. Such injuries are often associated with poorer Oral Health-Related Quality of Life (OHRQoL). Treatment and rehabilitation of such complications can be both expensive to the individual and complex for the dental professional to perform. Traumatic dental injuries occurring early during childhood have a long-lasting and life-changing impact on the Quality of Life (QoL) of that individual due to the impact injuries sustained to the permanent teeth and the surrounding dentoalveolar structures and the jaw bones themselves.

Additionally, injuries to the TMJ complex can result in acute or chronic outcomes including fracture, dislocation of the joint (acute) or subluxation, displacement, dislocation, and ankylosis of the joint (chronic). Pain, crepitus, deviation of the mandible upon opening the mouth, difficult or reduced mouth opening, pain in the neck, and difficulty in chewing food may indicate injury to the TMJ. Such injuries hinder the performance of the athlete and burden his/her QoL. Chances of re-trauma are relatively high in individuals who have a history of traumatic dental injuries. There is an established close association between history and recurrence of trauma and therefore, a preventive plan for such athletes should be formulated which includes wearing a protective gear including a mouthguard. Table 3 enumerates the consequences of traumatic dental injuries among adult athletes and children. Athletes who regularly wear a mouthguard have a significantly reduced recovery time after a traumatic dental injury and are less prone for instance of re-trauma. According to the ADA, mouthguards have helped in preventing close to 2,00,000 injuries occurring in school and college football events alone.

Table 3: Consequences of traumatic dental injuries

1.	**Adult athletes**	Dentoalveolar structures do not have inherent healing capability. Traumatic dental injuries may potentially cause esthetic, functional, and psychological problems.
2.	**Children**	Traumatic dental injuries may change the pattern of the exfoliating primary teeth as well as the erupting permanent teeth. Such injuries can be the chief etiological factor for hypoplastic teeth or tooth-related facial abscesses.

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VI. MOUTHGUARDS

A mouthguard is an essential part of the personal protective equipment (PPE) used by a sportsperson/athlete. It is defined as a ‘resilient device or appliance placed inside the mouth to reduce oral injuries, particularly to teeth and the surrounding structures.’ Mouthguards are recommended by the American sports authorities to minimise the deleterious effects of traumatic dental injuries on both primary and permanent dentition.

1. **Need for a Mouthguard:** During a sporting event, the shielding equipment available to protect the head and neck region of the athlete includes a helmet, facemask, and mouthguard [Table 4]. A mouthguard is an intraoral device that is worn in the oral cavity on the upper teeth to reduce the impact of force to the teeth and other oral tissues in the event of an injury. There is a reported 1.6 to 1.9 times increased risk of dentofacial injury when not wearing a mouthguard as compared to when the athlete is wearing a mouthguard. Athletes who regularly wear a mouthguard have a significantly reduced recovery time after a traumatic dental injury and are less prone for instance of re-trauma. According to ADA, mouthguards have helped in preventing close to 2,00,000 injuries occurring in school and college football events alone.

Table 4: List of protective equipment used in sporting events

Device/equipment	Protection offered to
Eyewear (Goggles)	Eyes.
Gloves	Finger, wrists, palms.
Footwear and shoes	Toes, soles, feet, ankles.
Helmet, face grill, face shield	Skull, brain, eyes, ears.
Safety pads and guards	Shoulder, elbow, wrist, tail, hip, thigh, knee, elbow.
Mouthguards	Teeth, tongue, gums and surrounding structures.

The American Organisation for Prevention of Sports-Related Trauma reports a 10% chance of traumatic dental injuries among athletes involved in contact sports. Even when safety equipment is used, there is an 8% prevalence of sports-related dental injuries. Mouthguards and other personal protective gear lessen the effect of impact forces on teeth and the dento-alveolar structures by distributing the impact forces to the adjacent structures and providing a cushioning effect to the TMJ and the surrounding structures.

Using a mouthguard will safeguard the athletes’ teeth and other intraoral structures. As sports, outdoor activities, contact sports, and playground events increase the risk of traumatic dental injuries, sports kits should include a mouthguard as protective gear. Parents and coaches should be educated about the advantage of using a mouthguard and they in turn must encourage athletes to wear a mouthguard. Evidence suggests that splinting devices like mouthguards, dental braces, and composite resin splints enhance the repairing conditions of injured teeth.

The American Academy of Pediatric Dentistry (AAPD), ADA and ASD (Academy for Sports Dentistry) recommend wearing an adequately fitted mouthguard when an athlete is engaging in sports or sports-related activities. Player-to-player contact sports/ sports-related activities require a mouthguard to prevent traumatic dental injuries while player-to-apparatus contact sports / sports-related activities mandate a mouthguard along with safe-guarding or padding of the apparatus used. Table 5 lists the ideal requisites for an athletic mouthguard.

