The Effect of Shell Geometry on the Impact Attenuating Capabilities of Ice Hockey Helmets Relative to Liner Structural Characteristics and Impact Conditions.

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Abstract

Shell geometry is one of the many variables that can influence the way energy is absorbed by the helmet during impact. The purpose of this study was to gain knowledge in how shell geometry affects the performance of the shell relative to liner structural characteristics and impact conditions. Samples, representing a section of a hockey helmet, consisted of a shell with one of nine geometric formations (width and angle), and a liner (Dertex or EPP). Each sample was impacted three times at three different levels of energy using a monorail drop test. Significant differences were observed for all main effects and two-way interactions for both liner types. Overall the 90 degree angle and 16mm width performed the best. It was found that geometry influences the elastic properties of the shell in a very specific way. It was also found that geometry can improve energy absorption by 4-35% depending on the combination of other variables involved.

Résumé

La géométrie de coquille est une des nombruses variable qui peut avoir des effets sur la facon dont l'énergie est absorbée par le casque pendant un choc. Le but de cette recherche était d'approfondir les connaissances a savoir comment la géométrie de coquille modifie la performance de la coquille en relation aux caractéristiques structurelles du doublure et les conditions du choc. Les échantillons, tirés d'une section d'un casque de hockey, étaient composés d'une coquille avec une des neuf formations géométriques (largeur et angle), et d'un doublure (Dertex ou EPP). Chaque échantillon a été mis a l'épreuve trois fois a trois niveaux d'énergie différents, appliquant le "monorail drop test". Des différences importantes ont été observées pour tous les effets principaux et les interactions bidirectionnelles pour les deux types de doublure. Dans l'ensemble, l'angle de 90 degré et la largeur de 16 mm ont eu la meilleure performance. Nous avons observé que la géométrie influence les propriétés élastiques de la coquille d'une facon tres spécifique. Nous avons aussi observé que la géométrie peut améliorer l'absorption d'énergie de 4-35% selon la combinaison d'autres variables impliquées.

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CHAPTER 1. INTRODUCTION

Sports have become an integral part of our society. Participants in sports activities can be found across all ages, sex, race and cultural backgrounds. The underlying health benefits associated with physical activity, as well as the enjoyment from participating in sports, have resulted in this increased involvement with sports. On the other hand there exists a certain risk of injury, especially in body contact sports. Ice hockey falls under this category.

Ice hockey is an exciting game due to its fast pace and relatively small playing area. Consequently, the velocity and confined environment in which ice hockey is played constitute an added potential for injury. This environment comprises of boards, metal goal posts, glass, ice surface, hockey sticks, the puck, the skates and other equipment, as well as the players of the opposing team and even teammates.

According to Meeuwisse and Fowler (1988) hockey has the highest rate of injury of any team sport (72%). A large body of evidence (Hayes, 1978; Jorgensen and Schmidt-Olsen, 1986; Lorentzon et. al, 1988; and Meeuwisse and Fowler, 1988) reveals that generally the location most frequently injured is the head and face. Priority, therefore, should be given to the study of the causes of head injuries, that may lead to life threatening conditions. In hockey, the helmet has been used as the primary means to protect the head against injury.

Two major types of head protective devices exist. The first type, a single impact device, is used in very high energy impacts. Such impacts generally occur in race car, motorcycle, and bicycle accidents where the helmet provides protection against a single crash and is considered unfit to further protect the bearer following the crash. The second type, a multiple impact device, usually withstands impacts of less energy but is more durable. It is more effective in handling multiple impact situations. The ice hockey helmet falls under the second type of protective devices. This is due to the likelihood of less severe repetitive impact situations in the game of hockey.

Since nearly all hockey organizational bodies have made the use of ice hockey helmets obligatory, injuries to the head have dropped significantly. There is no doubt that protective equipment have changed the course of the game of hockey. A perfect example is the goalie face mask. Even though the decrease in injury occurrence is a step forward, the degree of protection to the head, with a helmet, should be studied further. When evaluating protective equipment many variables must be considered. Some of these variables for a hockey helmet include safety capabilities, weight, field of view, fit and stability to name a few. Improvement in one area does not necessarily mean improvement in the other elements. For example, using a thicker helmet may improve impact absorption but at the same time result in a limited field of view, increased weight, awkward feel and higher potential for a neck injury. The ideal would embody improved safety and performance, otherwise an optimal compromise between the two should be found. Shell geometry is one of the variables of a helmet that can be modified to provide design choices that can steer the compromising scenario in favor of the particular goal of the designer. Further study of protective equipment and more specifically the study of a particular variable, such as shell geometry, can bring about a knowledge base that can be very useful in solving such a complex problem.

Hodgson and Thomas (1972), demonstrated that impact tolerance between different locations of the skull varied, signifying the need to protect certain areas more than others. Currey (1979) found that the ability of bone to absorb energy decreases as the person grows older. Therefore the protection needs of people of different age groups, involved with the sport, will vary. In addition to the physiological differences, skill differences among age groups and level of play should be considered when developing protective equipment. For example, Hayes (1978) reported that there was a higher rate of injuries as level of play (quality, competition) increased. This latter finding was attributed to the increased speed of play and the larger size of the players at the higher levels. On the other hand, with younger less skilled players, the environment (boards, goal posts, etc.) is responsible for most of the injuries due to inexperience (less control) and lack of strength. Therefore, there are two things to be considered. First is the extent to which protective headgear can absorb impact. Secondly how this piece of equipment can be altered to address the specific needs of a particular group must be considered.

To date, research on hockey helmets has focused on comparisons between different models of hockey helmets, between impact sites on a helmet and impacts under various energy levels. In early studies of ice hockey helmets, the authors found differences in energy absorption characteristics of a number of different models of ice hockey helmets when impacted at various locations and from different drop heights (Bellow et. al, 1970; Bishop, 1976,1977, and 1978). No study has been able to substantially pinpoint the cause of the differences and better understand the impact absorption characteristics of helmets. To gain some understanding, with respect to impact absorption characteristics, greater control over the variables of the helmet is needed. In addition, inclusion and study of the necessary variables is also important. For instance, shell geometry cannot be studied independently from the inner liner upon which it lies. Following impact, the outer shell is deformed and how it performs will depend on the amount of movement allowed by the material under it, which is also deformed. Variables that influence this deformation are the type, thickness, and density of the inner liner material. Thus, one has to incorporate these variables so that a more complete picture is obtained.

Therrien and Bourassa (1982) suggest that enhanced protection against brain injury is associated with helmets possessing lower mass and smaller outside diameter, without any losses to the ability of absorbing translational components of the impact. This lower mass and smaller outside diameter translate to a decrease of the moment of inertia of the head-helmet system and subsequently a decrease of the angular accelerations experienced at impact.

Geometry is one variable that can provide specific solutions to the issues previously mentioned. In addition to providing an extra option to the designer, geometry can have an effect on the stiffness characteristics of the material depending on particular needs. An investigation therefore is warranted to further understand the characteristics of materials and certain material variables, such as geometry that has not received much attention, and find out how these characteristics react under varying impact conditions. Information of this type is needed in the development of a helmet that is lighter and thinner (less diameter) without compromising the absorption characteristics. Shell geometry is one area that has not received any attention and its study can reveal information of significant impact in understanding the impact characteristics of head protective gear.

1.1. Statement of the problem

The purpose of this study was to investigate the effect of geometry (side inclination angle and top surface width) on the impact attenuating characteristics of the ice hockey helmet and its interaction with inner liner structural characteristics (liner type and density) and environmental conditions (energy of impact and multiple impacts).

1.2. Research Hypothesis

- Impact absorption will be significantly different between the samples with different side inclination angles (A).
- Impact attenuation characteristics will differ significantly among samples with varying top surface widths (W).

Interaction will be observed between the following variables:

- side inclination angle (A) and top surface width (W).
- side inclination angle (A) and liner density (D).
- side inclination angle (A) and: i) energy of impact (E), ii) impact trial (T).
- top surface width (W) and liner density (D).
- top surface width (W) and: i) energy of impact (E), ii) impact trial (T).

1.3. Delimitations

- The spherical impactor was used as representing the human head and will react to impact in a similar way.
- The samples tested correspond to a section of an ice hockey helmet and exhibit similar impact characteristics.
- The impact procedure that took place reflects the type of impacts occurring within the environment of ice hockey.

1.4. Limitations

- The data that were collected are only valid for the particular type of impact that the samples were exposed.
- Rotations or any other movements of the head that take place during impact in an ice hockey environment were not considered.

1.5. Operational Definitions

The following definitions are based on the Canadian Standards Association (CSA) definitions.

Drop height -- the vertical distance between the lowest point (impact point) of the raised helmet and the impact surface.

g -- acceleration due to gravity.

Gmax -- the maximum value of acceleration, measured in g, encountered during impact.

Helmet -- a device intended to reduce the risk of head injury to ice hockey participants.

Helmet shell -- the outer covering that gives form to the helmet, and absorbs part of the impact energy.

Inner liner or cushioning material -- material used to provide a comfortable fit of the helmet on the head, and to absorb some of the impact energy.

Impact sights

Crown -- a point in the median plane that is equidistant (chord length) from the anterior and posterior intersections of the median and reference planes.

Front -- a point on the median plane that is 50 mm above the intersection with the reference plane.

Front boss -- a point 25 mm above the reference plane and 45 degrees in a clockwise direction from the anterior intersection of the median plane with the reference plane.

Rear -- a point at the intersection of the median and reference planes in the rear.

Rear boss -- a point 25 mm below the reference plane and 135 degrees in a clockwise direction from the front of the median plane.

Side -- a point on the reference plane 90 degrees in a clockwise direction from the median plane (Intersection of the reference and coronal planes).

Planes

Basic plane (Frankfurt horizontal) -- a plane that is located at the level of the external openings of the ears and the inferior margin of the orbitale.

Coronal plane (Lateral or frontal plane) -- a vertical plane that is perpendicular to the median and reference planes and passes through the crown of the headform.

Sagittal plane (median plane) -- a vertical plane that passes through the headform from front to back and divides into right and left halves.

Reference plane -- a plane that is located 27.5 mm above and parallel to the basic plane.

CHAPTER 2. REVIEW OF LITERATURE

In this study the focus will be on how shell geometry influences impact attenuation relative to inner liner structural characteristics and environmental conditions. Since the present knowledge base of how shell geometry works in attenuating energy is minimal, acquiring information from studies on helmets in general and other material variables is worthwhile. In addition, reviewing information on the environment in which hockey is played, the nature of injuries and how they are caused will provide the researcher and the designer with a realistic perspective of the role geometry plays in protecting the head against impact. To prevent injury and improve safety standards, a review of the history of ice hockey injuries as well as some factors involved in causing injury are required (Sim et al., 1987). A better understanding of the nature of the injuries will help the manufacturer to set standards and improve the design of ice hockey helmets in order to provide optimal head protection.

