14
Biomechanics of Head Trauma: Head Protection

James A. Newman

Protection from injury caused by a blow to the head has been of interest since the beginning of recorded time. Injuries to the brain and its container, the skull, and to the outer covering of the head, the scalp, can be inflicted through a variety of mechanisms. Injuries include lacerations, abrasions, fractures, and other forms of tissue disruption. These are nearly always caused by excessive movement[1] of one part of the head relative to another. A scalp laceration is the result of a mechanical action (cutting or tearing) that separates formerly contiguous pieces of scalp. A skull fracture will occur when the skull bone bends more than it is capable of doing without breaking. A brain contusion, for example, is a collection of blood caused by the rupture of blood vessels that have been stretched too much. Separating, bending, and stretching are merely descriptors of somewhat different kinds of movement. To protect against all these kinds of injuries may require a variety of approaches. Basically, however, it comes down to padding and load distribution.

To appreciate the influence of the relevant variables, a basic understanding of head injury mechanisms is helpful (see Chapter 13). The head injury of most interest is, of course, that to the brain. Brain injury can occur if any part of it is distorted, stretched, or compressed, or if it is torn away from the interior of the skull. An impact to the head can cause the skull to deform and, even if it does not fracture, the underlying brain tissue can be injured as it distorts under the influence of the deforming skull. Even if the skull does not bend, if it is caused to move violently, distortion within the brain will occur. It is the minimization of brain tissue distortion that is the object of head protection.

This chapter examines the basic physics and design considerations related to head protection devices. The principles reviewed apply to padded surfaces as well as to helmets. Protective headgear systems encompass a large number of user and functional variables. These could include penetration resistance, retention, stability, ventilation, aesthetics, etc. Most of these will not be addressed here. The primary emphasis here will be on impact energy attenuation and the means by which this can be optimized.

The helmet is the most common form of head protection. Worn on the head, its purpose is to reduce the severity or probability of injury, to which the head would otherwise be subjected, caused by an inadvertent[2] impact to the head. A cross-sectional view of a typical motorcycle helmet is shown in Fig. 14.1. The basic features

[1] The deformation of certain parts of the head also constitutes relative movement. "Excessive" movement is meant to imply that there is some limited amount of relative motion below which injury would not occur.

[2] It may be argued that military and some forms of athletic head impacts are purposeful rather than inadvertent. It depends, one would suppose, if one is the giver or receiver of such blows.

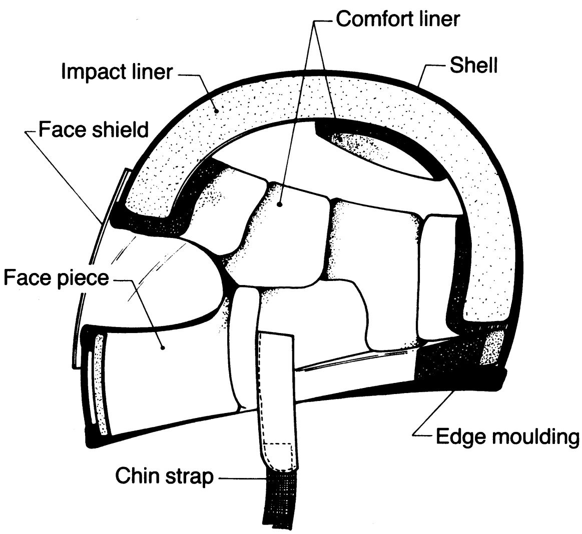

FIGURE 14.1. Cross section of a typical motorcycle helmet.

of all head protection are embodied in the concepts illustrated there.

A helmet, like other forms of head protection, accomplishes its protective function by "cushioning" the blow to the head. As shown in Fig. 14.1, it does this by encasing the head of the wearer in a specialized type of padding. To understand this cushioning process, which has to do with reducing the forces that produce the kinds of movement referred to above, some elementary physics are in order.

Physics of Motion

It is common in discussing head injury mechanisms and the performance of protective devices, to refer to the acceleration of the head. Usually, this is in terms of *g*'s, or gravity units. It is important to recognize that acceleration (expressed in *g*'s or any appropriate unit) is merely a measure of movement. By itself, it tells us nothing about forces, stresses, energy, or any other physical quantity. Only in its relation to other variables does its meaning becomes clear.

There are two basic kinds of motion, both of which can play a role in the head injury process. They are translational and rotational. There is considerable discussion about the relative importance of each kind of motion in head protection. The following review discusses the similarities and differences between the two types. The theoretical study of motion, kinematics, applies to any real object, including the human head.

Translation means, quite simply, that the object does not rotate. The movement is often simply called linear. The motion may be rectilinear or curvilinear. *Rectilinear* means the body moves in a straight line. The velocity may, however, change as the body moves. *Curvilinear motion* means the body moves on a curved path. In the latter case the body does not rotate but the velocity of the body does change direction.[3] In both cases, the velocity of every point within the body will always be the same. If this were not true, the body would be either deforming or rotating. Figure 14.2 illustrates the two kinds of linear motion.

Rotation means the angular orientation of the body changes. If the rotation is about some fixed point, like the axle of a wheel, the motion

[3] A body tends to move in a straight line unless a force acts upon it to cause it to deviate. Hence, curvilinear motion can only occur if forced to occur. In fact, a body moving at constant velocity along a curved path is accelerating (i.e., centripetal or centrifugal acceleration).

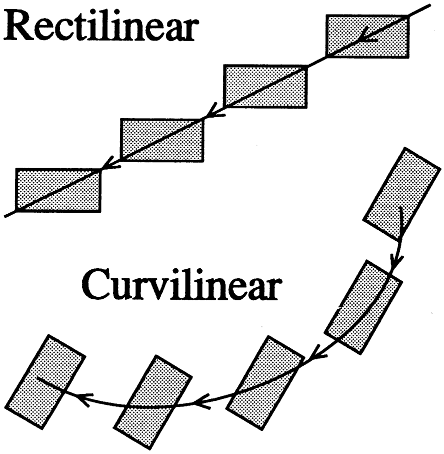

FIGURE 14.2. Rectilinear and curvilinear motion.

is referred to as plane circular motion. In general, the point about which the body will rotate is not fixed to the body and its location may change with time. A body that is rotating is one for which the translational movement of every point within the body, though related, is different. If the body can be considered to be rigid, certain simple, fundamental relations between the linear and angular kinematics exist.