Table 5: Ideal requisites of a mouthguard

Biocompatibility	Be non-toxic and non-irritant to oral tissues
Fit to size	Fit properly to accommodate all teeth and closely adapt to the oral tissues
Retention	Be well retained in the mouth without clenching the teeth
Functions	Allow free breathing and not interfere with speech.
Coverage	Adequately cover incisal edges of anterior teeth and the occlusal surfaces of posterior teeth
Extension	Provide adequate coverage to all teeth of the upper arch (maxilla) up to the second permanent molar or to the posterior-most tooth erupted into the oral cavity
Thickness	Maintain adequate thickness to reduce stress on teeth and minimise the risk of injury during impact
Occlusion	Provide a balanced occlusion and not disrupt tooth position
Maintenance	Be easy to clean and maintain

2. Properties of a Mouthguard

The properties of a mouthguard depend upon the following:

- Material used for its fabrication [Table 6].
- Thickness: A thicker mouthguard better safeguards the intraoral structures than a thinner one. However, a very bulky mouthguard has the chance of increasing the pressure difference between the intraoral and the extraoral regions causing difficulty in functioning (breathing and speech) and discomfort to the athlete. A mouthguard with an optimal thickness of 4 mm on the labial and the buccal surfaces achieves optimal shock absorption. A minimal thickness of at least 3mm should be maintained.
- Shape: A properly shaped mouthguard provides acceptable protection without disproportionate thickness.
- Inclusion of air cells within the structure of the mouthguard.
- Areas covered within the oral cavity: ASTM F697 (American Society of Testing and Materials) provides guidelines regarding the intraoral areas to be covered by a mouthguard, but does not specify the optimal thickness needed.

Table 6: Requisites of materials suitable for fabricating a mouthguard

1.	Biocompatibility
2.	Flexibility
3.	Low fluid absorption
4.	Lower hardness – for ease of use

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5.	High damping capacity (ability to dissipate elastic strain during impact)
6.	Lower resistance to physiological forces of oral and peri-oral musculature
7.	Ability to reduce transmission of forces to surrounding structures

3. **Classification of Mouthguards:** In 2013, the ADA Standards on Dental Care Products Specification No.99, classified mouthguard into three types:
   - Type 1 – Stock
   - Type 2 – Mouth-formed
     - Class 1 – Thermoplastic/boil and bite
     - Class 2 – Shell-liner mouthguards
   - Type 3 – Custom
     - Class – Vacuum-formed
     - Class 2 – Model-formed

Type 1 or Stock mouthguards: Stock mouthguards are preformed, ready to wear, available as over-the-counter (OTC) devices, and come in predetermined shapes and sizes. They are U-shaped with a central groove that houses the teeth (Figure 4). This device helps in covering the dentition but does not specifically adapt closely to an athlete's individual jaw and tooth morphology. Clenching the teeth helps in holding the device in the mouth as the device itself does not have an inherent retentive feature. Because the size and shape are predetermined, the size and fitting cannot be altered which may cause discomfort and irritation to the sensitive orofacial tissues. They can be used as protective gear to prevent traumatic dental injury but are less effective and less protective.

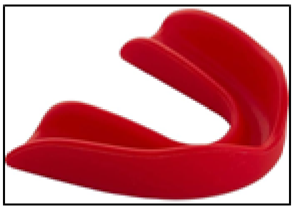

Figure 4: Stock mouthguard

Type 2 or Mouth-formed mouthguards:

Class 1: Thermoplastic or boil-and-bite mouthguards: These are available as thermoplastic material of a predetermined shape (Figure 5). The material is adapted to the teeth by immersing it in boiling water for about 10 to 45 seconds. It is then transferred to cold water and placed in the oral cavity to be molded onto the teeth (Figure 6). Such heat softening allows for some amount of adaptation to the morphology of an individual athlete's jaws and teeth and therefore, this 'Boil-and-bite' type of mouthguard offers better fit and retention compared to the 'Stock mouthguard'. Though 90% of athletes use this type of mouthguard, there are a few disadvantages:

Figure 5: Mouth-formed mouthguards

- Poor fit and stability.
- Interference with normal ventilation.
- Variable thickness during fabrication.
- Thinning out when stretched and molded under increased temperature.
- Different materials have different ranges of temperature for adequate manipulation and adaption in mouth.

Class 2: Shell liner mouthguards: A pre-formed mouthguard that has a silicone rubber or a plastic/acrylic liner. This liner is adapted to the individual athlete's oral cavity. The soft liner can become hardened due to repeated cycles of biting. This type of mouthguard may also cause discomfort due to increased vertical dimension, bulkiness, and reduced retention within the mouth.

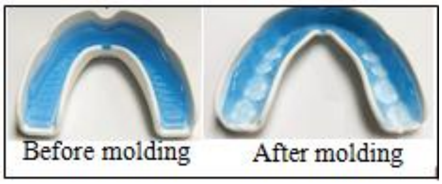

Figure 6: Boil-and-bite mouthguards

Figure 7: Custom mouthguard

Type 3 or Custom-made mouthguards:

Table 7: Advantages and disadvantages of custom-made mouthguards compared to stock mouthguards

Advantages	Disadvantages
Accurate adaptation of the mouthguard to teeth and the surrounding oral tissues.	Cost of fabrication and require visiting a dental personnel
Adequate coverage and thickness with vestibular extensions enhance protection and stability.	A dental appointment is needed for fabrication and further replacements.*
Reduce muscular activity in peri-oral musculature compared to stock mouthguards – helps in energy preservation and lessens muscle fatigue	Thin out unevenly at some areas when the thermoplastic sheet is stretched and moulded under increased pressure
Lesser hindrance to breathing and speech	Time taking
Customisable for patients with orthodontic braces	Need replacement due to wear and tear
*Alternatively, Do It Yourself (DIY) kits are also available commercially. But, they require a meticulous impression of the individual's teeth, etc., which needs skill and training.	

