Helmet Development and Standards

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Summary

The application of medical and engineering principles to the development and evaluation of trauma protective helmets is traced from the 1940's to the present. The development of performance standards, standards organizations, standards programs and the relation of all three to commercially available helmets is discussed. Particular attention is addressed to the development and central issues of methods for testing helmet performance in impact.

Introduction

The basis for any protective device is two-fold: there must be the perception of risk and there must also be the perception that the device somehow attenuates that risk. From antiquity to the present, protective headgear prevail whenever both these perceptions are present and disappear whenever either perception is questioned. This basis is particularly true for trauma protective headgear. Military headgear provide an excellent illustration.

The risk of head injury, particularly in warfare, has been acknowledged throughout history. The use of protective headgear may be as old as warfare itself. Gurdjian [1] recounts head injuries mentioned in the Iliad and refers to accounts that Alexander the Great had been saved many times by his fluted helmet. He describes military helmets in use thirteen centuries BC. and traces developments through to modern times.

However, protective helmets almost disappeared from combat after the rise of the musket. Headgear that had proven useful against swords, slings and arrows, served little purpose dealing with thrusting weapons like the bayonet or flat trajectory missiles like musket rounds. By the wars of the American Revolution, helmets had either disappeared or had shed their protective functions to serve other purposes. The armies of the United States Civil War were issued cloth hats and caps throughout the conflict.

The re-emergence of the metal combat helmet at the end of the nineteenth century may have been due to the advances medical treatment had made against bullet and shrapnel wounds to the extremities and torso. These helmets may have also been useful bump caps in the ramshackle constructions built into the trenches of World War I. However, they probably owed their existence to the new economy with which industry could produce them. They were inexpensive, rugged and identical; ideal issue for the millions that would be fielded in this century.

The protective capabilities of all headgear including combat helmets are continually being balanced by their wearers against other features such as visual impact, comfort and ease of use. The importance of visual impact, what sociologists might describe as the headgear's ceremonial and decorative function, is particularly strong in our species. Although the head contains a cluster of sensory organs and the brain itself, all of which should merit protection, it also contains an elaborate signalling device, the human face. Our eyes are drawn to others' heads and faces for identification. Facial recognition even has a unique locus in the brain separate from other functions. The visual impact of headgear will always weigh heavily in subjective evaluations of its worth.

The Modern Age

Western civilization is now just over fifty years into a new age of protective helmets. Protective headgear are commonplace for activities for which bare heads or cloth caps were once considered sufficient. This helmet renaissance owes much to technical advances in trauma care and materials science but these are not the driving force. The source of this renaissance is that helmets have finally come to the attention of the same analytical spirit that revolutionized Western science and industry.

Epidemiology is now providing strong objective evidence to support the two perceptions so basic to protective helmets: that injury risks exist and that helmets are effective countermeasures. [2,3,4,5,6] Medicine and engineering are uniting to improve helmet protection. Government and private organizations are fostering the development and sale of effective helmets to consumers. Helmet evangelists are preaching to the multitudes and lobbying legislatures and government agencies.

Although protective helmets have been used to advantage for more than three millennia, the first systematic investigations of helmet function and effectiveness appeared only recently, in England in the 1940's. Cairns in 1941 reported that in a study of over a 100 motorcyclist fatalities, 92% suffered from head injury and 66% had multiple injuries [7]. He also discussed 7 cases of nonfatal injury in which helmets had been worn and in which the injury had been "unusually mild." He discussed the structure of the helmets, noted accident damage and speculated as to how the helmets may have intervened to prevent more serious injury.

Even in the 1940's, motorcycle crash helmets had been available for some time. The helmets worn by Dr. Cairn's subjects were described as crash helmets, were British Army issue and differed substantially from standard combat gear. Dr. Cairns did not discover the crash helmet but he demonstrated conclusively that motorcyclists were exposed to a substantial risk of serious head injury and that crash helmets could be used to attenuate this risk. He also began the process of relating the mechanical behavior of crash helmets to the mechanisms of head and brain injury.

Before Dr. Cairns, helmet effectiveness was anecdotal and helmet design was based on intuition and armorers' lore. His 1941 [7] and 1943 [8] papers established the value of crash helmets as head protection and declared them fit subjects for medical and engineering study.

A Brief History of Helmet Standards and Programs

After World War II the Ministry of Transport in Great Britain began a serious effort to investigate crash helmets. The Road Research Laboratory of the Department of Scientific and Industrial Research searched the scientific literature for information on head injury mechanisms and the mechanical properties of human tissues. They also conducted series of experiments to identify potential helmet materials and helmet test methods. Their work led directly to the first performance standards for protective helmets.

The first of these standards was British Standard 1869:1952, Crash Helmets for Racing Motor Cyclists. [9] It was followed by British Standard 2001:1953, Protective Helmets for Motor Cyclists; British Standard 2095:1954, Industrial Safety Helmets (Light Duty); British Standard 2495:1954, Protective Helmets and Peaks for Racing Car Drivers and British Standard 2826:1957, Industrial Safety Helmets (Heavy Duty) [10,11,12,13].

Unlike earlier specifications which defined objects in terms of their materials, dimensions and production, performance standards defined helmets largely in terms of their function. That is, instead of describing the helmet they told how to test them.

This performance testing was a new concept. Helmets were being presented as an intervention in a chain of accident dynamics that would otherwise lead directly to injury. Break the chain and prevent the injury. The test methods did not simulate the entire accident but instead attempted to reproduce the significant dynamics at the instant before the helmet intervened. The test outcome was then based on measures of the significant dynamics just after the helmet intervention.

The nature of the intervention itself suggested appropriate test inputs and outputs. The tests for motorcycle helmets applied shock loadings to a helmeted headform. The test technicians would drop a hardwood block weighing ten lbs. from a height of nine feet onto a helmeted headform. The output consisted of dynamic force measurements recorded from a gauge mounted between the base of the headform and a massive reaction block. The test criterion required that the output force not exceed 5000 lbs.

