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Bioengineering Considerations in the Design of Protective Headgear

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Bioengineering aspects of headgear design are surveyed to illustrate the interactions and contributions of different engineering disciplines to military headgear design. Illustrations are drawn from the fields of anthropometry, human factors, heat transfer, acoustics, and applied mechanics. In addition, a helmet design procedure is described which takes into consideration such interactions. The procedure was successfully used in the design and development of a new ballistic protective infantry helmet. This methodology is equally applicable to the design of civilian head protective devices. Possible applications are pointed out.

Introduction

One aspect of the mission of the US Army Natick Research and Development Command is to provide appropriate and effective head protection for the individual soldier. Many problems of military head protection have similar counterparts in civilian headgear designs. However, the outstanding factor which constrains military headgear designs in ways not found in civilian applications is ballistic protection. Ballistic protection usually means increased weight of helmets and decreased options for materials selection compared with civilian design parameters. Ballistic protection is of paramount importance to the Army, but since it is not of wide interest outside the Army, it will not be elaborated on here. Instead, attention will be focused on several areas which are common to the engineering of both civilian and military protective headgear.

Hazards to the head are shown schematically in Fig. 1. Many engineering and scientific disciplines contribute to the design of protective devices to defeat those hazards. In each case, it is necessary to quantify as far as possible the hazard in engineering terms so that the performance of a particular protective device can be evaluated in engineering terms. Current head protective devices range from specialized helmets for flyers, firemen, and electrical workers to facial devices such as gas masks, respirators and eye goggles.

In this paper, the topics of anthropometry, human factors, heat transfer, acoustics, and applied mechanics are discussed. The applicability of these particular disciplines to the bioengineering of head protective devices is described and illustrated. Then a design methodology is presented which synthesizes the technical information form preceding sections into a usable form.

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Anthropometry

Anthropometry, the study of body dimensions, provides the physical definition of the head with which the equipment designer must work. The statistical variations of head and face dimensions throughout a particular population of people must be taken into account by the designer in order to arrive at a suitably functional design. The major objective in considering head dimensions is to achieve proper fit of the item. Dimensions for the US Army population are reported by White and Churchill [1].[1] Head and face dimensions are presented in a design limit

[1] Numbers in brackets designate References at end of paper.

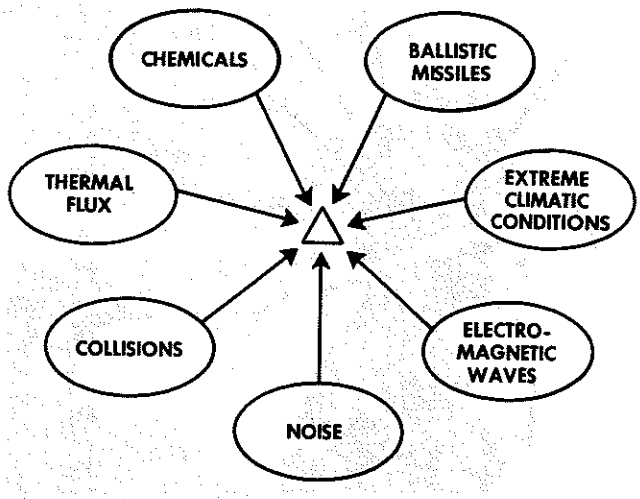

Fig. 1 Schematic representation of threats to the survivability of the head

Table 1 Major head and face dimensions (cm) of the US Army population reported as design limits for selected percentage coverages (courtesy of R. M. White, USANARADCOM, unpublished)

