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PRINCIPLES OF CRASH SURVIVABILITY

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HISTORICAL APPROACHES

A comprehensive review of the history of impact protection is clearly beyond the scope of this review. The interested reader is referred to the bibliography for the chapter on Biodynamics: Transitory acceleration in DeHart's Fundamentals of Aerospace Medicine. Suffice it to say here that the endeavor to protect occupants in aircraft crashes began with the pioneers of aviation and continues to the present day. It has met with considerable success but remains limited by the remarkable violence that can be wrought when fast moving objects meet fixed ones. The human body has a meager ability to cope with such violence without assistance and practical methods of assistance can only go so far.

The basic lines of attack on the problem have generally been to provide a container to surround the occupant, provide a seat and restraint to hold him there, limit the accelerations of the container to tolerable levels, provide personal protective equipment such as helmets, and control for post-crash factors such as fire or water landing. Ejection seats, capsules or modules were something of a special case, since they were intended to allow the occupant to avoid the crash altogether. However, they posed their own set of risks such as the ejection accelerations, windblast, altitude exposure, parachute opening shock, parachute landing, and a host of others. They made a real contribution in many cases, but they didn't make the problem of impact injury go away.

Historically, the function of the container was to prevent the occupant from being struck by something from the outside and to keep him from being crushed like a grape. The restraint was thought of as a means to keep him from being ejected from the container and to prevent harmful impacts with the inside structure of the container. The accelerations of the container were expected to be limited to tolerable levels through the use of crushable structure serving the function of our deforming balls in collisions as described in the earlier portion of this paper. Helmets were expected to do the same thing for head impacts. When injury did occur, investigators would ascribe the occurrence to deficiencies in the protection or crash severity beyond the range in which protection could be reasonably relied upon. This was often considered a simple decision, particularly in very severe crashes with aircraft disintegration and multiple, extreme injuries.

The problem really arose in assessing injury in severe crashes where it seemed people might, or ought to, survive. Some have thought in terms of crashes being survivable or non-survivable. Death or serious injury in a survivable crash meant that a deficiency existed in protection. When people survived non-survivable crashes, it was ascribed to the realm of the miraculous. Human tolerance data for crash accelerations were based on tests with volunteers or cadavers in which maximum acceleration was referenced to the vehicle's center of mass or some similar point. All these approaches fail to consider the ways in which injuries come about.

The fact is, there is no magic dividing point between survivable and non-survivable crashes. Instead, there is an increasing probability of death with increasing severity for given kinds of crashes. Furthermore, injuries are produced in various ways and are not simply or most proximately related to the peak acceleration of the vehicle center of mass. A realistic view of crash survivability must be based on an appreciation of how injuries are actually caused and the techniques available to interrupt the process.

The Physical Basis of Injury: Stress-Strain Relationships

Impact injury typically refers to structural disruption of biological tissue as a result of a short duration physical event. The duration of an event that can be termed an impact usually is less than a second or two. The best distinction between an impact and a sustained event however, is that the body's principal response to an impact doesn't develop a sustained component. Impact causes tissue disruptions by placing stress on the tissue. Tissue can be stressed in different ways. Force which tends to compress tissue produces compression stress. The negative of compression stress is tension or distraction stress, produced by force which tends to pull tissue apart. A single number positive or negative can therefore be used to describe compression-tension stress.

It is important to note that compression force and the compression stress it produces are two different things. The same force can produce a wide range of stresses. If I apply a force of 40 newtons to your thumb using a thimble, it will be less stressful than the same force applied using a needle. Compression-tension stress is defined as the force per unit area over which it is evenly applied. This stress therefore varies with the cross-sectional area of the compressed structure.

It is somewhat unfortunate that stress is so difficult to measure, particularly for internal stresses within tissues. As a result, stresses on similar anatomic structures are usually compared by assessing the forces that produce them. For example, compression stress in the cervical spine may be assessed by measuring the axial force measured with a load cell placed in the neck of the dummy. This may allow meaningful comparison of internal stresses in the neck for similar neck orientations for similarly sized subjects. However, the internal stresses will change for the various load-carrying components of the vertebral elements if the same axial force is applied with varying degrees of cervical flexion. It is therefore a hopeless oversimplification to simply state that injury tolerance is so many newtons of axial force on the neck.