These are the mouthguards that suit each athlete based on their individual jaw structure, tooth morphology and position. They are fabricated by dental personnel using the model of the teeth and jaws of each individual athlete. The dentition is replicated into a model and a mouthguard is fabricated that adapts accurately to the teeth and the surrounding oral and perioral tissues. Mouthguards need to be changed every year in younger due to physiological changes occurring during growth and development. Table 7 lists the advantages and disadvantages of custom-made mouthguards over stock mouthguards.

Stock mouthguards v/s Custom-made mouthguards: Stock mouthguards are associated with reduced auditory switch-response reaction time, visual reaction time, sprint time and vertical jump height. This may cause mild deteriorations to the performance of athletes. Customised mouthguards do not have such undesirable affects and hence, the Academy for Sports Dentistry (ASD) recommends utilisation of a properly fitted mouthguard.

There are two types of custom-made mouthguards [Table 8]:
- Vacuum-formed mouthguards
- Pressure-laminated mouthguards.

Table 8: Comparison of common methods of fabricating a custom-made mouthguard

Vacuum-formed mouthguard	Property	Pressure-laminated mouthguard
A thermoplastic material is adapted onto a model under vacuum	Method used for fabrication	Compressed air is used to adapt a plastic material onto the model.
Uneven due to uneven vacuum & heat	Thickness	Even thickness, better retention
Offers sufficient protection	Protection offered	Best protection due to near-perfect adaptation
Most widely used method, simple and cost-effective.	Ease of fabrication	More time taking than the vacuum method.
Shape distortion	Long-term use	Negligible deformation
Minimal interference to functions (breathing and speech)	Others	Provide balanced occlusion.

4. **Fabrication of a Custom-Made Mouthguard:** Custom mouthguards shield the stomatognathic system from the impact forces during a traumatic dental injury. They provide uniform distribution of occlusal forces which reduces the chances of injury to the muscles of mastication. A dentist or a dental personnel fabricates and fits a custom-made mouthguard. These custom-made mouthguards can be prepared from various materials like plasticized acrylic resin, vacuum-formed plastic sheets, latex or reinforced latex. The current gold standard for the fabrication of protective mouthguards is Polyethylene vinyl acetate (EVA) vacuum-formed mouthguards.

   - **Design for mouthguard fabrication:** A well-fitted mouthguard provides the best protection when worn on the most exposed teeth or the most commonly injured dentofacial structures.

     Jaw: Mouthguards are commonly worn in the upper/maxillary arch. In individuals with a Class III molar relationship, it can be worn in the lower/mandibular arch also.

Extensions:

- **Anteriorly:** Should be at a height of 20 mm at the central incisors with an inclination of 30^0 to 45^0.
- **Posteriorly:** Should be at a height of 15 mm at the first permanent molar region and should cover the distalmost molar at the posterior end.
- **Palatally**: Should extend 6 to 10 mm

Temperature: A temperature of 120^0C is used to mold EVA materials.
Thickness: The mouthguard should not inhibit lip closure and a thickness of 4 mm is considered to provide adequate protection. Though a thicker mouthguard offers better impact resistance, the increased bulk causes discomfort.

Requirements for achieving optimal thickness during vacuum forming method are:

- The position of the model should be centered on the platform in the vacuum former with minimal distance between the model and the material frame.
- Angulating the model.
- Adequate manipulation of the laminated sheet.
- A few modifications suggested to achieve better results include placing a central groove in the laminate sheet, using two laminate sheets, notching the laminate sheet, and using frames of different shapes to hold the laminate sheet.

- **Modifications of a mouthguard design and model**
  - **Contact sports:** Close contact sports like rugby and boxing require protection against the possibility of jaw fractures. In such situations, a bimaxillary mouthguard provides stability for both the maxilla and the mandible thereby protecting them from any possible fractures.
  - **Scuba divers:** Scuba divers wear protective gear that /involves a mouthpiece head in the oral cavity. This mouthpiece postures the mandible in a forward position leading to an imbalance in the loading of forces on the TMJ and the masticatory muscles. Combined with the lack of occlusal support in the posterior region, inflammation of the TMJ can block the eustachian tube and cause labyrinthine dysfunction resulting in disorientation and vertigo. This is labelled as ‘Diver’s Mouth Syndrome’. Since the protective gear is exposed to water for prolonged periods of time, a water-resistant material should be used to fabricate the mouthguards in divers.
  - **Edentulous patients:** A modified bimaxillary mouthguard gives better protection in a completely edentulous patient.
  - **Sleep apnea and bruxism:** Mouthguards are also used to counter the deleterious effects of sleep apnea and bruxism on the TMJ complex.