In the case of pure translation, the movement of the whole body can be characterized completely in terms of linear kinematics of *any* point on the body. These kinematic parameters include the familiar displacement x, the velocity v, and linear (or translational) acceleration a. The displacement, velocity, and acceleration vary in time during an impact and there are fundamental relations between each of them. The general relations are of the form:

$$v(t) = \frac{dx(t)}{dt}$$
$$a(t) = \frac{dv(t)}{dt} \tag{14.1}$$

That is, velocity is numerically equal (exactly) to the instantaneous rate of change of displacement. Similarly, acceleration is the rate of change of velocity. Given the displacement time-history of a point on the body $x(t)$, it is thus possible to determine the changes in velocity and acceleration of that point on the body. Likewise, knowing $a(t)$ is sufficient to completely characterize the velocity and displacement (i.e., the relative movement) of that point. For a body that is deformable, and we can assume that the head is (i.e., some parts can move relative to some other parts), the motion $x(t)$ of different points on the body can be different. In fact they can be different even if the body is considered nondeformable (i.e., rigid). In this case, however, the body must be rotating.

In the case of rotation, the movement of the body can be characterized in terms of the rotational kinematic terms; θ, the angular displacement; ω, the angular velocity; and α, the angular acceleration. The relationships between these terms is analogous to the linear equations:

$$\alpha = \frac{d\omega}{dt}$$
$$\omega = \frac{d\theta}{dt} \tag{14.2}$$

Unlike the case of linear motion, rotational motion is not with respect to a point but rather is a description of the motion of a body. A wheel rotates about its axle. A boxer's head following an uppercut rotates about some undetermined, and moving, center of rotation. In fact, the rotation of a rigid *body* can be fully characterized by the linear motion of *points* within the body without reference to a center of rotation per se. Consider the movement of points A and B on the body shown in Fig. 14.3.

If the body is rigid, the distance between the two points, r, cannot change. That is, the velocity of point B toward A is always zero.[4] If point B moves relative to A at all, it can only move at right angles. If it does, the body is considered to be rotating. The angular velocity is, by definition:

$$\omega = \frac{(V_A - V_B)}{r} \tag{14.3}$$

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[4] Said differently, point A moves away from point B as fast as point B moves toward it.

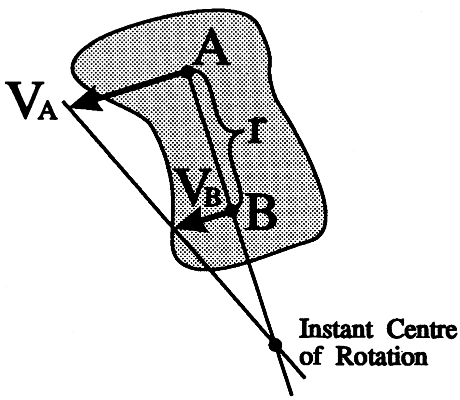

FIGURE 14.3. Free body in motion.

At any time when the linear velocity difference is not equal to zero, there is a point somewhere in space where the velocity is zero. This point can be located by extrapolation as shown in Fig. 14.3. This point, by definition, is the instant center of rotation. It may be fixed in space (on or off the body itself), as in the case of a wheel on an axle, or it may move if $(V_A - V_B)$ changes.[5]

If $(V_A - V_B)$ is *changing in time*, the body is undergoing angular acceleration. The relationship between these linear velocity changes and the angular acceleration is:

$$\frac{\frac{d}{dt}(V_A - V_B)}{r} = \alpha \qquad (14.4)$$

As stated earlier, head injury comes about principally by the movement of some part of the head relative to another. That is, the head is deformable. Thus, the application of the above rules for rigid body motion must be treated with some caution when applying them to head injury mechanisms. This is important because, as stated earlier, the effectiveness of various forms of head protection will often be described in terms of the acceleration of the head. To discuss acceleration, it is appropriate to review some additional physics that have a bearing on these matters.

Dynamics of Impact

A body will accelerate (linearly) when a force F is applied to it. During an impact, acceleration[6] occurs because of the forces generated by the collision of the body with something else. If the body does not deform, the relation between force and acceleration is the well-known expression:

$$F = ma \qquad (14.5)$$

where m is the mass of the body in question.

A rigid body will undergo *angular* acceleration when a torque T is applied to it. During an impact, angular acceleration occurs because a torque is generated. This is usually associated with impacts that have a component that tries to induce rotational motion. The equivalent expression for rotational motion is:

$$T = I\alpha \qquad (14.6)$$

where T is the applied (generated) torque, I the moment of inertia, and α the angular acceleration.

Since torque is a force acting about a lever arm, it is important to note that efforts to reduce force will typically reduce torque. Thus reductions in a will be accompanied by reductions in α.

A head, or any other body of mass m moving at a velocity V, possesses translational kinetic energy defined as follows:

$$KE = \frac{1}{2}mV^2 \qquad (14.7)$$

A body in rotation, will possess a rotational kinetic energy defined as follows:

$$RKE = \frac{1}{2}I\omega^2 \qquad (14.8)$$

If the head is caused to accelerate (or decelerate) its velocity will change according

[5] Note that if V_A equals V_B, ω equals zero. That is, translation is rotation about a point infinitely far away.

[6] The term *acceleration* will be used interchangeably with *deceleration*. In general, acceleration means with increasing velocity; deceleration, decreasing.

to the principles of equations 14.1 and 14.2. That is, it will be caused to possess more (or less) energy. This process will be associated with the application (or creation) of a force F in accordance with equations 14.5 and 14.6. The relationships between these variables is not important for the moment. What is important is:

1. The process of energy transfer takes time; and
2. The head is not rigid.

The head can, during the energy transfer process, deform under the influence of the force. It can thus be injured.

It is a fundamental tenet of physics that energy cannot be created or destroyed. When the kinetic energy of a body changes, that energy is either transferred elsewhere (by changing the velocity of the colliding objects) or is used to do work (i.e., it is used to deform something[7]). The energy of deformation is often considered to be "absorbed." The basic principle of head protection is to reduce the forces that could injure the head by absorbing some of the kinetic energy through the deformation or destruction of something else (i.e., padding, helmet).[8]

If the moving head strikes some object, and that object absorbs some of the kinetic energy of the head, the forces generated in the impact will be less. The extent of this reduction is a function of how much deformation is achieved and the force required to deform the object. The simplest relationship between the forces produced and the space required to absorb the energy is:

$$Fd = \frac{1}{2}mV^2 = KE \qquad (14.9)$$

where d is the stopping distance, F is the average force during the impact, and V the change of velocity. Clearly, for a given kinetic energy of the head, the larger the d, the lower the force F.[9] The actual force that will be developed will be a function of the strength, the amount, and the shape of the padding material on the impacted object or in the helmet itself and, of course, the mass, shape, and stiffness of the head.