There are several other reasons why such a description is an oversimplification. One is that axial compression or tension stress is not the only kind of stress that can be placed on the neck or on other tissue. Mathematically, there are enough other kinds of stress that can be placed on a structure such as the neck or a femur to require a total of six numerical values for a complete description, namely

Compression-Tension Load
Fore - Aft Bending
Left - Right Bending
Fore - Aft Shear
Left - Right Shear
Clockwise - Counterclockwise Torsion

In general, real world tissue stresses in impacts involve some of each, but there are often one or two primary stresses. To complicate matters further, the significance of any given stress will typically vary with the orientation of the stressed structure as with neck flexion, for example.

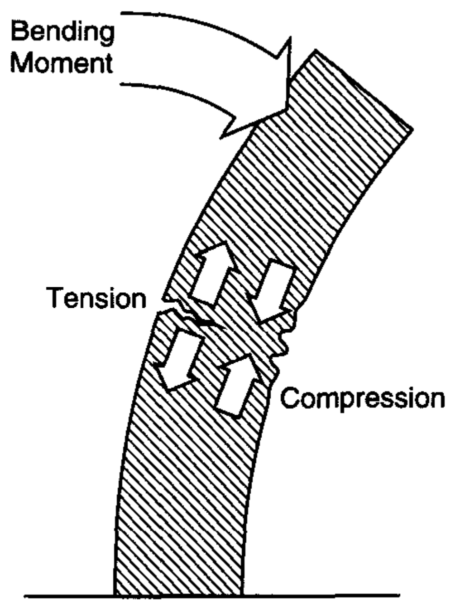

Figure 1. Example of forces and response of a material.

Bending stress is not produced by force but by torque which is measured in newton-meters or foot-pounds. Bending of a beam structure results in a number of internal stresses. For example, bending will place one side in tension and the other side in compression, as shown in Figure 1. Since it may occur in two dimensions, it requires two numbers for its description. The resulting stress also varies with the cross-sectional area of the bent structure.

Shear stress is produced by a non-aligned force couple which, if aligned, would have produced compression or tension. Since the force couple is non-aligned, it tends to produce slip. The name for shear stress is the same as that applied to a pair of shears for cutting cloth, with the stress being the same. The amount of shear stress for a given force couple again varies with the cross-sectional area. Since it is also two dimensional, two numbers are required for its description.

The final stress to be considered is torsion or twist. Only one number is necessary to describe it since it is one dimensional. Axial torque produces it and the resulting stress depends again on cross-sectional area. Internally, it produces local tension, compression, and shear.

Since all these stresses are typically involved to varying degrees in producing an injury such as a long bone or neck fracture, it is clearly inadequate to simply ask how many newtons or pounds were necessary to produce the fracture. Another reason that question is inadequate relates to the concept of strain.

The Physical Basis of Injury: Strain

Strain is the degree of deformation produced by a stress. Compression stress produces strain which decreases an axial dimension. The strain is measured as the amount of decrease in the dimension divided by the initial value. Bending stress distorts tissue about a cross-axis. Torsion stress produces angular distortion about the long axis. Shear produces distortion that might best be described as slip.

Resistance to strain is known as stiffness. The stiffer something is, the harder it is to deform. Most biological tissues and many other structures have stiffnesses which vary with the rate of change of the stress. If you apply stress very slowly, these objects behave as if they were less stiff than if you increase the stress rapidly. This property is known as viscoelasticity. As a result, the same stress can produce different amounts of strain depending on how the stress is applied. This is another reason why injury cannot be simply related to a single stress level or the force that produces the stress. Biological tissues are capable of experiencing varying degrees of distortion or deformation without being disrupted. When the stress is removed, the strain decreases. Ultimately, however, enough stress can be applied to create strain which causes permanent disruption of tissue which is the condition of injury. The disruption generally occurs in the following manner. Increasing stress results in increasing strain until a point where the tissue yields. From there on, the tissue's resistance to being deformed decreases and the strain increases even as the stress falls off. The point of transition is called the yield point or the yield strength of the material. On the near side of the yield point, permanent injury typically does not result. A continued attempt to impose stress beyond the yield point results in increasing injury up to structural disruption. Injury then is simply strain beyond the yield point.