5. **Effects on a mouthguard in the Oral Environment:** Mouthguards are placed in the oral cavity where the environment is constantly moist with temperatures up to 55^0C. Under such conditions, the physical load on the mouthguard by the teeth increases the levels of CO_2 in the bloodstream and reduces the pH. Furthermore, deformation occurs at lower stress levels when the oral cavity reaches the glass transition temperature (Tg) of the mouthguard's material. Wear and tear in the oral environment may lead to

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changes/deterioration in the properties of the mouthguard like energy dissipation, hardness, stiffness, resistance, tear strength, tensile strength, and water absorption. Over a period of time, the surface of the mouthguard also undergoes deterioration increasing its vulnerability to microbial colonisation on the surface.

6. **Maintaining cleanliness of a mouthguard:** The oral cavity harbors millions of microbes in its various niches and a mouthguard provides an additional surface for the microbial flora to colonize. It can become a source of contamination and an origin for disease transmission. Microbes like S. mutans, S. sobrinus, L. acidophilus, and L. casei have been found on the surface of a mouthguard.

   Long-term use causes the surface of a mouthguard to become rough due to functional friction (during usage in the oral cavity) and mechanical abrasion (due to cleaning and brushing). This increased surface roughness increases the chances of microbial contamination. Additionally, the porous structural design of the mouthguard favours harbouring of microorganisms. A spray of 0.12% chlorhexidine reduces the microbes on the surface of a mouthguard. Disinfectant solutions like sodium hypochlorite or chlorhexidine do not alter the surface roughness of a mouthguard. The durability of a mouthguard can be enhanced by maintaining its hygiene and storing it appropriately in a ventilated and dry container/space.

7. **Evaluating the properties of a mouthguard:** There are several testing methods to evaluate the various properties of a mouthguard. Testing for resistance and resilience can be done using a ‘drop tower test’, or a ‘Pendulum test’. However, these methods cannot accurately reproduce dentoalveolar tissue compliance and there has been no standardized test available to date. A few other testing methods include in-vitro impact tests and in-vivo drop tower tests. Custom testing methods using models of human heads and the oral environment have also been suggested.

8. **Replacing a mouthguard**

   - **In children:** Mouthguards need to be changed every year in children due to physiological changes occurring during growth and development.
   - **In adults:** The properties of a mouthguard deteriorate after some time. Replacement is required after every 2 to 3 years of use. The main changes occurring in the material used to fabricate a mouthguard are physical distortion, general wear-and-tear, changes in retention and fitting and also changes in resilience.

9. **Concerns among athletes regarding using mouthguards:** Despite the several advantages of using a mouthguard, many athletes do not choose to use it. Some of the concerns among athletes regarding the usage of a mouthguard are:
   - Irritation to the soft tissues leading to hyperkeratosis, erythema or ulceration
   - Surface microbial colonization due to improper disinfection may result in asthma or other allergic reactions.
   - Discomfort and forgetfulness have also been cited as reasons by some athletes.

10. **Reporting of traumatic dental injuries:** An Athletic Exposure (AE) is defined as ‘Athlete participating in one practice, competition, or performance where he or she can be

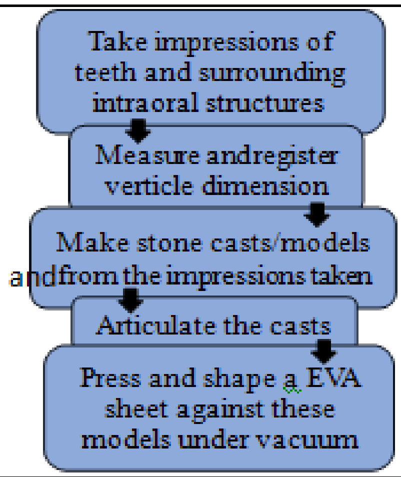
exposed to the possibility of athletic injury.' Sports and sports-related activities have various modes like practice and training sessions, as well as field events and competitions. Among these, competitions are the commonest mode where traumatic dental injuries occur with player-to-player contact or player-to-apparatus contact being the frequent reason. Though such organized sporting events are one of the prime reasons for traumatic dental injuries, very few of them are reported. For example, out of the 50 million athletic exposures, only a meagre 459 traumatic dental injuries were reported. The reason for such under-reporting could be:

- Personnel are not adequately trained to identify/diagnose such injuries
- Minor injuries may be neglected when multiple injuries occur
- No clear instructions as to whom to report the injuries to.

Unfortunately, not reporting sports injuries due to any issue results in disadvantages like:

- The ignored collective result of repeated uneventful impacts.
- Cumulative damage from repeated exposure to such uneventful impacts may result in progressive and permanent neurological damage.

Therefore, it is of vital importance to educate parents, coaches, trainers as well as athletes not only regarding the use of properly fitted standard mouthguards but also about reporting any injuries occurring during the training sessions or on-field events, however minor in nature.

