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Evaluation of Laminated Structures for Sports Mouthguards

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Abstract. Most of the past studies have concentrated on the properties of mouthguard materials rather than their ability to protect the underlying substructure. Previous work has indicated that the incorporation of a shock absorbing layer into the sports mouthguard reduces the likelihood of injury to the head, neck and oral cavity of the wearer. The purpose of this study is to develop an optimum laminated structure that protects an easily deformable structure during an impact.

Dropweight impact tests were conducted on a series of moulded samples which were circularly clamped and force-time and displacement-time plots obtained. Single thickness specimens of ethylene vinyl acetate (EVA), 1-5mm thick were compared with laminated structures of EVA, incorporating 1mm thick layers of polymethylmethacrylate (PMMA) and a silicone or synthetic rubber up to a thickness of 5mm. It was observed that the multi-layered structures exhibited less deformation thereby transmitting less of the harmful effects through the laminate. It was concluded that laminated systems for mouthguards using different materials appear to offer better protection to the wearer.

Introduction

Mouthguards have been worn by sportsmen since the turn of the century, in one form or another. The English boxer Ted 'Kid' Lewis, in 1913, began using a 'mouthguard' made from a piece of natural rubber that had been trimmed and hollowed out so that it would fit over the maxillary dentition, he wore it to prevent chipped or broken teeth resulting from blows to the head. It was not adapted to the teeth and so retention was very poor, the jaw had to be clenched to hold the mouthguard in place making it difficult for the wearer to breathe [1,2]. Despite its rather obvious drawbacks other professional boxers and officials in the sport tried to prevent him from wearing the mouthguard as it was thought that it gave him an unfair advantage by preventing injury so he would not have to retire early from a fight. Remarkably this kind of 'unfitted' mouthguard can still be bought today, although the materials have changed - ethylene vinyl acetate being substituted for rubber. Most sports shops sell them and, surprisingly, are sometimes recommended to sportsmen and women by their dentist. This type of mouthguard offers a very low level of protection to the wearer, it also has the added danger of the possibility that it may become dislodged and obstruct the air passage causing asphyxiation. Sportsmen should be actively discouraged from wearing such a mouthguard [3].

There are three types of mouthguard that are generally available today:

i) Stock mouthguards - which come in differing sizes and are ready to use, mostly these types are made from either polyvinyl chloride (although the use of PVC for mouthguards has now been outlawed by the E.U.), polyurethane or a co-polymer of vinyl acetate or ethylene. Generally stock mouthguards are thought to be the least favourable as they offer the least protection and may even be thought of as dangerous as they may give a rugby player, for example, a false sense of security [4].

ii) Mouth-formed – known as a 'boil and bite' type, where a thermoplastic rim is heated in hot water then placed in the mouth and moulded by biting and sucking.

iii) Custom-made - this type of mouthguard is made in a dental laboratory on a cast taken from an impression supplied by a dentist. A thermoplastic material is heated in a pressure or vacuum forming machine and when soft enough it is placed over the cast and air pressure or a vacuum is applied which closely adapts the soft material to the cast.
Of the types listed it is generally thought that the custom-made mouthguards are the best and offer the most protection [5].

During the 1950's and 1960's in America mouthguard technology went through a period of rapid development. At this time many field studies were carried out and materials testing was undertaken. From this research it was decided that the mouthguard should be worn on the upper (maxillary) teeth as they were the most prone to damage. It was around this time that mouth-formed and custom-made mouthguards were developed, the early studies that were carried out did not seem to agree as to which type of mouthguard was the best. However, surveys of player opinion did report that the custom made mouthguard was the best option with regard to retention, cleanliness, ease of speech, lack of odour, taste and durability [6].

The cost of the custom made mouthguard was and still can be somewhat prohibitive, which may deter many people from wearing such a mouthguard, regardless of the fact that nearly all the literature recommends that custom made mouthguards are the most effective type of protection.