One reason all this is important in understanding injury is that strain takes time. Suppose you apply a stress to a material sufficient to produce strain past the yield point, but you remove it rapidly before yield strain is achieved. Catastrophic injury would then be avoided. Tissues can tolerate normally injurious stress levels if they don't have to tolerate them for long.

Even without developing the detailed mathematics of stress - strain relationships for all the kinds of stresses, we now have enough understanding of the injury process to appreciate the need for increasing the sophistication of our descriptions of the forces that produce injury and the body's ability to resist being injured. It is not adequate to simply specify some level of force or acceleration as being injurious or tolerable. You must understand the kinds of stresses imposed by the force, the duration of the force, its variation with time, the condition, characteristics, and orientation of the stressed material, and the potential interaction of other stresses. The wide variation in data on human tolerance to injury can be better accounted for when these factors are considered. They similarly must be considered in assessing an accidental injury event.

Injury Mechanisms

Injury mechanisms are descriptions of the process by which an injury occurs. Defining the mechanism of an injury ultimately involves specifying the principal stress or stresses which proximately produce an injury. Even though six kinds of stresses may be applied to a neck which sustains an injury such as bilateral locked facets, the principal injury producing mechanism is consistently found to be a bending stress resulting from forced forward flexion. Increasing amounts of concurrent axial compression increase the likelihood of associated facet fracture with the dislocation and associated vertebral body damage as well.

As an example, consider the spiral femur fracture portrayed in Figure 2.

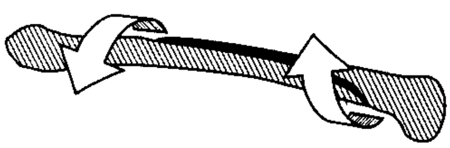

Figure 2. Spiral femur fracture.

The mechanism is principally torsion, with associated compression or tension potentially interacting with it. By contrast, the fracture in Figure 3 with the characteristic "butterfly" fragment is a classical bending fracture. We can say even more about the mechanism. Since we know that bone fails first in tension, we know that the failure will originate on the side of the bent bone that is placed in tension rather than compression. The fracture will then typically propagate along two diverging planes as the two ends slide around or push out the free fragment. We can therefore specify not only a bending mechanism, but also the direction of the bend, with the apex of the fragment pointing toward the tension side of the bend.

Other mechanisms can be found in the literature or often deduced from the characteristics of the injury when viewed from a stress-strain standpoint.

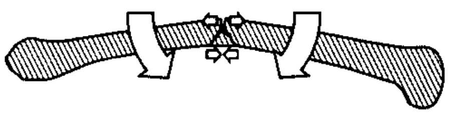

Figure 3. Bending femur fracture.

Injury Criteria

Injury criteria have been defined and used with mixed success in often conflicting ways through the literature. The problems not only reside in a frequent failure to understand the physical basis of the injury event but also in the necessity to apply injury criteria to dissimilar force-time profiles and dissimilar human beings who are experiencing them. Injury by its nature is still a stochastic process even in a relatively uniform population exposed to a reasonably similar stressor. There is no single binary threshold in impact stress below which nobody gets hurt and above which everybody is injured. Instead, there is generally an increasing probability of injury for an increasing level of severity. The problem is how to define severity in a way which will allow different kinds of impacts to be compared in terms of their injury potential.