These standards served two immediate purposes: they were tools for the evaluation of available headgear and they also served as guides for the design of new headgear. The stresses of the accident and estimates of human tolerances had been translated to engineering terms directly applicable to helmets. However, the standards were and remain elements in efforts to regulate the manufacture, marketing and use of protective headgear.

Qualifying helmets were to be marked to identify the manufacturer, country of origin, helmet size and the number of the British standard. The helmet was also to bear the kite shaped certification mark of the British Standards Institution (BSI). This 'kite mark' could only be used under license obtained from the BSI and required the manufacturer participate in quality assurance and testing programs administered by the BSI.

Certain products must bear the BSI certification mark to be sold at all in England. Certain activities, such as motorcycling, require the use of equipment bearing the mark and certified to the appropriate BSI standard. Even when the mark was not legally required either for sale or for use, the BSI 'kite mark' served as a guide to English consumers, distributors and retailers concerned about the capabilities of protective headgear.

In the United States, helmet development was pursued mostly by the military. By the late 1940's, the U.S. Navy was funding investigations into head impact at at least two universities. One of these investigations was conducted by Dr. C.F. Lombard, who originated the use of expanded polystyrene as a helmet material. He and his colleagues at the University of Southern California studied shocks applied directly to the helmeted heads of research personnel and graduate students [14].

However, these US efforts did not lead directly to the development of headgear for civilian use or to performance standards like those being formulated in England. The impetus for this effort arose as a result of the death of William Snell in 1956 in an amateur auto racing accident in northern California. Snell died of head injuries sustained in what was described as a survivable accident. His crash helmet had failed to protect him [15].

At the urging of members and officials of the Sports Car Club of America (SCCA), George Snively began an investigation of crash helmet performance. Snively, a medical doctor, was an SCCA Course Physician and had already been investigating protective headgear on his own for some two years. He began a survey of auto racing headgear that precipitated a revolution in the helmet industry.

A magazine article, "Skull Busting for Safety", appeared in the July 1957 issue of Sports Cars Illustrated detailing Snively's findings. Snively found fault with almost every auto racing helmet then available but, remarkably, the crash helmet industry was receptive to the criticism. In a note published with the article, the magazine's editor observed that the helmet industry had almost unanimously gone into emergency operation to improve crash helmet performance.

That same year, the Snell Memorial Foundation was incorporated as a non-profit organization in order to sponsor Snively's continuing work in crash helmets. By 1959, the Foundation had published the first American performance standard for protective helmets [16]. In the early 1960's the Foundation began to administer a helmet certification program similar in some ways to the programs of the British Standards Institute but with a fundamental difference.

The British Standards Institute set performance levels that every crash helmet should satisfy. Snively and the Snell Memorial Foundation set higher levels that only the best helmets would meet. As more and more helmets began to meet the standard, Snively would revise the test levels upward. He intended to create a continuing revolution and hurry the industry toward the best helmet a driver could be expected to wear.

The motivation for manufacturers to participate was purely economic. Snell certification helped sell helmets. Snively and the Foundation adapted free market principles to promote the rapid evolution of headgear.

Throughout the 1960's the Foundation's helmet standard was revised steadily upward. During this time, the standard was also taken up for motorcycle helmets. From 1970 to the present, the revision cycle stabilized to five year periods. As part of the 1985 revision, the standard was split into an 'M' series for motorcycle helmets and 'SA' for special applications which applied to auto racing helmets [17,18,19,20,21,22,23,25,26].

Other developments followed. In 1961 the American Standards Association (ASA) established a committee for protective headgear [27]. ASA, later the American National Standards Institute (ANSI) was and remains an umbrella organization which promotes standards development for a broad range of products, services and activities. ANSI polices the formation of committees and the standards writing process. They ensure that the committees are balanced over all facets of interest including providers, consumers and knowledgeable individuals. They require standards to be written according to a given format and subject them to a general ballot before adoption. Once a standard is adopted, ANSI requires that the committee reconsider the standard at least every ten years making revisions as necessary. ANSI then conducts the same general ballot before the standard is readopted.

ANSI Standards are consensus standards. Financial interest is not a barrier to participation. Some of the most energetic participants in the process are the manufacturers of the very products to which the ANSI standards apply. As a result, ANSI requirements should be met by every product and service. However, ANSI does not administer any corresponding certification programs.

The two standards makers discussed previously, the British Standards Institute and the Snell Memorial Foundation, each conduct programs involving pre-market and follow-on testing for all those products for which certification is claimed. Before a manufacturer can advertise Snell certification or apply the BSI kitemark, he must submit to the standards policing programs that each of those organizations administers.

ANSI imposes no such obligation. The manufacturer himself determines whether he may claim qualification to ANSI helmet standards. He need not provide any supporting documentation or even notify ANSI of his claim.

The first ASA helmet standard was Z90.1-1966, Protective Headgear for Vehicular Users published in 1966 [28]. The first revision was published by ANSI in 1971. A supplement, ANSI Z90.1a-1973 was released in 1973 in order to correct a technical error [29].

The International Standards Organization (ISO) also formed a technical subcommittee to consider protective headgear in 1960. This activity led directly to the promulgation of ISO Recommendation R 1511, Protective Helmets for Road Users in 1970 [30] and, later, of ISO draft standard, DIS 6220-1983, Headforms for use in the testing of protective helmets [31].

ISO itself arose in 1946 out of a United Nations effort. ISO standards are intended to promote international trade and are recommended as models for governments and others to use in developing national standards. Like ANSI, ISO publishes standards but does not administer any corresponding certification programs.

Another United Nations effort produced Regulation No. 22, Uniform Provisions Concerning the Approval of Protective Helmets and of Their Visors for Drivers and Passengers of Motor Cycles and Mopeds [32]. This was part of a general agreement concerning motor vehicle equipment and parts enacted in 1958. This document is currently in its fourth revision and, like ISO standards, is intended to promote international trade by harmonizing standards and enabling mutual recognition of approval.

In 1972, the United States Government announced a draft motorcycle helmet standard, Federal Motor Vehicle Safety Standard 218 (FMVSS 218) which would come to be known as the DOT standard [33]. The draft was taken almost directly from the most recent revision of the ANSI standard, Z90.1-1971, but included plans to impose more stringent requirements in September, 1974, eighteen months after the standard would take effect.

While the DOT draft was still being considered, ANSI published the supplement, Z90.1-1973a, to repair a technical flaw discovered in ANSI Z90.1-1971. The 1971 standard specified a newer test method but applied criteria developed for an older method. ANSI Z90.1-1971 was more difficult as written than the committee had intended. Furthermore, many considered that the additional difficulty would not necessarily lead to better helmets.

The National Highway Traffic Safety Administration (NHTSA), the responsible agency within DOT announced in 1973 that they would continue with the original criteria from ANSI Z90.1-1971 but did defer any decision on the changes scheduled for 1974[34]. The DOT standard took effect in 1974 essentially unchanged from the original draft except that the scheduled changes had been dropped altogether [35]. Although slight revisions have been made since its inception, the standard remains essentially unchanged from its original form. However, NHTSA has recently begun to consider an overhaul [36].

Like the BSI motorcycle helmet standard, the DOT standard is mandatory. Once it took effect, every helmet sold for use in street motorcycling in the United States was required to meet it. However, like ANSI, manufacturers claimed the certification for themselves. Once the manufacturer had claimed DOT qualification for his products, he was obliged only to label them with the DOT emblem. Manufacturers were not required to make any submission of samples, test data, production records or even notify the government before introducing a new helmet onto the market.

A group of motorcycle helmet manufacturers formed an industry organization, the Safety Helmet Council of America (SHCA), to provide a third party certification program to the new DOT standard. The program required manufacturers to submit test data for each new motorcycle helmet model before introducing into the market and to make annual submissions of test results for each model already on the market. Participating manufacturers were allowed to mark their products with an SHCA label. The SHCA collapsed during the 1980's.

When the DOT standard took effect, it was accompanied by a Federal push for State laws requiring motorcyclists to use appropriate headgear. Mandatory use laws were enacted in a number of states but many were repealed a few years later. For a time, NHTSA linked distribution of Federal highway monies to the passage of state helmet laws. This practice has been disallowed.

Bicycle helmets were also attracting attention. In 1970 BSI published British Standard 4544:1970, Protective Helmets for Pedal Cyclists [37]. In 1972, the Snell Memorial Foundation released three appendices to their 1970 general helmet standard, one of which applied to bicycle helmets [38]. The Snell standard was revised upward in 1984, 1990 and 1995 [39,40,41]. In 1984 ANSI published a bicycle helmet standard, Z90.4-1984 [42]. In 1993 the American Society for Testing and Materials (ASTM) published a bicycle helmet standard, F1447-1993, which was revised a year later in F1447-1994 [43]. Currently, the Consumer Product Safety Commission (CPSC), an agency of the US Federal government, is drafting a bicycle helmet standard which may take effect in the spring or summer of 1998.

ASTM is an umbrella standards organization very similar in scope and practices to ANSI. As with ANSI, ASTM standards are consensus standards that every product should be expected to meet. Also, as with ANSI, manufacturers determine for themselves whether they may claim ASTM qualification and then may proceed to do so with no submission of documents or notification of ASTM authorities.

CPSC began drafting a bicycle helmet standard as a result of an act of Congress, The Children's Bicycle Safety Helmet Act of 1994. The Commission had been petitioned directly to do so in 1989 [44] but had rejected the petition. A review of the US bicycle helmet industry and of existing voluntary standards and programs for bicycle helmets had persuaded CPSC that regulatory action was not justified.

CPSC has circulated two successive draft standards since the act was passed. The helmet requirements seem well reasoned and are stated clearly. As with FMVSS 218, the DOT motorcycle helmet standard, manufacturers will determine whether their products qualify and will then proceed to claim the qualification. CPSC requires no submissions or notifications but does oblige manufacturers to maintain a set of test records to support their claims.

Football helmets came in for scrutiny particularly after rising trends in head and neck injuries were observed in the 1960's. In 1973, two medical doctors, H. A. Fenner and A. F. James published a football helmet standard, JF73 [45]. The foreword to the standard states that it had been prepared and printed at the personal expense of the authors. The authors had previously participated on an ANSI committee established for the specific purpose of promulgating a football helmet standard but the committee had been disbanded just when a final draft seemed near. JF73 was and remains a particularly demanding standard but it was well within the technology that existed at the time.

In 1975 the National Operating Committee for Sports and Athletics Equipment (NOCSAE) published a football helmet standard that has since gained wide acceptance in the United States. More recently, the American Society for Testing and Materials has also published a football helmet standard [46].

Competing standards have proliferated in the United States and throughout Europe. In the US the effect is confusion. Since all the standards and programs promise safety, manufacturers and users often apply other criteria.

Manufacturers choose whichever makes the most business sense while user groups often select for helmet aesthetics.

In Europe the standards acted as trade barriers. One of the changes the Common European Market imposed on its members was the formulation and adoption of new Common European Norms or CEN Standards. In so doing, the Common Market will enforce mutual recognition of standards, certifications and products among its member nations.

These CEN standards are to be taken from ISO Standards whenever possible. The system is administered by 'notified bodies' that is, agencies throughout Europe empowered to consider applications for acceptance and to award the 'CE' mark which identifies each product meeting appropriate requirements. Once a product is CE marked, it may be transported and sold freely throughout member countries.

For protective equipment and, particularly, helmets, there is still much concern that the CEN standards will represent an amalgam of the least stringent national standards. Although one or more 'notified bodies' have been designated in each member country, there is much uneasiness that manufacturers and others may direct applications to the least demanding of them. Finally, there is no provision for proving the performance of products already awarded the CE mark.

Legal Influences

There is another uniquely American aspect of helmets that is also catching on in Europe, helmet liability. Helmet manufacturers, distributors and retailers may be liable for damages if a helmet fails to protect its wearer. Since the consequences of head injury are often severe, damage awards can be very large. The industry has turned to insurers to provide liability coverage. They have turned to standards as a means demonstrating the due diligence necessary to produce effective headgear which may in turn obtain lower insurance premiums and favorable court judgements.

When a more stringent standard exists, it may not be sufficient to produce helmets to a lower standard even if that standard is set by the government. Although there have been attempts to hold standards makers responsible for inadequate standards, the manufacturer, the distributor and the retailer have usually been held responsible to select and adhere to a proper standard.

Evidence presented by the plaintiff in helmet liability cases often includes performance testing conducted on samples of the model. Frequently, such testing is the first manufacturer-independent testing performed. Except for the certification programs of the Snell Memorial Foundation and those of the Safety Equipment Institute, all the current United States product qualifications are claimed by the manufacturer. NHTSA has done some spot checking of the performance of DOT labelled motorcycle helmets in the US markets but far too little to be considered effective policing.

Thus, civil liability is often the only check on large segments of the helmet industry. Since the issue in civil liability is whether and in what amount damages are due, it may not be a reliable means of removing ineffective headgear from the market or encouraging the industry to produce better, more protective helmets.

Helmet Standards - Tests

Standards facilitate trade. They codify expectation for both provider and consumer and relate the expectation to measurable product attributes. Standards require either that there be some general agreement on expectation and attributes or confidence in the integrity and capability of the standards maker.

Since the BSI standards issued in the early 1950's, every helmet standard specifies tests for protective performance. Although each standard specifies tests for several different aspects of helmet performance and some standards test aspects not considered by any other standard, all the standards specify tests for impact protection.

Helmet Impact Testing - Impact Input

Impact protection is the primary consideration of almost every helmet standard. The prescribed tests seek to reproduce the significant aspects of impacts to a helmeted head and then to measure and evaluate the significant aspects of the outcome.

The impacts as reproduced are highly simplified interactions. Virtually every test is a one dimensional exchange of momentum between a helmeted headform and an impactor. Rotations are minimized by careful alignment of the centers of gravity of the impacting bodies, careful alignment of the impact surfaces and sometimes by the mechanical test apparatus itself. It is generally considered that this one dimensional test configuration is sufficient to evaluate impact protective performance but one standard does prescribe an oblique impact test which is discussed further along in this development.

The standards also specify the masses of the impacting bodies, the headform properties, the surface configuration and properties of the impactor, and where on its surface the helmet may be impacted.
Finally, the standards call out impact severity.

The critical differences between standards in the issues discussed so far involve the impact sites, the impactor surfaces and the impact severities. Impact sites are most often prescribed by procedures that map a test area onto the surface of the helmet. The helmet is first placed on a special headform appropriate to the helmet size. Planes and points in the headform geometry are traced on the helmet surface. These markings then guide the construction of a test line. Test impacts must be sited on or above the test line. Thus, the headform determines the impact sites rather than the helmet.

Since the helmet may extend below the test line, especially on the sides and back, there is some concern that users may infer protection from lower impacts. However, most standards makers resist the conclusion that helmets should be tested over their entire surface. There are two reasons. The first is that although impacts involve areas, their sites are described as single points near the center of the impact area. An impact on the test line must necessarily include an area that extends below the test line. Whether stated or not, this impact 'footprint' is usually a consideration in the test line definition.

The second reason is that parts of the helmet extending below the test line almost always provide some protective benefit even if not at the level required on and above the test line. If these parts are not specifically required but will be tested if present, a manufacturer could conceivably turn a failing helmet into a passing one merely by trimming these extensions away. A standard that rejects more protective headgear in favor of less protective units is not acceptable.

Almost every standard specifies a flat impact surface for some of the test impacts. Most also require impacts against a shaped surface that delivers a much more focused shock to the helmet surface. Traditionally, this shaped surface has been a spherical section with a radius of curvature of about 48 mm however, other shapes are also used either in addition or as an alternative. These shaped surfaces challenge the helmet in ways that the flat anvil does not. The use of both varieties may also facilitate better helmet evaluation given the nature of the instrumentation used to monitor the test response.

Impact severity is generally specified as a velocity measured just before the impact. Most descriptions usually include a theoretical drop height. However, mass is also an important parameter in the specification. The Snell Memorial Foundation typically specifies impact severity in terms of energy but this energy reduces to a velocity requirement once the impact mass is specified.

Impact severity requirements vary widely across helmet types and even across standards prepared for the same helmet type. At this time, there are no objective determinations for prescribing impact severities for helmet tests.

Although some suppose that certain activities may actually require less protection than others, even the most demanding standards state that helmets meeting all the requirements may still fail to prevent injury or death in reasonably foreseeable accidents. Helmet standards do not specify all the protection a person might reasonably need. At best, standards specify only as much helmet as a person might reasonably be expected to wear.

If ideas such as style and tradition are not considered, reasonable expectation might lead standards makers to consider much higher requirements for impact severity. However, since helmet thickness necessarily increases with test severity, people will often refuse to wear serviceable helmets in favor of less protective but more aesthetically pleasing headgear.

There is a tension between these two ideas: all the helmet people can wear versus all the helmet people will wear. If standards cannot resolve the issue they should at least maintain the tension. Fashion is malleable. It will yield, however slowly.

Impact Test Output and Evaluation

The preceding account describes most of the issues in impact test inputs. There are also impact test outputs. Generally the outputs consist of a single axis of force or translational acceleration for the entire test headform. These outputs are captured and compared to a test criterion in order to evaluate the helmet's performance.

There are several criteria in use. The two simplest are peak criteria and duration criteria. Peak criteria require that the highest value of force or acceleration recorded does not exceed some maximum permitted value. Duration criteria limit the amount of time for which the output may exceed a specified value.

Some standards use more complex criteria such as the Gadd Severity Index (GSI)[47] and the Head Injury Criterion (HIC)[48] which are empirical attempts to relate injury to the time history of head translational acceleration. There has always been uncertainty whether these criteria are any more reliable than peak criteria or whether they even apply to helmeted head impacts at all. However, the biggest barrier to their use had been computational complexity. Now that computers are used routinely to acquire test outputs, HIC is receiving more attention.

All these criteria attempt to relate the test output to injury. However, there is little solid information on which to base these criteria. The peak criteria seem to have come about through experiments producing skull fracture in cadaveric heads and George Snively's investigations of auto racing accidents. The first BSI standards stated that the human head could withstand forces on the order of 5000 lbs and set peak force levels accordingly. This level corresponds to accelerations of about 500 times gravity (500 G's) which has been revised downward in succeeding standards to 300 G's.

The time duration criteria may have been an attempt to acknowledge information developed at Wayne State University in the 1960's showing that the tolerance of the human head to force vary with the duration of the exposure. The first time duration criteria were written into the ASA Z90.1-1966 standard for auto racing helmets [28]. However, these time durations did not have any practical effect since none of the helmets of the time ever failed to meet them. The 400 G peak was the only significant criterion in ASA Z90.1-1966.

The succeeding ANSI Z90.1-1971 standard [29] introduced changes in the test method which increased the values of the durations observed for all helmets. The duration criteria suddenly began to eliminate many of the products that had easily met previous requirements. Since this effect was entirely unexpected, the ANSI committee released ANSI Z90.1-1973a with new values for the duration criteria adjusted to match the new procedures.

The Gadd Severity Index was an attempt to reduce injury data from a number of sources to a single algorithm that could be applied to time histories of head acceleration data. The essence of the calculation raises acceleration in G's to a power of 2.5 and integrates with respect to time in seconds. So long as the product of this operation does not exceed 1000, the acceleration pulse was considered noninjurious. GSI was used to set design and evaluate vehicle interiors where bare headed impacts with dashboards and other obstruction had been a growing concern.

The Head Injury Criterion is a refinement of GSI that was adopted as Federal Motor Vehicle Safety Standard 208 (FMVSS 208). The calculation now raises average acceleration to the 2.5 power and multiplies by the length of the time period in seconds. The peak value for any time period of up to 32 milliseconds over the duration of the acceleration pulse must not exceed 1000.

The first drafts of the DOT motorcycle helmet standard FMVSS 218 intended eventually to substitute HIC for peak and duration criteria taken from the ANSI Z90.1-1971. However, HIC would have eliminated every helmet then available. When the standard took effect, HIC was dropped but the authorities also refused to revise the duration criteria to those of ANSI Z90.1-1973a.

Recently, United Nations Regulation 22 Revision 4 [32] applies the HIC algorithm to evaluate motorcycle helmets. The maximum HIC value permitted is 2475. This level is well above the 1000 limit set in FMVSS 208 and is also well above the level of 1500 advanced by some as appropriate for helmet tests. It does appear to be within the capabilities of many currently available helmets.

Even when there is agreement on the type of criterion, standards differ on the criterion limits. Some of the differences reflect concerns about the needs of the populations who will wear the helmets. Some are in response to injuries like slight concussion which had previously not been considered threats to life or quality of life. Finally, some believe that helmets may be evaluated reliably at substandard levels of impact severity merely by applying more stringent criteria.

Most helmet criteria are based on the needs of adult males. The information available is sparse but virtually all of it comes from accidents involving young adult males and tests conducted on adult male subjects or adult male cadaveric segments. Older people may have different needs. It has been noted that aging tissues become less flexible and that older people require longer recovery times for similar injuries. Very young children may also have different needs but, for these, the picture is not so clear. Children's tissues are much more flexible than those of even young adults so that higher levels of force and acceleration may actually be tolerable.

Helmet criteria are also based on levels of force or acceleration thought to produce death or profound non-recoverable injury. Concussion had only been considered when the circumstances of the incident required that the wearer be able to execute escape maneuvers. Combat pilots, for example, need to be able to activate ejection seats, exit sinking or burning aircraft and possibly evade hostile forces afterward.

However, multiple concussions and even multiple blows of subconcussive strength may lead to permanent injuries [49]. For this reason, some have suggested that helmets should be required to prevent concussion. These same people have also suggested that concussion protection requires softer helmets than those currently available. Therefore, test criteria must be made more stringent so as to force the production of softer headgear.

If softer helmets are to withstand test impacts at current severities, they must be substantially thicker. Otherwise, some of protection from the sorts of head injuries that immediately kill or disable must be sacrificed. It is unlikely that the public would immediately accept thicker helmets.

Currently, there is no reliable information concerning test criteria and the risk of concussion. There is no basis either to set new criteria to reduce the incidence of concussion or to evaluate a trade off between concussion protection and the sorts of protection for which helmets traditionally have been worn.

Finally, some suppose that impact severity and impact criteria are somehow linked so that tests conducted at lower levels of impact may still be made useful merely by evaluating the results according to more stringent criteria. There is no such linkage. Helmets may test well up to a certain severity but beyond that the outputs spike upward beyond any test criteria and, usually beyond the range of the instrumentation. The transition is sudden. It depends on the test severity and on the design and construction of the helmet. There is no known way to examine output for a helmet tested at a severity below this transition and determine performance at higher levels of severity.