To justify the methods being used in the evaluation of helmets, information must be gathered to understand some important characteristics of the game. This information will be used to simulate, in the laboratory, a condition that will be as close as possible to what happens in the real world. Otherwise we would not be able to make any conclusions, and what is found in the lab could be significant but would have no implication to the real situations occurring in the arena.

2.1. Injuries in Ice Hockey

Hockey has the highest rate of injury per team sport at 72% (Meeuwisse and Fowler, 1988). The purpose of examining the injuries that happen in a particular sport is to try to find any distinctive trends that might be apparent in the causation of the injuries. Trends of "how," "when," "what," and "where" injuries occur should be examined. Information regarding helmet design will provide better protection to the user.

In 1978, Hayes tried to develop an injury profile for hockey. He found that injuries occurred at a higher rate as level of play increased (0.008 injuries/game at the age level of 9-10 compared to a rate of 1.15 injuries/game at the professional level). Improved speed and the bigger players were identified as being responsible for this trend according to the same author. From this it can be concluded that the level of protection varies with age. When examining injuries according to the position of a player, offensive and defensive players have a similar rate of injury unlike the goalie who seems less vulnerable (Jorgensen and Schmidt-Olsen, 1986). Hayes (1978) found a 9:6:1 injury ratio for forwards, defencemen and goalies respectively. Of course, the equipment and responsibilities of goalies differ from the rest of the players. The ice hockey stick is the factor most often associated with injury (Hayes, 1978; Jorgensen and Schmidt-Olsen, 1986; Lorentzon et al., 1988a and 1988b). However in younger players, the environment (boards, goal posts etc.), plays a greater role in injury causation. The latter observation is largely attributed to inexperience and the lesser skill level in the younger players.

The most frequent types of injuries are contusions, followed by lacerations and the most frequently injured location is the head and face (Hayes, 1978; Jorgensen and Schmidt-Olsen, 1986; Lorentzon et al., 1988b; Hornof and Napravnik, 1973; Ranney, 1985). Other factors are very closely related to injuries in ice hockey, the velocities of collision with an object (i.e., puck), another player or the ice hockey environment (i.e., the boards).

2.2. Environmental Factors Involved in Causing Injury

In this section, some quantitative characteristics of the game of hockey are examined. Environmental factors can better help us understand some of the parameters responsible for injury. These factors aid the researcher in simulating impacts of the game in the lab and serve as valuable feedback in setting safety standards for protective equipment. As we mentioned earlier, hockey is a fast paced game. It has been referred to as a game of fractions of a second.

Since the boards, glass, goal posts and playing surfaces are rigid and since impacts with these rigid surfaces constitutes a potential risk to injury, it is important that the players speed, both when skating and when sliding after a fall on the ice, as well as the stick and puck velocities, be examined closely.

High speed cinematography has allowed the measurement of on-ice activities of players. According to Norman (1980) and Sim and Chao (1978) a senior amateur player can develop speeds of up to 27-30 mph (43-48 km/h) whereas lower calibre players have displayed speeds of up to 20 mph (32 km/h). The sliding speed of players, after a fall to the ice, has been recorded to be up to 15 mph (24 km/h). These values provide information on the energies that can be developed during impact and help in establishing the evaluation procedures.

The puck consists of 170 gr of processed rubber and measures 7.62 cm in diameter and 2.54 cm in thickness. It can travel at very high velocities (up to 120 mph [193 km/h]). Sim and Chao (1978) measured puck velocities produced by professional, recreational and younger players. The maximum figures found were 120, 90 and 60 mph (193, 145, and 97 km/h), respectively. The maximum impact force developed by the puck was found to be 567.5 kg (5567 N). In the same study it was also found that the angular velocity of the stick during shooting was 20 to 40 rad/s. Impacts in hockey can be classified as low mass - high velocity, for example the puck striking the player or as high mass - low velocity, such as when a player falls and slides into the boards, collides with another player or falls on the hard ice surface (Canadian Standards Association, 1990).

2.3. Human Factors Involved in Injury

After identifying the injuries and some contributing factors involved in hockey, the next step is to determine the extent of damage to the skull or brain to better quantify helmet performance (Therrien and Bourassa, 1982). Head injuries include: scalp damage, skull fractures, brain damage, and others (Norman, 1983).

Bishop (1976b) has suggested that injury to the head during impact may be related to three factors. These factors are skull deformation, intracranial pressure and rotational motion. Skull deformation refers to the elastic properties of the skull since it is not rigid. He suggests that a localised blow to the head is more severe than a more widespread impact. Due to the inertia of the brain relative to the skull there is a positive intracranial pressure (increase in pressure) at the location of impact and a negative intracranial pressure (decrease in pressure) at the opposite site of impact. This may cause injury to brain tissue. Shell geometry in this instant can be used to prevent a localised blow but at the same time, due to its protruding nature, can also increase the potential of angular accelerations. After impact, rotation of the head takes place. Rotational acceleration contributes considerably to injury (Bishop, 1976b; Norman, 1983). Angular accelerations between 1800 and 3500 rads/s^2 may produce cerebral concussion (Bycroft, 1973). Average accelerations of 112 G and a peak acceleration of 200 G were considered sufficient to result in skull fractures (Lissner et al., 1960). An impulse of 22 N.s can also cause injury (Hirsch, 1966). Evans et al. (1958) produced fractures in cadavers with kinetic energies between 363 and 788 J. In another study, forces applied on different locations of the skull in cadavers were used to decide impact tolerance. The frontal bone tolerated a force of 3,736 N on a rigid surface whereas a force of 4,181 N was tolerated on the side (Hodgson and Thomas, 1972).

A head injury evaluation criterion, used by the Canadian Standards Association (CSA), in addition to peak G is the Gadd Severity Index (GSI), which measures a weighted impulse that estimates the injury hazard to the human head from an acceleration time pulse curve (CSA, 1990). In the same report a GSI of 1500 was considered safe.

Evans et al. (1958), suggest that when evaluating the damage caused by a blow, one should not solely rely on the magnitude of the energy but the rate of absorption as well. As the authors further explain, "other things being equal, a greater amount of energy can be safely tolerated if it is absorbed slowly than if it is absorbed rapidly".

There is great biological variability among people of different ages, sex, size and other factors that make it difficult to generalize (Currey, 1979; Evans et al., 1958; Norman, 1983; Ranney, 1985). Therefore, these parameters should be taken into account when testing and setting safety standards and designing a helmet. Currey (1979) in his work states that, the energy absorbed by the femoral cortical bone of a human, decreases almost threefold from the age of three to ninety (from 2.8×10^4 Jm^{-2} to 10^4 Jm^{-2}). This decrease in energy absorption, according to the author can be explained by the increasing mineralization of the older bone, which in turn has a negative effect on the elastic properties of the bone. This information on human factors can give us an idea of "how much" the human head can tolerate, and thus set a reference point to see how effective the helmet really is in preventing injury.

2.4. The Helmet as a Protective Device

The Canadian Standards Association has referred to the helmet as a device intended to reduce the risk of head injury to ice hockey participants (CSA, 1990). The helmet includes the shell (outer covering), the cushioning material (also called the liner) used to insure a comfortable fit and absorb some energy, and the chin strap. Most helmets are adjustable to a certain degree and come with a one or two piece shell. Some foams used for the liner are vinyl, polyfoam and ensolite (Bishop, 1977).

2.4.1. Dynamics of Impact

Part of the energy absorbed by the helmet is due to the deformation of the shell with the remaining energy being absorbed by the liner. During collision (impact), reactionary forces are produced which in turn signify the presence of an acceleration (or deceleration). The presence of acceleration (or deceleration) means change in the velocity of one or both the colliding bodies. Therefore the body or bodies will possess more (or less) energy which means we have transfer of energy. This energy transfer, under the influence of the impact force, can deform the head and thus cause injury since the head is not rigid. A fundamental law in physics indicates that energy cannot be created nor lost but can be transformed from one form to another or one object to another. Hence kinetic energy can be transformed to elastic energy for example. It becomes evident that deformation or destruction of the protective gear absorb (transfer) some of the energy and prevent it from reaching the head.

The ultimate goal of impact absorption in helmets is to reduce the energy reaching the head. The extent of this reduction is a function of the magnitude of deformation and the force that produces this deformation. Deformation can be described as the change of length between the original shape of the structure and the point where the deformation stops. By increasing this distance we can improve the performance of the protective headgear, but increasing this distance can augment the angular acceleration of the head during impact and therefore the risk of injury to the head, due to increased moment of inertia. To better describe the interaction of the impact forces and deformation of the protective gear, the linear spring formula is necessary ($F = k \cdot x$), where, F is the impact force deforming the material, k is the elasticity constant which indicates the stiffness of the material being impacted, and x is the magnitude of deformation. Since we mentioned already that an increase in the distance between the shell and the head will result in a greater moment of inertia value, the only alternative is to optimise the stiffness characteristics of the material. The stiffness of the material affects how and to what extent the material will deform. Geometry on helmets (i.e. shell) can help control stiffness and subsequently adjust the deformation of the material at a particular site to achieve optimal absorption of impact force. Therefore it becomes a problem of optimisation and more specifically what level of material deformation will result in maximum absorption of forces without bottoming out.

2.4.2. Material Characteristics

Two main types of deformations exist: plastic and elastic. The plastic material will not recover to its original shape following impact whereas elastic material will recover. In the first case the kinetic energy of a striking object is completely absorbed when the material has been fully compressed. Under a plastic deformation, the material sustains a deformation which is beyond the elastic limit and permanent damage is done. When the load is released, the material will not regain its original shape but will be distorted and its mechanical properties will be different due to the deformation of the material at the molecular level. In the second case, the important feature is that while maximum force developed is not affected, the time to peak force is doubled. Under an elastic deformation the material can return to its original shape without any permanent damage. The bulk of material display both elastic and plastic properties to a certain degree. Depending on the use of the helmet, the material it is composed of should possess more or less of the material properties discussed (elastic vs plastic). For example, in hockey where the possibility of a repeated impact scenario exists, material with more elastic properties would be suitable since recovery of the material is crucial in dealing with subsequent impacts. Bishop (1990) indicates that these material consist of medium density resilient foams.

The type of material used and the area loaded will influence the force developed when impact occurs. Stress-strain relationships can better define these material characteristics. Stress is a quantity that is proportional to the force causing a deformation (stress = F/A, where F = force that deforms material and A = cross-sectional area of material used). Strain is a measure of the degree of deformation (strain = $\Delta l/lo$, where Δl = deformation and lo = original shape). According to the generalized Hooke's law stress is proportional to the strain. There exists a constant of this proportionality that depends on the material and the nature of the deformation. This proportionality constant is called the elastic modulus, which is the ratio of the stress to the strain.

By the definition of stress and strain, one easy way to lower stress and strain is to increase the area of the material being impacted and the thickness of the material respectively. The force being generated and applied on the material is dependent upon the environment in which hockey takes place. The area of the padding is limited to space and shape of the head, and since increasing the thickness of the material beyond a reasonable level poses an injury threat, the only alternative is to manipulate the deformation. To affect the degree of deformation, material type, density, and the elasticity constant k should be altered. If shell elastic properties are altered, another option is provided to the designer. This latter can be achieved through geometry and material properties.

The purpose of the helmet is to diffuse the blow over an area that should be as large as possible, in order to reduce local loading, and secondly to increase time over which the blow is maintained on the helmet (Bishop, 1976 and 1977). The first variable can be achieved by using a rigid exterior shell while the second one can be satisfied by mounting a more energy absorbent liner material (Bishop, 1976). The basis for using a semi rigid shell in helmets is to involve more of the liner in the absorption of energy. This spreading of the force can be improved by incorporating geometry in the design of the outer shell. Geometry can be used to divide the force being applied and thus create the means for more efficient dissipation of energy.

Polystyrene liners can absorb greater loads than resilient liners but cannot be used for subsequent impacts since it does not rebound to its original shape. Liners like polypropylene and polyethylene on the other hand can both dissipate large amounts of energy and recover to original shape, making them suitable for multiple impact situations.

In one study (Bishop, 1976), a side board collision method was used to evaluate the performance of the liner. It was discovered that in order to keep the average linear acceleration transferred to the head, at 100 G or less for an impact velocity of 6.1 m/s, a helmet liner 2.54 cm thick should have stiffness ranging from 1,050 N/cm for a damping coefficient of 0.45 to 2,100 N/cm for a damping coefficient of 0.15. In another study by Bishop (1976a), it was suggested that higher damping and lower stiffness was more advantageous in sustaining accelerations to the lowest possible levels. The same author and his co-workers in a study of football helmets (Bishop et al., 1984), investigated two liner types, a padded helmet and a helmet with a 12-point suspension system. Their results indicated that the padding had a fairly uniform slowing effect on the headform upon impact, using the resultant acceleration-time curve, unlike the effect seen on helmets employing a 12-point suspension system. The padded helmet showed, a longer time to g peak (6.6 ms), a lower g peak, and the acceleration curve was spread over a longer time period (12 ms). The authors recommended the use of padded helmets.

2.5. Evaluation Techniques for Ice Hockey Helmets

According to Hodgson (1985) two approaches exist in dealing with the problem of testing protective equipment. One is an engineering approach, where the goal is to evaluate the protective equipment from a strength of material point of view. The other approach is a biomechanical one. With the latter approach according to the author, one seeks to incorporate to a certain extent the body part to be protected (humanoid surrogate), a response limit that is related to human tolerance, and a situation that mimics a worst case impact scenario in the hockey environment. The author also mentions that the nature of the biomechanical approach allows for a compromise between the degree of protection provided by the equipment and the athletic performance achieved. This means that the advantage of the biomechanical approach of evaluation is twofold.

The variables that have been measured for the evaluation of impacts on helmets are: angular and linear accelerations, rate of onset of acceleration, force, kinetic energy, pressure, linear momentum and impulse (Norman, 1983). Helmets are mounted on headforms and then either dropped on a surface or hit by an object while being held still. With the headform one tries to imitate as closely as possible the shape, mass distribution and response characteristics of the human head, as described by Hodgson (1985). The Hodgson headform was produced from one of thirteen cadavers that best represented the average values of the variables mass moment of inertia, weight, and anthropometric measurements, of all thirteen cadaver heads (Norman et al., 1980). Two other headforms that have been used are the ANSI Z-90 Metal Headform (MHF) and the National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform (Hodgson, 1975 and 1985).

Both static and dynamic tests are used (Hodgson, 1985). During the static procedure a force is applied on the helmet at a constant rate. The dynamic test involves either the helmet or an object moving with a certain velocity before it impacts or is impacted. The second type is more realistic since the game itself never involves impacts at a static condition. In a study by Bellow et al. (1970) a pendulum-like motion was used to impact a helmet-headform system at a set velocity. The peak acceleration, kinetic energy absorption and the shape of the acceleration-time curve, were measured. These parameters were recommended as being appropriate for the evaluation of helmets. They found differences between helmets as well as between different locations being impacted, with the front location offering better protection. Even more pronounced differences were observed at higher velocities of impact. Two more conclusions were drawn from the above study: the incompleteness of peak acceleration (or deceleration) alone, in the assessment of impact absorption characteristics of a helmet and the importance of multiple site impact testing, which is in agreement with Bishop's position (1978). The latter author notes that after an initial impact, the force absorbing characteristics of helmets are greatly reduced. Bellows et al. (1970), propose the use of the integration under the acceleration-time curve, which reflects the kinetic energy absorbed.

Several studies have used drop tests to evaluate helmets (Bishop et al., 1984; Bishop, 1977 and 1978; Hodgson, 1975). Bishop in 1977, used a Hodgson headform and a drop test apparatus to evaluate helmets. The drop height was set at 0.6 m and the helmets were tested at three locations. The parameters were resultant peak deceleration, rate of peak deceleration, and Gadd Severity Index. He found differences between helmets and among different locat-ions. The side and rear of the helmet were found to be better protected than the front. A few more points drawn from the above study were: total pulse durations were all less than 20 ms and the time to peak deceleration fell in the 4 to 7 ms range, in which range, according to the author, the lower the average rate of peak deceleration the better the performance of the helmet. Another study undertaken by Bishop (1978), revealed similar results but this time three different drop heights were used. Their investigation showed that the GSI never exceeded 1500 up to a drop height of 1.2 m and that the performance differences were amplified as the drop height increased.

CHAPTER 3. METHODOLOGY AND PROCEDURES

The purpose of this experiment was to evaluate and compare the impact attenuating capabilities of material used in the development of an ice hockey helmet. More specifically, a variety of outer shell geometries were compared, using two liner foam types of two different densities to determine if there exists a main effect and interaction of the shell geometry and cushioning material when absorbing impact. This chapter is organized in four sections: (3.1) Sample; (3.2) Instrumentation; (3.3) Preparation and Procedures; and (3.4) Design and treatment of the data.

3.1. Sample

A sample in this experiment consisted of an outer shell made out of high density linear polyethylene sheet stocks and a liner. The shell had a thickness of 2.5 mm while the inner liner was 12.5 mm thick. Both the shell and the liner were joined together with glue to form a 145 x 85 mm sample. Two types of inner liner material were used, Expanded Polypropylene (EPP) and Vinyl Nitryl Foam (DERTEX). The liners had two density levels: 80 and 96 kg/m^3. All material used were new and three consecutive impacts were performed on each sample since most standards use the same number of impacts. Impacts two and three demonstrate higher acceleration values part because of some degree structural destruction and part because of material memory characteristics.

In order to vary the geometric configuration of the outer shell, a parallelogram box-like shape was formed in the middle of the shell. To create the geometric shape of the shell a thermoforming procedure was used. Each sheet of polyethylene was heated in a 350 degrees Celsius oven for twelve minutes, at which time, it was immediately placed on a maquette. This maquette contained all nine geometric formations and was made out of epoxy material with an empty box underneath to create a vacuum. As soon as the heated polyethylene sheet was placed on the maquette the vacuum was turned on for two minutes and a female maquette was fastened with clamps to prevent shrinkage of the sheet during cooling down. This pressure was maintained for another six minutes for a total production time of 20 minutes. Cutting the sheet to produce the nine different samples was the last step in the shell making process. This formation had a length of 100 mm and a height of 10 mm. The variables that were manipulated to alter the geometry of the shell were the angle (α) of inclination of the sides of the box as well as the width (w) of the top surface, as shown on figure 3.1. Variable α was studied at three levels (30, 60, and 90 degrees) while variable w was studied at the 8, 16, and 24 mm levels. Finally two values that remained constant for all samples were, the inner and outer radius of all round corners of the formation, with values of 2 and 4.5 mm respectively.

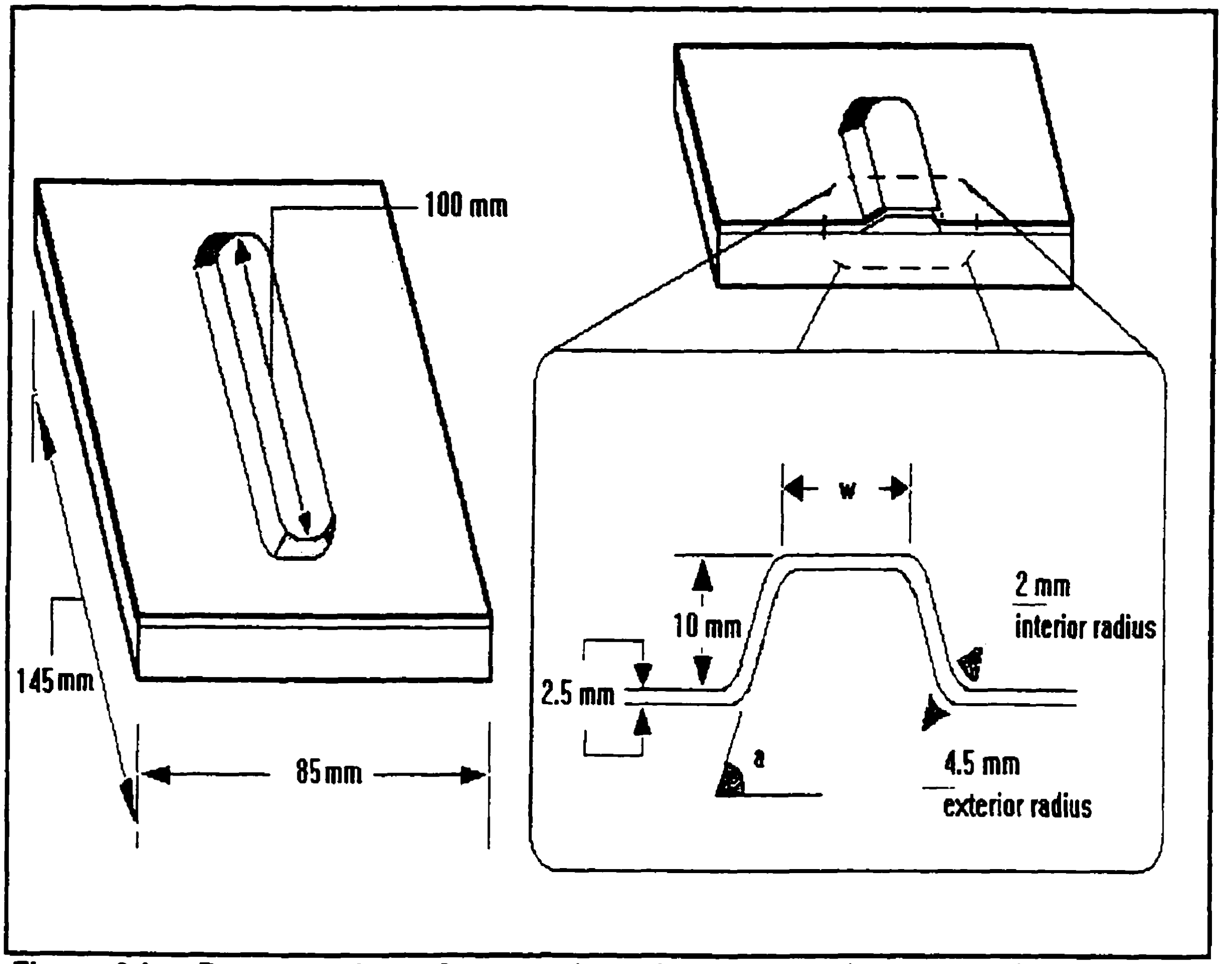

Figure 3.1. Representation of a sample and its geometric characteristics with a description of the independent variables angle (a) and width (w).

Four samples were tested three times for each of the 108 combinations of the independent variables (3x2x2x3x3=108; detailed description of levels follows), for a total of 1296 impacts. These independent variables were:

- Angle of inclination (α) -- 30, 60, and 90 degrees
- Width of top surface (w) -- 8, 16, and 24 mm
- Inner liner -- Expanded Polypropylene, and
  Vinyl Nitryl Foam (DERTEX)
- Density of liner -- 80 and 96 kg/m^3
- Impact energy -- Dertex:
  Low(15J), Medium(20J), and High(25J)
  EPP:
  Low(30J), Medium(40J), and High(50J)
- Repeated measures -- Three trials per sample

Dependent variable: peak acceleration (G_{max}).

All levels of the independent variables were chosen as representative of the features most common to the helmets presently being used in the market and of the approximate impact conditions that helmets might be exposed to in the real world.

3.2. Instrumentation

3.2.1. Monorail System

The impact testing apparatus used in this study is called the monorail or guided-fall system (figure 3.2 on next page), which consists of a cylindrical metal guide supported on an I-beam. The I-beam in turn, is supported on a cement block at the lower end and the ceiling at the upper end. This arrangement provides stability and consequently a more uniform movement of the spherical impactor, also called the calibrated ball, a component mimicking the human head used to impact the samples.

The monorail system includes a carriage assembly that supports the spherical impactor, by way of the universal ball. A socket-like opening in the middle of the spherical impactor places the universal ball at the center of the impactor. It is in the center of gravity of this universal ball that an accelerometer is attached. Four studs on the spherical impactor prohibit any movement of the impactor during impact. Finally, an adjustable automatic release mechanism is used to free the carriage assembly in such a way so that there is no initial velocity, by pressing a button. This release mechanism can be adjusted at any height, by means of an automatic lift (MOVAN AUTO-LIFT), to achieve the desired impact energy level.

The surface upon which the samples are placed, to be stricken by the spherical impactor, is a flat steel anvil with a minimum surface area of 0.09 m^2. In turn this anvil is attached to a steel slab base having a mass of 136 kg that provides a solid foundation. This arrangement results in an almost vibration free condition that is important for obtaining reliable impact data. An aluminum spherical impactor was used to impact the samples, with a 14.605 mm diameter and a 4005 +/-5 grams mass. Complying with CSA standards the spherical impactor and carriage assembly have a combined mass between 5.0 and 5.15 kg, with the carriage assembly alone not contributing more than 20% of the entire mass. Four screws are found on the spherical impactor that are used to mount the impactor on the universal ball.

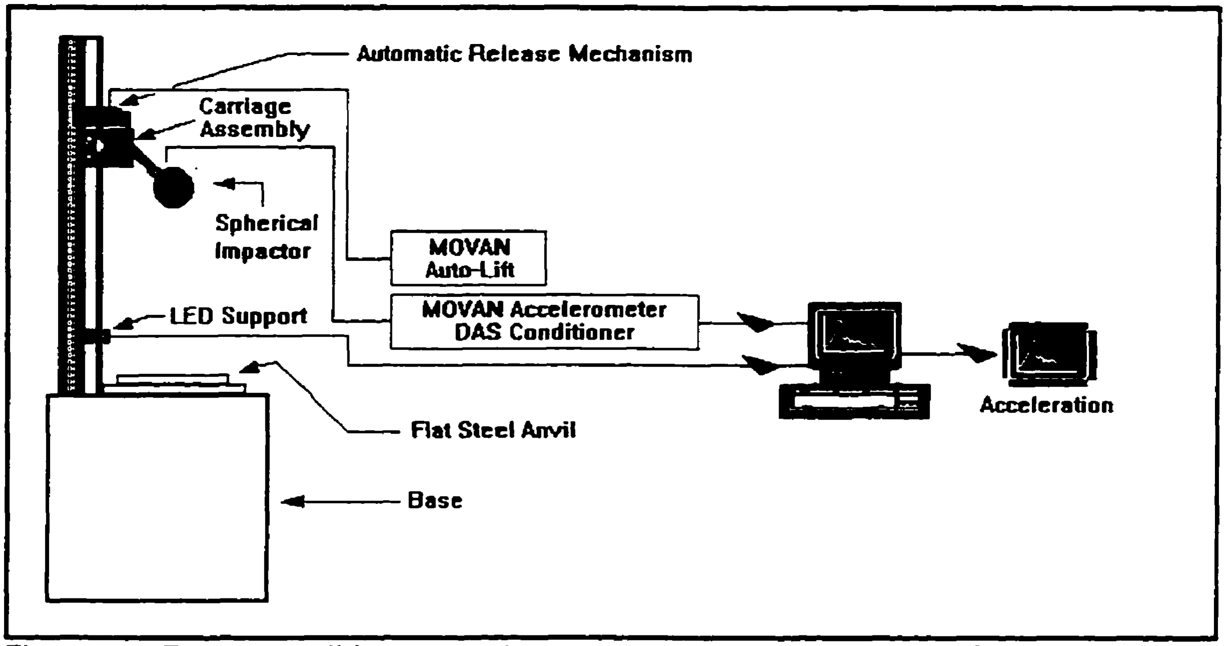

Figure 3.2. The monorail impact testing apparatus with a description of its components and the means of data acquisition.

3.2.2. Measurements and Data Acquisition

The uniaxial accelerometer (2221D) is inserted at the center of gravity of the universal ball. This is due to the fact that the measure of interest is g_{max} in the direction of impact. Another reason is the fact that the vertical positioning of the transducer is important, since the closer the accelerometer is to the contact point, the more variable the measurements will be due to vibrations. Therefore the center of gravity provides a neutral point. The transducer is capable of withstanding a shock of 1000 g without damage and has a frequency response that ranges from 0 to 1000 Hz with a +/- 1.5% variation.

It was vital to the study that all samples were impacted with the same specified energy level. Although, theoretically, this energy level can be achieved by drop height, considerable friction may be developed by the apparatus, having an adverse effect and more specifically a lowering of the energy with which the samples are impacted. For this reason, calculating the impact velocity was essential. The stability of the monorail apparatus makes it possible to measure the impact velocity.

A light-emitting diode (LED), supported on a U-shaped metal base was used to measure impact velocity. This measurement was obtained by a metal flag of a precise width, attached to the carriage assembly that interrupts the light beam just prior to impact. The time that the light beam is interrupted is recorded by the computer's clock and further processed to calculate impact velocity. Since it was imperative to measure the impact velocity just before contact, a metal base that carries the LED with a magnetic hook had been devised that makes it very easy to adjust, so that the metal flag cleared the LED just prior to contact with the sample's highest point.

Both the time interval that the LED is interrupted and acceleration signals are fed into a 486DX 33Hz microcomputer. The impact data are collected on channel one of an analog to digital (A/D) converter board after being amplified (Movan Accelerometer DAS Conditioner) at a sampling rate of 10 kHz and an input voltage range of +/-5 V. Custom made software is used to process these signals and calculate impact velocity and g_{max}. The data were stored on the hard disk.

3.3. Preparation and Procedures

3.3.1. Sample Preparation

Prior to testing the impact site was marked on each sample and an identification number was written on it. The reason for this marking was to consistently impact the same site since there were three drops per sample. The identification number was used to keep track of the particular material specifications of the sample being tested. All the samples were tested under ambient conditions.

3.3.2. System Check

A system check was performed prior to initiating a series of tests. The spherical impactor alone was impacted at a velocity of 5.52 m/s +/- 2%. A Modular Elastomeric Programmer (MEP) was used as the impact surface for the calibration with a 58-60 +/-5 Shore A Durometer Hardness, a 125 mm diameter, and a 25 mm thickness. This impact surface is attached firmly on the flat support base. Three drops were recorded and if peak acceleration did not record a mean value of 394.85 +/-5.13(one sigma) g, testing would not commence unless the system was adjusted or repaired. This system check procedure is standard for the spherical impactor.

3.3.3. Drop Procedure

After the system was calibrated, the sample was placed on the flat steel anvil, making sure that it is properly positioned so that the point of impact, previously marked on the sample, contacted the lowest point of the spherical impactor first. Three energy levels were used for each of the two liner types under this experimental arrangement. These three energy levels for the Dertex liner were: low at 15 Joule; medium at 20 Joule; and high at 25 Joule, which theoretically corresponds to drop heights of 0.3, 0.4, and 0.5 m respectively. For the EPP liner the three energy levels were: 30, 40, and 50 Joule, with corresponding drop heights of 0.6, 0.8, and 1 m respectively. All samples were impacted repeatedly three times with a 30 to 60 s interval between the three impacts. Before any set of drops were initiated, the impact velocity was assessed, making sure that it lies within the limits of the corresponding energy level (+/- 2%). An impact velocity of 2.43 m/s corresponds to the 15 J energy level of impact, 2.80 m/s to the 20 J energy level, and 3.13 m/s to the 25 J energy level. In the case of the EPP liner, the respective impact velocities for the three energy levels are 3.43, 3.96, and 4.43 m/s. These impact velocities as well as the respective drop heights are easily obtained using the fundamental kinematic formulae. Subsequent to the impact velocity assessment the drop height was adjusted as necessary. Also prior to impacting a particular sample, the headform was brought to the lowest point (just before impact) in order to adjust the LED system so that the flag clears the LEDs just before the spherical impactor contacted the sample being tested.

3.4. Design and Treatment of the Data

The experimental design that was used in this study is a split-plot factorial design with four between-block treatments and one within-block treatments ($SPF_{3233.3}$). The design notation for this type of design is as follows:

$$\mathbf{S_4 (E_3 \times D_2 \times A_3 \times W_3) \times T_3}$$

where:
S = sample
E = energy level
D = density of inner liner
A = angle of inclination (α)
W = width of top surface (w)
T = impact trial

From this split-plot experimental design we can generate and investigate six main effects, for each of the treatments involved. Also under this design, two-way interactions can be examined to provide information on how combinations of treatments influence the absorption performance of the sample. Systat, a statistical software package, was used to analyze the data.

CHAPTER 4. RESULTS

A five-way Analysis of Variance (ANOVA) with one repeated measures (trials 1, 2, and 3) was used to analyze the data, for each of the two liner types, Dertex and EPP. The two liners were evaluated separately in order to test them throughout their functional range, which is considerably different. Therefore direct comparisons were not feasible between the liners. To evaluate sample performance, peak acceleration (Gmax) was used as a criteria. Tables 4.1 and 4.2 summarize the means and standard deviations for all the levels of the independent variables studied for the EPP and DERTEX liners respectively.

Initially in this chapter the main effects are presented, in order to describe how each of the variables influenced, if at all, the impact attenuating performance of the sample. Therefore the main effects: energy, density, angle, width and trial will be described. Interactions will follow with the most emphasis placed on the geometry related variables, angle of inclination and top surface width. The reason for this preference is the

EPP		Energy	30 J		30 J		40 J		40 J		50 J		50 J	
		Density	80 kg/m3		96 kg/m3		80 kg/m3		96 kg/m3		80 kg/m3		96 kg/m3	
	Angle	Width	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Trial 1	30 Deg	8 mm	105.088	2.521	105.568	2.714	142.190	2.998	134.498	3.136	219.230	10.833	176.118	14.894
		16 mm	106.850	3.172	106.300	1.117	148.535	7.397	134.868	2.829	226.938	14.562	175.935	9.102
		24 mm	104.593	3.522	106.543	0.807	141.713	1.982	126.078	1.788	263.295	21.613	176.178	5.862
	60 Deg	8 mm	102.028	1.565	102.578	2.036	137.978	1.845	132.058	0.414	195.853	1.968	167.560	3.036
		16 mm	100.928	1.47	104.285	1.134	141.885	4.803	132.485	1.943	203.728	11.850	167.575	6.194
		24 mm	104.103	2.806	103.673	0.957	140.543	3.472	133.960	3.133	250.503	10.199	181.733	5.375
	90 Deg	8 mm	104.118	1.671	105.385	0.660	139.570	0.958	133.215	2.755	194.633	4.155	170.623	3.446
		16 mm	101.478	1.749	102.943	1.557	137.548	3.753	129.373	0.644	195.133	1.511	158.660	2.402
		24 mm	105.263	0.314	105.568	1.220	146.888	1.365	133.643	2.432	258.088	18.977	170.075	5.468
Trial 2	30 Deg	8 mm	145.058	3.453	133.033	4.269	261.450	18.650	193.093	8.352	496.940	6.001	344.330	55.859
		16 mm	147.013	4.841	134.378	2.130	284.583	27.885	191.383	7.341	488.090	15.324	334.135	30.847
		24 mm	144.448	6.682	134.315	2.279	266.120	6.050	172.585	4.949	500.970	0.000	336.335	24.753
	60 Deg	8 mm	142.128	5.94	131.935	3.815	241.368	7.318	190.410	2.885	478.690	2.925	311.308	8.863
		16 mm	139.078	1.749	131.325	1.935	262.855	19.174	190.773	6.752	452.685	23.879	293.003	18.703
		24 mm	145.728	7.863	130.653	1.611	263.405	15.436	194.863	7.051	500.970	0.000	344.943	15.763
	90 Deg	8 mm	140.845	3.22	136.230	1.160	231.728	4.073	187.415	4.915	471.918	19.549	303.250	11.147
		16 mm	136.633	3.921	130.103	1.637	241.370	21.335	175.148	1.976	430.575	18.815	259.430	13.097
		24 mm	144.995	4.681	134.988	1.329	282.263	4.306	190.468	6.652	500.970	0.000	316.203	16.164
Trial 3	30 Deg	8 mm	180.030	7.707	149.573	7.549	394.998	22.719	252.783	14.446	500.970	0.000	471.285	35.039
		16 mm	182.718	10.042	150.858	2.609	420.143	44.956	259.975	23.067	500.970	0.000	483.553	21.180
		24 mm	176.855	12.149	151.400	3.222	377.618	8.179	209.693	6.907	500.970	0.000	489.100	24.000
	60 Deg	8 mm	168.003	11.013	144.813	4.500	361.795	15.741	238.258	5.202	500.970	0.000	471.223	12.309
		16 mm	166.055	3.524	147.375	3.052	386.328	27.949	251.015	18.279	500.970	0.000	431.548	26.472
		24 mm	178.383	12.914	145.788	1.721	381.020	35.391	259.130	17.966	500.970	0.000	497.788	6.037
	90 Deg	8 mm	164.955	6.668	153.053	2.030	343.973	5.528	230.870	10.504	500.970	0.000	457.835	24.395
		16 mm	162.390	9.063	144.398	2.892	358.010	38.429	219.703	5.426	500.970	0.000	377.718	22.939
		24 mm	176.675	9.246	151.590	0.986	425.210	10.712	255.958	11.201	500.970	0.000	471.790	22.535

Table 4.1. Gmax means and standard deviations for all levels of the independent variables examined for the EPP liner type.

DERTEX		Energy	15 J		15 J		20 J		20 J		25 J		25 J	
		Density	80 kg/m3		96 kg/m3		80 kg/m3		96 kg/m3		80 kg/m3		96 kg/m3	
	Angle	Width	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Trial 1	30 Deg	8 mm	67.565	8.243	50.140	5.205	226.415	22.649	74.543	8.950	322.160	36.613	120.480	22.843
		16 mm	83.750	16.026	50.208	4.855	211.398	36.534	72.648	7.601	302.265	18.869	108.578	10.583
		24 mm	77.040	25.504	47.395	0.315	233.555	38.835	71.858	5.548	317.015	33.629	154.048	26.924
	60 Deg	8 mm	64.340	7.205	47.273	0.528	151.020	23.619	70.635	2.101	269.833	38.523	109.735	17.664
		16 mm	72.338	6.920	47.580	0.645	180.680	16.619	65.080	1.219	279.413	19.928	110.895	1.604
		24 mm	77.403	17.368	46.725	1.149	180.190	16.736	76.740	3.826	270.865	16.161	142.270	17.109
	90 Deg	8 mm	74.950	4.591	51.060	0.923	200.148	20.168	78.570	5.955	323.358	60.454	108.270	5.150
		16 mm	78.545	14.379	47.885	2.037	138.135	18.029	68.560	2.050	246.150	31.163	111.263	13.549
		24 mm	87.700	21.509	48.558	0.805	194.045	29.395	73.873	8.463	302.058	13.903	164.670	19.215
Trial 2	30 Deg	8 mm	115.430	13.126	62.408	3.601	317.113	24.239	129.353	26.132	427.878	38.940	238.030	35.218
		16 mm	148.630	15.679	65.280	6.883	305.760	33.986	127.338	22.974	401.445	22.864	225.873	17.508
		24 mm	134.350	43.897	59.728	3.438	328.708	31.844	129.228	17.622	426.388	31.000	271.050	25.137
	60 Deg	8 mm	93.518	16.593	59.788	0.234	268.753	22.029	99.628	3.203	424.435	50.222	214.655	50.689
		16 mm	131.175	15.729	59.420	1.908	255.445	18.632	98.530	6.311	365.263	20.665	216.548	11.269
		24 mm	145.210	30.251	60.518	4.872	267.713	9.113	141.193	11.139	368.770	10.210	257.628	14.091
	90 Deg	8 mm	112.850	14.435	64.670	2.729	335.770	22.112	116.413	12.462	473.320	33.586	219.113	18.591
		16 mm	127.740	18.094	60.093	4.145	216.628	20.267	100.665	6.543	349.360	39.894	200.375	25.791
		24 mm	150.813	24.464	62.593	1.897	272.598	29.482	128.315	25.314	394.648	7.905	276.058	16.464
Trial 3	30 Deg	8 mm	142.163	9.583	69.673	5.373	349.888	41.815	164.203	29.112	473.165	31.082	296.503	41.685
		16 mm	179.025	24.068	75.848	7.612	336.520	32.452	161.945	23.416	448.285	36.258	274.533	25.578
		24 mm	161.938	51.255	66.745	4.056	358.253	31.410	169.513	18.368	454.158	27.745	317.010	18.602
	60 Deg	8 mm	121.348	25.523	67.600	1.116	349.195	24.306	132.038	10.008	488.335	12.575	316.218	40.487
		16 mm	155.770	12.063	66.318	1.882	286.513	16.026	122.943	12.309	402.888	27.287	257.198	11.273
		24 mm	172.983	30.129	67.843	6.035	299.025	7.552	184.223	12.218	398.675	20.015	307.005	15.914
	90 Deg	8 mm	148.983	15.52	74.253	5.326	409.313	22.476	154.868	24.636	501.150	0.000	286.983	12.040
		16 mm	152.825	13.906	66.320	6.605	249.893	23.045	126.238	6.698	396.540	38.773	245.418	22.581
		24 mm	177.970	19.126	70.958	2.137	295.790	30.671	163.045	27.843	458.795	27.626	315.058	19.046

Table 4.2. Gmax means and standard deviations for all levels of the independent variables examined for the DERTEX liner type.

fact that the main interest of this study is geometry and how it influences the impact absorption characteristics of the shell and subsequently the sample.

4.1. Main Effects

By looking at the ANOVA Tables included in the appendix, it is clear that all five main effects, four between blocks (energy, density, angle, and width) along with the within blocks trial main effect, showed significant differences at the .05 significance level. This was true for both the DERTEX and EPP liners

4.1.1. Post Hoc Tests

A Tukey HSD Multiple Comparisons post hoc test using model MSE of the SYSTAT statistics software package further revealed significant differences ($p< 0.05$) between all three levels of energies for both liner types (EPP and Dertex). These differences were maintained for all three impact trials.

The Tukey post hoc test was also used to identify the source of variation between the levels of the angle and width variables. For the DERTEX liner, significant differences ($p< .05$) were found between the 30 and 60 degree angles, as well as between the 30 and

90 degree angles, with the third pairwise comparison (60 and 90 degrees) showing no significant differences and the 30 degree angle performing the poorest. This was characteristic in all three impact trials. The EPP liner was similar to the DERTEX liner for only the first trial. In the second and third trial all three angle levels (30, 60 and 90 degrees) were significantly different between them with the 90 degree angle doing better than the others overall followed by the 60 degree angle.

The width variable, when studied with a DERTEX liner, demonstrated significant differences between levels 8 and 24 mm (8 mm performed better) along with levels 16 and 24 mm (with 16 mm width doing better), whereas in the second and third trial the significant differences appeared with the 8 and 16mm and 8 and 24mm pairs of which the 24 mm width was the worst performer except at trials 2 and 3 and with a 90 degree angle where the 8mm was the poorest performer. On the other hand when the EPP liner was used the 8 and 24 mm levels of width, along with the 16 and 24 mm pair were significantly different at the first and third trials with the 24 mm width showing the higher accelerations. On the second trial of impact the three possible pairwise comparisons all revealed significant differences with 16:8:24 mm being the order of performance from better to worse (always at the .05 level of significance).

4.2. Interactions

Only two-way interactions were studied to identify how each independent variable related to each other, to better understand how these relationships affect the performance outcome of the sample. Of particular interest in this study is shell geometry, thus the focus revolved around the two variables responsible for geometric configuration, namely angle of inclination and top surface width.

4.2.1. Angle by Width Interaction.

When looking at the angle variable the 60 degree angle maintained the best results (176 g compared to 210 g for 30 degree angle overall), with the exception of the 90 degree angle with the 16 mm width, which was first overall. When studying the overall angle by width interaction, taking the averages for all energy, density and trial levels, the 90 degree angle with a 16 mm width was the best combination, recording the lowest gmax value of 115 g for Dertex liner (figure 4.1 for the DERTEX liner and figure 4.2 for the EPP liner). The worst observation was seen at 30 degree:24 mm geometry (150 g). The 16 mm width shows a linear decrease as the angle increases, and at 30 and 90 degrees performs better than the other two widths. The 24 mm width consistently performs the worst at all three angles.

Overall Angle by Width Interaction (Dertex liner)

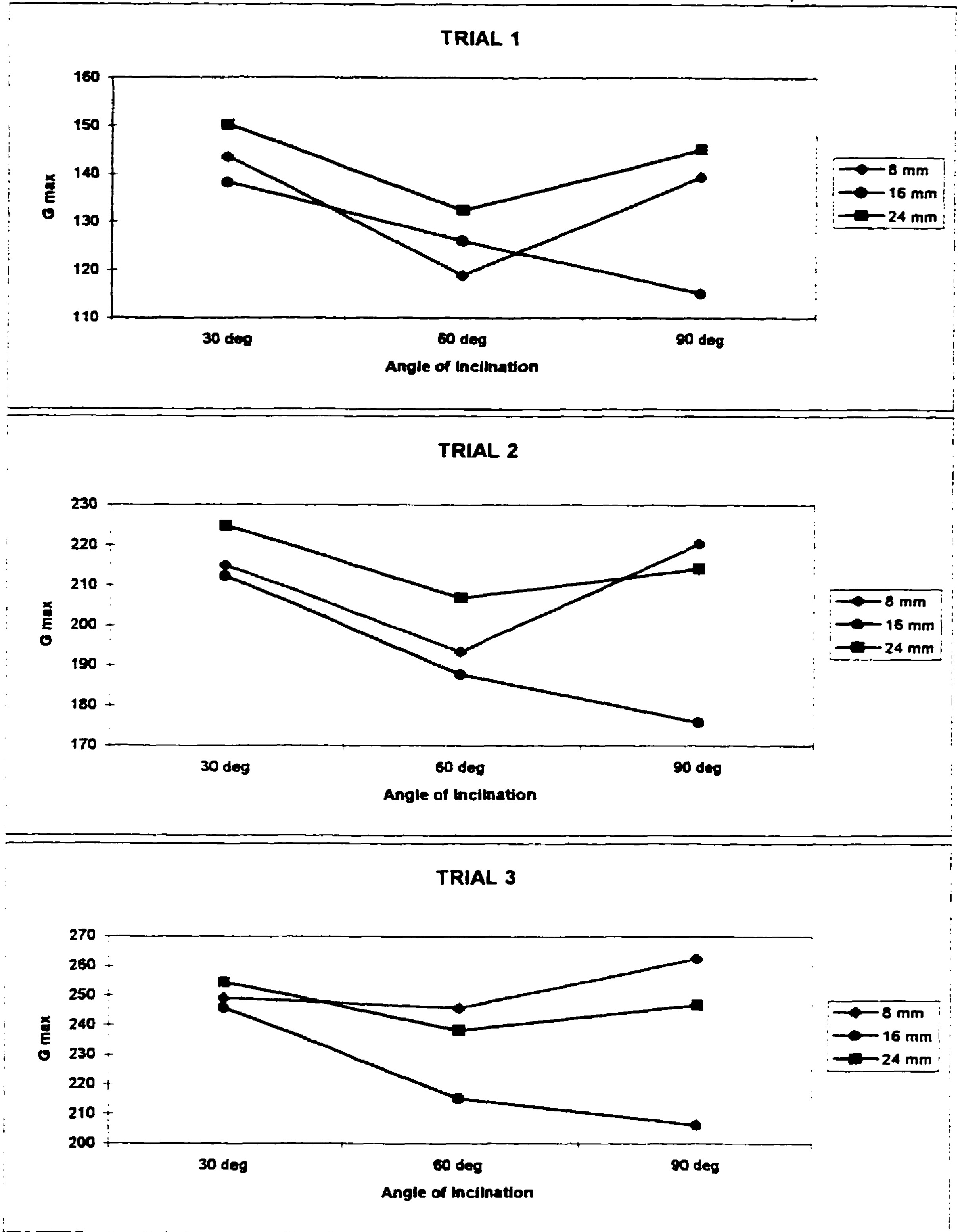

Figure 4.1. Overall angle (30, 60, and 90 degrees) by width (8, 16, and 24 mm) interaction performance expressed in peak acceleration (Gmax). Each graph corresponds to each of the three impact trials. The Dertex liner was used.

Overall Angle by Width Interaction (EPP liner)

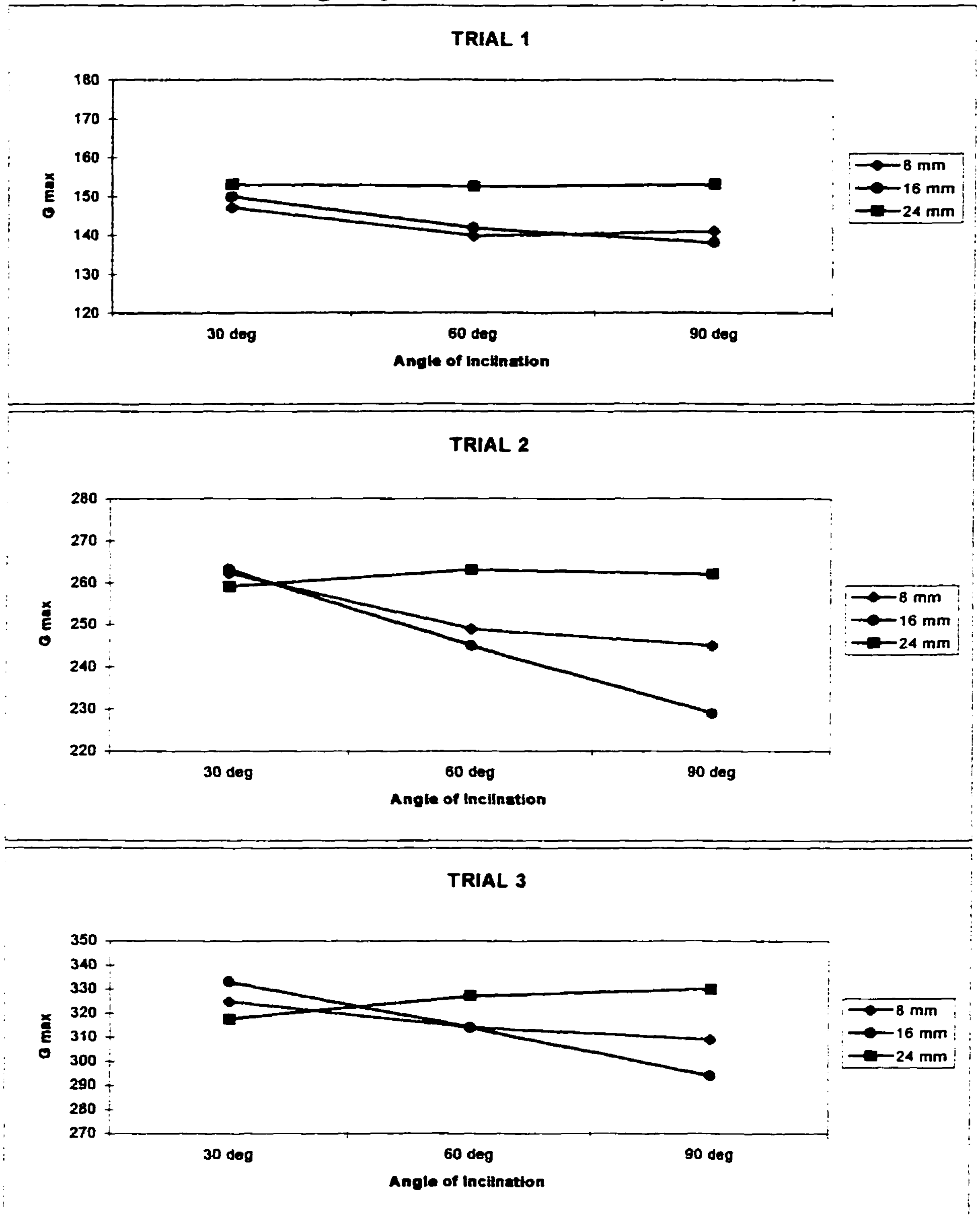

Figure 4.2. Overall angle (30, 60, and 90 degrees) by width (8, 16, and 24 mm) interaction performance expressed in peak acceleration (Gmax). Each graph corresponds to each of the three impact trials. The EPP liner was used.

In the second trial the 16 mm width outperforms the other two levels, at all the angles and again the 60 degree angle performs better with the exception of the 90 deg:8 mm geometry which was also better than the others. The range for this trial is from 176 g the lowest to 225 g the highest (30 degree:24 mm). As was the case for the second trial the 16 mm width displays the best performances with the 90 degree:16mm geometry being the best performer. The performances for this trial range between 206 g (90 degree: 16 mm) and 263 g (90 degree:8 mm).

To summarize, a significant interaction is observed for the variable angle and width at the $p<.05$ level. For all three trials the 90 deg:16 mm geometry proves to be the one with better performance output, while in more general terms the 60 degree angle seems to do the best at all three levels of the width variable.

4.2.2. Geometry Performance Relative To Energy and Density

4.2.2.1. Energy: 15J - Density: 80 kg /m^3

The deceleration recorded during impact in this combination of energy and density of liner ranged from 64 to 87 g for the first trial. The lowest value which also indicates the best performance was observed by the sample with the 60 degree angle and 8 mm width, while the 90 degree angle with a 24 mm width had the poorest showing.

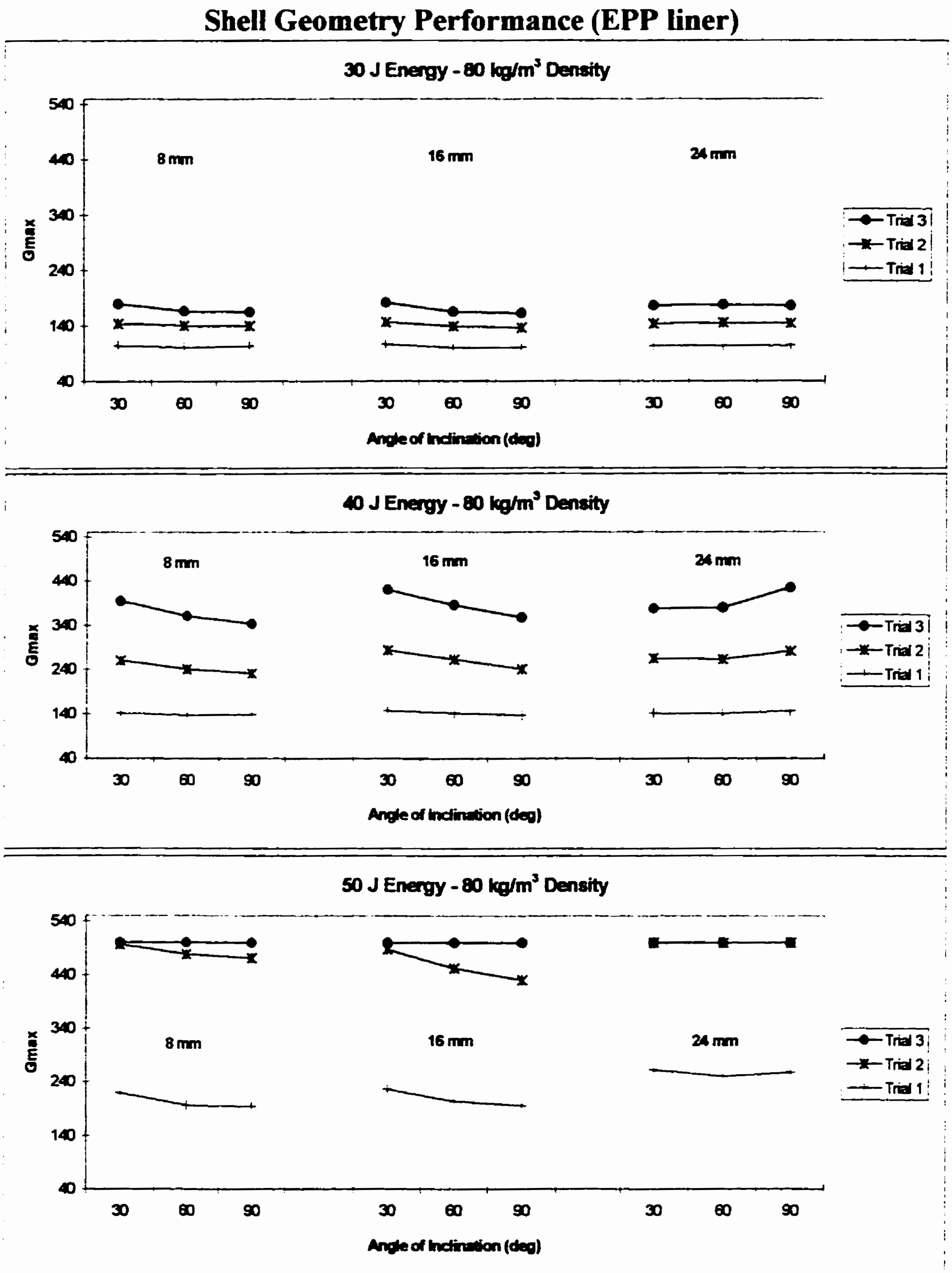

Figure 4.3. Shell geometry performance when EPP liner is used with a density of 80 kg/m3. Each graph corresponds to one of three impact energies (30, 40, and 50 J).

For the second trial the accelerations varied from 92 to 150 g. The most interesting observation, for this second trial is that the three best performances were demonstrated with a 8mm width. The same as in trial two applies for the third trial where performances ranged from 121 to 179 g.

4.2.2.2. Energy: 15 J - Density: 96 kg/m^3

At this higher density level initially the angle is important (60 degrees.) with the first trial. By the third trial width and more specifically the 16mm width was more important. Values here range from 48 to 51 g on the 1st trial, 59 to 65 g for the 2nd trial and 66 to 76 g on the last trial.

4.2.2.3. Energy: 20 - Density: 80 kg/m^3

Throughout all three trials the 90 degree-16 mm geometry displayed the best absorption characteristics. (142, 221 and 248 g for the three trials respectively). The worst performances were 231, 343 and 416 g for each trial. An important point in this category of results is the constant performance decline of geometries with an 8 mm top surface width across trials that shows a structural change in geometric shape at this level.

4.2.2.4. Energy: 20 J - Density: 96 kg/m^3

Although at the same energy level (20J), the difference in density results in an additional interesting observation. This time the 8mm width does not fluctuate in performance, as it did with the 80 kg/m^3 density, between trials. The 60 degree-16mm geometry did best in all three trials.

4.2.2.5. Energy: 25 J - Density: 80kg/m^3

At the highest energy with a soft liner the 90 degree-16 mm geometry regains top performance while on the opposite end we find all geometries with an 8 mm width component performed the worst. The interesting thing here is that the 60 degree-8mm geometry starts out at second spot on the first trial and then drops significantly.

4.2.2.6. Energy: 25 J - Density: 96 kg/m^3

This last combination of the energy-density variables the results are more grouped. The poorest performances are displayed by the geometries with a 24 mm width at all three trials with the 16 mm geometries doing the best and the 8 mm ones starting out well but declining in performance at the second and third trials.

CHAPTER 5. DISCUSSION

Performance of an ice hockey helmet depends on a number of variables. Although the helmet itself comprises of only two energy attenuating components, namely the shell and the liner, many variables within these two energy absorbing components, can significantly influence the impact absorption characteristics of a helmet, which is clearly supported by this study.

In the present experiment the two variables related to the shell component of the helmet that were evaluated were the angle of side inclination and top surface width. These two variables in turn play a key role in defining the geometric arrangement of a formation that can be present on a hockey helmet design. Other such variables controlling the geometric definition of a helmet are thickness of the shell, height and length of the formation.

The results obtained from this study revealed that geometry substantially affects the impact attenuating capabilities of the helmet after witnessing variations in performance in the range between 4 and 35%, only due to varying geometry. In doing so it effects the elasticity of the shell covering the liner. Each parameter influenced the elastic properties of the formation in a very specific way. For instance the angle of inclination was found to be responsible for controlling the bending of the formation along its length. On the other hand, the top surface width variable was responsible for bending occurring along the longitudinal direction of the structure. The above mentioned means that the two parameters examined act perpendicular to each other. This observation is attributed to the fact that the 90 degree angle performed better in this study overall, for both EPP and DERTEX liners, and all three impact trials. The length of the geometric shape formed on the sample in this study was constant at 100 mm. This meant that the length of the formation was at least four times greater than the width which was one of the independent variables and such a formation can be found on present day helmets. Consequently the geometric formation was vulnerable in bending along the width and in bottoming out easier. Therefore, the 90 degree angle, under the circumstances, provided more rigidity against denting in the direction along the width, as compared to the 30 and 60 degree angles. As for the width variable the best overall performer was the 16 mm level which provided average elasticity of bending in the longitudinal direction of the formation for which it is responsible.

From the above information, one can separate geometries into three categories: Very flexible geometries, which provide elasticity in both directions of bending, (along length and width of structure); geometries that are rigid in one of the two directions with the other directions being more flexible and to those geometries that provide less elasticity in the two directions (high rigidity).

An interesting observation that arises from the categorization of the geometries according to their elastic characteristics, is the importance of shell elasticity relative to liner elastic properties. In one instance, a relatively more flexible geometry (30 degree angle and 24 mm width) showed the highest absorption capabilities, when the liner used was EPP with a density of 96 kg/m^3, which was the stiffest among other combinations of the liner component. This scenario occurred only at the middle value of the energy variable (40 Joule). At the next level (50 Joule), the need for protection against bending along the length at the structure, meant that 90 degrees was more suited for the situation. Hence it is valuable for the designer of a hockey helmet to understand how a particular feature of the equipment, under construction, will react when one or more variables are altered. Even with the present study the main effects showed significant differences but the challenge lies in finding out where the differences occur for a particular variable when observed under different combinations of the other variables.

Often a designer is limited to work within a certain range of a variable. This limitation can have many sources such as limited space on a particular area of the helmet, cost limitations, comfort, the helmets' appearance (which would affect its marketability).

The inclusion and understanding of the interaction of a larger number of variables will assist in choosing the next best alternative. The results supported this strategy. For instance, if there is not enough space at a certain part of the helmet and only an 8 mm width can be used, as one of the variables controlling geometry, and when the liner used is DERTEX, an angle of inclination of around 60 degrees would be the designers best option. If an EPP liner is used then the optimal option is an angle of 90 degrees. Thus it becomes an issue of optimization, which means finding the best combination of levels of certain variables are best under specific material or impact conditions.

Geometric configuration plays an integral role in the absorption of impact at the higher energy levels, the later impact trials, and when the liner is softer. Under such conditions the differences between geometries is much more evident, unlike the differences seen between geometries at the lower spectrum of the energy variable. The above finding has serious implications in the design of hockey helmets destined for use by players of varying age, and level of play, (recreational versus elite).

Several studies have investigated some of the environmental factors that may cause injury. These studies mention that the falling energies or puck velocities produced by younger players after a shot, are not as severe as when compared to older players. The same is true for level of play. On the other hand, younger players, because of their lower level of skill and strength are more vulnerable to neck injuries. Geometry configurations on a helmet can contribute to a certain degree in injuring the neck, by providing an easy catch to an object such as the stick, puck, goal posts, etc. A helmet can be designed in such a way so to prevent this catching action from happening, thus reducing the possibility of increased angular acceleration, which combined with the increased vulnerability of a younger player to neck injury can have a detrimental effect.