Material properties

Ideally a mouthguard material should be odourless, tasteless, non-toxic, have good resistance to abrasion, have low water absorbency and be tough enough to last at least one season, or maybe two, of wear during competitive sport and training.

Craig and Godwin [6] carried out tests on thirteen different products (some commercially available, the rest experimental) used in the construction of mouthguards; three were polyurethane, six were polyvinyl polyethylene acetate polymer, one was latex rubber, another was said to be Geon 135F1 based vinyl resin plastisol while one was simply listed as thermoplastic ! Their testing of the materials was extensive and covered such aspects as, water sorption, strength, hardness and energy absorption. In the discussion that followed Craig and Godwin went on to say that caution should be exercised when interpreting the energy absorption results, "since a high energy absorption does not necessarily indicate protection of the underlying teeth." The harder urethanes may transmit more energy to the underlying teeth than some of the softer materials, such as polyvinyl polyethylene acetate which was found to have lower energy absorption than the urethanes. The latex that was tested had the lowest energy absorption and due to its exceptional softness would allow the highest penetration during impact loading, therefore transmitting a large percentage of the energy to the teeth. Somewhat ambiguously Craig and Godwin [6] went on to decide that a material with intermediate hardness and moderate energy absorption would be best for a mouthguard and that the degree of protection offered by a single material could be altered by changing the thickness of the material used.

To find the right material for a mouthguard; Bishop, Davies and von Fraunhofer [7] carried out tests on nine materials that were all essentially the same but with differing mixtures of polyvinyl acetate and polyethylene. The specimens contained between 7.5% and 33% polyvinyl acetate (PVA) and were tested for the following properties: water absorption, tear strength, compressibility, along with static and dynamic energy absorption. Their findings were that the material used for a mouthguard should indent easily but be capable of absorbing energy under both static and dynamic loading. Polyvinyl polyethylene acetate (EVA) had a far higher ability to absorb energy when higher percentages of PVA were present. Another factor that was found to be of great importance was that of the compressibility characteristics of the material, or as Bishop *et al* described it, the depth the material is compressed under a known force in the initial purely elastic phase; which was referred to as the elastic gradient. A low elastic gradient (penetration vs force) would indicate a material that requires too high a force to compress it, while a high elastic gradient indicates a material that is compressed far too easily. It was concluded that the most satisfactory composition of a polyvinyl polyethylene acetate mixture for a mouth protector was one that had between 18 -24% PVA, and in the overall summing up the material with 18% PVA appeared to be the best for a sports mouthguard.

Godwin and Craig [8] investigated the effectiveness of different mouthguards that were commercially available in 1968 with some interesting results. It was found that the thickness of the protector does have a direct influence on the effectiveness of a single material, but it is not true to say that all thick materials are as effective as each other. In tests, the material 'Featherbrite' (Featherlax Corp.) that was 5.3mm thick provided a very similar amount of protection to the material 'Shield Protector' at a thickness of only 2.7mm. However, it is not clear what these materials are made from but it can be deduced that the former is polyurethane and the latter is either latex or polyvinyl polyethylene acetate.

Park *et al* [9], after testing five different types of material that are used in the construction of mouthguards reported that "the thicker the material is, the greater the resulting energy absorption is." The materials tested were polyvinyl polyethylene acetate (EVA), polyvinyl chloride (PVC), natural rubber, soft acrylic resin and polyurethane (PU). In the tests that were carried out the mouthguards that were made from EVA, PVC and PU were grouped together as there were no significant differences in the parameters measured of these materials. Overall a 4mm thick sheet was deemed to be the best choice for constructing a mouthguard. One of the materials tested, Proform, had a harder material laminated into the sheet which is intended to reinforce the mouthguard after fabrication from behind the anterior teeth, but this harder material did not seem to have any positive effects - the EVA without it performed better in all the impact tests. Park *et al* went on to say that more interesting results may be gained by sandwiching harder materials, such as 99% acetate in the middle with 28% acetate on the outside so giving maximum protection and comfort.

A more recent test by Greasley, Imlach and Karet [10] however, found that "the incorporation of the stiff and hard styrene butadiene material into the guard had no observable beneficial effects. It made the mouthguards difficult to fit and susceptible to crack damage in the impact zone."

Assessment of mouthguards and materials

The testing of mouthguards and the materials from which they have been made has been done in much the same way over the years. Many comparative studies have been made of the various types of mouthguard available and of the materials from which they are made (which may vary slightly between manufacturers). In typical tests on the material alone none of the tests really reveal the ideal properties that are being looked for in a mouthguard material. Tests that have utilised mouthguards on some form of model or on the maxilla of a cadaver (Hickey *et al* [11]) may give a clearer indication of the protection that is offered by the various mouthguards and materials tested.

In tests carried out by Hoffmann *et al* [12] several commercially available mouthguards were studied to determine their mechanical and physical properties. The mouthguards were fitted onto a specially made study model so that tooth deflection caused by an impact from a pendulum ram could be recorded. Data from the teeth protected with a mouthguard were compared to unprotected teeth so that the cushioning effects of the various mouthguards could be evaluated. It was surmised that the cushioning effects are directly correlated to the thickness of the mouthguard and that the force distribution is governed by the rigidity of the mouthguard. Oikarinen *et al* [13]compared the 'guarding capacity' of several mouth protectors whilst on a standard sized maxillary plaster model, two tests on models without a mouthguard acted as a control. A dropweight impact tester was constructed for the purpose of the experiment, the falling weight was designed to simulate an ice hockey puck. The mouthguards were constructed from two layers of material with a resilient layer next to the teeth, using stepwise regression analysis the only variable that had any statistical significance on the guarding capacity was the thickness of the soft layer next to the teeth.

To determine the effect of mouthguards on pressure changes and bone deformation within the skull, Hickey *et al* [11] constructed an impact producing mechanism that was attached to an American football helmet. In doing so a blow of known force could be delivered to the chin of an intact male cadaver. The research that was carried out did not examine the design of the mouthguard or the material from which it was made but did give a great insight into the protection capabilities of mouthguards with regard to concussion.

Kim and Mathieu [14] studied the lamination of mouthguards using finite element analysis. A flat-ended indentor and a disc representing a colliding object were produced so that the stress distribution within mouthguard materials could be recorded. The laminates that were tested consisted of a hard and soft material, a bi-laminated structure, rather than a sandwich panel or a multi-layered structure. When the soft layer was uppermost (in contact with the indentor) no significant difference from a monolithic test piece was recorded. However, when the test specimen was inverted so that the hard layer was uppermost there was found to be a significant effect on stress distribution and the effect could be increased by controlling ratios of modulus and volume fractions of the top and bottom layers. It was also found that the magnitude of the impact force increases with the increasing effect of stress distribution, but this competition can be reduced to some degree by decreasing the volume fraction ratio of top to bottom layers.

A visco-elastic polyurethane, Sorbothane, that has been used in orthopaedic and sports applications due to its shock absorbing properties was tested by Bulsara and Matthew [15] as an intermediate layer between two layers of EVA. A piezo-electric transducer was used to measure the peak force transmitted through samples with and without the Sorbothane layer from a free falling steel ram. Bulsara and Matthew concluded that using an intermediate layer of Sorbothane may dissipate significantly the force of impact from a blow to the teeth and jaws.

In an attempt to develop a standard test procedure for mouthguard assessment Greasley and Karet [16, 17] constructed an upper jaw made from a rubber arch containing replaceable ceramic teeth and a renewable composite jawbone on which mouthguards were to be tested. Different profiles of projectile, at various energies, were impacted into the model jaw by dropping them down a clear plastic tube whilst a mouthguard was in situ and the damage to the teeth and jaw was recorded. The objective of the exercise was to produce a testing regime that could easily be applied to any mouthguard that was made to fit the standard model that they produced.

Westerman [18] used an impact test rig similar to that of a Charpy or Izod impact machine that was fitted with a blunt striker on the pendulum. Acceleration of the pendulum was measured to calculate the peak force transmitted through the mouthguard material. Tests showed that the force transmitted through the mouthguard materials was inversely related to the thickness of the material and that a small reduction in thickness of 1 mm resulted in an increase in transmitted force of 34%.

Westerman *et al* [19] also assessed the energy absorption properties of a material that contained pockets of air. It was reported that the inclusion of air cells within an EVA copolymer mouthguard material produced a reduction in transmitted forces when the impact was less than 10 kN.

Further to their previous work Godwin and Craig [8] examined the stress transmitted through mouth protectors. Brittle lacquer coatings on maxillary models that were then fitted with mouthguards, demonstrated quite graphically the effectiveness of the individual mouthguards. By studying the cracks in the lacquer on the models the amount of protection that the individual mouthguards gave could be recorded. It was reported that the results obtained illustrated that energy absorption tests or rebound tests are not adequate indicators of the most effective mouthguards and that the brittle lacquer coating method provided better information.

Physical and mechanical tests were employed to discover the basic properties of 57 different mouthguard products by Going *et al* [20] in 1974. As well as determining material properties tests for impact energy absorption and resistance to impact penetration were performed using a rebound pendulum method. It was concluded that the interpretation of the dynamic energy data from the rebound test should be viewed cautiously and that a high energy absorption level does not necessarily mean that the material will give maximum protection, since some of the absorbed energy may be transmitted directly to the underlying tooth structure.

Hypothesis

It is proposed that a mouthguard should be made of a composite laminate construction and that a typical structure would have a very compliant centre region with a more rigid outer layer. Combinations of compliant/rigid materials could be built up in a multi-layered composite system with materials and layer thicknesses being adapted according to the requirements for a particular sport or individual. For example, if a mouthguard is made with a softer more compliant material sandwiched between two layers of a more rigid material, such as EVA, (see Fig. 1) there will be a reduced impact force transferred to the teeth due to the shock absorbing capability of the compliant material layer. Harmful rebound energy will also be reduced as the composite laminate will return to its original shape more slowly than a single material system.

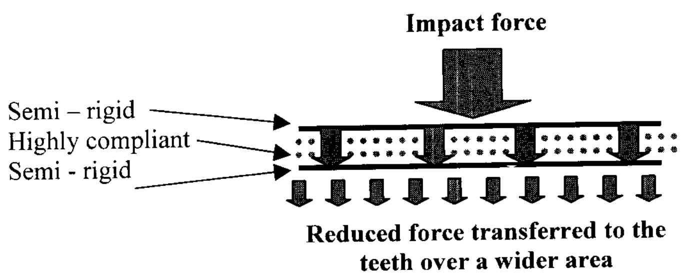

Fig. 1 Force distribution for laminate design

The aim of this study is to develop a method for the assessment of mouthguard materials and designs with the objective of improving the degree of protection provided by a mouthguard.

Experimental procedure

In designing the experiment it was felt that the amount of protection a material, or composite material, demonstrated the more valid the experiment would be. Previous studies have tended to show the amount of resilience present in a material by using a 'rebound test'. This kind of test was felt to be inappropriate as not enough information about the way in which a material reacts under impact loading conditions could be obtained from such a simple test.

An instrumented dropweight rig has been developed, within the Department of Mechanical Engineering at the University of Sheffield, enabling impact tests and static indentation tests to be conducted on circularly clamped panels, Found *et al* [21]. The test rig has recently been modified to permit clamping of smaller panels, i.e. mouthguard blanks. The impact rig is equipped with four transducers namely, an accelerometer, a strain-gauged load cell, a displacement transducer and opto-electronic triggering and timing sensors. The accelerometer is a miniature piezoelectronic transducer, which is connected via a signal conditioner to the data acquisition system. An infrared LED/phototransmitter reflective transducer is used to determine the displacement of the test specimen during impact. Calibration of the transducer is from static load tests performed under identical clamping conditions using an LVDT to measure the deflection at the centre of the test specimen.