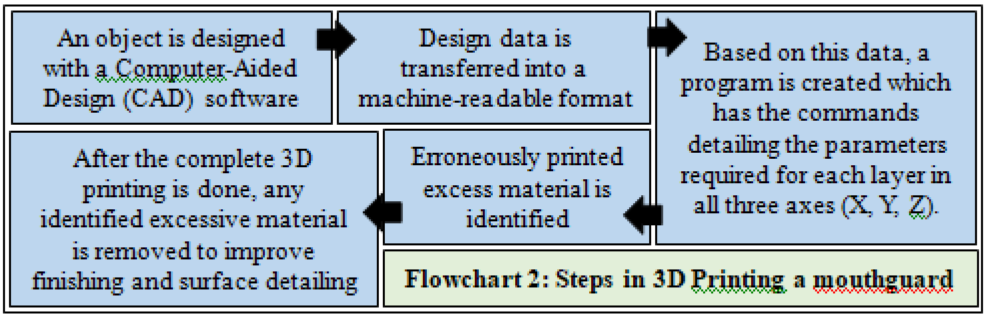


Flowchart 1: Steps in fabricating a mouthguard by vacuummethod

VII. RECENT ADVANCEMENTS

The current gold standard for the fabrication of protective mouthguards (EVA vacuum-formed method), has a few shortcomings [Table 7]. Consequently, several modifications and additions to the existing mouthguard fabrication methods and materials are being researched and tested to enhance the usefulness of a mouthguard. Conventionally, to fabricate a custom-made mouthguard, an impression is taken to create models of teeth and the surrounding structures. A sheet of EVA is then pressed against these stone or plaster models which are then shaped under vacuum in a vacuum-forming machine [Flowchart 1]. The materials and the methods of fabricating a mouthguard have seen several recent modifications and developments.

1. **3D printing:** Three-dimensional printing was first introduced in the late 1980s. It is also known as additive manufacturing and involves the construction of solid three-dimensional objects. A computer-aided design (CAD) or a digital model is used as a reference to lay down successive layers of a thermoplastic material to create a complete geometrically complex object of various shapes, sizes, and textures (Flowchart 2). Several methods are used to form the layer-by-layer structure. This 3D printing technology can be used to print mouthguards with materials like polyvinyl siloxane and rubber-like polymers. The disadvantages encountered during the vacuum-formed or pressure-laminate methods are overcome in 3D printing method by providing controlled fabrication, and accurate detailing of internal features (resulting in enhanced retention and performance). Though the procedure is slower than other methods of manufacturing solid objects like casting and molding, it enables the construction of high-precision complex shapes with detailed spatial composition. Furthermore, a variety of materials like polymers, ceramics, metals and biological inks (materials containing materials mixed with live cells) can be used for fabrication.



Flowchart 2: Steps in 3D Printing a mouthguard

- **Classification of 3D printing techniques:** The American Society for Testing and Materials International Committee categorizes 3D printing techniques into seven different categories based on the basic principle of the process:
  - Binder jetting
  - Directed energy deposition
  - Material extrusion
  - Material jetting
  - Powder bed fusion
  - Sheet lamination
  - Vat photopolymerization

- **Materials used for 3D printing of mouthguards:**
  - EVA – Polyethylene vinyl acetate.
  - Other suggested materials include:
    - Thermoplastic copolyesters.
    - Polystyrene.
    - Polylactic acid.
    - Polyurethane.
    - Polymethyl methacrylate.
    - Proprietary polymers.

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- Polyetherketone (PEEK) – used in the subtractive method.

- **Techniques in 3D printing:**
  - Polyjet technique: Liquid photopolymers are jetted onto a printer bed and cured (Figure 8).
  - Drop-on-demand technique: Droplets of a thermoplastic material are selectively deposited and cured on a plate to fabricate a layer-by-layer construct. The material is plasticized either by heating or by the piezoelectric method (Figure 9).

Using these two techniques, several methods are employed for printing mouthguards:

- Double nozzle 3D printing
- Fused filament printing – cheaper and faster method. However, the finished product has an uneven surface with high porosity which can potentially increase the chances of surface microbial contamination.
- CAD/CAM by subtraction method using polyetheretherketone (PEEK). The subtractive method involves creating an object by removing material from a solid shape.
- 3D printing using photopolymerizable composite.
- 3D printing using stereolithography (SLA) gives a smooth surface and accurate details. Laser scanning is used to fabricate the components layer-by-layer with light-curable photopolymer resin. This method has the advantage of having the ability to fabricate objects in high resolution and construct intricate shapes that incorporate undercuts. Additionally, no complex preparation of the material is needed and no post-treatment of the appliances after printing is required. Some of the disadvantages include slower processing due to the use of liquid resin.

2. **Inclusion of air/air cells:** The mouthguards are conventionally solid in structure. Incorporating air/air cells, or pockets into their design will reduce the effect of impacted forces. The performance of 3D-printed mouthguards with air cell structures was better than conventional EVA and solid 3D-printed models. Under experimental conditions, a one millimetre thick EVA sheet incorporating 3x3x2 mm air cells in between three EVA sheets provided the highest reduction in the impact force. So, including such air/air cells can potentially aid in dissipating the impact energy encountered by an athlete during a traumatic dental injury.

3. **Performance tracking:** Since the mouthguards are placed in the oral cavity in close vicinity of the skull and its internal structures, they can be employed to monitor several parameters. A small cavity within the structure of the mouthguard can be used to incorporate smart technology components which will not add any extra, unwanted bulk to the mouthguard. Such wearable technology incorporated into the structure of a mouthguard can help in monitoring cardiac activity, rate of respiration and other vital parameters. It can also aid in Global Positioning System (GPS) navigation.

