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Comparison of forces transmitted through different EVA mouthguards

Duhaime CF, Whitmyer CC, Butler RS, Kuban B. Comparison of forces transmitted through different EVA mouthguards.

Abstract – Athletic mouthguards have been recommended for decades with varying levels of athlete acceptance. Issues related to compliance center around the ability to breath and speak while wearing the mouthguards. Fabrication techniques have changed over time to a two-layer ethylene vinyl acetate mouthguard fabricated on a high-pressure machine. The reported ideal thickness of these mouthguards has been somewhat variable depending on the sport and anticipated level of risk. Recent research however, has identified 4 mm as the optimal thickness of EVA. In this study an acrylic dental cast was fabricated and mounted to a drop impact fixture. Mouthguards of varying ply, thickness and palatal coverage were fabricated and tested in the fixture. Strain gauges and load cells were used to evaluate the effect of ply, thickness, and palatal coverage on the ability of these mouthguards to minimize transmitted forces. The purpose of this study was to identify those variables of mouthguard construction that will minimize the overall transmitted force of impact to the anterior dentition.

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Mouthguards were first introduced in 1913 to the sport of professional boxing (1). Today, mouthguards are being used both at the amateur and professional levels of several sports. In 1998, it was reported that most studies classify dental injury to be the most common orofacial injury attributed to sports (2). Our goal as sports dentists is to increase player acceptance while concomitantly maintaining some standard of dental protection.

By the year 2000 there were five amateur sports that mandated the use of mouthguards: boxing, football, ice hockey, men's lacrosse and women's field hockey (1). However, regulation does not always equal compliance (1). 'In 1998, the Endodontic Department at Louisiana State University volunteered to fabricate mouthguards for the local professional ice hockey team.' (1) The results indicated that 'some players reported that wearing a mouthguard was likely to be seen as a sign of weakness and they expressed little desire to protect their teeth.' (1) At the Cleveland Clinic Foundation, several mouthguards are fabricated annually to serve the local professional sports teams. A recurring concern deals not only with peer perception, but whether or not the mouthguard has an effect on speech, breathing, and comfort.

Thickness of the mouthguard has been an ongoing question. Several authors have stated that the ideal mouthguard should be as thin as possible while still providing adequate protection, maximum speaking efficacy and maximum respiratory efficiency (2–5). Stokes et al conducted a study that compared laboratory and intraorally formed mouthguards (6). In the study, they found that both forms of EVA prevented dental injuries in all subjects. That degree of protection may be compromised however, if the material is too thin in an attempt to improve comfort (2–4). A 2002 study comparing forces transmitted through various mouthguard thicknesses concluded that the optimum mouthguard thickness was approximately 4 mm for EVA material with a shore A hardness of 80 (7). According to Westerman et al. (7), the thickness of mouthguard materials is directly related to energy absorption and inversely related to transmitted forces when impacted.

Other mouthguard studies have attempted to compare force transmission through materials of various designs and thicknesses using drop-ball and/or pendulum devices designed to deliver impact forces (2, 7–16). Takeda et al. (17) took this a step further by applying actual sports related impact objects (i.e. hockey puck, baseball, wooden bat) to the model as opposed to the traditional steel rod/sphere. In an additional study by the same author, strain gauges were found to be the most sensitive to measure the shock absorption abilities at the impact point when considering a relatively soft impact object such as a hockey puck (18).

This study attempts to compare transmitted forces of EVA mouthguards with varying thickness, design, and ply using strain gauge/load cell sensors and a hockey puck as the impact object of choice.

Materials and methods

A dental cast was prepared which was used to evaluate various mouthguards. A polyvinyl impression (Imprint, 3M ESPE, St Paul, MN, USA) was made of a healthy maxillary dental alveolar arch and the teeth were poured in auto polymerizing acrylic resin (Cold-Pac, Motloid Co., Chicago, IL, USA). The anterior teeth were given 'root structure' in this initial pour. This was accomplished by adding 6–8 mm conical 'roots' to the coronal pour. Upon setting, the roots were painted with a thin coat of soft denture liner (Coe-Soft, G-C America, Alsip, Ill, USA). This allowed for application of greater impact forces to the resin teeth without fracture of these teeth. The remainder of the impression was then poured in pink resin.