The approaches that have been used have included terms relating to the motion of the vehicle and terms relating to forces or motions experienced by parts of the occupant. Vehicle-related examples include:

Average Acceleration
Peak Acceleration
Velocity change
Energy change

It should be recognized that velocity change is a measure of momentum change or impulse. Occupant-related examples include similar terms measured for a part of the occupant instead of the vehicle and other terms relevant to the occupant such as:

Belt Loads
Seat Loads
Femur or other long bone Loads or Torques
Spinal Loads, Torques or Shears

Data for these criteria derive from crash tests with instrumented anthropometric manikins. Curves have been developed to try to assess when certain types of injuries are likely to occur for a human on the basis of the instrumentation outputs from the manikins. Neither the curves nor the instrumentation cover all combinations of stresses at all potential injury locations. Moreover, humans differ from manikins in their characteristics and their dynamic response.

Various severity indices have been used to assess the comparative severity of dissimilar pulse shapes by manipulating acceleration-time profiles using various integration and weighting schemes. The GADD Severity Index (SI) was an early example of this approach with the Head Injury Criterion (HIC) as a more recent example.

Unfortunately, the HIC only addresses translational accelerations and the translational component of rotational acceleration, ignoring rotational acceleration and rotational velocity. The ignored terms have been shown to be significant particularly in the occurrence of diffuse axonal injury. Even more fundamentally, none of the listed indices or terms addresses the causation chain from force to stress to strain to yield point.

Some attempts along this line have been made and have met with some success. The Dynamic Response Index (DRI) is particularly noteworthy. It defines injury probability for spinal fracture in terms of the maximum strain of a simple viscoelastic model exposed to the vertical acceleration profile of the impact. The success of this approach likely relates to its general correspondence with the physical basis of spinal compression fracture which also is based on strain of a viscoelastic structure. Attempts have been made to generalize the DRI approach to three dimensions and to more generalized injuries. Other strain-based approaches have been employed with varying success for the head and chest.

More complex geometric modelling approaches have been developed to attempt to recreate body segment motions and compute internal stresses. While some of these have been useful in understanding body motion, they have not fulfilled the overly optimistic expectations of some for a fully validated means of comprehensively assessing internal stresses, strains, and injury likelihood.

In light of the deficiencies, injury criteria must be applied cautiously in assessing injury potential of a given crash. Dynamic testing with adequately instrumented manikins can, however, demonstrate gross occupant kinematic tendencies and highlight the applied stresses of greatest potential concern. One can also arrive at estimates of how these stresses may be affected by protective interventions.

PREVENTING IMPACT INJURY

Force and Stress Management

Since injury is simply strain beyond the yield point, the prevention of injury reduces to the problem of managing strain and limiting it to the recoverable portion of the stress-strain curve. The way you do that is to limit stress and the way that is done is to limit the force application that produces it and/or apply the force over a larger or more tolerant portion of the body.

Unfortunately, misunderstandings of the physical basis of impact injury have produced some cloudy thinking in this area, particularly with regard to energy absorption. Many seem to think that energy is almost like some kind of fluid that can be transferred around in an impact, concentrated in one place, or sucked up and absorbed so that occupants in a crash vehicle don't get it transferred to them. It isn't so. An occupant of a crashing vehicle, as viewed from a ground reference, has translational kinetic energy of $1/2\ mv^2$ before the crash and zero when the crash is over. His energy must change, and it doesn't change by getting absorbed like water in a sponge. To change the energy of an occupant you must change the velocity, because you can't do much about the 1/2 or the m in the energy term. The only way to change the velocity is to produce an acceleration since $v = a \cdot t$. The only way to produce an acceleration is to apply a force since $F = m \cdot a$. So you change the occupant's energy by applying force. You can't "absorb" it somewhere else or in some other way. The problem of impact protection can be viewed as the problem of rapidly applying substantial force to the body in as benign a way as possible. The management problem in crash survivability is fundamentally one of managing force and the resulting stresses rather than managing energy since you can only "manage" energy by applying force.