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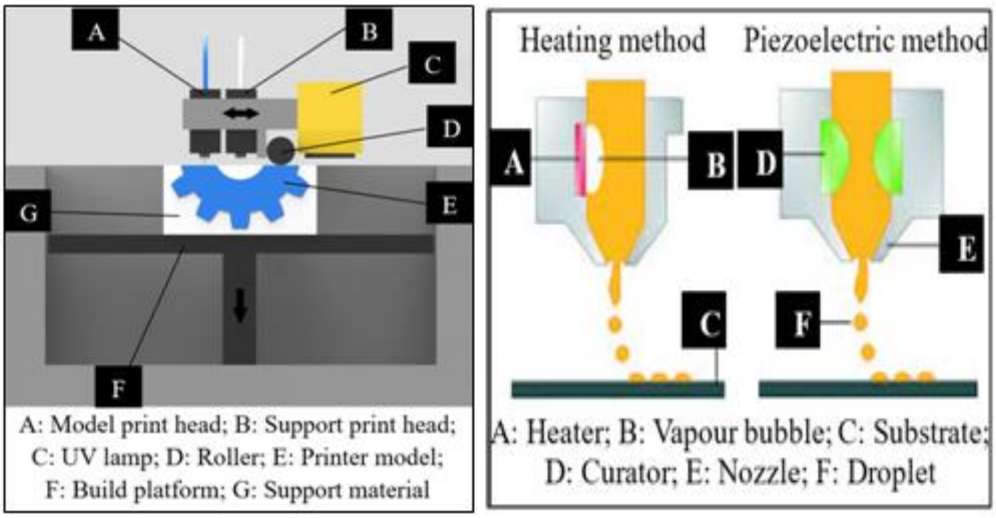


Figure 8: A model of polyjet printing

4. **Instrumented Mouthguards (IMGS):** During sporting events, a direct impact to the head may result in Head Accelerated Events (HAEs). Such events can be monitored by iMGs that are equipped with sensors to measure the blow impact. This provides information about concussions and injuries occurring during sports and sports-related events. Live as well as retrospective monitoring of HAEs can enhance preventive and clinical care given to athletes. Additionally, cumulative data from all the HAEs of an athlete (practice sessions, on-field events, etc) can be used to map the long-term brain health of athletes. Players that need assessment for such impact injuries can be identified to detect concussion, monitor contact load and return-time to practice sessions. The real-time data provided by such devices allows trainers and coaches to formulate personalized training sessions and game strategies for each individual player in order to improve and maintain player welfare and safety.

5. **4D printing:** Following long-term use, 3D printed mouthguards tend to show wear-and-tear and deterioration due to occlusal forces. The resulting structural alterations over time lead to loss of retention, reduced biocompatibility, and a need for re-fabrication. To overcome these problems, 4D printing has been employed for constructing a mouthguard. 4D printing is similar to 3D printing technology with the addition of the fourth dimension of ‘time’. This method uses a shape memory polymer (SMP) with a shape memory effect (SME) to create an object that recovers its predefined shape over time as a result of its response to external stimuli such as temperature, humidity, and pH. The normal intraoral temperature is up to 55^{0}C. So, materials like thermoplastic shape-memory polyurethane elastomer (TPU) and thermoplastic elastomers that have an inherent glass transition temperature (Tg) closely matching the intraoral temperature are used for constructing 4D-printed mouthguards. Such SMP materials cause minimal discomfort to the user.

   - **Advantages of 4D Printed Mouthguards**: Following are the advantages of 4D printed mouthguards as compared to 3D printed mouthguards:
     - The material used in 4D printing is an SMP composite TPU filament which offers better fitting and accuracy with minimal deformation under occlusal forces and stresses during insertion and removal of the mouthguard into the oral cavity.

- The 4D printed mouthguard consists of two layers. The softer outer layer provides shock absorbance while the harder inner layer prevents deformation and deterioration under occlusal forces thus providing better functioning capability.
- Since the tooth morphology is not linear in nature, all the intraoral undercut areas between the individual teeth and between the teeth and the alveolar mucosa and bone need to be closed or blocked in the CAD software for conventional 3D printing method to ease the insertion and removal of a mouthguard. This step is eliminated and all the intraoral undercuts need not be closed in 4D printing as the edges of the materials used easily accommodate around the intraoral structures with minimal discomfort.

6. **FDM Processing**:

Table 9: Materials used in FDM technique
ABS – Polyacrylonitrile-butadiene-styrene
ASA – Polyacrylonitrile-styrene-acrylate
HIPS – High impact polystyrene
Nylon
PC – Polycarbonate
PET-G – Polyethylene terephthalate glycol-modified
PMMA – Polymethyl methacrylate
PLA – Polylactic acid
Polypropylene
PVA – Polyvinyl alcohol
TPU – Thermoplastic polyurethane

This is the fused deposition modelling (FDM) invented and patented by Scott Crump in 1989. It is also called as ‘fused filament fabrication’ (FFF) and uses filaments of thermoplastic polymers pushed through a hot nozzle onto a building plate. The polymer melts and gets deposited layer-by-layer on the vertically moving building plate. Molecular bonding is enabled by the heat. This results in the fabrication of a single uniform plastic device (Figure 10). Several novel materials can be used for the fabrication of mouthguards using the FDM technique. (Table 9). The FDM technique has been used to print wearable medical devices including mouthguards.