Impact Test Apparatus

There have been many different systems for performing helmet impact tests since the 1940's. The following descriptions detail the progression to current methods.

The Brinell test [11,13] employs an apparatus that resembles an oversized office stapler. A headform is supported atop the stapler arm so that shocks applied to the top of the headform press a hardened steel ball into the surface of a small aluminum impression bar in much the same way that a staple is pressed into sheets of paper. A helmet is placed on the headform and an iron ball is dropped from a measured height onto its crown. The diameter of the impression left in the aluminum bar is directly related to the peak force transmitted through the helmet.

There are several disadvantages. The most serious is that only crown impacts are well accommodated. Cairns and almost every investigator since has pointed out that crown impacts are rare. Crash helmets receive most impacts in the front and, to a lesser degree, on the sides and rear.

This Brinell technique was used well into the 1950's in the BSI standards for industrial safety helmets. However, the BSI standards of that time for motorcycle and auto racing helmets [10,11,12] made several improvements on the technique. The iron ball was replaced with a heavy block that was guided to impact by wires. The stapler mechanism was discarded. Instead, the headform was mounted directly on a force transducer that converted the vertical component of force into an electric signal that could be captured and analyzed. The headform itself had been redesigned to permit helmet impacts in the brow and rear as well as the crown. Essentially, the helmet could be positioned with either the brow, the crown or the rear uppermost.

These improvements corrected many of the problems associated with the Brinell device. The lower surface of the heavy block could be shaped to simulate a range of impact surfaces. The entire time history of the force was available for study. However, the impact sites on the helmet were still limited. Hat band impacts, that is, lateral impacts and impacts low on the brow or the rear of the helmet were still not possible.

After experimenting with pendulum devices, George Snively at the Snell Foundation began to work with a 'swing away' test rig that would facilitate these hatband impact configurations. The origin of the swing away rig is uncertain. Correspondence from the mid 1970's [50] suggests that it was developed by the Snell Memorial Foundation but neither Snively nor the Foundation has ever claimed credit.

The swing away device replaced the floor mounted headform and force transducer with a headform mounted on a pivoting armature. The armature, stabilized in a horizontal orientation by a brittle glass rod, held the headform in position until it was struck by the wire guided impactor. At the instant of impact, the rod shattered and allowed the arm to swing down and away under the force of the blow. An accelerometer mounted at the center of the headform produced an electronic signal proportional to the headform acceleration and to the forces applied to the headform.

The advantage was that impacts could be delivered easily to the front rear and sides of the headform. The disadvantage was that the swing away device was mechanically complex and many of its parameters directly influenced the test. The interaction was between two movable inertial bodies and differed significantly from the one body systems used before and since.

Although the system was technically feasible, it did not have the intuitive appeal of previous methods or of the ones that followed. Comparisons between swing-away tests and tests on other devices have been plagued with misunderstandings merely because many people failed to consider the mechanics of the interactions. One of these misunderstandings led ultimately to the time duration controversy in the ANSI Z90.1-1971 and FMVSS 218 standards. Snively and the Foundation moved on to falling headform devices in the mid-sixties but swing away devices were used in England through the Seventies.

There are now a number of falling headform devices being used in helmet impact testing. A helmet is tested by placing it on a headform of a given mass and allowing it to fall onto an appropriately shaped anvil supported by a massive reaction block. As with the swing away devices, the headform response is taken from an accelerometer mounted at its center. The methods are appealing because of the obvious similarity with accidents in which a falling person's head strikes a rigid unyielding surface.

There are two broad classes of falling headform devices, guided fall devices which control the orientation and position of the headform and free fall devices in which much of that control is foregone. The advantage of the guided fall devices is that a single axis accelerometer may be used. Acceleration is a vector quantity with two horizontal components in addition to the vertical component. Since the vertical component far outweighs the other two, guided fall systems are set to orient the accelerometer to capture this component and the two horizontal components are left unmeasured.

There are two types of guided fall systems in use, twin wire and monorail. In both, a metal ball is mounted on a frame with bearings that slip along the wires or the monorail. The ball fits into a socket in the headform so that the headform may be adjusted in a broad range of orientations. A simple clamp may then be tightened to lock the headform in position. Since the orientation of the ball with respect to the guidance system never changes, the dynamics of any impact may be monitored by a single axis accelerometer positioned inside the ball with the sensitive axis aligned along the direction of motion.

One disadvantage is that the helmet may interfere with the guidance mechanism for certain extremes of headform position. Another is that the guidance device itself may complicate the dynamics of the impact by introducing extraneous resonances. Attempts to minimize interference problems usually add to the size and mass of the guidance frame and increasing the interference from these resonances. These problems are particularly true for twin wire systems.

The monorail also has some interference problems but the guidance frames are generally lighter and less resonant than for twin wire systems. Unfortunately, the bearings are subjected to much greater stresses during a test complicating maintenance and test reproducibility.

At this time, there is no clear choice among the various configurations of monorail and twin wire systems. There are several configurations of each type currently in use in the United States.

Free fall devices do away with guidance frames and the ball and socket articulation on the headform. Instead, the helmeted headform rests over a hole on a platform. The entire platform is dropped in a guided fall, usually guided by three wires, toward the rigidly fixed anvil. The entire anvil fits through the hole in the platform and makes direct contact with the helmet. The helmet and headform are then free to move in response to the impact while the platform continues to drop away. Since the dynamics of the event are over within ten to twenty milliseconds, the helmet is often loosely held by a net or basket attached to the platform.

The advantage is that there is no guidance frame or bearing system to interfere with the positioning or with the impact dynamics. The disadvantage is that a full three axes of accelerometer data must be acquired because there is no reliable means of correctly orienting a single axis transducer. Furthermore, for any non-planar impact surface, it is almost impossible to position the center of gravity of the headform with respect to the surface axis of symmetry. The result is that many of the impacts on these surfaces are glancing blows that neither test the helmet to the maximum allowable limit nor yield reproducible results that could be compared with other tests.