But what, then, is all this attention to energy absorption? Energy absorbed is simply work done on an object that doesn't come back in the form of elastic recoil. Crushed metal structure is an example of energy absorption. It has two benefits during an impact. The first benefit is that absorbed energy decreases the total energy change of the impact by decreasing the required velocity change to a minimum. In other words, it doesn't eliminate the "stop" in a crash, but it can decrease the "bounce back". This can have great benefit for the occupant who might not have stopped before he hits a part of the vehicle that is already bouncing back. Such a collision could occur at a velocity greater than the crash velocity. Perfect energy absorption reduces the required velocity change to that of the crash, which in turn reduces the required force during the available distance or time.

The second benefit of energy absorption is that it can allow longer stopping distances and times, reducing the required stopping forces. A very rigid vehicle hitting a barrier stops very quickly with very large accelerations and forces over very short times. A more crushable vehicle hitting the same barrier stops less quickly with smaller accelerations and forces over longer times. The perceptive reader will note that this benefit is actually related more to lower stiffness than to energy absorption since the same benefit would accrue even if the crush had a complete elastic rebound and no energy was absorbed. From a practical standpoint however, very stiff vehicles tend to be more elastic while more crushable vehicles tend to be less elastic and "absorb" more energy. Increased stopping distances and times from deformable structures is therefore a benefit that is reasonably related to the process of energy absorption.

The techniques of managing force in an impact include increasing the stopping time and distance by employing suitable stiffness for the vehicle structure and minimizing elasticity or rebound to decrease the required velocity change. The critical problem is to define what stiffness is most suitable. For a vehicle of given weight, the optimum stiffness depends on how much crush space you can afford and how severe the impact is going to be. The optimum stiffness for one impact severity will not be optimum for another. The ideal situation in a crash is to use up all of the available crush space or stopping distance just as you come to a stop. If you come to a stop without using up all the potential stopping distance, you have been applying more stopping force than you absolutely had to because the stiffness was too high. If you haven't come to a stop when you run out of stopping distance, you "bottom out" and experience very high accelerations and forces at the end because the stiffness was too low.

Unfortunately, you can't have a different vehicle design for each crash, even though some exotic adaptive techniques may eventually prove practical. The basic current approach is to optimize the stiffness - crush space design around some impact severity level which is reasonably likely to occur and where there is significant risk of injury or death. This is done with the recognition that the stiffness will be too high at lower severity levels where injury is less likely anyway. It is also recognized that the stiffness will be too low at higher severity levels where survival is less likely anyway. The chosen design represents a compromise which attempts to provide the most realized benefits over the expected range of crashes, knowing that the design is not likely to be the absolute optimum for any given crash.

Occupant-Oriented Protection

Thus far we have addressed crash survivability techniques relating to the management of forces and accelerations at the center of mass of the crashing vehicle. These accelerations will generally be different from those experienced by some body part of an occupant. The accelerations would only be the same if all parts of the occupant were perfectly coupled to the vehicle at the center of mass. This brings us to another compromise. Perfect coupling to the vehicle allows optimum benefits to accrue from vehicle crush during a significant impact but it is extremely uncomfortable during normal operation. Vibrations of modest amplitude can be tolerated better if occupants are somewhat uncoupled from the vehicle through the use of cushioning for example. Restraints also must allow some room for required motion, particularly for the head and extremities. Occupant decoupling from the vehicle means that, during an impact, the vehicle begins stopping before the occupant, ultimately resulting in shorter occupant stopping times or distances and higher occupant accelerations and forces. The compromise is between some decoupling for normal operation while preserving reasonable coupling for impact protection. Again, some adaptive techniques like belt pretensioners may improve coupling but benefits are likely to accrue only for certain impacts.

Occupant coupling is generally provided with restraint systems. Restraints bring their own set of protection issues, some of which are in conflict with one another. Restraint elasticity may counter some of the energy absorption benefits of inelastic vehicle crush by increasing the occupant's velocity change. At the same time, however, the elasticity of the restraint may allow longer stopping distances and times and lower the peak forces and accelerations. This in turn may promote contacts between some occupant part and internal or external structures which could constitute extremely short duration impacts with high forces and accelerations and lots of bounce.