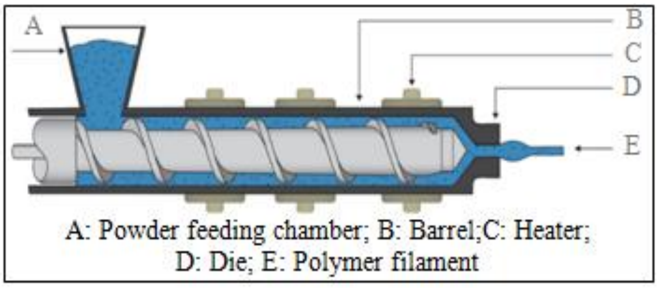
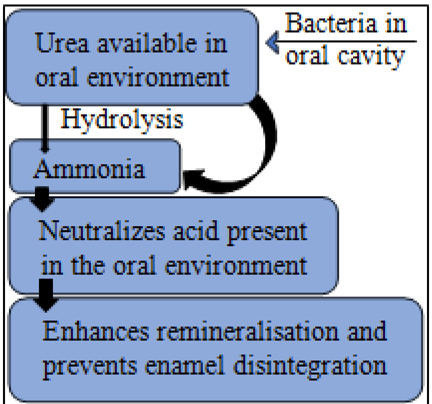


Figure 11: Hot melt extrusion.

7. **Drug-eluting Mouthguards:** Pharmaceutical grade materials can be used in 3D printing to fabricate objects that can be used for personalised drug delivery/therapy. These devices

can be fabricated without using toxic organic solvents, and without post-fabrication processing. They are suitable for clinical use and reduce potential health risks. The filaments needed for this process are manufactured by the hot melt extrusion (HME) method where powder form of the material is fed from a container (hopper) onto a rotating screw. This screw carries the powder material along a hot barrel towards a circular die and a homogenous filament is extruded from the barrel (Figure 11). To incorporate a pharmaceutical agent into the filament, a double screw extruder is used.

Dental caries is the most common oral health problem. Several therapeutic agents have been used to prevent and reduce the progression of caries in teeth. Mouthguards incorporating filaments of polymers poly ethyl-caprolactone and polyvinyl alcohol or polyethylene glycol (PCL-PEG) combined with sodium fluoride have been tested to generate composite filaments. This material demonstrated tunable release of fluoride along with other mechanical properties suitable for dental intraoral use. Ex-vivo studies using decayed human teeth showed reduced demineralization of enamel when fluoride-infused 3D-printed caps were placed on such teeth. An increased fluoride content was noted in the lesions covered by these devices as compared to decayed teeth that were not covered by such devices.



Flowchart 3: Enamel remineralization and urea

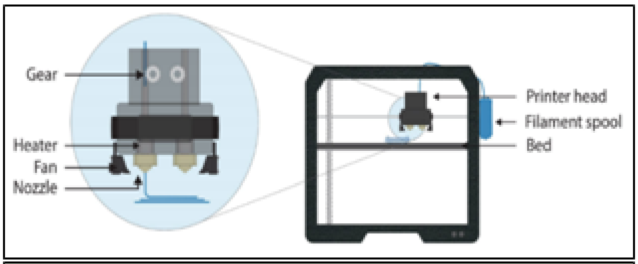


Figure 10: Fused deposition modeling (FDM) 3D printer model

Similarly, urea is another compound that can be utilised to protect teeth from the hyper-acidic environment created by the acid-producing, carbohydrate (from the food particles) processing bacteria. Under in vitro conditions, urea released from 3D printed filament models of tooth caps has shown the ability to reduce the carbohydrate induced pH drop seen in the presence of S. salivarius. Flowchart 3 shows the process by which urea can enhance tooth remineralisation and prevent further tooth decay.

8. **Testing the Properties of a Mouthguard:** With the advent of newer materials and methods for the fabrication of mouthguards, there are many recent developments in testing the properties of a mouthguard. Conventionally, 'shock absorption capacity' is measured by pendulum or the dropped weight method that impacts the materials directly, 'impact force damping' is calibrated by Charpy impact hammer and 'compressive and tensile strength' are measured by the force required to completely rupture the material. In addition to these, the recent methods in stress absorption tests include:

- Fiber Bragg grating strain sensor
- Strain gauge sensors
- Film sensors
- Laser triangulation sensors
- Solid-state NMR pulse measurement
- Laser Doppler vibrometers
- 3D image correlation strain analysis
- Thermal analysis – simulates intraoral temperatures to analyse the properties of materials.
- Finite element analysis (FEA) – 2D FEA can analyse planar stress and strain. 3D FEA can analyse stress dissipation and biomechanical responses.

VIII. FURTHER RECOMMENDATIONS

With advancement in materials happening by leaps and bounds in the past few decades, there are several areas in which the mouthguards can see modifications and additions to the existing models and method of fabrication.