The instrumented indentor is released by an electromagnetic switch from a height of 0.5m to produce an impact velocity of the impactor of about 3m/s. The data acquisition system is triggered when an aluminium flag, attached to the indentor assembly, passes the first opto-interrupter. The indentor velocity immediately before the impact event is determined by measuring the time taken for the flag, of 15.5mm depth, to cross the line of sight of the second opto-interrupter. The sensors are also used to determine the rebound velocity when energy is returned to the indentor after the impact event. A schematic arrangement of the indentor and assembly showing the location of the accelerometer, IR displacement transducer and other details are given in Fig 2.

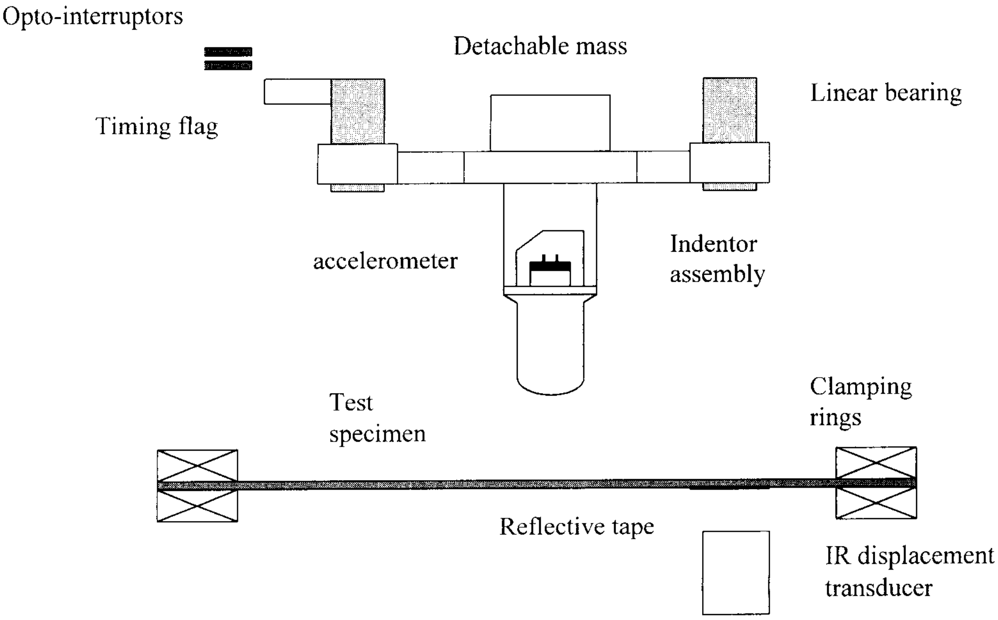

Fig 2 Schematic arrangement of indentor assembly

The transducers are connected to a data acquisition board which is installed in an IBM PC/AT compatible desktop computer as shown schematically in Fig 3.