The simplest type of relationship between crushing force and stopping distance is that of a simple spring:

$$F = kx \qquad (14.10)$$

where k, the proportionality constant, is the stiffness of the spring.[10] Many materials are springlike, though most do not follow the above simple linear relationship (i.e., k is not a constant). Nevertheless, the force generally increases with increasing deformation. Since x changes with time, i.e., $x(t)$, the force also changes with time. Given that force is proportional to acceleration then acceleration changes with time. The relation between $x(t)$ and $a(t)$ will always be governed by equation 14.1.

Material Considerations

Materials can be classified in two broad categories: plastic and elastic. If the material is plastic, it will not recover from any deformation that occurs during loading. When fully compressed, the velocity of deformation is zero. That is, all of the kinetic energy has been dissipated (absorbed). If the padding material is elastic, it will recover its original shape. As it does so, the force will follow a similar relationship but will decrease as the recovery takes place. In this situation, there is no net energy absorbed and the object will resume its initial velocity (but in the opposite direction). The

[7] When a car crashes into a rigid barrier, for example, the forces generated are used to destroy the front end of the car. The kinetic energy that the car possessed before striking the barrier is numerically equal to the work done on the car.

[8] It may also be appropriate to reduce the *duration* of the force to the extent possible, as injurious effects may be exacerbated if the loading persists for too long. The extent to which this is a significant consideration will be discussed later.

[9] The force generated by impact can never be reduced to zero unless there is an infinite amount of space in which to do it.

[10] The torsional analogy is that of an old-fashioned alarm clock spring. The torque required to wind the spring is proportional to the angle through which it is twisted.

maximum force developed will not be affected but the time during which the head is loaded will be doubled.

Most real materials are neither perfectly elastic nor perfectly plastic but fall somewhere in between. If the duration of loading is a significant concern, materials that are essentially plastic should be used. If the particular application is one where the helmet is to function more than just once (for example, in football), materials that recover their shape and their material properties are to be preferred. The best of all possible material options would be one that deforms plastically, then slowly recovers its shape and its strength, and is able thereby to deal with subsequent impacts.

The actual force that is produced when a material is crushed depends not only on the extent of crush x, but also on the inherent strength of the material and the size of the area loaded.[11]

The force developed when a helmeted head strikes something, or as the head strikes a padded surface, depends on the crushing characteristics of the material impacted and the amount of it used.[12] These characteristics are defined in terms of material stress–strain relationships.

Stress is defined as force per unit area, whereas *strain* is deformation divided by the initial undeformed thickness. The effect of area is quite simple. To compress 1 square inch of material to a certain strain requires the application of a specific force F. To crush twice the area requires twice the force. Hence, the greater the area of padding crushed, the higher is the force developed. Conversely, increasing the initial undeformed thickness of the padding reduces the strain for the same deformation, thereby maintaining a lower force.[13]

Curiously, perhaps at first glance, one of the primary objectives of good helmet design is to maximize the area of padding that can interact with the head during impact. Since higher forces induce higher acceleration and are associated with higher deformations (which in turn are related to higher injury severity), this seems to be something of a contradiction. It is not, for the following reason:

Maximizing the amount of material used in the collision maximizes the kinetic energy absorption, thereby minimizing the transfer of energy to the head. If the "high" force that is developed in this process is less than that necessary to produce injury, then this constitutes effective design. Doing that in practice, however, is another matter. In an accident situation, one cannot always know how much energy is to be dealt with, what the relative velocities are going to be, what are the shapes and stiffness of the things that the head might strike, and so on. Obviously, no known form of head protection can completely protect the wearer against all foreseeable head impacts. To consider these limitations, let's get back to a few basics.

Figure 14.4 illustrates a number of different stress–strain profiles, during the loading phase, for a number of hypothetical materials. Curve A corresponds to the linear spring, curve B to a stress behavior that is unchanging with strain, and curve C to a more realistic stress–strain curve of typical padding material.

For a given area loaded, and a known thickness of padding material, the curves translate directly to force-deformation curves. The area bounded by the curve and the deformation axis is numerically equal to the energy absorbed. It has been suggested that

[11] It may also depend on the velocity of deformation, being higher when compressed faster. Such materials are called rate sensitive and are often viscoelastic. Most padding materials are not particularly rate sensitive.

[12] It also depends on the stiffness of the head, which, as discussed, is not infinitely high, i.e., rigid. However, for the time being it can be assumed that the stiffness of the skull is so much greater than the padding material that the rigid head assumption is not an unreasonable one. Notwithstanding, it is indeed the deformation of the head that corresponds to injury.

[13] These generalizations are for an essentially flat piece of material being compressed across its thickness over a constant area. When the surface being compressed, or when the impacting object, is not flat, these simple relations will not hold exactly, as, for example, for a helmet or for a head impacting a flat, padded surface.

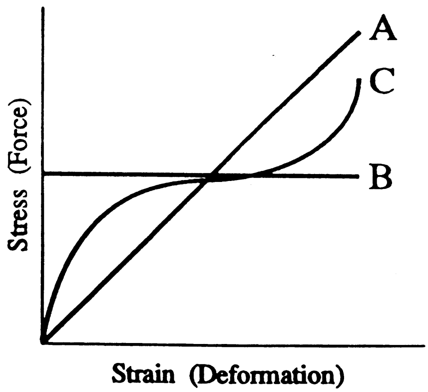

FIGURE 14.4. Hypothetical stress–strain curves.

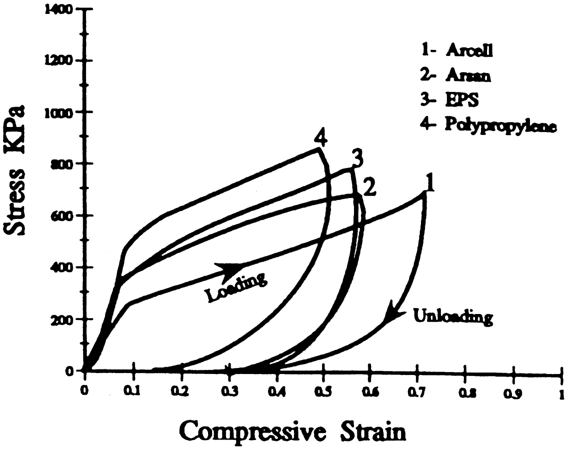

FIGURE 14.5. Stress–strain of padding.

curve *B* in Fig. 14.4 is the optimum type of material to use for padding. To confirm this, consider the following:

As a constant area impact is delivered to each of the materials depicted above, the material will begin to deform. Each will continue to deform until all the kinetic energy of the colliding object has been used up. At this point, the deformation will have reached its maximum value. The area under the force-deformation curve will be numerically equal to this energy. As the energy being absorbed increases, the force generated will be governed by the stress–strain (force-deformation) characteristics of the padding material. For material A, the force increases continually as the energy is absorbed. For material B, the force remains constant throughout the deformation process. Initially, material A produces a lower force than does B. If the energy of impact is low, material A will actually generate a lower force than B. As the energy increases, there comes a point at which the forces generated are the same. If even more energy is to be absorbed, the force produced by material A continues to increase, whereas that of B remains low. Hence, material B is capable of absorbing more energy, at lower force than material A. If the force, as limited by B, is lower than that which would produce an injury, then it clearly is a better choice than A. Even though at low energy A seems better, when it counts, i.e., when the energy is high, B is better.

Most real materials do not behave like A or B. However, materials whose stress–strain behavior approaches B are better. Though curve *C* in Fig. 14.4 is typical of a good hypothetical padding material, it will be recalled that most materials recover somewhat following impact. Figure 14.5 illustrates the stress–strain characteristics of several real padding materials during impact. The net energy absorbed is that absorbed during the loading phase *minus* that given back during the recovery phase. One important feature to observe for all these materials is that there is a definite limit to their energy-absorbing capability. They cannot crush more than their original thickness. When a real material is nearly fully crushed, it will become very stiff and the forces then developed become very high. When the material is no longer capable of absorbing additional impact energy, the unabsorbed energy is transferred to the head by accelerating it or deforming it and, potentially, injuring it. Thus, the head can be protected if the following two general conditions are met:

1. The reduction in the kinetic energy of the head during impact (i.e., that absorbed by the padding) is less than that which would completely crush the padding material.
2. Both the area and the depth of the padding crushed are small enough that, for its particular crushing characteristics, the force

developed is less than that necessary to produce sufficient relative movement within the head to constitute an injury.

The probability of meeting these criteria increases with:

Increased padding thickness
Increased padding area
Decreased crushing strength of the padding
Uniform crushing strength.

The first two maximize the energy absorbed; the last two minimize the force developed. Given that there is some limit beyond which increasing the padding thickness is impractical, the potential conflict presented by these criteria should be readily apparent.

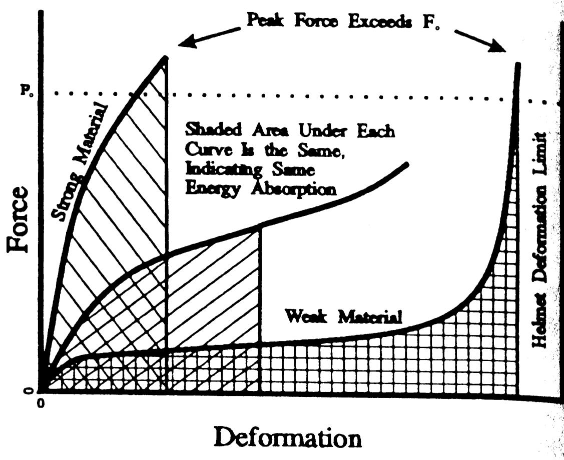

FIGURE 14.6. Effect of padding strength when the same energy is absorbed.

Helmet Design

Notwithstanding the generality of the above concepts, helmet design is further complicated by the following additional facts:

- A helmet is more or less spherical in shape, not flat.
- The amount of energy that will be delivered in any accident situation can never be forecast with great accuracy.
- The shape, mass, area, and stiffness of the striking object cannot always be anticipated.
- The user of the helmet will have specific needs that will limit the choices of design options.[14]

The object of good helmet design is to ensure that, regardless of the characteristics of the striking object, the loading area is sufficiently high that x does not exceed some critical value x_c. Furthermore, the force that is developed must be less than some critical value F_c if injury is to be avoided. The dilemma facing the helmet designer is illustrated in Fig. 14.6. If the helmet is too strong (high stiffness, high crushing strength, high area), the force developed, for a given amount of energy to be absorbed, can exceed F_c. Conversely, if the helmet is too weak, the deformation will become excessive and, as the helmet deformation approaches its limit, again F will exceed F_c.[15] These two extremes are illustrated in Fig. 14.6. Also illustrated is the force deformation response of a more suitable padding system.

A helmet usually consists of two primary elements. They are the outer shell and an energy absorbing liner.[16]

From a functional point of view, the object of the shell is to provide a hard, strong, outer surface that serves to distribute the impact load over a large area. It also provides a penetration shield against high-speed objects and, in addition, serves to protect both the wearer and the underlying liner of the helmet from abrasion with the impacting surface. In engineering terms, this means that the shell must be:

- rigid, i.e., high stiffness
- tough, i.e., high bulk strength
- hard, i.e., high surface strength.

[14] Helmets for different applications, e.g., football, hockey, motorcycling, etc., not only look different from each other, but are different for these reasons.

[15] This behavior of the material is frequently referred to as "bottoming out."

[16] Though usually true, some contemporary bicycling helmets have virtually no shell and others, principally military and industrial headgear, have a webbing suspension to manage impact energy rather than padding.

In addition, it should have a high strength-to-weight ratio and, usually, a smooth[17] exterior finish.

Interior to the shell is the liner of the helmet. It is this element that, through its partial destruction, is largely responsible for absorbing the energy of impact. To perform its function effectively, it must deform at force levels below that which would cause head injury.[18] Its strength should be largely insensitive to impact velocity and, to maximize net energy absorption, it should have slow recovery (rebound) characteristics. These requirements dictate that the liner should:

- have a well-defined, relatively constant low crushing strength
- be relatively strain-rate insensitive
- be essentially plastic in its crushing behavior.

These elements must be fitted together in such a fashion that the entire assembly satisfies the primary functional criteria. The choice of particular materials that meet the above requirements is but one aspect of the decision-making process. In principle, a great number of materials, if properly used, can be made to exhibit the desired properties. Within the constraints imposed by the intended application, however, the choice is somewhat limited.