- **Modifications to materials (EVA)**: Since the current gold standard for fabrication of a mouthguard is EVA under vacuum-formed method, several additions to this material are being considered to improve the various properties and functions of a mouthguard:
  - ➢ Adding silver nanoparticles to EVA renders antibacterial properties.
  - ➢ Addition of porous rubber, silicon nylon mesh, silicone interlayers, and urethane improves shock absorbance.
  - ➢ Inclusion of air cells alone within the structure of the mouthguard, inclusion of air cells in combination with closed cell foam, hard material inserts or 'honeycomb' internal mesh, and A-silicone interlayers enhances properties like shock absorbance capacity and durability.
  - ➢ Adding microstructure polystyrene-polyolefin copolymer-based materials to EVA improves performance when compared to EVA alone.
  - ➢ Adding 'Click' polymer systems that are modified with acrylate and urethane to EVA increases flexibility.
  - ➢ Adding polyolefin copolymer-based materials to EVA gives reduced water absorption and higher impact resistance than EVA alone.

- **Therapeutic agent infusion**: Sustained tuned release of fluoride incorporated into a mouthguard can combat dental caries. In vitro experiments with tooth caps of PCL or

PEG composite matrix have shown to release fluoride consistently for more than a month. Similarly, fluoride can be incorporated into the 3D printed mouthguards which can be released in a sustained and tuned fashion over a longer period of time to enhance chances of remineralisation in decayed hard tooth structure. Furthermore, other therapeutic and desensitizing agents can also be infused into mouthguards for such targeted sustained release and their efficacy can be tested in vivo conditions.

- **Sensors**: Sensors adapted into the structure of a mouthguard can provide real-time data about the impact force. They may also be used to monitor the complete system of an athlete including all the vital circulatory and respiratory status in real-time.

- **Data collection and reporting:** Homogenous data regarding the various aspects of the usefulness of mouthguards in sports is lacking due to:
  - Data from various types of sports – each sport has a different set of rules, patterns, and arenas. So the data regarding the various types of scenarios, events, and training sessions cannot be generalized or set into one particular list.
  - Data from various types of mouthguards – There are many types of mouthguards available from custom made to stock varieties. Among these, there are several disparities in the material used, method of fabrication, colour, thickness, etc,. So, standardization is challenging.
  - Data regarding the time duration to wear a mouthguard is not available.
  - Challenges and difficulties in testing such a wide range of mouthguards are not available under in vivo conditions to date.

2. **Standardized Protocol:** Currently there is no existing standardized protocol for fabrication, usage, time period of intraoral placement, etc.

3. **Property Testing:** There are several parameters of a mouthguard yet to be tested and evaluated in real-time under in vivo conditions like retention, hardness, intraoral stability, water absorption, dimensional changes due to loading masticatory forces upon clenching, time dependent wear-and-tear. Additionally, changes in the oral and peri-oral muscles, affects on physiological functioning (breathing and speech), colour, adaptability and efficiency of different materials also needs to be assessed.

IX. SUMMARY

Using a mouthguard during sports and sports-related events lowers the incidence of traumatic dental injuries. Athletes who use a mouthguard are less likely to sustain injuries as compared to those who do not. Thermoplastic mouthguards undergo lesser dimensional changes compared to other materials. Custom fabricated mouthguards provide better fit and comfort, are less likely to affect speech, and do not tend to become loose intra-orally as compared to stock mouthguards. Lack of knowledge among athletes and sports coaches about the close correlation between traumatic dental injuries and the use of a mouthguard could be the reason for the limited use of a mouthguard. With the latest technological developments in the field of materials and the fast-paced progress in artificial intelligence, individualised mouthguards with mechanical and therapeutic benefits may soon be fabricated. These personalised wearable intraoral devices will afford protection during sports and provide vital information if an unfortunate traumatic dental injury should occur.

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ANNEXURES ABBREVIATIONS

0-9
3D – Three-dimensional
4D – Four-dimensional

A
AAPD – American Academy of Pediatric Dentistry
ABS – (Poly) acrylonitrile-butadiene-styrene
ADA – American Dental Association
AE – Athletic Exposure
ASA – (Poly) acrylonitrile-styrene-acrylate
ASD – Academy for Sports Dentistry
ASTM – American Society of Testing and Materials

C
CAD – Computer-aided Design
CAD/CAM – Computer-aided Design and Computer-aided Manufacturing

D
DIY – Do-It-Yourself
E
EVA - Polyethylene vinyl acetate

F
FDM – Fused Deposition Modelling
FEA – Finite Element Analysis
FFF – Fused Filament Fabrication

H
HAE – Head Accelerated Event
HIPS – High Impact PolyStyrene
HME – Hot Metal Extrusion

I
IASD – International Association of Sports Dentistry

iMGs – instrumented mouthguards

O
OHRQoL – Oral Health-Related Quality of Life
OTC – Over-The-Counter

P
PC – Polycarbonate
PCL-PEG – Poly(ε-caprolactone)-poly(ethylene glycol)
PEEK – Polyetherketone
PET-G – Polyethylene terephthalate glycol-modified
PLA – Polylactic acid
PMMA – Polymethyl methacrylate
PPE – Personal Protective Equipment
PVA – Polyvinyl alcohol

Q
QoL – Quality of Life

S
SLA – Stereolithography
SME – Shape Memory Effect
SMP – Shape Memory Polymer

T
Tg – Glass transition temperature
TMJ – Temporomandibular Joint
TPU – Thermoplastic PolyUrethane

W
WHO – World Health Organisation

LEGENDS OF TABLE, FIGURES AND FLOWCHARTS

Tables:

Figures:

Flowcharts: