UMTRI-94-31

DEVELOPMENT OF ANTHROPOMETRIC ANALOGOUS HEADFORMS

Final Report

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16. Abstract

This report discusses the technical support tasks that UMTRI provided for the study by Conrad Technologies, Inc., **Development of Anthropometric Analogous Headforms**, which was conducted for USAARL.

The overall goal of the CTI study is to design three manikin headforms--small, midsized, and large--for use in military ejection seat and crashworthiness testing, as well as retention and fit assessment, of helmet and head-supported devices. The headforms will be applicable to military male and female aviator populations.

UMTRI conducted a literature search and review to help establish the most appropriate design specifications for headform characteristics and properties.

The U.S. Army Anthropometric Survey (ANSUR) database was selected from the literature review as the most suitable existing database for use in design of headforms. It includes data for 1,774 men and 2,208 women. An ANSUR data subset, obtained from the U.S. Army Natick Research, Development and Engineering Center, includes, for each subject, 16 head and face traditional anthropometric variables and the

- (continued on next page) -

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16. Abstract (continued)

(X,Y,Z) coordinates of 26 head and face landmarks.

One major task of CTI's design effort was to establish the three-dimensional surface geometry of the face and head for headforms. The literature review identified candidate anthropometric modeling methods for this need. CTI developed a clustering method based on four head and face variables as independent variables and three subpopulations from which median values define 5th-, 50th-, and 95th-percentile surface geometries.

Other head properties for which headform design specifications are required include head mass, head principal moments of inertia, locations of the head center of gravity and the head-neck pivot point, and friction and force-deflection properties of the headform surface. Information relevant to these properties is discussed, as well as scaling of basic properties from midsized to small and large heads. Both cadaver data and Hybrid III crash dummy headform data are reviewed. Except for surface geometry and orientation of principal axes of inertia, it is recommended that the headform specifications be the same as for the Hybrid III headform (50th-percentile and scaled for small and large).

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ACKNOWLEDGMENTS

I am grateful to Dr. Claire C. Gordon and Steven Paquette of the U.S. Army Natick Research, Development and Engineering Center for making ANSUR data available for use in this project and for consultation, and to Dr. Brian Corner of GEO-CENTERS, Inc., who prepared the requested data files of head and face variables and landmark coordinate data. I am grateful, also, to Dr. Herbert M. Reynolds of the Biomechanics Department at Michigan State University and Dr. Ints Kaleps of the Air Force Armstrong Aerospace Medical Research Laboratory. Dr. Reynolds provided helpful guidance and suggestions in relation to anthropometric modeling and analysis of anthropometric data and also provided a number of useful references. Dr. Kaleps provided important clarification of some matters pertaining to principal axes of inertia of the head.

EXECUTIVE SUMMARY

The research reported here was conducted by the University of Michigan Transportation Research Institute (UMTRI) as a subcontractor to Conrad Technologies, Inc. (CTI). This report discusses the technical support tasks that UMTRI provided for the CTI study, *Development of Anthropometric Analogous Headforms*, which was conducted for the U.S. Army Air Research Laboratory (USAARL) and the U.S. Army Medical Research and Development Command (USAMRDC) under contract DAMD17-94-C-4065.

The overall goal of the CTI study is to design three manikin headforms--small, midsized, and large--for use in military ejection seat testing, crashworthiness testing, and retention and fit assessment of helmet and head-supported devices. Data from an anthropometric survey of military personnel were used in development of headform designs. The headforms will be applicable to military male and female aviator populations and will be able to interface with the Hybrid III-family dummies.

UMTRI conducted a literature search and review to help establish the most appropriate design specifications for headform characteristics and properties. Subjects of primary interest were anthropometric modeling, head anthropometry, inertial properties, skin and surface properties, and location of the center of gravity and head-neck pivot.

The database developed by the U.S. Army Anthropometric Survey (ANSUR), conducted in 1987-1988, was selected as the database of greatest applicability for meeting project goals. The primary reasons that ANSUR was selected are the currency of the data, accuracy due to computerized data acquisition and reduction, inclusion of head and face landmark data, availability of data for individual subjects, and inclusion of separate male and female populations. The ANSUR database includes data for 1,774 men and 2,208 women from among a total of approximately 26,000 subjects who participated at 11 Army bases. UMTRI obtained a subset of the ANSUR data for Conrad Technologies, Inc., from the U.S. Army Natick Research, Development and Engineering Center. The data subset obtained include, for each subject, 16 head and face traditional anthropometric variables and the (X,Y,Z) coordinates of 26 head and face landmarks.

One major task of CTI's design effort was to establish the three-dimensional surface geometry of the face and head for headforms. To assist this effort UMTRI identified and obtained a large amount of literature pertinent to data analysis and anthropometric modeling. After considering a number of possible modeling approaches CTI determined that a clustering method was the best for establishing head-face variable values for small, midsized, and large headforms. The modeling was conducted at CTI and is not discussed in this report. In summary, however, CTI determined three head variables and one face variable to be the best to use as independent variables for defining clusters. These are head length, head breadth, and head circumference and face length --the menton-to-sellion (nasion) distance. The databases for males and females were merged into a single database. The three subpopulations of subjects clustered within ±2½-percentile halfwidth bands about 5th-, 50th-, and 95th-percentile "fourtuple" locations in a 4-space of the four independent variables were extracted. From these three subpopulations, then, determination of values for variables for the three headforms was completed. Specifically, for each subpopulation, the median values for all other head and face (dependent) variables were determined and used for the respective headform.