Material Options

Shell

Common alternatives for this purpose are fiber-reinforced plastics (FRP) (e.g., fiberglass/resin composites) and thermoplastics (the most popular being polycarbonate). There are, however, others whose attractiveness depends on the particular application (e.g., racing, police, military). These include ABS, high-density polyethylene, ABS/polycarbonate alloys, and even metal. Recently, polyaramide fabrics have been found suitable.

The FRP materials can be compression molded, or a hand lay-up process can be used. The former, in conjunction with so-called chopped-strand techniques, produces a relatively homogeneous structure of broken fibers embedded in a plastic matrix. The latter produces a laminated structure that, properly made, is inherently stronger per unit weight in the normal direction for the fabric layers.

The thermoplastic shells are, for large-scale production, cheaper to produce as they can be readily injection-molded. For the same volume of material, they are also lighter than the FRP materials. However, they also tend to be less rigid unless molded with a very high wall-thickness. Furthermore, they are susceptible to stress concentrations set up, for example, around rivet holes, and in these areas they can be inherently weak.

One final factor is that, relative to FRPs, the thermoplastics can be brittle. This particular behavior may be amplified under certain environmental conditions (e.g., extreme cold). FRPs, on the other hand, tend to crush or delaminate rather than fracture on impact and are far less sensitive to environmental conditions.

Liner

The most widespread materials used for energy-absorbing liners are either semirigid polyurethane foams or expanded polystyrene bead (EPB) foams.

The former is produced by introducing, into a closed mold, two liquid constituents. The resulting exothermic process produces a foaming reaction that, given sufficient time, cures to produce a pliable helmet liner. The resultant properties of the foamed liner are highly dependent on such factors as initial mixture ratio, mold temperature, and curing time, and great care must be exercised to ensure consistent physical properties.

The EPB liners are produced by introducing a known amount of preexpanded polystyrene

[17] Smoothness is desirable as it limits the generation of tangential forces. It is these forces that can generate a torque that in turn may produce angular acceleration. Thus, smoothness reduces the probability of brain injury that might be associated with angular acceleration of the head.

[18] Or, if at a magnitude for which some minor injury might be expected, for as brief a time as possible.

bead into a closed mold and injecting steam. This causes the individual beads to expand and to adhere to each other. The resulting liner is a relatively stiff homogeneous structure possessing desirable stress–strain properties. The one governing factor that determines the crushing properties of the material is its bulk density, and this can be controlled quite accurately.

Both of the above materials are generally considered suitable. Both are relatively inexpensive.

Other materials that have either been used or have been considered include cross-linked polyethylene foams and synthetic rubber-based foams. Even honeycomb structures and inflatable bladders (filled with liquid) have been found to be effective for some situations.

The above-discussed alternatives provide some insight into the considerations regarding material selection and production methods. This clearly is only part of the design process as the geometric design itself leaves many areas in which decisions must be made.

To ensure that reasonable levels of impact protection are maintained regardless of the specific design requirements, performance standards have been developed for different helmet applications.

Helmet Impact Performance Standards

All helmet standards for impact performance are essentially the same in their overall approach. They each entail the following:

- The helmet is placed on an artificial head form in the way it would be worn by a real person. Different standards use different head forms, though all try to model the important features of the human head.
- The helmeted head form is subjected to an impact. The impact typifies the type of blow that could be encountered in the specific application. Energy level, environmental factors, and impact surface characteristics are considered.[19]
- The linear acceleration $a(t)$ of the head form is monitored throughout the duration of the impact.[20]

A typical helmet impact vertical drop test setup is shown in Fig. 14.7.

In these kinds of tests, the helmeted head form is raised to some predetermined height and released. At the moment of impact, the assembly will have acquired a kinetic energy proportional to the drop height and its weight. This energy will be dissipated during collision with the impact anvil. The downward motion of the head form is arrested by the force that is developed on it during this process. It is this force, changing in time. That causes the head form's velocity to change from its preimpact speed to zero. A typical helmeted head form acceleration trace is shown in Fig. 14.8. Regardless of the particular standard, to be considered acceptable the response of the head form must fall within prescribed acceleration limits. Some examples of these limits and their corresponding impact parameters are given in Table 14.1.

The Future of Head Protection

Improvements in head protection are always going to be limited by the laws of physics. In terms of acceleration, the minimum values achievable for various velocities and padding-liner thickness, are shown in Fig. 14.9. These levels cannot be achieved in practice as they

[19] For example, football helmets will be struck by surfaces that represent the playing surface and other players; hockey helmets are expected to perform when striking a hard flat surface when cold; military helmets are to protect against high-speed low-mass fragments; equestrian helmets are impacted by an object intended to represent a horse's hoof.

[20] Helmet performance standards do not monitor for a helmet's ability to moderate angular acceleration of the test head form. The reason for this is that the helmeted head form is constrained to move in an essentially linear fashion during impact. This feature of the test protocol is usually related to matters of test repeatability and impact site location.

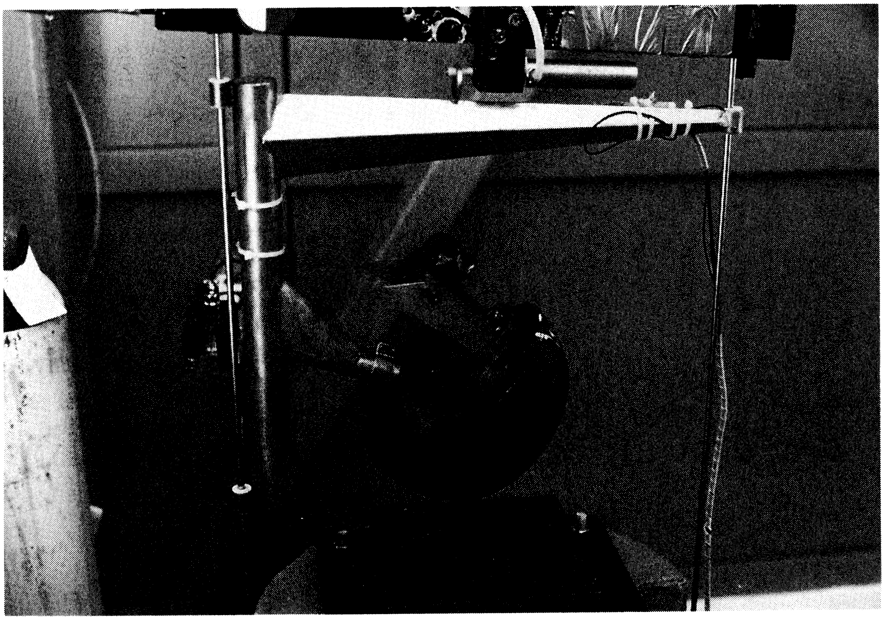

FIGURE 14.7. Typical helmet-impact vertical-drop test setup.