The study mouthguards were fabricated using ethylene vinyl acetate (shore A hardness of 80) of differing thickness, ply, and palatal coverage. Each mouthguard was fabricated on a pressure-forming unit at 80 psi (Drufomat-TE, Dreve, Unna, Germany). In multiple ply mouthguards, acetone was used to clean the surface of each preceding layer. As a baseline of comparison a standard mouthguard in this study is defined as single ply EVA material with a thickness of 3 mm to partial palatal coverage. Partial palatal coverage is defined as extending 6 mm on to the palate from the gingival margin.

The dental cast was mounted on a custom-made impact fixture that allowed a reproducible impact force to be applied at a chosen location on the mouthguard-protected cast. The fixture holds a steel

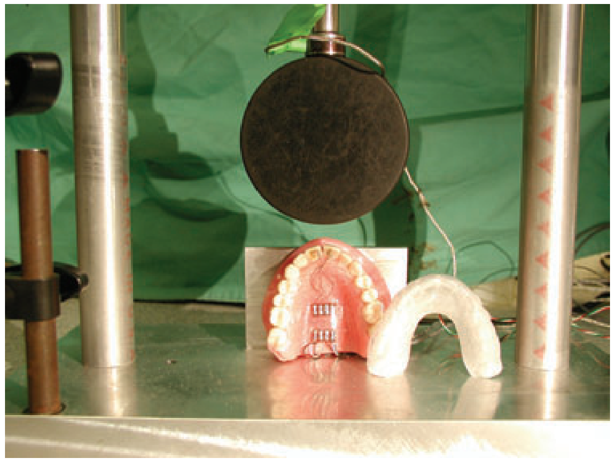

Fig. 1. Acrylic model, mouthguard, impact device.

impact rod. The bottom of the rod was drilled and tapped to accept a 10-pound load cell (Honeywell Sensotec, Columbus, OH, USA). A common hockey puck had a 1″ flat spot milled on the edge (Fig. 1). A hole was drilled and tapped in the center of the flat to accept the other end of the load cell (Fig. 2). The load cell was excited with a precision 5 V source, and amplified with a custom instrumentation amplifier based on the INA128 (Texas Instruments/Burr-Brown, Dallas, TX, USA) with a gain of 100 (Fig. 3). The load cell-amplifier combination was calibrated with static weights and had an output of 115 mV per pound. Although the impacts in this experiment did exceed the 10 pound force rating of the load cell, they were of short duration, and the linearity and reproducibility of the impact measurements was verified.

The measurement chosen for analysis was peak transmitted force. This was computed by taking the difference between the peak recorded force for the drop dart sensor and the appropriate peak recorded force from the sensors mounted behind the teeth. For force transmission on the right side the difference was between the drop dart sensor and the right mounted strain gauge and similarly for the left side. For the force on the center, the average of the two measurements was used for analysis.

A 350-ohm constant strain gauge (Micro-Measurements, Bishay Intertechnology Inc., Malvein, PA, USA) was cemented to the back surface of each incisor on the cast (Fig. 4). The strain gauges were each connected as half-bridges using 350 ohm 1% metal film resistors, and were excited and amplified using the same instrumentation amps used for the load cell. As we were interested only in comparing strains among different trials, and not in absolute strain measurements, we did not calibrate the strain measurement system for absolute strain. However, linearity was confirmed with static weight measurements.

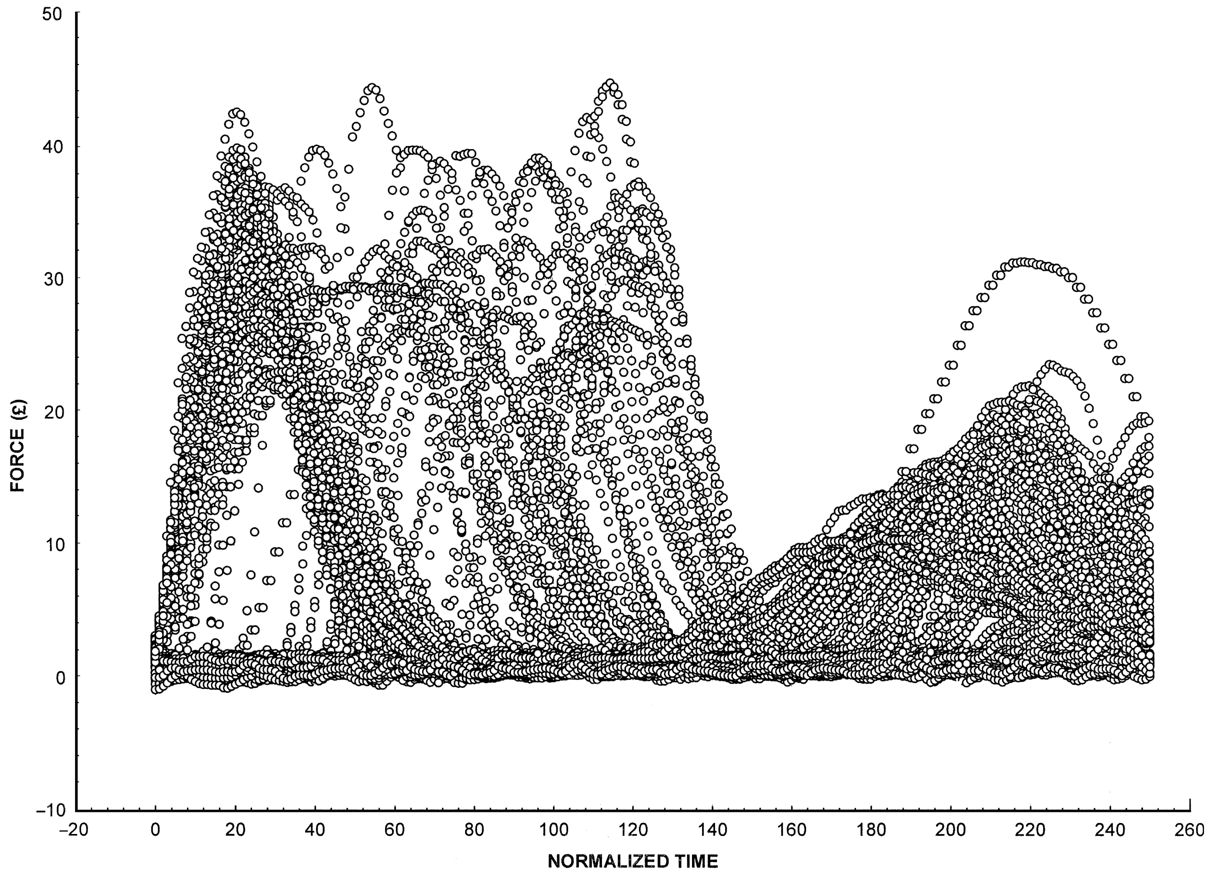

Fig. 2. Raw data – recorded force by location for 9mm drop height.

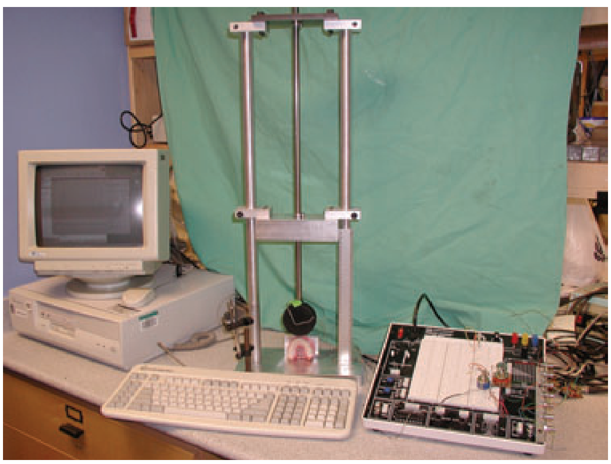

Fig. 3. The impact device and custom amplifier.

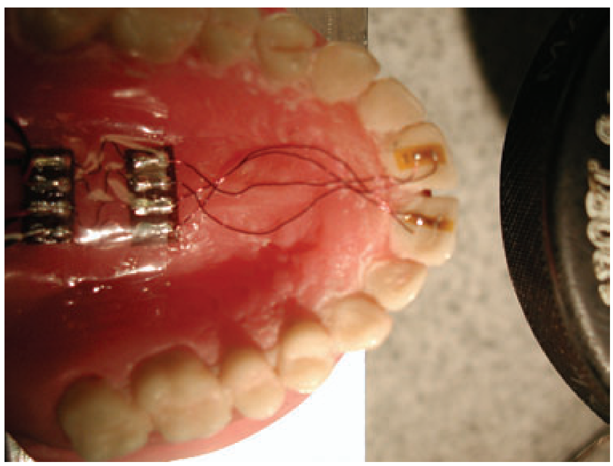

Fig. 4. Strain gauges in place.

The voltage outputs of each instrumentation amplifier were captured using a 4-channel digital oscilloscope (Agilent Infinium 54825A, Agilent Technologies, Palo Alto, CA, USA) interfaced to a personal computer using a GPIB to USB interface device (Agilent 82357A). The data was thereby transferred directly into a Microsoft Excel (Microsoft Corporation, Seattle, WA, USA) spreadsheet.

Statistical method

Data

The data consisted of measured transmitted force of impact on mouthguards of varying construction. The mouthguard variables were the number of ply, thickness of individual ply, actual mouthguard thickness and surface coverage of the palate.

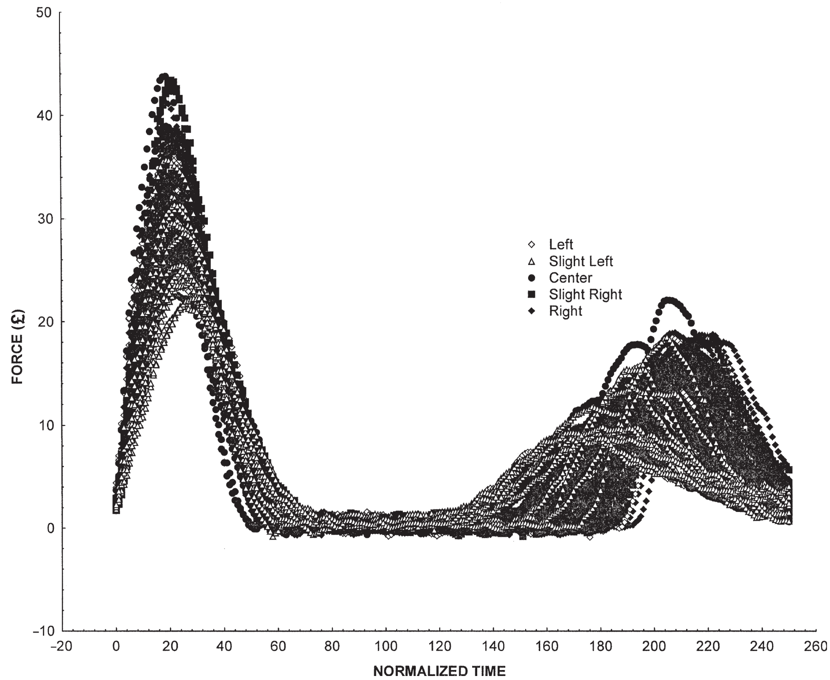

Fig. 5. Force by location for 9mm drop height.

Measurements were taken at three drop heights 9, 15, and 20 mm and at six locations on the fixture.

The measurements were made at five locations on the mouthguards. This precludes treating the data as if it were a single data block. Thus, the measurements at each test location on the mouthguard were treated as independent responses. The data was examined by test site and models correlating the peak transmitted force with ply thickness, actual thickness, and palate coverage were constructed for each site.

Analysis

Because of the ordinary variation present in a system of this nature the data had to be examined graphically before analysis to insure that the statistical methods that were employed were appropriate. Figure 2 illustrates the 9 mm data before these adjustments were made and Fig. 5 illustrates the data after these differences had been eliminated.

The data matrix (combinations of ply, individual ply thicknesses, and surface coverage) for gum line and 20 mm would not permit an assessment of all of the model terms of interest consequently this data was excluded. Graphical analysis indicated inconsistencies in the 15 mm data. Thus, the analysis was restricted to the 9 mm drop data (Fig. 5). The matrix of drop test location, drop height, number of ply, ply thickness, and palate coverage that remained allowed an examination of these main effects and several of their interactions as well.

Each mouthguard had a maximum of five peak measurements of transmitted force (delta force left, slightly left, center, slightly right, and right). A one-way analysis of variance of these measurements across mouthguard types was used to test for significant differences in peak transmitted forces. This analysis permits the ranking of the mouthguards relative to one another with respect to force transmission but does not identify those factors of mouthguard construction critical to the minimization of transmitted force.

Results

Table 1 is a summary of the physical characteristics of the mouthguards used in this study as well as a summary of the peak force (in pounds) transmitted through the mouthguard as measured at five different mouthguard locations. The peak transmitted force was computed by taking the difference between the peak recorded force for the drop dart sensor and the appropriate peak recorded force from the sensors mounted behind the teeth (for force transmission on the right side the difference was between the drop dart sensor and the right mounted strain gauge and similarly for the left side. For the force on the center, the average of the two measurements was used for analysis.

Discussion

In this experiment, a method for comparing force absorption among various mouthguards was demonstrated. The variables in this study (ply, thickness, and surface coverage) were examined in a

Table 1. Summary of mouthguard constructs and peak transmitted force by location on mouthguard

Palatal surface coverage	Actual thickness (mm)	First ply thickness (mm)	Second ply thickness (mm)	Force left central (lbs)	Force mesial facial line angle left (lbs)	Force midline (lbs)	Force mesial facial line angle right (lbs)	Force right central (lbs)
None	0.75	0	1.5	15.1	0.0	29.1	20.6	9.3
Partial	0.8	0	1.5	13.7	0.0	26.6	19.9	16.6
None	1.25	0	2	2.6	0.0	19.2	11.4	4.6
Partial	1.25	0	2	5.1	0.0	18.8	14.2	8.4
None	1.75	0	3	2.1	0.6	17.9	14.7	3.9
Partial	1.75	0	3	0.0	0.0	10.2	11.2	3.2
None	2.15	2	1.5	1.8	0.0	14.8	11.9	4.0
Partial	1.5	2	1.5	1.5	2.7	7.1	3.1	0.00
None	2.25	2	2	0.0	0.0		10.2	8.5
None	2.25	2	2	0.0	0.0		88.5	73.3
Partial	1.7	2	2	0.0	0.0		9.7	0.8
None	1.925	3	1.5	0.0	0.0	6.2	2.3	0.0
Partial	1.95	3	1.5	0.0	0.0	2.2	0.0	0.0
None	2.75	3	2	0.0			8.4	3.8
Partial	2.2	3	2	0.0	0.0		6.9	0.0
None	3.175	3	3	0.0	0.0	3.2	5.6	0.04
Partial	2.5	3	3	0.0	0.0	4.3	6.2	0.0

manner consistent with industrial experimental design. This design permitted the construction of regression models that may be used in future experiments to quantify and predict the potential of various mouthguard constructions to absorb shock.

The final models (Table 2) are very good predictors of the measured data and, allowing for the usual vagaries of location-to-location measurements, they are in very good agreement with one another. Correlation equations permit the identification of variables important to minimization of force transmission. These equations can be used to identify combinations of thickness, and palate coverage with performance equal to some standard. Depending on the performance criteria, it may be possible to identify combinations of these variables that either give performance superior to the existing mouthguards or which give the same performance but are of thinner construction. Figures 6 and 7 illustrate ways in which these equations could be used to identify thinner mouthguards that provide protection equal to an established standard such as 3 mm thick single ply with partial coverage.

The analysis indicates that when controlling for ply and thickness, there was little difference between partial palate and no palatal coverage mouthguards. While individual ply thicknesses were significant, there was also a significant synergistic effect of the ply thickness combinations. If confirmed with additional work, this effect would suggest the possibility of thinner, more conservative, multi-ply mouthguards with protective properties equal to existing mouthguard construction.

From a laboratory standpoint the enhancement associated with multiple ply may be understood when one examines the pressure formed technique associated with mouthguard fabrication. As the heated EVA material is applied to the cast, the material is impeded by the incisal edges, hence 'thinning out' the mouthguard as it forms around the labial aspects of the anterior teeth. With multiple ply, this "thinning out" may be compensated for.

In a study conducted by de Wet et al, a double-layered mouthguard with a sponge insert registered the highest shock absorption (19). A study by Westerman et al found that the incorporation of

Table 2. Summary of correlation equations

Force equations by location	Root MSE	R^2
Left side $= 8.66 \times \exp[0.18 - (0.23 \times nt1) - (0.18 \times nt2) + (0.20 \times nt1 \times nt2) - 1]$	0.14	0.84
Slight left = no model – most of the differences were zero	–	–
Center $= 8.66 \times \exp[0.77 - (0.38 \times nt1) - (0.13 \times nt2) + (0.1 \times nt1 \times nt2) - (0.08 \times surface) + (0.09 \times nt1 \times nt2 \times surface) - 1]$	0.12	0.97
Slight right $= 8.66 \times \exp[0.73 - (0.27 \times nt1) + (0.14 \times nt1 \times nt2) - 1]$	0.19	0.70
Right $= 8.66 \times \exp[0.31 - (0.25 \times nt1) - (0.12 \times nt2) + (0.13 \times nt1 \times nt2)]$	0.21	0.67

nt1, normalized thickness of first ply; nt2, normalized thickness of second ply; surface, partial or no palatal coverage.
R^2 in Table 2 is a measure of the amount of variability observed in the data that is explained by the correlation equation. It can vary from 0 to 1 with 1 being a perfect fit. R^2 is only one measure of the statistical success of a regression equation and by itself it should never be used to judge the worth of a correlation. The Root MSE is the root mean square error of the regression equation. It is one measure of the uncertainty of the model prediction.