In addition to information pertinent to head-face anthropometry and anthropometric modeling, UMTRI obtained and provided information relevant to other head properties for which headform design specifications are required. These include head mass, head principal moments of inertia, locations of the head center of gravity and the head-neck pivot point (the occipital condyles), and friction and force-deflection properties of the headform surface. Information about scaling basic properties from midsized to small and large heads was also obtained. Findings relevant to all of these aspects of headform design are discussed in this report. Data include values reported in the literature for cadaver studies and for the Hybrid III crash dummy. Since in essentially every aspect specifications for the Hybrid III derive from the best available cadaver data, the conclusion is reached that, except for surface geometry and principal axes of inertia, the headform specifications of the present study should be the same as for the Hybrid III headform (50th-percentile and scaled for small and large).

This report includes a list of all references identified by UMTRI that were useful in reaching the specific and general conclusions of the study.

DEVELOPMENT OF ANTHROPOMETRIC ANALOGOUS HEADFORMS

1.0 OBJECTIVES

The objective of the project is to design three headforms (small, midsized, and large) for use in military ejection seat and crashworthiness testing, as well as retention and fit assessment, of helmet and head-supported devices. The designs, applicable to military male and female aviator populations, are based on a scientific review of available anthropometric surveys of head and facial dimensions, as well as available data for mass properties, biodynamic response, skin properties, and occipital pivot locations of the adult head and neck. The headforms will be compatible with the Hybrid III anthropomorphic dummy family with interfacing at the Denton 6-axis load cell of the Hybrid III neck.

Primary design activity was conducted at Conrad Technologies, Inc. This report discusses technical support provided by the University of Michigan Transportation Research Institute.

[This statement of objectives was derived from the Technical Abstract of the project proposal written by the prime contractor, Conrad Technologies, Inc., of Paoli, Pennsylvania.]

2.0 LITERATURE SEARCH

A literature search intended to help establish the most appropriate design specifications for headform characteristics and properties was conducted in a continuing manner over the course of the project. References of potential interest were those that have pertinence to anthropometric modeling, head anthropometry, inertial properties, skin and surface properties, and location of the center of gravity and occipital condyles. Over 500 references were identified on the basis of keyword, author, corporate author, and title searches as being of potential usefulness; these were obtained and examined. A large proportion of those references were identified by keyword searches. Searches for keywords within titles of articles and in keyword fields were conducted. Keywords (and stems), sometimes used in logical 'and' combinations, included: manikin, dummy, head, headform, face, facial, neck, force, load, friction, helmet, mask, goggle, fit, strap, retention, nape, chin, skull, dura, skin, scalp, hair, cranial, anthropom, Hybrid III, Hybrid 3, AATD, ATD, inertia, mass, 3-D, 3-dimensional, surface, contour, and others.

Approximately half of all identified references were found to be of no interest upon perusal. Additional references were found not to be of interest after somewhat more careful examination. Of all references obtained, 150 were found to contain information of direct or indirect usefulness in this project. Most of the references were found in the UMTRI library at the University of Michigan, but a number were obtained through outside contacts. The last section of this report is a list of these 150 references, ordered alphabetically by first author.[1]

There are two general subject areas for which references were identified and reviewed but which are not discussed in this report. These are *helmet retention* and *fit testing*. Pertinent papers, articles, and reports are included in the List of References (Section 8.0) and are listed in Table 1, but they are not, in most instances, otherwise referenced in this report.

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[1] The last item of each entry in the List of References is the UMTRI reference number, which has the form "UMTRI-nnnnn." Several references that were important to include in the list but are not available have "(not available)" in place of the UMTRI reference number. (Most of those are references that are cited in available references.) Other references in the list have no UMTRI reference number but they are available and were reviewed; these are identified by "(no UMTRI number)" or "(from H. M. Reynolds)." The List of References has 150 entries.

Table 1. Helmet Retention and Fit Testing References

Helmet Retention

1969. Head protection for the military aviator. National Academy of Sciences-National Research Council.

Andersson, T.; Larsson, P.-O.; Sandberg, U. 1993. Chin strap forces in bicycle helmets.

Carter, R.M. 1992. A new generation of U.S. Army flight helmets.

Gilchrist, A.; Mills, N. J. 1992. Critical assessment of helmet retention system test methods.

Haley, J. L., Jr.; Turnbow, J. W. 1966. Impact test methods and retention harness criteria for U.S. Army aircrewman protective headgear.

Haley, J. L., Jr. 1971. Analysis of U.S. Army helicopter accidents to define impact injury problems.

Hines, R. H.; Palmer, R. W.; Haley, J. L., Jr.; Hiltz, E. E. 1990. Development of an improved SPH-4 retention assembly.

Hodgson, V. R. 1990. Impact, skid and retention tests on a representative group of bicycle helmets to determine their head-neck protective characteristics.

Palmer, R. W. 1991. SPH-4 aircrew helmet impact protection improvements 1970-1990.

Reading, T. E.; Haley, J. L., Jr.; Sippo, A. C.; Licina, J.; Schopper, A. W. 1984. SPH-4 U.S. Army flight helmet performance, 1972-1983.

Thom, D. R.; Cann, M. 1990. Motorcycle helmet retention devices: convenience and comfort.

Fit Testing

Alexander, M.; McConville, J. T.; Tebbetts, I. 1979. Anthropometric sizing, fit-testing and evaluation of the MBU-12/P oral nasal oxygen mask.

McConville, J. T.; Tebetts, I.; Alexander, M. 1979. Guidelines for fit testing and evaluation of USAF personal-protective clothing and equipment.

Robinette, K. M. 1993. Fit testing as a helmet development tool.

Robinette, K. M.; Whitestone, J. J. 1994. The need for improved anthropometric methods for the development of helmet systems.

Whitestone, J. J. 1993. Design and evaluation of helmet systems using 3D data.