	Measurement	100%		98%		95%		90%		80%		50%	
1	Head circumference	51.0	63.8	52.4	60.0	53.0	59.3	53.5	58.8	54.1	58.2	55.0	57.2
2	Head length	16.6	22.4	17.8	21.2	18.0	20.9	18.2	20.7	18.5	20.4	19.0	20.0
3	Nasal root-occiput	16.4	22.0	17.4	20.8	17.7	20.5	17.9	20.3	18.2	20.0	18.6	19.6
4	Pronasale-occiput	18.8	25.4	20.2	24.1	20.5	23.8	20.8	23.5	21.1	23.2	21.6	22.8
5	Ectocanthus-occiput	13.8	20.8	15.1	19.4	15.4	19.2	15.7	18.9	16.0	18.6	16.6	17.9
6	Tragion-occiput	6.8	14.6	7.9	12.9	8.2	12.7	8.5	12.4	8.8	11.9	9.4	11.1
7	Head breadth	12.8	17.4	13.9	16.7	14.1	16.4	14.3	16.3	14.6	16.0	14.9	15.6
8	Bitragion breadth	11.4	15.6	12.2	14.8	12.4	14.6	12.6	14.4	12.8	14.2	13.1	13.9
9	Head height	10.0	16.0	11.3	15.0	11.6	14.8	11.9	14.5	12.2	14.2	12.7	13.8
10	Face length	9.6	14.6	10.5	13.6	10.8	13.4	11.0	13.1	11.2	12.9	11.6	12.5
11	Face breadth	12.0	16.3	12.7	15.4	12.9	15.1	13.1	14.9	13.3	14.7	13.6	14.4
12	Interpupillary breadth	4.8	7.9	5.2	7.1	5.4	6.9	5.5	6.8	[illegible]	6.6	5.9	6.4

format in Table 1. Since those dimensions reflect the variability of segments of the Army population, any head protective device must account for those variations.

The dimensions in Table 1 do not, in themselves, yield shaped headforms. To generate anthropomorphic shapes, the unique head measuring device shown in Fig. 2 was built. A network of points distributed over the head is measured to produce head contours. The data reduction procedure can be used to generate an arbitrary number of sizing systems—one size, two sizes, three sizes, etc.—depending on the application.

Three sizes were generated for the new infantry helmet. The headforms are shown in Fig. 3. Details of this work are contained in Claus, et al. [2].

No recent faceforms have been developed by the Army or any other organization. Most design work is done with the set of ten CWS cast bronze faceforms made during WW II for designing gas masks (see Brues [3]). A recent analysis of available face data is contained in McConville, et al. [4].

Human Factors

No matter how sophisticated a piece of equipment may be, the crucial aspect is whether the man can perform successfully the desired task. The complex interactions between the man, his equipment, and his task must be determined, and these human factors accounted for in order to achieve a successful equipment design. These problems are considered to be of such importance that all such design work is subjected to a Department of Defense level standard [5].

The Human Engineering Laboratory, Aberdeen Proving Ground, Md., developed a methodology for evaluating candidate infantry helmet designs by considering the spectrum of tasks required of the infantryman [6]. Tasks ranged from simple mobility to firing individual and crewserved weapons, from wearing goggles to using communications equipment. This study defined the edgecut of the infantry helmet discussed in the fothcoming design section. The only other system oriented human factors headgear study appears to be McKenzie [7] on combat vehicle crewmen.

Heat Transfer

The majority of adults today, particularly those of age for the Army, seldom wear a hat of any kind. Consequently, when people wear a piece of military headgear out of necessity, many complaints are received as to the headgear being uncomfortable, too heavy, and too hot. The discipline of heat transfer contributes a quantitative description of thermal characteristics of headgear in order to provide insight into subjective estimations of comfort. Besides the area of comfort, the thermal properties of headgear are important under severe climatic conditions from the tropics to the Arctic.

The heat transfer properties of clothing and protective equipment are evaluated at the unique facilities of the US Army

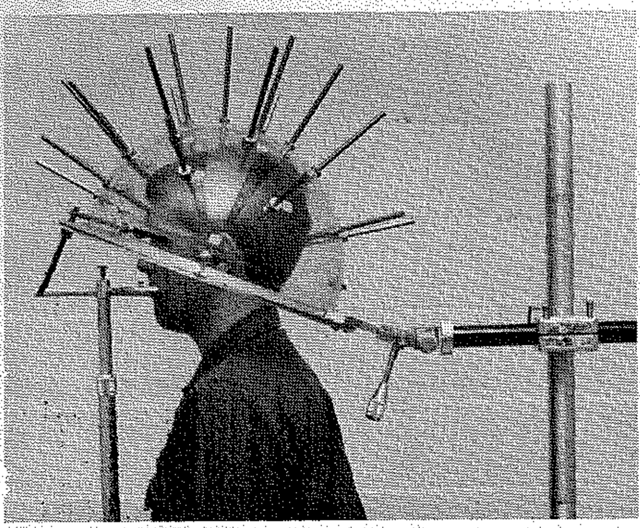

Fig. 2 Twenty-seven-point head measuring device with subject positioned for measuring