Two possibilities can prevent the above scenario. One is to use a helmet with no geometric configurations, or manipulate some of the variables inherent in the geometry, for instance angle of inclination of the formation. The second solution is more appropriate since it can reduce the means to produce angular accelerations. This reduction can happen by decreasing the angle of inclination, thus reducing rotary component of the force delivered by the striking object. The designer can then choose a combination of variables that will provide maximum protection at the particular angle. This information can be used to assess the needs in other situations where a helmet is used - workplace or other sports - and provide feedback in deciding if geometry is necessary and if so to what extent.

With more weight placed on the angular accelerations and their contribution to head injury, the need to produce helmets that are lighter in weight and have a smaller thickness overall, has gained support. However, these alterations to the helmet may hinder the protection from head injuries, particularly in those areas where the skull is more prone to injury. Geometry as a result of this, can be used to help achieve the desired reduction in weight and thickness of the helmet while at the same time protecting the weaker areas of the head to a certain extent.

At this point another component of the helmet that can contribute significantly in protecting these areas requiring added protection, is the liner type and density. Although, the EPP is the liner that can withstand much more severe impacts than the DERTEX liner, the EPP liner is much harder and therefore a helmet with such a liner may be uncomfortable to wear. The same situation applies for the density variable. It was shown in this particular study that a sample with the higher density performed significantly better at both liner types. Once more the problem of drawing the optimal line in deciding which liner or density to use is presented. A possible solution to such a problem would be a combination of liners and/or densities that will accommodate both the comfort level and protection desired. Once more the influence of the liner-density combination on geometry performance that was investigated in this study becomes important.

The fact that the impact energies applied to the samples were different between samples with EPP and Dertex liners, no concrete conclusion can be drawn on whether a particular liner is more effective after sustaining repeated blows. On the other hand there were geometries that performed poorly after the first impact. This fact leads us to the conclusion that a particular geometric arrangement can undergo through some permanent structural damage after even a single impact. Addressing this issue is important since many people keep on using their helmets after sustaining a serious collision. With all the samples there was a significant difference between impact trials, especially between the first impact and the two subsequent ones. The difference observed can be explained by a lack of enough time to allow the material to recover (in a future study this point can be addressed by increasing recovery time as much as several hours or even days) or permanent deformation at the molecular level or both. The deformation of the geometric structure was apparent when observing the samples after the second impact.

In the future, incorporating more variables - such as height, shell thickness, and other structural characteristics of the geometric shape - involved in the performance of the helmet should be examined to better understand the problem of head protection. Investigating also how geometry plays a role in preventing angular accelerations from occurring, is an interesting undertaking. Finally, the discovery of ways to better simulate the reality of the environment within the lab should become a priority. Related to this study for instance, would be incorporating a sample that mimics the natural curvature of the actual helmet, which definitely would have an effect on how the geometry of a helmet attenuates the impact energy.

Conclusion: To conclude all hypotheses tested in this experiment demonstrated significant differences which indicates that shell geometry can play an important role in designing a helmet with improved performance.

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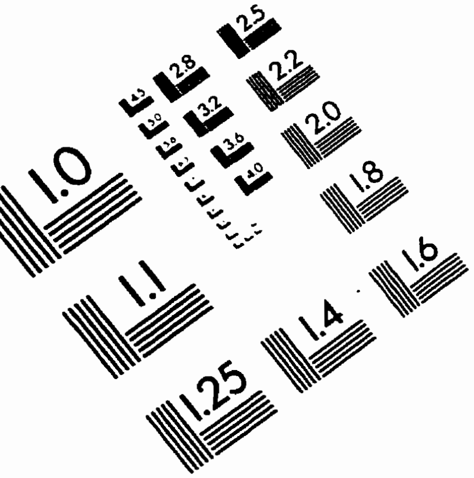
ANOVA TABLE
Summary of all Effects; DERTEX liner
1-ENERGY, 2-DENSITY, 3-ANGLE, 4-WIDTH, 5-TRIAL

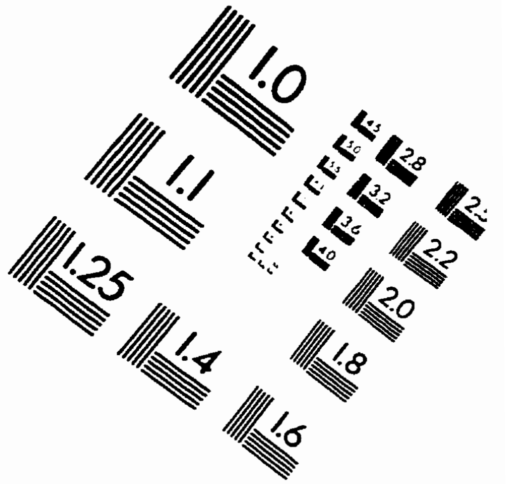
	df Effect	MS Effect	df Error	MS Error	F	p-level
1	2	2356696	162	1266.01	1861.515	0.000
2	1	2557270	162	1266.01	2019.945	0.000
3	2	19652.5	162	1266.01	15.52318	0.000
4	2	28640.7	162	1266.01	22.62281	0.000
5	2	633591.2	324	86.42081	7331.465	0.000
12	2	172410.4	162	1266.01	136.1841	0.000
13	4	3744.052	162	1266.01	2.957364	0.022
23	2	6696.394	162	1266.01	5.28937	0.006
14	4	11947.09	162	1266.01	9.436805	0.000
24	2	8491.551	162	1266.01	6.707334	0.002
34	4	7766.444	162	1266.01	6.134584	0.000
15	4	56453.88	324	86.42081	653.244	0.000
25	2	18988.03	324	86.42081	219.716	0.000
35	4	118.2356	324	86.42081	1.368138	0.245
45	4	2473.427	324	86.42081	28.62074	0.000
123	4	1642.245	162	1266.01	1.297182	0.273
124	4	12069.02	162	1266.01	9.53312	0.000
134	8	2046.203	162	1266.01	1.616262	0.124
234	4	5005.999	162	1266.01	3.954155	0.004
125	4	7345.813	324	86.42081	85.0005	0.000
135	8	76.98512	324	86.42081	0.890817	0.524
235	4	464.7121	324	86.42081	5.377316	0.000
145	8	1331.082	324	86.42081	15.40233	0.000
245	4	867.4171	324	86.42081	10.03713	0.000
345	8	786.2758	324	86.42081	9.098222	0.000
1234	8	1366.858	162	1266.01	1.079658	0.380
1235	8	303.487	324	86.42081	3.511734	0.001
1245	8	1475.973	324	86.42081	17.0789	0.000
1345	16	405.4328	324	86.42081	4.691379	0.000
2345	8	329.4789	324	86.42081	3.812494	0.000
12345	16	359.7573	324	86.42081	4.162855	0.000

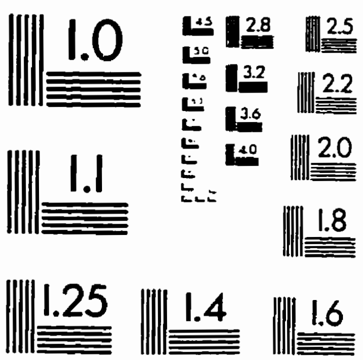
ANOVA TABLE
Summary of all Effects; EPP liner
1-ENERGY, 2-DENSITY, 3-ANGLE, 4-WIDTH, 5-TRIAL

	df Effect	MS Effect	df Error	MS Error	F	p-level
1	2	2756840	162	343.021	8036.944	0.000
2	1	523351.5	162	343.021	1525.713	0.000
3	2	8096.724	162	343.021	23.60417	0.000
4	2	9009.427	162	343.021	26.26494	0.000
5	2	1628296	324	73.90675	22031.76	0.000
12	2	86559.02	162	343.021	252.3432	0.000
13	4	2277.36	162	343.021	6.639126	0.000
23	2	770.1576	162	343.021	2.24522	0.109
14	4	5691.459	162	343.021	16.59216	0.000
24	2	2172.866	162	343.021	6.3345	0.002
34	4	5346.862	162	343.021	15.58757	0.000
15	4	258741.4	324	73.90675	3500.917	0.000
25	2	57374.69	324	73.90675	776.3119	0.000
35	4	579.1984	324	73.90675	7.836881	0.000
45	4	263.934	324	73.90675	3.571176	0.007
123	4	1368.781	162	343.021	3.990372	0.004
124	4	506.7348	162	343.021	1.477271	0.211
134	8	1192.112	162	343.021	3.475332	0.001
234	4	431.6418	162	343.021	1.258354	0.289
125	4	54411.2	324	73.90675	736.2142	0.000
135	8	282.1828	324	73.90675	3.818092	0.000
235	4	180.6877	324	73.90675	2.444807	0.046
145	8	701.1923	324	73.90675	9.487527	0.000
245	4	939.8637	324	73.90675	12.71689	0.000
345	8	605.3911	324	73.90675	8.191283	0.000
1234	8	334.2391	162	343.021	0.974398	0.458
1235	8	668.2594	324	73.90675	9.041926	0.000
1245	8	1647.764	324	73.90675	22.29518	0.000
1345	16	417.1341	324	73.90675	5.64406	0.000
2345	8	183.1716	324	73.90675	2.478416	0.013
12345	16	219.6035	324	73.90675	2.971359	0.000

IMAGE EVALUATION TEST TARGET (QA-3)







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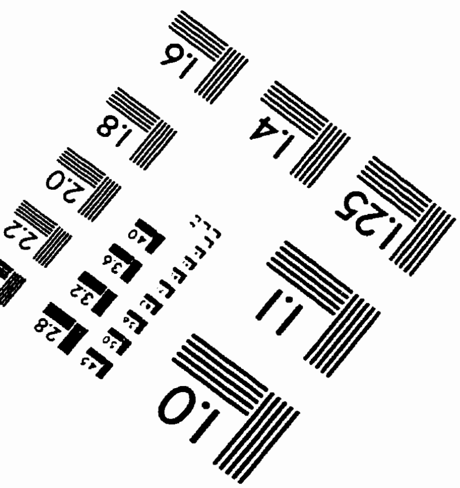

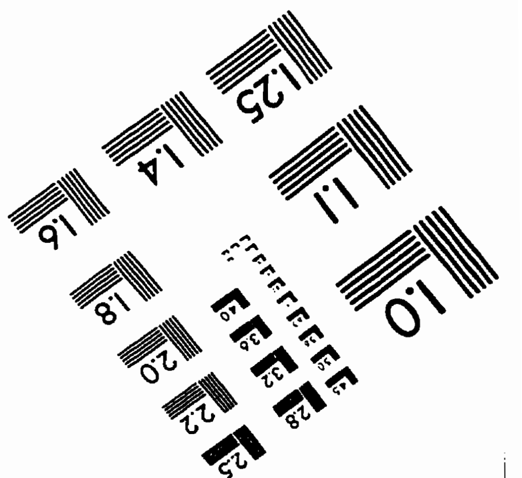

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