In general, there will be a different acceleration-time profile for each part of the occupant's body, none of which may duplicate the acceleration time profile for the vehicle center of gravity. Despite all these differences, it is still usually helpful to describe a vehicle impact for comparative purposes, in terms of the acceleration profile for the vehicle structure at or near the occupant's position. We just have to remember that such a profile does not characterize the proximate stresses for a particular body part.

A further complication relates to occupant size. The population of potential occupants includes a wide range of anthropometric dimensions which may significantly alter the impact for all or portions of the body. For high performance aircraft, the severity of this complication has increased in some countries with the inclusion of female aircrew. The problem does not only relate to issues such as flail envelopes, tissue strength, and load variations for given acceleration profiles. In some cases, the imposed acceleration profiles may change as in the case of ejection seats with fixed thrust occupied by different masses. Restraint fit and function issues are also present in such areas as belt and harness angles and chosen seat positions affecting proximity to structure.

The protection strategy is typically to accommodate the broad range of potential occupant sizes and weights with provisions for excluding outliers who just don't fit. The exclusion strategy is usually more difficult in civilian vehicles than in military combat aircraft. Critical dimensions are sized around those who challenge them most. As an example, if a horizontal angle shoulder harness is defined for the tallest practical mid-shoulder sitting height, the angle for the shortest occupant is then assessed. If the range is too great to allow the required coupling, adjustable anchors or a "Just don't fit" category becomes necessary. Adjustable anchors also imply the potential for maladjustment. Care should be taken in analyzing crash injury in occupants of unusual size, since the urge to implicate mis-fitted protective equipment must be balanced by the recognition of the needs of occupants of more typical size and those at the other extreme.

Two other occupant-oriented approaches deserve mention. One is the range of techniques used to limit force and increase stopping distance within the vehicle. The use of stroking seats for helicopter crashes is perhaps the best example. Such seats may be designed to displace at a given applied force, with the seat bottom displacing downward with respect to the floor when more than that force would be required to prevent it. This is a force limiter and it defines the maximum upward acceleration that can be placed on a mass supported by the seat. It is clear that a smaller occupant will get a larger acceleration than a larger occupant exposed to the same force. A larger occupant exposed to a severe impact will stroke the seat more than a smaller occupant. Some systems even allow the occupant weight to be manually set or automatically sensed and adjusted for, at the risk of mis-adjustment and increased complexity. Stroking seats are often called energy-absorbing seats because they have no appreciable elastic rebound, but their role is really to provide force limiting and increased stopping distance for certain combinations of occupant weight and impact severity. If the design force is inadequate to stop the occupant in the available stroke distance, a relative velocity will exist between occupant and floor at the bottom of the stroke which must be rapidly stopped by large accelerations and forces, potentially worse than if the occupant had been in a non-stroking seat from the start. This problem is encountered with heavier occupants and/or more severe crashes. When encountering a fully stroked seat in a crash, the bottom-out velocity may be estimated using the energy equations if the crash velocity change component along the stroke direction and the effective occupant mass acting against the seat bottom can be estimated. Care should be taken in evaluating the significance of the stroke distance for crashes in which the forces are not consistently in reasonable alignment with the stroking direction.

The other occupant-related issue is that of padding. Padding may be vehicle-mounted as on a headrest or occupant-mounted as in a helmet liner. Padding serves three primary functions. First, it may increase the area of force application in an impact which lowers the locally applied stress. This may reduce skull fracture likelihood without meaningfully altering brain injury likelihood. Secondly, padding increases the stopping distance which can lower the magnitude of the applied peak force. Finally, if the deformed padding does not rebound elastically, the padding may serve to absorb energy and decrease velocity change, but only to the extent that the unpadded impact would have had rebound.