3.0 ANTHROPOMETRIC SURVEYS

Three military anthropometric projects were identified from the literature search as being of potential usefulness in the present study. These are 1) the Tri-Service database, 2) the CARD database, and 3) the ANSUR database. The database selected for use in the study was the ANSUR database. The factors that resulted in this choice are discussed in Section 3.3.

A fourth database, the CAMI database of adult civilian head and face anthropometry was given brief consideration. The description of this database may be found in *Head and Face Anthropometry of Adult U.S. Citizens* (J. W. Young; 1993). This database might have been useful except for its small size (195 females and 172 males) and the fact that no facial landmark coordinate data are available.

3.1 The Tri-Service Database. The Tri-Service database is the culmination of a project begun at the U.S. Army Aeromedical Research Laboratory (USAARL) in 1980. Its development was coordinated by the Tri-Service Working Group on Biomechanics of the Tri-Service Committee of the Tri-Service Aeromedical Research Panel. While the Army, Navy, and Air Force all participated in the development of the database, the data are mostly from a 1967 survey of U.S. Air Force rated male aircrew. Data represent 3rd, 50th, and 95th percentile aircrew as defined from stature and weight multiple regression equations. The 1967 data were projected, by a technique of Churchill and McConville (1976), to reflect assumed increases in body size from 1967 to the 1980-1990 time period. Some dimensions not measured in the 1967 survey were derived from other data in that survey or estimated from other surveys. There are no (X,Y,Z) data for anatomical landmarks in the Tri-Service database; i.e., only "standard" anthropometric dimensional measurements are available.

Head and face dimensions in the Tri-Service database, like all other dimensions--such as sitting height, hip width, etc.--are based on multiple regressions on stature and weight. That is, head and face dimensions, like all other dimensions, are assumed to be proportional to stature and weight, being of the form

$$(\text{head/face dimension}) = C_1 * (\text{stature}) + C_2 * (\text{weight}) + C_3$$

where C_1, C_2, and C_3 are regression constants. This is not a good assumption, however, as head sizes and facial dimensions of adults tend to be independent from body size.

The unavailability of (X,Y,Z) data for anatomical landmarks and the implicit assumption of a proportional dependence of head and face dimensions on stature and weight are factors which make the Tri-Service database of questionable usefulness for the particular application of the present study, i.e., development of small, midsized, and large headforms. An additional factor is that the database includes no data for female subjects, which need to be utilized in the present study.

The Tri-Service database is described and documented in a Tri-Service report: *Anthropometry and Mass Distribution for Human Analogues--Volume I: Military Aviators* (1988). Other pertinent reports are *The AMRL Anthropometric Data Bank Library: Volumes I-V* (E. Churchill, P. Kikta, and T. Churchill; 1977) and *Sampling and Data Gathering Strategies for Future USAF Anthropometry* (Churchill and McConville; 1976).

3.2 The CARD Database. The Anthropometric Database at the U.S. Air Force Computerized Anthropometric Research and Design (CARD) Laboratory is operated by AL/CFHD at Wright-Patterson AFB, Ohio. Access to the database is through menu-driven applications software. The database presently contains data for anthropometric variables collected in nine different surveys. Five of the surveys are of Air Force personnel, and there are three for Army and one for Navy personnel. There are databases for both males and females. The earliest survey in the CARD Anthropometric Database is 1965 and the latest is 1977.

Data may be selected by body region, of which head and neck is one, as well as by type, e.g., arcs, breadths, circumferences, etc. The numeric data available are summary statistics and frequency data for each measurement. As with the Tri-Service database, there are no (X,Y,Z) data for anatomical landmarks in the CARD Anthropometric Database; i.e., only "standard" anthropometric dimensional measurements are available, and it would therefore be difficult to establish facial surface contour details using this database. Further, as with the Tri-Service database, data for individual subjects seem not to be available, which makes it impossible to do regression studies for independent variables not selected by the CARD Laboratory for determination of summary statistics (even though regression coefficients for some independent variables may be available). These two factors, together with the fact that the data are 20-30 years old and thus not entirely representative of the 1990s population, make it doubtful that this database could be used effectively to meet the particular goals of the present study.

The CARD Anthropometric Database is described and documented in a CARD report: *User's Guide to the Anthropometric Database at the Computerized Anthropometric Research and Design (CARD) Laboratory: Second Edition* (J. Robinson, K. Robinette, and G. Zehner; 1992). Another pertinent report is *User's Guide to Accessing the Anthropometric Data Base at the Center for Anthropometric Reseach Data* (same authors; 1988).

[The U.S. Air Force also has a database called the AAMRL Biodynamics Data Bank, which contains both dynamic test response data and anthropometry data. This database is described in *The AAMRL Biodynamics Data Bank* (J. Abrams, I. Kaleps, J. Brinkley;

1988). This database was not given consideration because its anthropometry data content is too limited.]

3.3 The ANSUR Database. The U.S. Army Anthropometric Survey (ANSUR) was conducted in 1987-1988. Approximately 26,000 subjects at 11 Army bases were screened for the survey. A sampling strategy described in the final report reduced the number of subjects to be fully measured to about 9,000. From the measured survey sample a final survey database of 3,982 subjects was determined in such a manner as to reflect the proportions of men and women in various racial/ethnic and age groups found in the June, 1988, Army. Measurement data for 1,774 men and 2,208 women comprise the working database.

At each Army base the subjects were measured for 132 dimensions at a series of measuring stations. Portable personal computers were independently operated at each of the measuring stations, from the in-processing station through the out-processing station, for recording and verifying data with a custom-designed computer data-entry and editing system. Each subject carried a floppy diskette with his/her data from station to station.

In addition to the 132 standard dimensions measured for each subject, head and face data were determined by use of an automated headboard device (AHD). Twenty-six head and face landmarks were selected for automated measurement of (X,Y,Z) coordinates. The landmarks selected were chosen on the basis of their usefulness in the design of helmets, respirators, goggles, and other personal protective equipment.