Headforms

The headforms themselves are a critical part of impact test systems. There are a number of specifications for impact test headforms. The two specifications commonly used in the United States are those in the DOT motorcycle helmet standard FMVSS 218 and ISO DIS 6220-1983. There are three DOT headforms, small, medium and large. The specification describes the external surface of the medium size and uses scaling factors to generate the small and large sizes. The specified mass for each size is proportional to the cube of the scale factors. The source for the specification is uncertain but is rumored to have come from an anthropometric survey of US soldiers conducted in the 1940's.

The ISO DIS 6220-1983 specification includes separate descriptions of headforms starting at 50 cm circumference and increasing in circumference by one centimeter increments. These headforms are not geometrically similar; that is, they are not scaled from a single reference. Only four sizes from the range are commonly used but some current standards have added the 'O' headform, 62 cm circumference, to the standard set.

The specification calls out a total mass of 5 kg regardless of headform size. However, CPSC and ASTM are considering lower masses for headforms used to test children's helmets. The current CEN headform specification calls out headforms with ISO geometry but with masses proportional to the cube of headform circumference.

Although both ISO and DOT headforms are intended to correspond to Western head anthropometry, the descriptions are not at all similar. For headforms of the same circumference, the AP (front to back) length of the ISO headform is smaller, the breadth is greater, and the head height, the distance from the plane corresponding to the anatomical Frankfort plane to the apex of the headform, is smaller.

These headform issues of mass and geometry are crucial. The mass determines the total momentum that must be exchanged in an impact involving a specified velocity differential. A qualified helmet may fail to meet test criteria if the headform is too light or if it is too heavy.

Human head mass data collected by Walker [51] and Beier [52] does not support any correlation between head mass and head dimensions. What correlation there is seems to be between head mass and whole body mass. The cubic relationship, in spite of its appeal to engineering intuition, is clearly not supported by anthropometric data.

Headform geometry is one of the determinants of helmet coverage. All the impact standards define how impacts may be sited in terms of planes and points fixed in the headform. Slight variations in headform geometry, misplacement of the helmet on the headform or the use of the wrong size headform will shift legitimate test impact sites and could conceivably cause adequate headgear to be rejected or inadequate headgear to be accepted.

All the headforms just mentioned are to be made of a hard non-resonant material. The ISO headform requirements [31] originally specified wood but, currently, almost all the above are made of low resonance magnesium or aluminum alloy. However, there is concern that rigid headforms may fail to duplicate the impact dynamics of the human head.

Saczalski [53] has described a phenomenon he observed in computer simulations of helmeted head impact. During simulated impact, portions of the finite element head model bulged laterally outward perpendicular to the impact axis producing what Saczalski referred to as 'squashing'. Clearly, rigid headforms will not reproduce this response. However, whether squashing or some other significant complex behavior actually takes place and actually bears on the injury outcome of a helmeted head impact is, as yet, uncertain.

What is certain is that compliant headforms are technically much more complex than their rigid counterparts. There is no confidence that compliant test headforms can be adequately manufactured or even specified. Currently, only NOCSAE standards call for the use of a compliant headform. The NOCSAE headform, which incorporates a soft outer surface and a glycerin filled brain cavity, has not gained general acceptance.

In addition to these headforms, there are other headform specifications that address the needs of different ethnic groups. The Japanese standards [54,55] , for example, call out headforms with the greater breadth to length ratios than the headforms typically used in the US and Europe.

Impact Surfaces

The standards also specify a variety of impact surfaces. Impacts with flat surfaces are thought to be the most common accident configuration. With the development of the wire guided impactor, flat surfaces have been a part of every helmet test procedure. The spherical impactor used in the Brinell tests has been carried forward to many current standards as the hemispherical anvil. Other currently used surfaces include the curbstone, various cylinders, narrow edges, a sharpened right angle and a horse shoe anvil.

These anvils have been devised to represent anticipated impact hazards but the pairing of flat and hemispherical surfaces also serves another purpose. One of the protective benefits of helmet use is that localized loadings applied to the helmet surface are distributed to a much wider area of the head. The impact tests described above cannot determine this effect directly because the forces and accelerations actually measured apply to the whole headform. The tests yield the sum of the shocks applied to the headform rather than the shock applied to any specific area. It is conceivable that a helmet with no load spreading capacity at all could be devised to meet the test requirements for either the flat or the hemispherical anvil. However, one such a helmet could not meet requirements for both anvils.

Although most helmet standards specify hard metal anvils, football helmets, hockey helmets and some others are frequently tested in impact against compliant surfaces. The modular elastomer pad (MEP) is composed of resilient but highly stable material usually molded into a pad of one inch thickness. MEP testing is considered non-destructive for many sports helmets intended to protect against repeated impacts. However, the MEP attenuates some the impact itself so that comparisons with tests against non-resilient surfaces may be misleading.

Impact Velocity

In addition to drop mechanisms, headforms and anvils, most current impact test stands also incorporate devices to measure the velocity of the falling headform just before impact. Current standards specify, in one form or another, the impact velocities for each test configuration. Drop height is generally not specified because frictional losses before the impact make it an unreliable parameter for impact severity.

A commonly used method to measure impact velocity is timing the passage of a tab or two tabs through a light beam. A light sensing device is set to detect the passage of the leading and trailing edges of the tabs. The velocity can be determined by measuring the time interval from leading to trailing edge or from the first leading edge to the second leading edge and dividing into the measured distance between these edges.

Other Helmet Tests and Considerations

In addition to impact tests, standards generally set labeling requirements for identification and warnings. They also set some limitations on helmet configuration, call out environmental conditionings, set the number of samples to be tested and describe the uses for which qualified headgear may be appropriate. Standards also prescribe tests for other kinds of performance.