The performance of padding varies with the contact velocity, the required velocity change, the mass and visco-elastic characteristics of the impacting object, and the thickness and viscoelastic characteristics of the pad. The contact velocity and the required velocity change are two different things. If a head is against a pad when a vehicle impact occurs with force along the head to pad direction, the contact velocity would be zero. The further the head starts out from the pad, the greater the contact velocity up to the required velocity change. For a defined impacting object such as a head, a pad with a given thickness would need different viscoelastic characteristics to deliver optimum performance for different contact velocities and required velocity changes. Padding design, therefore, represents yet another compromise in injury protection. Any benefit can be estimated in a given crash by computations using the energy and momentum equations if the pad characteristics are known and estimates are available for contact velocity and required velocity change. Depending on the factors above, padding may be helpful, irrelevant, or harmful in a given impact. Harm would derive from circumstances in which the padding serves to decouple the occupant from the vehicle undergoing an impact. In any event, potential benefits of padding are largely confined to the structure sustaining the proximate impact such as a head for example. Potential for neck injury as a result of head impact is less likely to be beneficially affected by padding but may be made worse if the head "pockets" into the padding while the body continues to move.

Protection at the Margin

The investigation of an aircraft crash in which injury has occurred necessarily turns at some point to the causes of the injury and what can be done to prevent similar injuries in the future. Investigators have often advanced specific, sometimes sweeping recommendations for change in protective modalities which would provide seemingly obvious benefits in the kind of crash being investigated. Sometimes the apparent benefits are not real because they are based on misunderstandings of the physical basis of impact injury as discussed previously. Even when actual benefits would result from the recommended changes however, such recommendations may still be inappropriate if they simultaneously introduce other risks which would outweigh any benefit to be realized. The attendant risks may be more subtle than the benefits. To appreciate the overall result, one must understand both the physical basis of impact injury and the nature of protection at the margin.

No practical impact protection system delivers optimum protection for a given occupant in a given impact. Any real protection system is the result of a host of compromises among factors such as system weight, comfort, mobility and the ranges of occupant position, weight and anthropometric dimensions. In addition, real protection systems must be designed for the entire range of normal and emergency operations and for the entire range of impacts. Some beneficial things you might want to do for one type of impact might be harmful in another and pose additional problems in normal operations.

To approach the truly optimum, an impact protection system might involve a system of restraints with broad coverage areas applied to an occupant completely immersed in a viscous fluid having a density similar to that of their human body. You would need a breathing system. The fluid would be contained in a rigid sphere completely surrounded by a thick crush zone for good measure. You would surely be able to ride out some spectacular impacts, but you would have no visibility, little mobility, and therefore little reason to be there. The weight would be prohibitive. The system would have no operational utility. Designers have appropriately chosen instead to apply basic protection principles in systems which employ reasonable trade-offs among the various, sometimes conflicting design requirements. This necessitates some choices in impact severity levels for which the system will be tailored.

It is difficult to gauge the success of a design since so many factors must be considered and the relative importance of each factor will be perceived differently by different evaluators. It is certainly not reasonable to conclude that the very occurrence of injury in an impact implies a deficiency. Any practical system can be exposed to an impact severity beyond its ability to provide effective protection. More critically to understand, injury will occur even in well-designed systems when exposed to impact severities in the range for which the systems do provide effective protection. This is so because injury is a probabalistic event. An effective protective system may reduce the likelihood of injury for a given impact severity from a high level to a low level. When injury does occur with such a system, the urge to recommend change must be balanced by a sober evaluation of the potential deleterious effects that may be introduced for occupants in other circumstances.

This is particularly true when evaluating unusual or especially severe impacts. Since injury will become increasingly common at the margins of a system's protective capabilities, the urge to recommend change for impacts at these margins becomes greater. The changes, however, generally tend to move the design's optimization point to the more extreme impacts and often degrade protection in the more commonly experienced severity ranges where injury and fatality reduction is most achievable.

Examples abound where well-meaning "improvements" have been incorporated into protective systems only to have the injury and fatality outcomes made worse. This is not to say that current systems cannot be improved. It is to say that the variables in today's systems are sufficiently great that it is difficult to be sure that a proposed modification will represent an overall improvement. Most changes carry with them both benefit and risk.

The thoughtful investigator will assess injury occurrence with reference to its physical basis and in the context of the impact event and the overall performance of the occupant protection systems across the entire range of requirements. This will allow carefully considered contributions to the evolution of improved protection. The easy gains and many harder ones, have already been made.

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