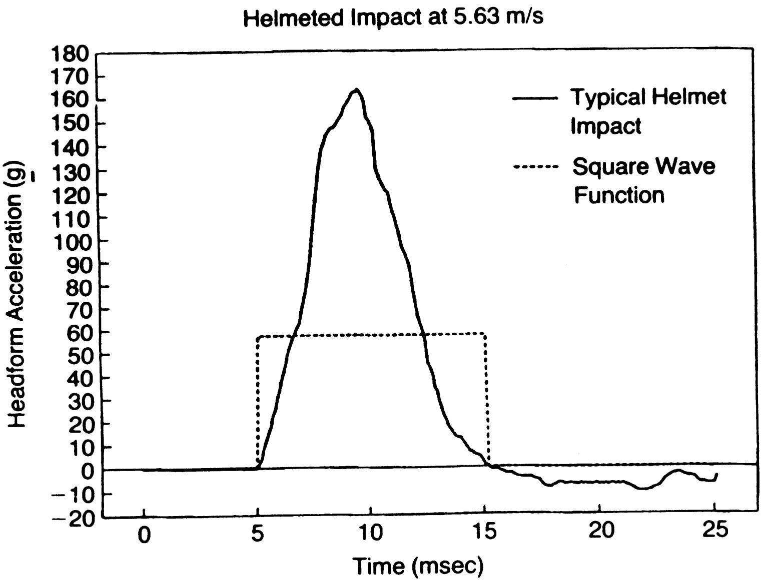

FIGURE 14.8. Typical helmeted head form acceleration trace.

represent theoretical limits. For a given velocity change and liner thickness, the optimum helmet minimizes the acceleration by maximizing the time duration of the impact event. To approach the theoretical limits, some refinements to current design and material technology are possible if not immediately feasible.

The curve in Fig. 14.8 shows a typical acceleration response for a "good" contemporary motorcycle helmet when impacted against a

TABLE 14.1. Helmet Test Standards—Impact Performance Requirements Summary.

Helmet type test method	Headform material	Drop assembly mass (kg)	Impact surface	Impact energy (joules)	Impact sites	Rejection criteria
Airborne sports						
EN 966-1996	Metal (EN 960)	3.1–6.1	Flat and curbstone	69 (mass of helmet incl.)	Two sites above defined test line	$a > 250g$
Auto racing						
Snell SA95	ISO metal	ISO—A, E, J, and M (5.0 min) (6.5 max)	Flat	150 (1st impact) 110 (2nd impact)	Sites above test line.	$a > 300g$
			Hemisphere	150 (1st impact) 110 (2nd impact)		
			Edge	150		
			Roll bar	150 (1st impact) 120 (2nd impact) 100 (3rd impact)		
Ballistic						
NILECJ 106	Metal	Headform (5)	Bullets		Front, sides, back	$a > 400g$
Bicycle						
ANSI Z90.4	Metal	Headform (5)	Steel flat	54	Four sites above test line	$a > 300g$
			hemicylinder	54		$a > 300g$
CPSC	Metal	ISO—A, E, J, M (5.0)	Steel flat, hemi	90	Four sites above test line	$a > 300g$
			V-anvil	56		
Snell B95	ISO metal	5.0 min 6.5 max	Steel flat	110 for certification testing	Four sites above test line separated by 120 mm	$a > 300g$
				100 for all other testing		$a > 300g$
			Hemispherical	72 for certification testing		$a > 300g$
				65 for all other testing		$a > 300g$
			Curbstone	72 for certification testing		$a > 300g$
				65 for all other testing		$a > 300g$
CSA D113.2—M89 rev. 5/96	ISO metal	5.0	Flat—2 sites	60	Each helmet will be impacted once at each of 6 sites.	$a > 250g$
			Flat—2 sites	55		$a > 200g$
			Cylindrical—2 sites	55	Impacts will be at any point above the test line.	$a > 250g$ GSI > 1,500
		Less than 5 years of age ISO—A, 3.1 E, 4.1	Flat—2 sites	50 and 67, depending on size	Each helmet will be impacted once at each of four sites.	$a > 200g$
			Cylindrical At least 1 site	34 and 45 depending on size		$a > 150g$

BS 6863	BS 6489	5.0	Flat and curbstone	52	Two sites with different anvils above test line	$a > 300g$
Crash						
NILECJ 105	Metal	Headform (5)	Steel flat	109 (1st) 95 (2nd)	Front, sides, back, top	$a > 400g$ $\underline{t@200}\,g > 3$ msec $\underline{t@150}\,g$, >5 msec
Equestrian						
ASTM F1163	Urethane/epoxy	ISO—A, E, J, M (5.0)	Steel flat, V-anvil	90 63	Four sites above test line	$a > 300g$
US Polo Assoc.	Urethane	Headform: three sizes—3.8, 4.5, 5.3	Steel cylinder 38 Shore A flat	56–82 80–95	Front, side, rear top, random	GSI > 1,500
EN 1384-1997	Metal (EN 960)	3.1–6.1	Flat	69 (mass of helmet incl.)	Two sites above defined test line	$a > 250g$ $\underline{t@150g} > 5$ msec
Firefighters						
NFPA	Metal	Headform (5)	Steel flat	78	Front, sides, back	$a > 400g$ $\underline{t@200g}$, >3 msec $\underline{t@150g}$, >5 msec
EN443-1997	Metal (EN 960)	5.0	Hemisphere	123	Top Top, 30° front, 30° rear, 30° left and right	$a > 150g$ F > 15 kN
Football						
NOCSAE-Jan/97	Urethane	Small 6.4 Medium 7.0 Large 8.1	38 Shore A flat	57 to 95 62 to 104 72 to 121	Front, front boss, side, rear boss, rear, top, random	GSI > 1,200
Hockey						
CSA Z262 1-M90	ISO headform	5.0 min. 5.0 max. 5.15	Steel flat	40 0	Three impacts per impact site Six impact sites; front; front base, side, lower rear, base, rear crown	>275g for a single impact HIC > 1,500
EN 967-1997	Metal (EN 960)	3.1–6.1	Flat	37	Crown, front, front boss, rear, rear boss, and side	$a > 300g$ and GSI > 1,500
Industrial						
ANSI Z89.1	Wood or metal	Missile (3.5)	Steel hemisphere	55	Top	F > 4.4 kN $F_{ave} > 3.7$ kN

