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The influence of strain measurement on the impact performance of sports mouthguards ☆

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Abstract

The aim of this paper is to study the behaviour of three tooth configurations protected by mouthguards under simple dropweight impacts. Frontal and uppercut impact tests were undertaken with one front tooth strain gauged on each set. The results showed that the performance of the mouthguard can be assessed by the use of strain gauges on the teeth whilst the photoelastic analysis are effective for monitoring the reduction in process stresses for the material. Simple theoretical solutions were suggested in order to differentiate between frontal and uppercut impacts and the influence of adjacent teeth were examined for their role on the local strain distribution for uppercut tests. A more realistic approach appears to be that of monitoring of the load path from the impact indentor.

Keywords: B. Impact behaviour; B. Fracture; B. Hardness

1. Introduction

The development and improvement of sports mouthguards has been an ongoing process for about a hundred years. Evidence of a form of mouthguard existed in 1913 when the boxer Ted "Kid" Lewis used a piece of natural rubber that had been hollowed out on one side so that it would fit over the upper teeth and was worn to prevent the teeth from being chipped or broken. The jaw had to be clenched to hold the mouthguard in place, making it difficult for the wearer to breathe. Whilst athletes may still purchase this type of "unfitted" mouthguard today, the materials have changed however—ethylene vinyl acetate (EVA) being substituted for rubber. Since this type of mouthguard offers a very low level of protection to the wearer, and has the added danger of becoming dislodged and obstructing the air passage, sportsmen should be actively discouraged from wearing them [1].

Three types of mouthguard are available today:

(a) Stock mouthguards come in limited sizes (usually small, medium and large) and are ready for use without any further preparation. These types of mouthguard are made from either polyvinyl chloride (although the use of PVC for mouthguards has now been outlawed by the EU), polyurethane or a copolymer of vinyl acetate or ethylene. Since they are unfitted these stock mouthguards offer the lowest level of protection and may even be dangerous as they may give an athlete a false sense of security [2].
(b) Mouth-formed, also known as a "boil and bite" type, are presently the most commonly used mouthguard available. Made from a thermoplastic material, they are immersed in very hot water, placed in the mouth and then formed by biting and sucking to the shape of the teeth. This biting thins the surface of the mouthguard and reduces its protection such that the fit is not adequate and these mouthguards do not last very long.

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(c) Custom-made mouthguards are moulded from an impression made by a dentist and formed by dental technician on a cast of the mouth. EVA is heated in a pressure or vacuum-forming machine near its glass transition temperature and placed over the cast and air pressure or a vacuum is applied which closely adapts the soft material to the cast. These mouthguards hence have the best retention and have negligible effects on breathing and speech.

Many different impacts occur in sports applications with a range of contact points and velocities that a mouthguard may be subjected to. The three main impact types are frontal, side on and uppercut with other impacts a combination of these three. Frontal impacts are common in rugby and from the impacts of cricket and hockey balls. Uppercut impacts are common in boxing and collisions with elbows and arms in many sports. At this stage in our studies, it was decided not to investigate side on impacts since the impacts to cause damage to the rear teeth would be extremely high and would probably result in a broken jaw. Generally testing energies have been aimed towards 10 J, with some energies up to 15 J, although Greasley and Karet [3] stated that the test became insensitive at 20 J due to the amount of damage.

Godwin and Craig [4] undertook pendulum impact rebound tests for frontal and frontal/side locations and demonstrated that the use of brittle lacquer was a more effective, if limited, way of measuring the strain transferred to the teeth for evaluating mouthguards. A comparative study of commercially available mouthguards was undertaken by Hoffmann et al. [5] using a model to which mouthguards could be fitted in order to record tooth deflections. They found that wearing a gum shield reduced the deflection of the teeth and that a laboratory-produced mouthguard achieved better ratings than a mouth-formed type. Greasley et al. [6] are developing a standard test procedure for the in vitro performance of mouthguards using a rubber arch containing replaceable ceramic teeth mounted in a composite jawbone located in a spring loaded support. Warnet and Greasley [7] used force–time traces to suggest that the mouthguard detachment and tooth fracture are related to a reduced maximum load and hence loss of integrity in the model. Greasley's group followed up their tests by heating the mouthguards at 35 °C for 30 min and concluded that custom-made mouthguards performed better than mouth-formed types.

The recommendations of Godwin and Craig [4] indicated that a measure of strain transferred to the teeth is a better estimate for the selection of the most efficient mouthguards. The strain can be obtained through brittle lacquer, photoelasticity or the use of strain gauges. The tooth can be sprayed with a lacquer such that cracks initiate at a determinate strain and grow with further increase in load, with the cracks perpendicular to the maximum strain. However, it is only a qualitative comparison, limited to a single mode of loading and has severe health and safety restrictions. A more accurate measurement can be made using reflection photoelasticity. Here a coating needs bonding to the surface to determine the strains, hence these will be on the mouthguard not on the teeth. The use of strain gauges would be a more obvious choice except for the difficulties in determining the areas of maximum stress and the physical problems associated with protecting the gauge lead wires.

The rebound tests undertaken by Godwin and Craig [4] for frontal locations using brittle lacquer showed the maximum principal stress along the longitudinal axis of the tooth consistent with a front tooth in bending. The most common injuries in sporting applications are chipped teeth, which is supported by a survey [8] of the oro-facial injuries suffered by rugby players in the 1995 world cup, which occurs at both corners of the front teeth. This suggests uppercut type loading with the bottom teeth compressing against the upper teeth to produce principal stress directions in the longitudinal direction and perpendicular to it to produce a compressive shear failure. In order to identify the maximum strains during our impact tests it is thought that the positioning of a twin (0–90°) strain gauge at the bottom centre of a front tooth would provide data for the most susceptible areas due to our frontal and uppercut impact tests.

The aim of this paper is to study the behaviour of three tooth configurations protected by mouthguards under simple dropweight impact tests. The reduction of strain due to heat treatment of the materials is analysed using photoelastic methods to optimise the energy absorption of the materials. Strain gauge studies are carried out on a tooth for each configuration protected by a heat-treated mouthguard. In addition, the influence of adjacent teeth are examined for their significance on the local strain distribution. Simple theoretical solutions are suggested in order to differentiate between uppercut and frontal impacts.

2. Experiments

Three sets of artificial teeth were used comprising of: (a) ceramic rod teeth, (b) a set of PMMA teeth and (c) hard dental stone teeth. The upper set of ceramic teeth were produced from alumina rods, with the four front teeth (incisors) cut from 10 mm diameter rod along a chord of the circular section to provide a shape conforming to a realistic approximation of the shape of the front human teeth. The four smaller back teeth (premolars) were made from the insertion of 5 mm rods and the four larger back teeth (molars) cut from 10 mm diameter rod to the appropriate length. Although machineable glass ceramic rods have properties much nearer to those of the enamel of real teeth their cost were extremely high in comparison to those for alumina. The 12 teeth were set in a silicone rubber of Shore A hardness of eight such that a damaged tooth could be replaced (see Fig. 1). Although a fewer number of teeth were used than normally exist, they were placed in contact with each other as in real life. The 14 PMMA teeth were