In the final report ("Methods and Summary Statistics") data for each measurement are given in terms of percentiles and frequency tables for males and females, separately. Values for percentiles 1, 2, 3, 5, 10, 15, ..., 90, 95, 97, 98, 99 are tabulated, and frequencies are given for steps of from 0.1 to 1.5 cm, depending on the particular dimension. The (X,Y,Z) data for head and face landmarks are not included in these tables, but, instead, tables are included for 48 dimensions derived from the (X,Y,Z) data (e.g., Z_{menton} minus $Z_{\mathrm{top\text{-}of\text{-}head}}$ is given as a measure of head height).

Several factors recommend the ANSUR data as preferable to the Tri-Service data or the CARD data for use in the present study. One is the currency of the data--1988 in contrast to 1967 data projected to 1980-1990 in the case of Tri-Service and 1965-1977, unprojected data in the case of CARD. A second is that the ANSUR database includes data for females, as well as data for males (separately). (The CARD database also includes data for females.) Third, "raw" data for head and face dimensions are present in the database; i.e., head and face data have not been reduced to values for small, midsized, and large *overall size* by regressions on *stature and weight* as in the case of the Tri-Services database. It is absolutely necessary to be able to establish shape and dimensions for small, midsized, and large *heads and faces* on the basis of independent variables specific to the head and face. Fourth, in order to do regressions or any other type of modeling, data for all subjects--not just reduced data, frequency data, and summary data--are needed, and those data are available for the ANSUR study. Fifth, the ANSUR data may be more accurate than the data in the other two databases--particularly the head and face data, which were determined from use of the Automated Headboard Device--since a computer data entry and editing system was used. Finally, (X,Y,Z) data for head and facial landmarks, while not in the printed report, are available (for all subjects), and such data are considered vital for establishing the shape and dimensional specifications for headforms in the present study.

The ANSUR database is described and documented in a series of reports. The primary ones relevant to the present study are: *1988 Anthropometric Survey of U.S. Army Personnel - Methods and Summary Statistics* (Gordon, C. C., et al.; 1989), and *The Development and Validation of an Automated Headboard Device for Measurement of Three-dimensional Coordinates of the Head and Face* (J. F. Annis and C. C. Gordon; 1988).

[Note: From the approximately 9,000 subjects who were fully measured, Natick also developed a subset database of 487 male pilots and 334 females who met the 1988 anthropometric criteria for entry into pilot training. That database is described in *1988 Anthropometric Survey of U.S. Army Personnel: Pilot Summary Statistics* (S. M. Donelson and C. C. Gordon; 1991). This database was not considered for use in this study because it is only one-fifth as large as the working database described, which we considered too small for the type of anthropometric modeling to be conducted. It was believed, additionally, that there would be no important differences in head and face dimensions between the pilot and general populations of the U.S. Army. That this is correct is suggested by the pilot-versus-general population comparisons of average values for variables such as arm length, chest depth, and sitting height on pages 2 and 3 of that reference. (No head or face measures are included in the comparisons.) Dr. Claire C. Gordon of Natick, a coauthor, has also stated in a personal communication that she agrees that pilot head and face data would not be significantly different from data for the general U.S. Army population.]

4.0 DATA ANALYSIS AND ANTHROPOMETRIC MODELING

The ANSUR data were used for determining the surface geometry of three headforms--one "small," one "midsized," and one "large." All data analysis and anthropometric modeling was done at Conrad Technologies, Inc., not at UMTRI, so this section does not contain an in-depth discussion of the methodologies adopted. Rather, it discusses briefly some of the primary references that played a role in decisions made regarding selection and development of methodologies. UMTRI participated in the modeling process by (1) identifying, obtaining, and reviewing relevant references, (2) interacting with physical anthropologists whose counsel was sought (Dr. Claire C. Gordon of U.S. Army Natick Research, Development and Engineering Center, and Dr. Herbert M. Reynolds of the Biomechanics Department at Michigan State University), and (3) providing important references to CTI and interacting with CTI in discussion of candidate modeling methods.

4.1 Data Analysis. After the decision was made that the ANSUR database is the one most suitable for meeting the objectives of the project, contacts were made with Dr. Claire C. Gordon of U.S. Army Natick Research, Development and Engineering Center, the principal investigator of the 1988 Anthropometric Survey of U.S. Army personnel. Dr. Gordon agreed to make all requested data available for use in the headform study. Dr. Brian Corner of GEO-CENTERS, Inc., a task-order contractor to Natick, prepared the data files and sent them on floppy diskette. The first data sets received were incomplete, so additional diskettes were obtained. The data files were put into a different format, and the head and face landmark (X,Y,Z) data were merged with the anthropometric variables data. The final data files were quadruply encrypted and sent via E-mail from UMTRI to CTI.

Table 2 shows the format of the data files provided for CTI. There is one file for the 1,774 male subjects and one file for the 2,208 female subjects. A subject-by-subject layout is used for these files. The files include data for several biographical variables (sex, age, race, and MOS), weight, stature, neck circumference, 16 head and face traditional anthropometric variables, and (X,Y,Z) coordinates of 26 head and face landmarks. The head and face anthropometric variables and landmarks are illustrated in Figures 1, 2, and 3.