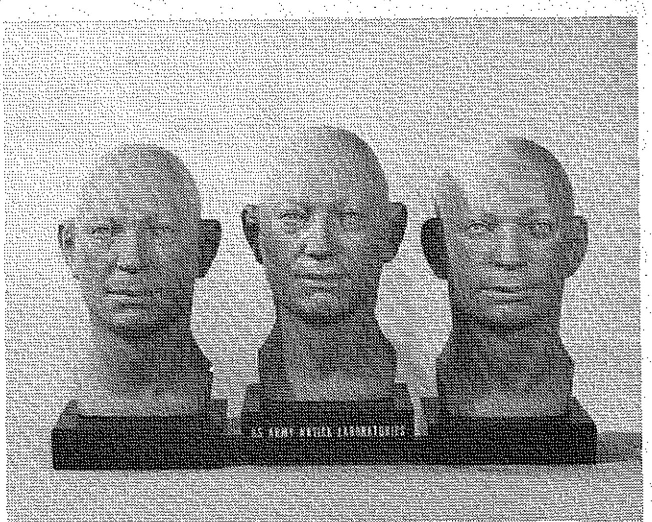

Fig. 3 Three plaster headforms developed for sizing a new infantry helmet

Table 2 Thermal characteristics of selected helmets—after Fonseca [8]

Helmets	"Still" air			Air flow 3 m/sec		
	CLO	im/CLO	im	CLO	im/CLO	im
Aircrew AFH-1	1.72	0.38	0.65	0.48	1.8	0.88
Aircrew APH-5	1.45	0.32	0.47	0.51	1.4	0.72
Standard CVC	1.28	0.36	0.46	0.43	1.9	0.83
English Infantry	0.97	0.45	0.44	0.37	1.9	0.70
Football Helmet	1.16	0.32	0.37	0.47	1.6	0.78
Experimental Hayes-Stewart	1.11	0.35	0.39	0.45	1.9	0.87
Italian Infantry	1.03	0.43	0.44	0.42	2.0	0.84
Experimental Parachutist Liner	1.36	0.37	0.50	0.54	1.5	0.81

Research Institute for Environmental Medicine, Natick, Mass. A fully instrumented "copper man" is used to measure the insulation values and the vapor transmission coefficients of clothing systems. Description of the test equipment and the methods used to evaluate ensembles are contained in Fonseca's survey report [8] of headgear. The physical model, the copper manikin, is sectioned with independent thermal controls so that the head alone can be considered the test section for headgear studies. The thermal characteristics of eight different helmets are shown in Table 2.

The quantities in Table 2, Clo and im, are used by physiologists to describe the thermal properties of protective clothing. The Clo unit, loosely speaking, is the amount of insulation or thermal resistance provided by a single business suit. Precisely, one Clo is 0.18°C m² hr/kg cal [9]. The nondimensional permeability index, im, is defined as $r_{mh}r_{mv}/r_{ah}r_{av}$ where r_{mh} is the resistance of a material to passage of heat, r_{mv} is the resistance of a material to passage of vapor, r_{ah} is the resistance of air to passage of heat, and r_{av} is the resistance of air to passage of vapor. Measurement techniques of Clo and im are contained in [9].

The designs vary greatly from the open English infantry helmet to the nearly closed aircrew helmet. The corresponding extreme Clo values range from 0.97 to 1.72 in still air.

Two important aspects of Fonseca's study [8] are the effects of ventilation holes in helmets and the effects of increasing the percentage of the head covered by a helmet. By removing differing amounts of material from a helmet to provide ventilation and then measuring the thermal properties of the modified helmets, Fonseca concluded that such holes did not increase the evaporative heat transfer from the head in a practically significant way. Also, by systematically removing strips of material from an experimental shell, evaporative heat transfer was increased little until nearly 30 percent of the helmet was removed. These findings contributed substantially to the design of a new infantry helmet which covers the ears and temple areas of the head and which provides a minimum 1.27 cm (0.5 in.) offset from the head.

The insulation provided by the helmets listed in Table 2 is unwanted and should be reduced to increase comfort. On the other hand, the head is deliberately insulated by the "Cap, insulating, helmet liner," which provides 2.5 Clo, 0.27 im/Clo and 0.68 im. When worn with the M-1 helmet the thermal properties are 2.5 Clo, 0.14 im/Clo and 0.35 im. This deliberate insulation is significantly greater than any helmet in Table 2.

Acoustics

Acoustics plays a major role in the design of certain headgear in at least three ways: 1 provision for the transmission of intelligible information from the mouth, 2 provision for the reception of intelligible information by the ear, and 3 protection from hearing loss due to excessive noise exposure. The electrical engineering of communications equipment will not be dealt with here.

Hearing loss is a major problem for the Army just as it is for civilians. The Army's awareness of this problem is reflected, among other ways, by the Department of the Army bulletin, "Noise and Conservation of Hearing" [10] and the military standard, "Noise Limits for Army Materiel" [11]. The acoustics problem, simply put, is that all military weapons [10] and some powered vehicles produce noise levels in excess of what are now considered to be acceptable exposure levels.

Several examples of acoustic hazards are shown in Fig. 4. The impulse pressure levels of rifles are seen to exceed 140 dBA, the impulse noise level when ear protectors are now mandatory in the Army [10], and the steady noise levels from engines are generally above 100 dBA. The performance of typical ear defenders are shown in Fig. 5 in terms of sound attenuation [13] characteristics. An example of a standard helmet which meets a noise attenuation requirement for providing ear protection is the SPH-4 flyer's helmet [14].

Exposure of military personnel to steady noise occurs in aircraft, armored vehicles, and motorized artillery, while civilians are exposed to steady noise hazards in various manufacturing operations and in powered equipment applications. The steady noise exposure limits from the Army's TB MED 251 [10] and from the Occupational Safety and Health Administration standards

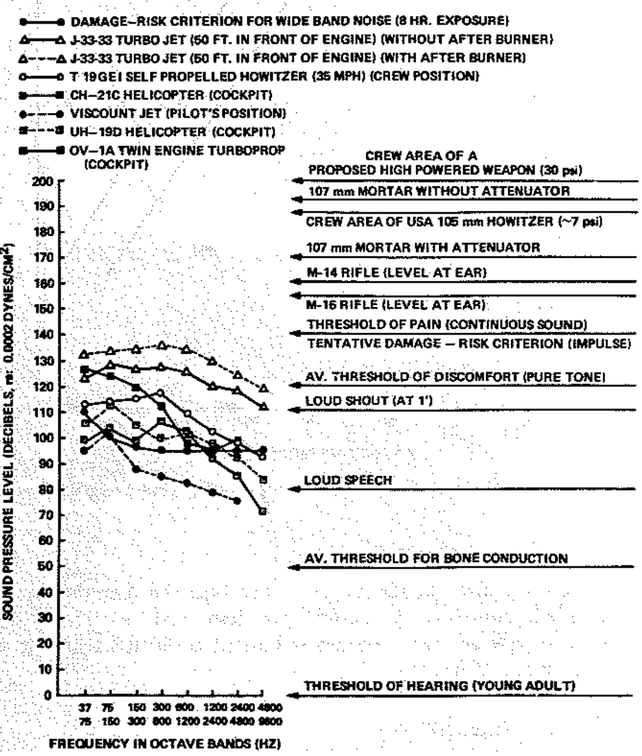

Fig. 4 Acoustic hazards—after Tanenholtz [12]

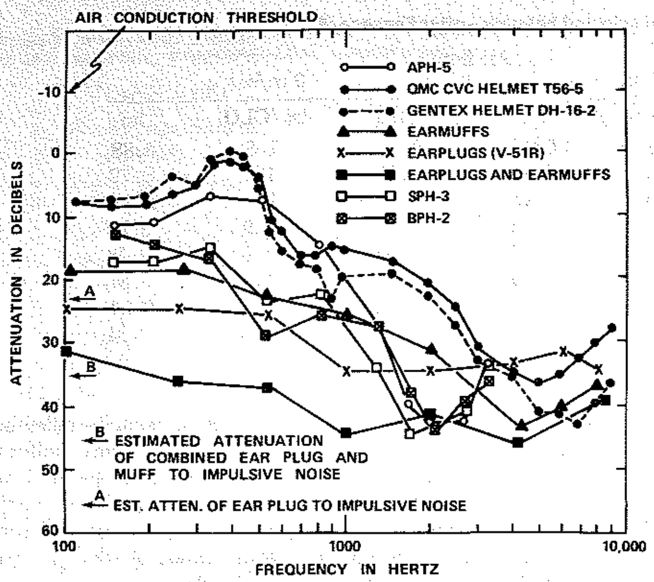

Fig. 5 Sound attenuation characteristics of sound attenuating devices and helmets—after Tanenholtz [12]

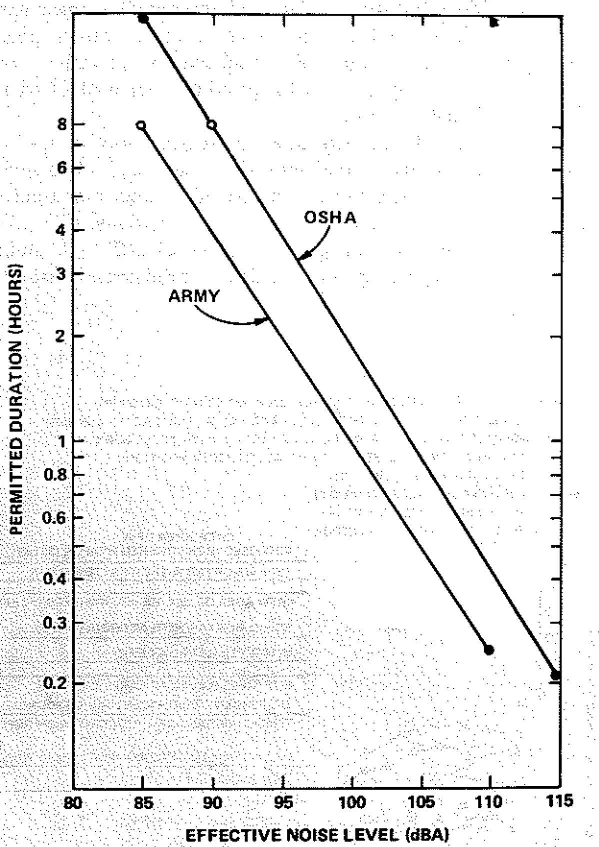

Fig. 6 Comarison of Army and OSHA permitted exposures to steady noise

[15] are compared in Fig. 6. It is seen that the Army's requirement is uniformly more conservative than OSHA's. The typical eight hour work day exposure is limited to 90 dBA and to 85 dBA by the Army.

Applied Mechanics

Interest in applications of established mechanics techniques to deformation of the human body has given rise to the subspecialty of biomechanics. A recent survey of the subject is contained in Fung, et al. [16].

In this section, four specific topics are discussed: coordinate systems, kinematics of the head with added weight, an impact model of the current standard M-1 helmet, and an example of crash protective headgear.

The first step in any mechanics problem, that of defining a suitable reference coordinated system, has not been taken often for headgear problems. Examples of studies employing coordinate systems are [2, 17, 18, 19, 20]. Coordinate systems are necessary in order that head anthropometrics, headgear dimensions, and the statics and dynamics of head/helmet motions will be reproducibly related. The choice of a particular coordinate system is arbitrary, but nonetheless, a choice must be made and consistently utilized.

The dynamics of the head are influenced by the presence of a helmet through a change in its inertial properties. Subjective studies of the effects of additional weight on the head have been conducted, but the only quantitative dynamic investigation appears to be Mertz and Patrick [17]. Their report focuses on the development of static and dynamic tolerance limits for the neck in extension and flexion. Their proposed tolerance limits are summarized in Figs. 7 and 8. In order to illustrate a change in inertial properties, data from Mertz and Patrick [17] were plotted as shown in Fig. 9. The data in Fig. 9 are illustrative only. The data are based on a single, volunteer subject with neck muscles tensed, and were fit with a least-squares straight line by this author. The additional weight was three lb. Additional eccentric weight on the head did cause an increase in the dynamic moments. These moments were all below the flexion pain threshold of 44 ft-lb.

As stated in the introduction, the entire subject of high speed (ballistic) impact is omitted from this survey. However, the mechanics of low-speed impact is illustrated because of its widespread importance to the design of military and civilian headgear. Impact mechanics of the head has been studied for many years [21] with a major impetus coming from automobile safety considerations.

Many models are available for the head and brain, but very

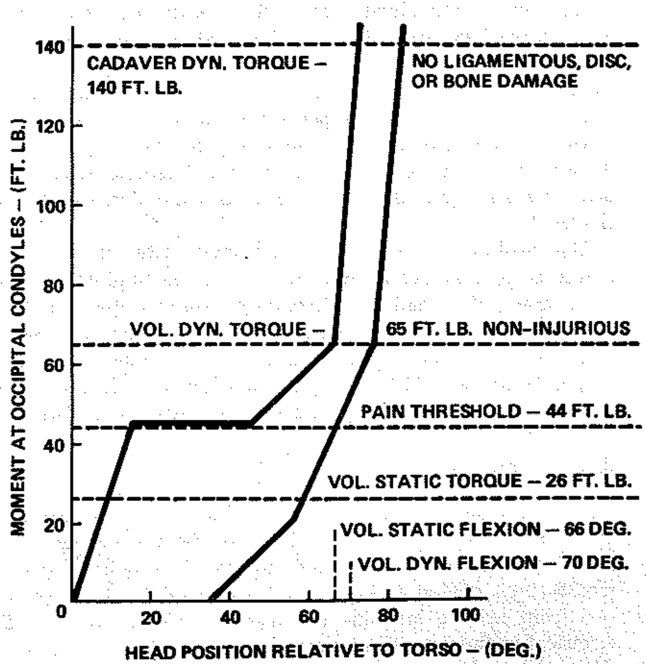

Fig. 7 Head-neck response envelope for flexion and various tolerance levels—after Mertz and Patrick [17]

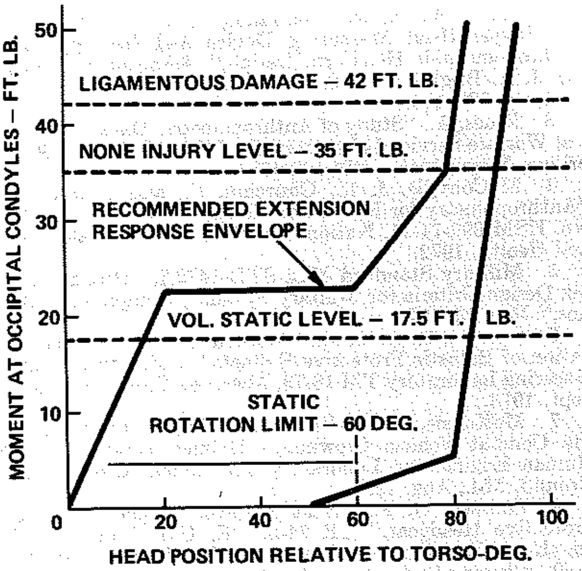

Fig. 8 Head-neck response for extension and various tolerance levels—after Mertz and Patrick [17]

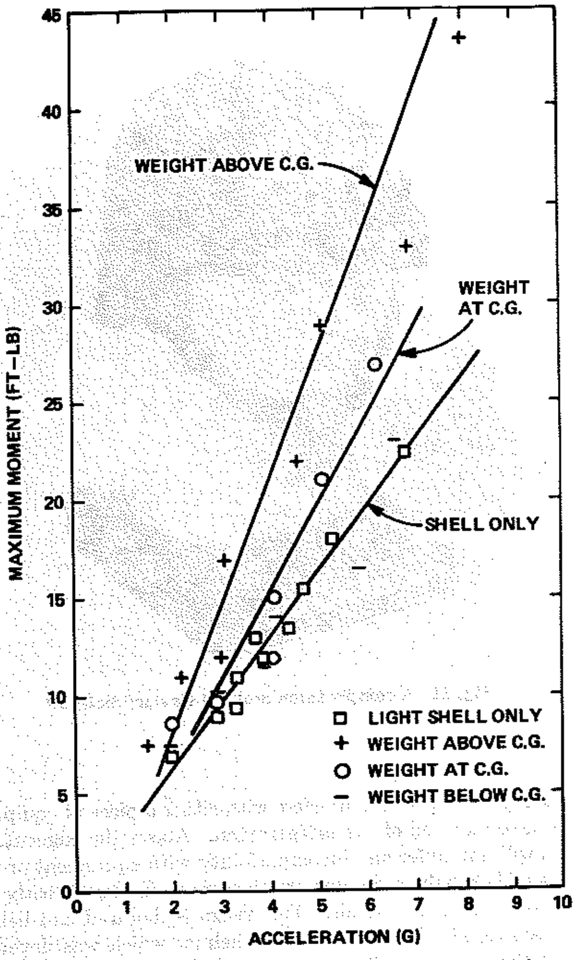

Fig. 9 Effect of added weight on head-neck response—based on Mertz and Patrick data [17]

few exist for the head/helmet combination. The study of Khalil, Goldsmith, and Sackman [22] included the standard M-1 steel helmet with reinforced plastic liner. Wave propagation effects in layered physical models were studied experimentally and numerically with finite element techniques. They showed that for short time impulses, a helmet can reduce by a factor of ten the amplitude of pressure pulses in the fluid simulated brain. They also found that the finite element model results were sensitive to the element material properties which are not known with high accuracy.