There are two types of retention system tests. Strength tests load the retention system components to ensure that they will not fail under certain levels of loading and, in some children's helmet standards, to ensure that the helmet will release to avoid hanging injuries. Positional stability tests attempt to determine whether the retention system will hold a helmet in position by applying a tangential shock load to snatch a helmet from a test headform.

Standards also call out visual field requirements. The visual field is generally specified in terms of a solid angle referenced to a test headform.

Auto racing helmet standards often call out flammability test requirements. Components of the helmet will be subjected to a flame and required to self extinguish within a given time period.

The shell penetration test measures a helmet's ability to withstand a conical pointed impactor. This test appears in almost all motorcycle and auto racing helmet standards from the earliest BSI specifications.

The Australian and Swedish bicycle helmet standards [56,57] call out force distribution tests. The helmet is placed on a headform equipped with a force transducer so that only the force applied to a limited area of the headform's surface will be measured. A shaped impactor of a given mass strikes the helmet at a given velocity directly over the transducer. The peak load must not exceed a certain value.

There are two approaches to testing facial protection provided by full face helmets. Full face helmets incorporate a chin bar, an extension of the helmet shell crossing laterally across the chin from the right to left temporal areas of the helmet. Snell Memorial Foundation Standards apply a measured shock loading to the chin bar of a rigidly supported helmet and measure the maximum intrusion into the helmet interior. If the chin bar intrusion exceeds a certain limit the helmet is rejected.

BS 6658:1985 Protective Helmets for Vehicle Users [58], which replaced separate BSI motorcycle and auto racing helmet standards, describes another chin bar test. BSI also applies a shock load to the chinbar but the helmet in this test is placed on a rigidly fixed full headform. The back of the helmet shell rests against a rigid surface topped by rubber pad. Thus the shock load may be transmitted through the helmet structure into the rubber pad or into the chin of the rigidly fixed headform. The deceleration of the striker imparting the shock load must not exceed 300 G's.

BSI standard BS 6658:1985 [58] also calls out an oblique impact test. The anvil surface is flat but slopes upward so that the falling helmet strikes glancing blow. Two different anvil faces are used, one is a sheet of abrasive material securely clamped in place. The other is a series of parallel steel edges that convert the anvil face into a sort of cheese grater. Load cells in the anvil capture the forces parallel to the surface. The test criteria limit the peak value and the first time integral of this force.

The standard states directly that the test is intended to assess frictional forces and forces resulting from projections. Glaister [59] describes the development of the test. He states that it is intended to address concerns about angular acceleration. Angular acceleration had been identified as a potential injury mechanism since the 1940's and is currently thought by some to be the primary injury threat. Although standard impact test performance implies a reduction in angular as well as translational acceleration, tangential forces applied to the helmet shell are not addressed. In fact, the standard impact test configurations are generally chosen to minimize tangential forces.

However, although angular acceleration may represent an injury hazard, there is no indication that tangential forces are producing either high levels of head angular acceleration or head injury. Furthermore, the oblique impact test as described cannot determine whether forces are transmitted to the headform and particularly what the resulting peak accelerations in the headform might be.

Helmet Effectiveness

Almost every critical assessment of crash helmet effectiveness has concluded that helmets reduce the risk of head injury. Hurt's study [2] showed that motorcycle helmets protected their wearers in a survey of accidents in Los Angeles. Williams [3] showed that bicycle helmets protected their wearers in a survey of accidents in Melbourne, Australia. Rivara [4] showed that bicycle helmets protected their wearers in an exhaustive survey of bicycle accidents in the Seattle area.

Each of these studies also concluded that helmet use had no discernible effect on neck injury. There seemed to be no adverse effect ascribable to helmets.

However, there are limits to what broad surveys can show. The majority of the incidents discussed in all three of these studies did not notably tax the protective capabilities of the helmets worn. The results were ample to prove the value of currently available helmets but they could render no conclusive determination as to whether some helmets were superior to others.

Even so, one of the charts taken from Rivara's study showed injury severity plotted against a helmet damage scale. The plot showed a fairly flat line suggesting that injury was insensitive to increasing helmet damage up to the level of damage the investigators called 'catastrophic'. At this point the injury severity took a sharp upward jump. The implication is clearly that there are accidents that exceed the capacities of current headgear and that better bicycle headgear would prevent more deaths and injuries.

Evans and Frick [5] have applied an elegant method to select only more serious incidents from among those detailed in the US Federal Government's Fatal Accident Reporting System (FARS). Anderson and Kraus [6] have recently used the same selection technique in a separate study. The method selects motorcycle accidents involving a passenger and driver in which one or both riders died.

The data studied by Anderson and Kraus is not as detailed as that collected by Hurt but it is composed of a much larger number of much more serious incidents. Hurt noted that even inexpensive and unknown helmets including at least one antique could provide adequate head protection. On the basis of his study, he concluded that there was no need for more stringent standards than the DOT requirement. The FARS data suggest something different.

The FARS data did not identify the headgear used so no direct helmet comparisons were possible. However, Anderson and Kraus showed that motorcycle helmet effectiveness appears to have improved steadily over the fourteen year period studied. Although they warn that this improvement could be due to artifacts and unidentified biases in the data, the authors suggest instead that the increase in effectiveness arose from improvements in helmet design over the period studied and the replacement of inappropriate headgear with qualified motorcycle helmets. Better helmets may indeed provide better protection.

The developments in helmets which are traced here back to Cairns in the 1940's begin in epidemiology and must be continually reexamined by fresh epidemiological research. The uncertainties about test severities and test criteria may never be resolved in any other way. The most recent studies suggest clear sailing but there are always those who will see rocks ahead and few who will insist the boat is already holed and sinking.

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