The head and face landmark (X,Y,Z) data provided by Natick were not rotated into Frankfort Horizontal (the anatomical coordinate system for the head, based on the so-called Frankfort Plane; see Section 5.0 and the footnote in Section 6.0). The data were, therefore, also not symmetrized in Y. Since rotated data could not be obtained from Natick without delay, CTI processed the data both for rotation and for symmetrizing in Y. (It was learned later that the rotated form of the data in the ANSUR database is not Frankfort Horizontal even though subjects had their heads oriented such that the Frankfort Plane coordinate system was approximately parallel to the laboratory frame of reference. Instead, the form of ANSUR rotated data is for a plane defined by right tragion, left tragion, and sellion--rather than right infraorbitale. The Frankfort Plane system is more standardly used. For the purposes of the headform development study, however, it is of no consequence which system is used.)

Table 2. Layout of ANSUR Data Files Sent to CTI by UMTRI

ANSUR HEAD/NECK DATA

LAYOUT FOR MERGED DATA FILES

```
--------------------------------------------------------------
MWDBXYZ.VAR (1774 subjects)**|
MEN1.VAR (5692 subjects)     |---> MWDBXYZ.MER (1774 subjects)**

WWDBXYZ.VAR (2208 subjects)  |
WOM1.VAR (3599 subjects)     |---> WWDBXYZ.MER (2208 subjects)
--------------------------------------------------------------
```

** NOTE: The MWDBXYZ.VAR originally received included complete data for only 1665 (male) subjects. The missing data for 109 subjects were requested and received on August 1, 1994. The files MWDBXYZ.VAR, MWDBXYZ.MER, and VAR.MER (this file) have been modified accordingly.

The files are sequential with ASCII format. Length variable values are in mm and are space delimited. Weight is kilograms multiplied by 10. Head/face X, Y, and Z values are in units of 0.1 mm (i.e., values are mm multiplied by 10).

line 1: SUBJNO, SEX, AGE, RACESUBJ, MOSPRIM
line 2: NECKCIRC (80), WEIGHT (124), STATURE (99)
line 3: SUBJNO ... ... (head/face dimensions: 7 values) ... ...

Field	
1	SUBJNO
2	HEADLGTH (62)
3	HEADBRTH (60)
4	HEADCIRC (61)
5	BITCHARC (15)
6	BITCOARC (16)
7	BITCRARC (17)
8	BITFRARC (18)

line 4: ... ... (head/face dimensions: 9 values) ... ...

1	BITSMARC (19)
2	BITSNARC (20)
3	BIZBDTH (21)
4	EARBDTH (43)
5	EARLGTH (44)
6	EARLTRAG (45)
7	EARPROT (46)
8	INPUPBTH (68)
9	MENSELL (77)

lines 5-30 are the head/face landmark X, Y, and Z coordinates:

The (X,Y,Z) coordinate data have units of 0.1 mm. The origin is in the upper left corner if you are facing an individual. The AHD machine was zeroed out above and slightly behind the right shoulder at the top of the head. X is positive forward, Y is positive to the subject's left, and Z is positive downward.

line 5: CRINON
line 6: GLABELLA
line 7: SELLION
line 8: PRONASALE
line 9: SUBNASALE
line 10: STOMION
line 11: PROMENTON
line 12: MENTON
line 13: R GONION
line 14: L GONION
line 15: R CHEILION
line 16: L CHEILION
line 17: R ALARE
line 18: L ALARE
line 19: R TRAGION
line 20: L TRAGION
line 21: R INFRAORBITALE
line 22: L INFRAORBITALE
line 23: R ECTOORBITALE
line 24: L ECTOORBITALE
line 25: R ZYGION
line 26: L ZYGION
line 27: R ZYGOFRONTALE
line 28: L ZYGOFRONTALE
line 29: R FRONTOTEMPORALE
line 30: L FRONTOTEMPORALE

- -

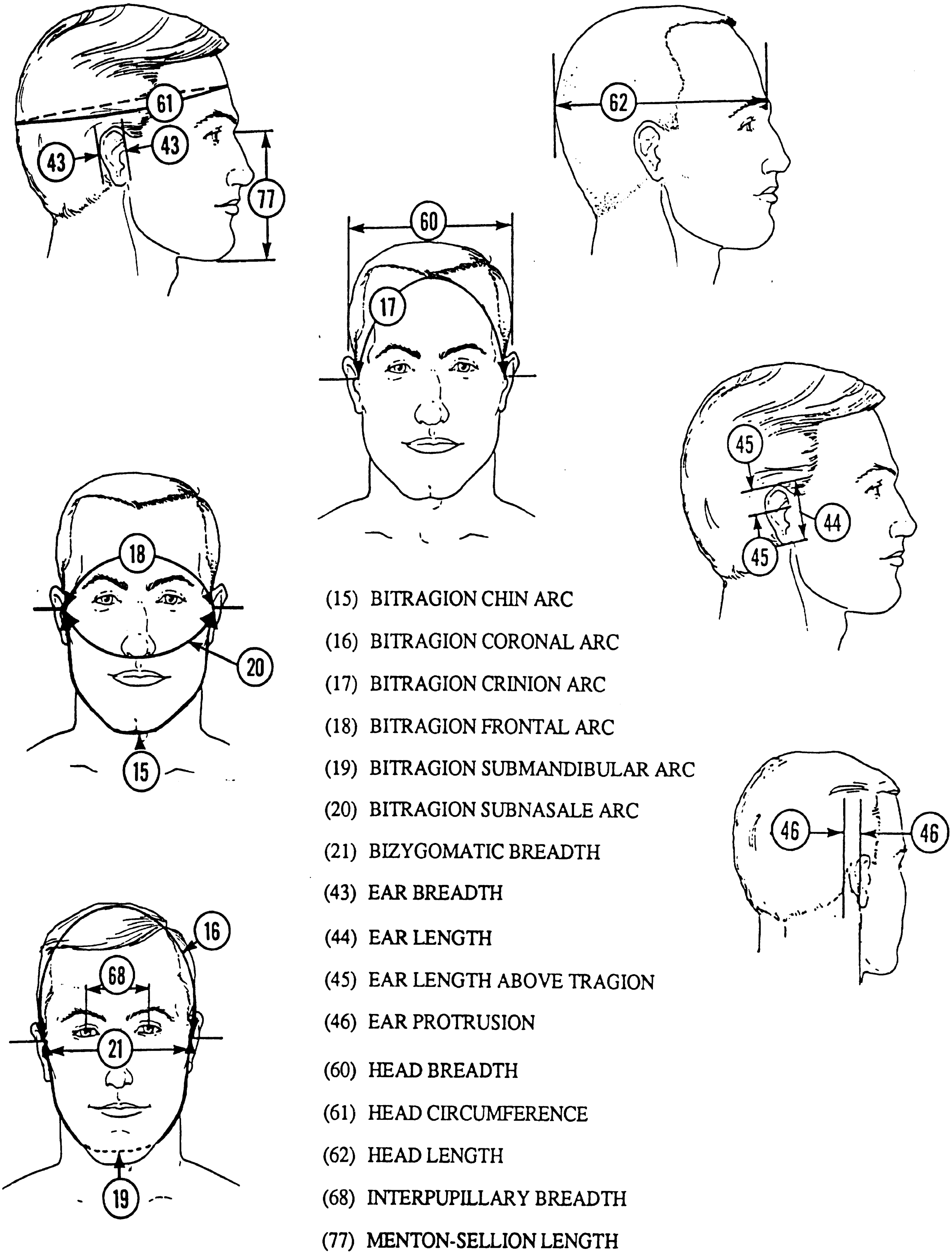
BIOGRAPHICAL DATA (line 1)