TABLE 14.1. *Continued*

Helmet type test method	Headform material	Drop assembly mass (kg)	Impact surface	Impact energy (joules)	Impact sites	Rejection criteria
CSA Z94.1-M1992	Not specified	Not specified	Flat	55 (crown impact)	Each sample will be impacted once on the crown (first site) and then impacted at a minimum of 2 other sites at the lower impact energy.	$a > 85g$
				50 (all other sites)		$a > 150g$
EN 397	Metal or wood	5.0	Hemisphere	49	Top	F > 5 kN
Motorcycle						
Snell M95	Metal	ISO—A, E, J, & M (5.0 min) (6.5 max)	Flat	150 (1st impact) 110 (2nd impact)	Two sites above test line	$a > 300g$
			Hemisphere	150 (1st impact) 110 (2nd impact)	Two sites above test line	
			Edge	150	One site above test line	
DoT 218 (rev. 1988)	Metal	DOT-A (3.5) DOT-C (5.0) DOT-D (6.1)	Flat (2 impacts per site)	60 (A) 90 (C) 110 (D)	Two sites above test line	$a > 400g$ t@200g, >2 msec t@150g, >4 msec
			Hemisphere (2 impacts per site)	47 (A) 68 (C) 82 (D)	Two sites above test line	
CSA D230-M85	Metal	ISO—A, E, J, and M (5.0 min) (6.5 max)	Flat (2 impacts per site)	70 (1st impact) 140 (2nd impact)	Any site above test line	$a > 200g$ $a > 300g$
			Hemisphere (2 impacts per site)	70 (1st impact) 140 (2nd impact)	Any site above test line	$a > 200g$ $a > 300g$
BS 6658 (a) Competition	Any, but no resonant frequency	5.0	Flat (2 impacts per site)	140 (1st impact) 76 (2nd impact)	Three sites above test line	$a > 300g$
			Hemisphere (2 impacts per site)	123 (1st impact) 63 (2nd impact)		
BS 6658 (b) general use	<3 kHz (BS 6489)	5.0	Flat	106 (1st impact) 53 (2nd impact)	Three sites above defined test line	$a > 300g$
			Hemisphere	90 (1st impact) 46 (2nd impact)		

ECE Reg 22 (03)	Metal (EN 960)	ISO—A (3.1) E (4.1) J (4.7) M (5.6) O (6.1)	Impact 1–4, flat curbstone	87 to 172, depending on size	Four impacts on one helmet at 4 specific sites	Resultant $a > 175$ HIC > 2,400
Police riot						
NILECJ 0.0104	Metal	Headform (5)	Steel hemisphere	110	Front, sides, back, top	$a > 400g$ $\underline{t@200g}$, >3 msec $\underline{t@150g}$, >5 msec
CAN/CSA Z611-M86	Urethane/epoxy	ISO—A, E, J, M (5.0 + helmet mass)	Cylindrical Anvil	140 70	All points above test line incl. face shield	$a > 300g$ $a > 200g$

Glossary of Terms:

ANSI American National Standards Institute
ASTM American Society for Testing Materials
BSI British Standard Institute
CPSC Consumer Product Safety Commission
CSA Canadian Standards Association
DoT US Department of Transportation
ECE Economic Community of Europe
EN European Norm (std)
GSI Gadd Severity Index
HIC Head Injury Criterion
ISO International Standards Organization
NFPA National Fire Protection Association
NILECJ National Institute for Law Enforcement and Criminal Justice
NOCSAE National Operating Committee on Standards for Athletic Equipment
Snell Snell Memorial Foundation
a acceleration
t time
F force

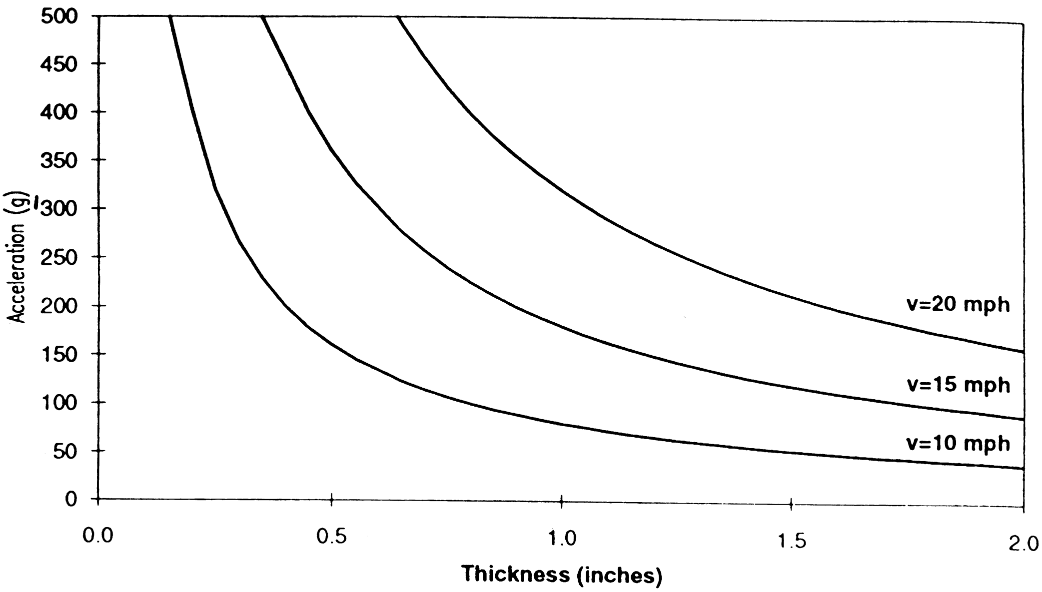

FIGURE 14.9. Minimum acceleration achievable.

flat, hard surface at a velocity of 5.63 m/sec. This helmet has a liner thickness of approximately 35 mm. The actual velocity change that occurs is the area under the acceleration–time curve. In this case, the velocity change is 7.7 m/sec, i.e., the helmet rebounds at a speed of 2.1 m/sec. Based on the acceleration response, it can be determined that the maximum liner compression was only 21 mm. That is, only 60% of the thickness available was used. Figure 14.8 also shows a hypothetical trace that, for the same impact velocity and using 80% of the available liner thickness, produces the lowest possible acceleration. The challenge for the helmet designer is to change the behavior of the headgear from that shown to, as close as possible, that theoretical limit.[21] To do this requires the following:

Compress all the available padding/liner material to the fullest extent possible (80% compression is a practical upper limit before bottoming).