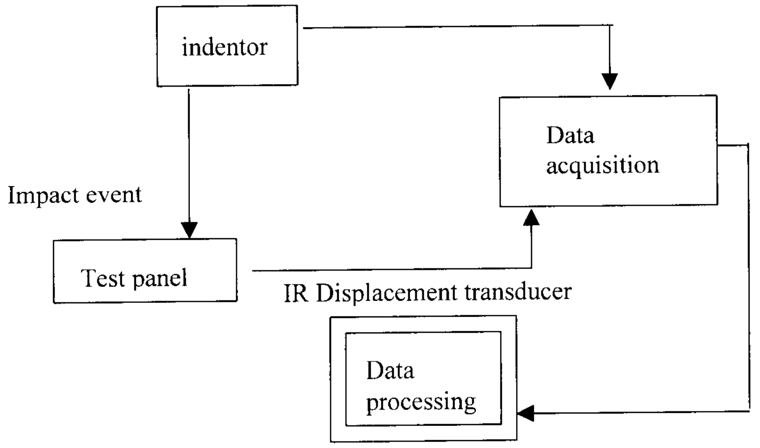

Fig 3 Schematic diagram of data acquisition system

The board is a multi-layer construction with integral ground plane to minimise noise and crosstalk. The system has a maximum sampling rate of 100kHz and allows the monitoring of up to eight channels of bipolar data. For monitoring of the transducers three channels are employed and the data sampled at a rate of 25kHz. The system is triggered via the reference or zero channel whilst the accelerometer, load cell and displacement transducer are connected to channels 1 – 3 respectively and the timer operates via channel 4. The data acquisition system is completed with the Easyest LX software from Keithley Asyst enabling storage, manipulation and filtering of the data. The impact forces and displacements were obtained from data that was processed through a low – pass filter at a cut – off frequency of 3.5 kHz.

Test specimens of 125mm diameter were constructed to fit the clamping mechanism of an instrumented impact testing rig, using a piezo-electric accelerometer to determine the peak impact force (PIF) and an infra-red sensor to measure the amount of deflection (Δ) respectively. Single thickness specimens of ethylene vinyl acetate (EVA), 5mm thick, were compared with laminated structures of EVA, (poly)methyl methacrylate (PMMA) using various combinations of materials and various thicknesses of each ply as shown in Fig 4

Fig 4 Mouthguard laminate designs

Results

A summary of the impact performance of each laminate design is presented in Table 1 in terms of the peak impact force and maximum displacements observed during each test series.

Table 1. Peak impact force (PIF) and maximum displacement (Δ max) for each laminate design.

Design	PIF (N)	Δ max (mm)
1	160	2.6
2	290	1.3
3	210	2.0
4	280	1.4

From the above it was found that the laminated structures using a multi-layered system exhibited less deformation (Δ max = 1.3 – 2.0 mm) than the single system EVA (Δ max = 2.6mm). The soft compliant materials absorbed more impact and so transferred less impact energy to the substructure.

As previously reported the laminates containing synthetic rubber exhibited greater impact absorption with a peak impact force (PIF) of 300N, compared with a single material system (PIF >400N) or laminates with PMMA (PIF >500N) (Patrick *et al.* [22]). However these laminates are 2mm thicker and therefore as expected show a higher peak impact force. From Table 1 it can be observed that changing the laminate structure influences the peak impact force but is still greater than that for the monolithic EVA.