SEX -- 1=male, 2=female

AGE -- in years

RACESUBJ -- a composite of all the ethnic/race components in a subject's family. Numbers reflect subject's identity and family background. The numbers are 1-white, 2-black, 3-Hispanic, 4-Asian, 5-Native American, 6-Caribbean islander, 7-East Indian (Continental India and surrounding areas), 8-Arab. Order reflects percentage in the Army population. Mixed race individuals are indicated by a RACESUBJ > 8. For example, a person with Hispanic and black parents who considers him/herself black would be coded 23. Thus, someone with a RACESUBJ of 435 would be Asian (primarily) with Hispanic and Native American admixture.

MOSPRIM (Military Occupation Specialty) -- See Table 25 in the ANSUR final report (pp. 50-51) for definitions.



(15) BITRAGION CHIN ARC
(16) BITRAGION CORONAL ARC
(17) BITRAGION CRINION ARC
(18) BITRAGION FRONTAL ARC
(19) BITRAGION SUBMANDIBULAR ARC
(20) BITRAGION SUBNASALE ARC
(21) BIZYGOMATIC BREADTH
(43) EAR BREADTH
(44) EAR LENGTH
(45) EAR LENGTH ABOVE TRAGION
(46) EAR PROTRUSION
(60) HEAD BREADTH
(61) HEAD CIRCUMFERENCE
(62) HEAD LENGTH
(68) INTERPUPILLARY BREADTH
(77) MENTON-SELLION LENGTH

Figure 1. Head and Face Anthropometric Variables

(from Gordon, et al., 1989; *1988 Anthropometric Survey of U.S. Army Personnel - Methods and Summary Statistics*; pp. 71, 72)

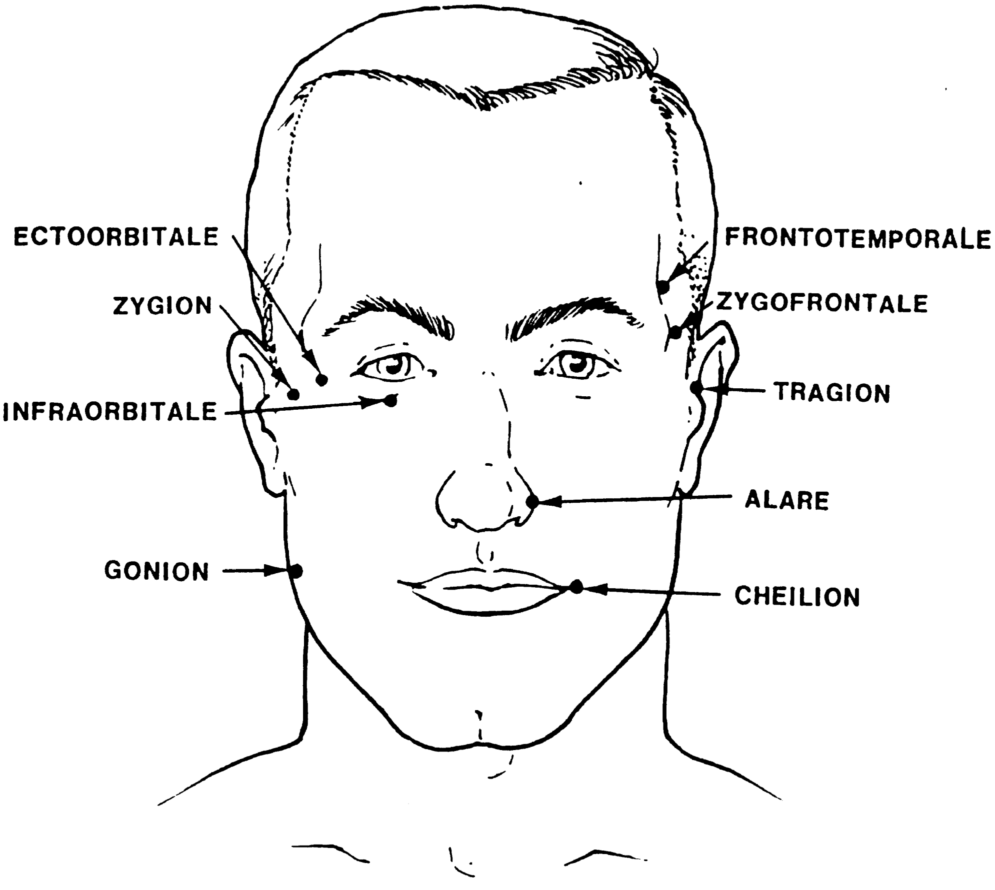


Figure 2. Locations of the Bilateral Landmarks (shown only on one side)