An example of crash protective equipment is the SPH-4 flyer's helmet [14] which must pass the ANSI Z90.1 [23] impact requirement on acceleration level. Much less severe impact requirements are placed on so-called "bump" protective headgear. Only recently has the engineering of football helmets been required to be careful enough in order to meet a new impact performance requirement [24].

Design Methodology

In this section, a step-by-step design methodology is described which was used successfully in the design and development of a new ballistic protective infantry helmet [25]. The order of the steps corresponds to the order to topics covered earlier in the paper.

First, the purpose of the headgear must be defined by specifying the hazards against which the head is to be protected. The hazards should be quantified as far as possible. Quantified estimates are more useful than any lengthy qualitative descriptions. Next, anthropometric data on the population to be fitted with the helmet or other device should be analyzed to determine the ranges of variation in selected design variables.

From the dimensional ranges and hardware fabrication considerations, the number of sizes required to fit the population can be determined. Headform shapes were defined by resetting the probes of the head measuring device (Fig. 2) and having a sculptor fashion headforms corresponding to those probe readings. The resulting sized headforms thus formed the foundation for design work.

Heat transfer and materials consideration led to the selection of 1.27 cm (0.5 in.) as the minimum offset (distance between head and helmet shell) required for the new infantry helmet. Using the head measuring device, the probes were moved out 1.27 cm and also symmetrized with respect to the midsagittal plane. A set of new forms were sculptured. These are referred to as the "working helmet molds," and one is shown in Fig. 10.

Human factors studies of the man, equipment, and mission envelope led to the edgecut definition which is scribed into the working helmet molds. The edgecut provides a line of demarcation such that if a helmet design comes below the edgecut, the

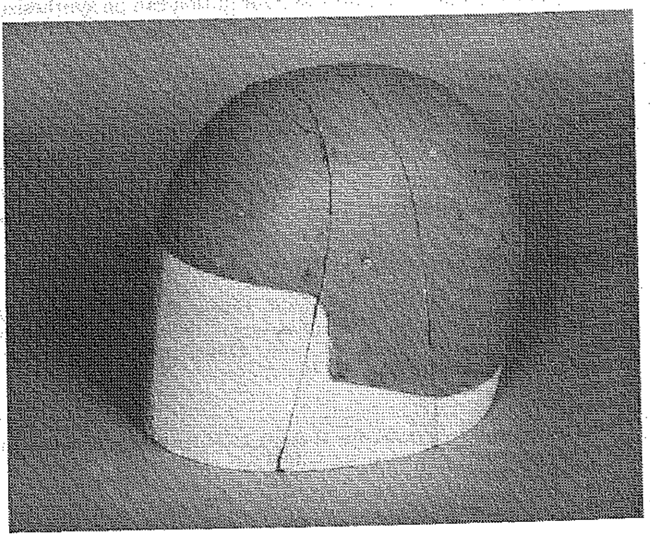

Fig. 10 A working helmet mold with edgecut inscribed

Fig. 11 A compression molded Kevlar® helmet[2]

resulting helmet would interfere with either a piece of equipment or a task required of the infantryman. Above the edgecut, helmets will not suffer any incompatibility with equipment or task.

Candidate helmet designs are then made in clay directly over the working helmet molds. The design is finalized and helmets are fabricated. The new infantry helmet which was developed using the above described procedure is shown in Fig. 11. An extensive evaluation of the infantry helmet was conducted. Detailed comparisons between the design objectives and the various helmet parameters is contained in Corona, et al. [26]. This methodology is equally applicable to football, hockey, automobile racing, and industrial safety headgear.

Summary

An attempt was made to show how the disciplines of anthropometry, human factors, heat transfer, acoustics, and applied mechanics contribute to the engineering of protective headgear. Also, a step-by-step design methodology was described which shows how the relevant technical information can be synthesized to yield functional protective equipment designs.

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