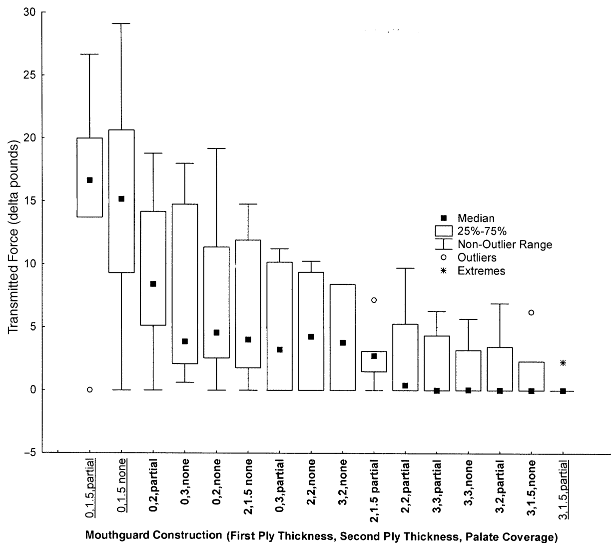

Fig. 6. Transmitted force – center (delta pounds).

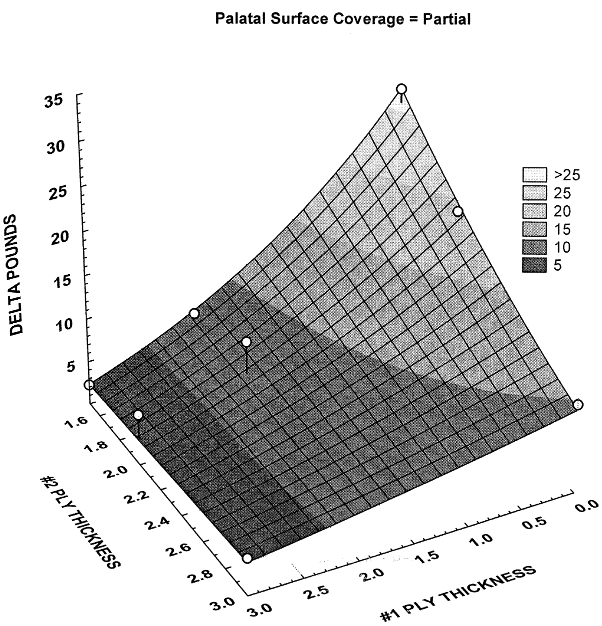

Fig. 7. Transmitted force – center (delta pounds).

air-cells in an EVA mouthguard produced a reduction in transmitted forces when impacted by forces less than 10 kN (20). Our study did not look at the inclusion of an intermediate material between layers of varying thickness EVA, nor did it look at air-cell inclusion, but the significance of the synergistic effect of ply thicknesses is in keeping with their findings concerning multiple layers and shock absorption.

The experiment may have more closely depicted in vivo circumstances if real teeth from a human cadaver maxilla were used as opposed to an acrylic model. (11). The fact that only one drop height yielded consistent, valid data suggests that greater care should be taken with respect to future experimental efforts. It is possible that load cells were "overloaded," for the 15, and 20 mm drops. Perhaps the greater drop heights caused the acrylic teeth to behave in a manner inconsistent with what we hypothesized. Perhaps they are more plastic than teeth and their deformation created unusable data. Control drops at the end of each drop test sequence would provide early detection and correction of inconsistent measurements. This procedure would have allowed us to detect the left sided load cell failure prior to completion of the data collection.

Conclusion

Future studies should focus on the confirmation of the existing correlation equations and the investigation of additional mouthguard variables and their interactions. Our work indicates that the area of multiple plys of material of similar or dissimilar properties may be worthy of further investigation. It also suggests that the amount of palatal coverage may minimally affect the mouthguard's ability to absorb forces. Such combinations of materials, design and thicknesses are easily examined using the methods of experimental design.

From this investigation we have concluded that:

1 The analysis indicates it may be possible to construct a thinner, more comfortable mouthguard that provides protection equal to those currently in use.

2 The developed correlation equations can be used to identify combinations of ply, thickness, and palate coverage that meet the criteria of point 1.

3 Once built, the experimental mouthguards should be tested under controlled conditions. A successful test will provide confirmation of the correlation equations and justify their use as a starting point for any future work in mouthguard development.

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