(from Annis and Gordon, 1988; *The Development and Validation of an Automated Headboard Device for Measurement of Three-dimensional Coordinates of the Head and Face*; pg. 48)

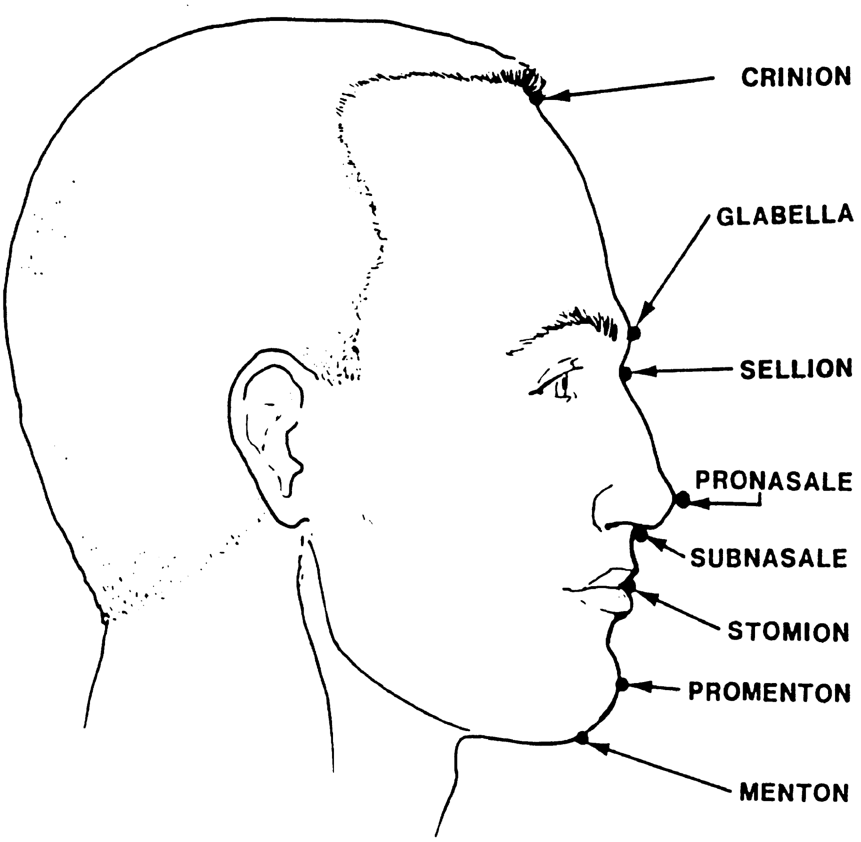


Figure 3. Locations of the Midsagittal Landmarks

(from Annis and Gordon, 1988; *The Development and Validation of an Automated Headboard Device for Measurement of Three-dimensional Coordinates of the Head and Face*; pg. 49)

4.2 Anthropometric Modeling. One major task of CTI's design effort was to establish the three-dimensional surface geometry of the face and head for headforms. To assist this effort UMTRI identified and obtained a large amount of literature pertinent to data analysis and anthropometric modeling. A synopsis of the modeling approach that was developed is given in the following section. Detail pertaining to the anthropometric modeling may be found in CTI's report on the study.

4.2.1 Synopsis of the Modeling Approach. After considering a number of possible modeling approaches CTI determined that a clustering method was the best for establishing head-face variable values for small, midsized, and large headforms. A method described by Haslegrave (*Characterizing the Anthropometric Extremes of the Population*; 1986) was adopted in part but considerably expanded upon. CTI determined three specific head variables and one face variable as the best to use as independent variables for defining clusters. The databases for males and females were merged into a single database. From this database a four-dimensional space was structured, with each of the independent variables serving as a dimension. The extent of the space in each dimension was normalized, i.e., all values in the database for each independent variable were mapped to a range [0,1]. Each dimension of the space was divided into cells of equal size, and values for the fourtuples for all 3,982 subjects were binned into the 4-space. The values for the four independent variables that define a "centroid" for each subpopulation were determined by a search in this space for the locality where the space is densest along 5th-, 50th-, and 95th-percentile surfaces, respectively, within the space. The three subpopulations of subjects clustered within ±2½-percentile halfwidth bands about these particular 5th-, 50th-, and 95th-percentile fourtuples were extracted. From these three subpopulations, then, determination of values for variables for the three headforms was completed. Specifically, for each subpopulation, the median values for all other head and face (dependent) variables were determined and used for the respective headform. The rationale for using median values rather than mean values is that "oddball" outliers cannot then weight the results inappropriately.

4.2.2 Subpopulations Represented by the Headforms. In most anthropometric modeling done for the purpose of characterizing an entire population it is necessary to make immediate decisions regarding two basic modeling parameters: (1) the number of subpopulations that will be represented and (2) the definition of those subpopulations. The need to specify these two parameters is particularly clear if physical forms of any sort are to be manufactured for representing the subpopulations, and the first --the number of subpopulations--is independent from the modeling method selected.