Minimize the velocity change, i.e., eliminate rebound.

Maximize the onset rate.

Maintain constant acceleration throughout the impact.

Maximize the finishing rate.

Let us consider each of these separately.

A helmet is essentially spherical in shape. An idealized sectional view of a head within a helmet having an infinitely rigid shell and within a helmet having no shell, or a zero stiffness shell, each with a liner of constant thickness, is shown in Fig. 14.10. Also shown is the maximum compression of the liner thickness that could be achieved subject to these geometrical constraints. Notice how much of the liner is not fully used! The liner is compressed to its maximum only at the central region of the deformation. It is apparent that the rigid shell causes more liner to participate in the impact than does the no-shell helmet. This is the basis for the rigid shell concept from the beginning. In terms of maximizing the amount of liner that participates in the impact, however, even the theoretical, infinitely rigid shell seems far from optimal. Two possibilities exist to improve this situation: One is to completely fill the space between the head and the

[21] In undertaking this exercise, it will be recognized that one can never anticipate exactly where on the helmet an impact will occur and of what violence it will be. A helmet must be designed to accommodate a range of possibilities.

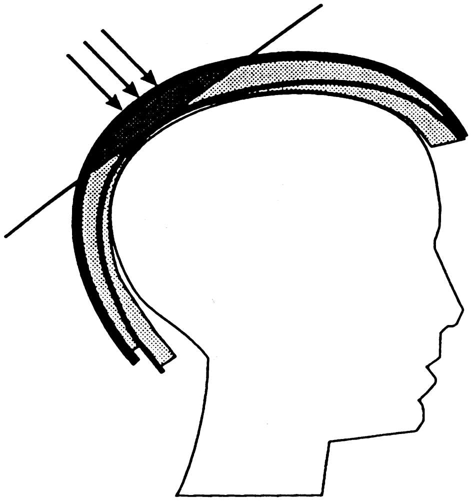

FIGURE 14.10. Liner compression shapes.

interior of the shell. The other is to cause the shell to somehow conform more closely to the shape of the head as it moves in toward the head. This, as illustrated in the shell-less helmet case, is opposite to the way the shell would want to deform.

Achieving the former might be feasible by custom fitting each helmet to each wearer. Indeed, such has been the practice with certain air-crew helmets. Of course, such a procedure can be expensive and may not be practical for widespread use. How the latter suggestion might be achieved remains something for future consideration.

The next consideration in creating the optimum helmet is to reduce the rebound velocity to zero. Most usual liner materials are permanently deformed when impacted and recover quite slowly if at all. Hence, they produce little rebound velocity. Helmet shells, on the other hand, because they are usually required to be rigid and strong, tend to be fairly elastic (until the loading causes a structural failure of the shell). Thus, after they deform, they bounce back. In doing so, some energy may be transferred back to the head. To minimize this, it is required, then, that the maximum deformation of the helmet assembly during impact also be the final shape at the end of the pulse. How zero rebound could be accomplished with contemporary helmet materials is also a subject for future consideration.

The third desirable feature to minimize head acceleration is to maximize the onset rate. That is, get the force generated by the crushing of the helmet up to the highest acceptable level as fast as possible. As seen in Fig. 14.5, the initial stiffness of a flat, uniform piece of typical padding/liner material, is not very high. If it could be made stiffer, without changing the crushing strength, such a material used in a helmet would produce a higher acceleration onset rate. Similarly, a high stiffness during the recovery phase, would maximize the finishing rate of acceleration.

Maintaining a uniform crushing strength for the padding/liner material has been a challenge for material technology for some time. One of the best examples of this kind of material is metal honeycomb. Unfortunately, it works best when flat and its properties are very unidirectional. Another interesting material is metal foam. Quite stiff up to a point, it then crushes very uniformly. Once crushed, it stays that way. Being a foam, its properties are preserved in all three directions. It is, as might be expected, rather heavy and expensive. Another potential candidate material consists of very small hollow glass beads embedded in a resin matrix. Lighter than metal foams it has certain potential that has not yet been fully explored.

In the absence of full contact between the head and the liner material, as in contemporary helmet design, or in the case of the unhelmeted head striking, for example, the interior padded surface of a car, the stiffness of the material should actually decrease with increasing deformation if a constant force/acceleration is to be maintained. This is because the area of padding being deformed increases as the nonflat head penetrates into the essentially flat padded surface. A material with such a reversed stiffness has yet to be invented. Possibly, in the not-too-distant future, some clever combinations of existing materials will be shown to possess such a characteristic.

Discussion

Helmets work. They do so by reducing the force that would be generated when an object strikes the head, or when the head strikes something. This force reduction is accomplished by the conversion of kinetic energy to work or deformation of something other than the head (i.e., the padding). Reducing the force on the head reduces its acceleration and, if well distributed, reduces the likelihood of skull bending. Both mechanisms reduce the likelihood of brain tissue distortion.

Thus, a helmet:

1. Cushions the blow to the head; and
2. Spreads the blow over a larger area.

Notwithstanding the advent of shell-less bicycle helmets, and the provision of very aggressive impact anvils in certain standards (equestrian headgear for example), few standards for protective headgear attempt to measure directly the ability of the device to perform the second function listed above. For impacts with common flat surfaces (such as the roadway), this should not be a problem. Protrusions of one form or another could, however, present some difficulties. In the future, it will be important to develop standard methods to measure load distribution and to set criteria of acceptability.

A second important feature of protective headgear is its relatively unknown capacity to protect against rotationally induced injuries. Since it is generally acknowledged that rotational movement is more likely to produce brain injury than is translation, and since contemporary helmets have been observed to be generally effective, one must conclude that they are effective in preventing injuries that would be due to rotation. Nevertheless, in the future, it may be important to try to develop standard methods to monitor for head form rotational acceleration and to set appropriate performance criteria.

A final area that needs future consideration is that of the head protection requirements specifically for infants and children. With the increasing emphasis on head protection for children riding bicycles or riding in bicycle carrier seats, it will become more important that children not be merely regarded as scaled-down adults. Their anatomy, anthropometry, and tolerance to brain injury cannot likely be adequately dealt with by extrapolating from adults. Additional research in this area must be conducted.

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