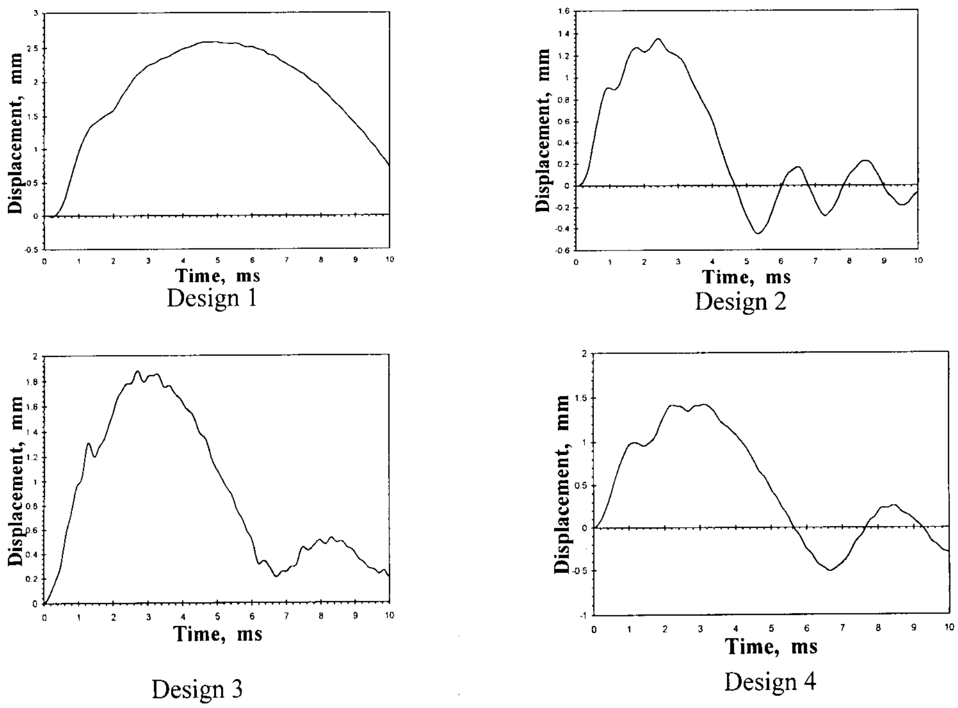

Fig 5 Displacement – time histories for each laminate design

From the displacement/time curves shown in Fig 5 it can be seen that Design 2 and 4 have similar curves although the layer of PMMA in Design 2 failed at the point of impact. The implications of this being that it would not be appropriate to use in a mouthguard as the mouthguard would be rendered useless after only one or two impacts. A compromise will have to be reached between the use of materials and thicknesses to provide the optimum laminate that could be encapsulated within a mouthguard for a particular application.

Discussion

A brief review of materials and test methods for sports mouthguards shows that a wide range of thermoplastic and rubber materials have been evaluated employing different test methods. Whilst many of the tests are often only determining material properties they however suggest; that EVA appears to be an appropriate material [7, 9], the importance of section thickness [8, 9, 12], the influence of a sandwich construction [9, 10, 14, 15] and the effect of force distribution [12, 14, 15] and hence the effectiveness of the mouthguard. Furthermore, in order to fully assess the influence of an impact and the resilience of mouthguards more appropriate tests need to be carried out [11 – 13, 16, 17].

Whilst it appears that EVA is an appropriate choice of material for mouthguards it should be noted, however, that the percentage of vinyl-acetate can be altered thereby changing the properties of EVA (Bishop, Davies and von Fraunhofer, [7]). It has been shown that an 18% content of vinyl-acetate in the EVA is the most suitable composition for mouthguard materials as it exhibited greater energy absorptive qualities over materials with a lower vinyl-acetate content. Conversely, a high vinyl-acetate content diminishes the energy absorptive capabilities of the resultant polymeric compound. Park *et al* [9] found that most commercially available mouthguards had a vinyl-acetate content of 28% and observed from their impact tests that a thicker mouthguard is more effective in withstanding a blow to the mouth and in some cases the thinner sheets of material used were destroyed.

We consider that an instrumented dropweight impact rig as used in this study is more appropriate for evaluating possible material/laminate configurations for use in sports mouthguards. It enables the force-time and displacement-time characteristics of the various material/thickness combinations to be evaluated and hence to obtain a more effective measure of the energy absorbed by the mouthguard.

The multi-layered structures exhibit less deformation than the monolithic structure of pure EVA. The incorporation of a compliant material to act as a shock absorbing layer may reduce the maximum impact force transmitted to an underlying substructure (teeth), but does not reduce to that of the pure EVA of similar thickness. Similarly, the duration of impact may be increased by modification of the layers and hence reduces the effect of a sudden sharp shock. Rebound energy, that is potentially as harmful as the original impact, is reduced as the composite laminated material returns to its original shape more slowly that less compliant materials.

At this stage of our work it is not possible to state which type of design would be best for a mouthguard but the need to compromise between force, displacement and duration of impact suggests that Design 3 with silicone rubber warrants further investigation. However, analysis of our results indicates that the variation in laminate construction influences the response of the mouthguard to impact and hence its ability to absorb energy.

Conclusions

A review of the literature indicates that ethylene vinyl-acetate (EVA) is a suitable material for sports mouthguards. We have undertaken dropweight impact tests on three laminated structures of EVA incorporating polymethylmethacrylate (PMMA) and a silicone rubber and compared the results with that of a similar specimen of 5mm thickness of EVA only. The multi-layered structures exhibited less deformation than the monolithic structure of pure EVA. It is therefore suggested that laminated mouthguards may offer better protection to the wearer since they reduce the transmission of harmful effects.

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