In the present study the design specifications for manufacturing headforms are determined. It was not established *a* *priori* what number of headforms would be needed. The number of physical forms, or sizes, needed for any application is, clearly, dependent on the application. There is no single correct number. Further, even a best number can be established only after considering not only the detail in which it is desired to be able to represent the entire population of concern, but also factors such as cost, anticipated lifetime for applicability of the forms, and the diversity of applications in which the forms will be used. Considering automotive crash test dummies, for example, there are currently more than six sizes in current use. These include three for adults--a 5th-percentile female dummy, a 50th-percentile male dummy, and a 95th-percentile male dummy--and three primary dummies for children, viz., a six-month-old infant dummy and three- and six-year-old child dummies (H. J. Mertz, 1993; also, 1993, *Guidelines for Evaluating Child Restraint System Interactions With Deploying Airbags, SAE J2189*). The number of dummy sizes was determined over a period of time on the basis of need as perceived by automotive safety researchers and the National Highway Traffic Safety Administration (NHTSA)--but with consideration of time and cost factors, as well. NHTSA, in fact, at one time approved a recommendation by UMTRI that a four-member family of adult-sized crash test dummies be developed, agreeing with the opinion of UMTRI researchers that four was an optimal number for representing the driving population (Schneider, et al., 1983; pg. 26). These four were a small female, a midsized female, a midsized male, and a large male. Cost considerations eliminated the midsized female from the family. A two-member family was proposed by UMTRI, as an option, in case the decision were made that a three-member family would be too costly. These two were a 75th-percentile male and a 25th-percentile female by height and weight. For some applications much larger numbers of forms are needed. In relation to oxygen mask sizing the Army Air Forces defined seven head types as the minimum number required for the population of concern (Damon and Randall, 1944; pg. 305). Twelve different glove sizes were selected as optimum in a sizing system study for high altitude gloves (Barter and Alexander, 1956; pg. 13).

The number of headforms recommended by CTI in the present study is three. Since both male and female anthropometry must be accounted for in the headform designs, it was originally believed that four headforms might be necessary. Cost factors were of concern, however, as was compatibility with existing full-body dummies, which exist for three adult sizes. Still, without regard to these factors, CTI has determined that three headform sizes will be sufficient if anthropometric modeling is done as outlined above, i.e., by combining the databases of male and female data and then defining small, midsized, and large headforms in terms of values from five-percentile width subpopulations centered at the 5th-, 50th-, and 95th-percentile levels.

Even the best selection of which three percentile levels to use, however, was not obvious. Maintaining compatibility with the sizes of existing full-body dummies is important, to be sure, and was probably the most significant factor in the decision to select 5th-, 50th-, and 95th-percentile levels. It should be noted, however, that the CTI definition of "Nth-percentile subpopulation," summarized above, is not the same as the definition used for full-body automotive crash dummies, viz., dummies designed by multiple regression with 5th-, 50th-, and 95th-percentile values used for two independent variables--weight and stature. Still, with respect to gross dimensions of the headforms for automotive crash dummies and the headforms from the present study, the discrepancy in "size" definitions cannot be significant. In any case such differences can have bearing only on dynamic testing and not on fit and sizing studies.

Fifth, 50th-, and 95th-percentile levels seem clearly to be most appropriate for the present application, but other subpopulation definitions are common. Examples are given above for two other proposed subpopulation representations in crash dummies as well as a more complicated population segmentation for seven different head types. Numerous others are found in the literature, each with its own definition of "percentile" as applied to multivariate anthropometry. These include 25th- and 75th-percentile males and 25th- and 75th-percentile females in a pelvis anthropometry study (Reynolds, et al., 1981), 10th-percentile females and 95th-percentile males in a seatbelt-fit study (Searle, 1974), ten cast bronze faceforms made during WW II for designing gas masks (Claus, 1976; pg. 3), 2.5th-, 50th-, and 97.5th-percentile males and females for evaluation of a belt-fit test device (Houston, 1989), 10th-, 15th-, and 20th-percentile females and 80th-, 85th-, and 90th-percentile males in a shoulder-belt-fit study (Ziegler, 1982), and both 20% and 25% equal stratification of data for males and females in an automobile-driver-control reach study (Hammond and Roe, 1972). Other examples are the 3rd-, 50th-, and 95th-percentile sizes defined for the Tri-Service database (previously discussed in Section 3.1), and size "A", "B", "C", and "D", headforms for motorcycle helmet testing (Frey and Theobald, 1980). Fit and sizing studies for both military and civilian clothing and equipment have produced a wide variety of other segmentations of the population. There are nearly as many approaches to defining subpopulations as there are studies, for each study has its own particular needs and constraints.

4.2.3 Consideration of Linear Regression as a Modeling Tool. On the basis of study of the literature on crash dummy design it was initially believed that multivariate linear regression was the most appropriate basic method to use for modeling small and large headforms from anthropometric data in the ANSUR database. Indeed, the intention to do a regression study for variables of the head and face--and, therefore, the need for data from individual subjects--was a factor in selecting the ANSUR database from among the candidate databases. The basic modeling method eventually decided upon (Section 4.2.1) does not involve regression calculations, but the need for a database of a large number of individual subjects is still required. The ANSUR database, for various reasons, is still believed to be the one most suited to the particular needs of this study. [Note: A limited amount of regression work was done by CTI as a part of the modeling, but only for the purpose of identifying the four head and face variables that would be best to use as independent variables for the clustering method that was adopted. Other considerations, as well, supported use of those four particular variables.]

Linear multiple regression modeling is an attractive approach partly because it is basically straightforward, in principle, and because the square of a correlation coefficient is a convenient measure of the degree to which the variance of a dependent variable is "explained by" a particular independent variable. A probably more important strength that linear multiple regression modeling lends to any anthropometric design study is that it produces length, breadth, and height values for component body parts that are additive. At the same time, however, the imposition of linearity on the resulting model--which is responsible for the attractive feature of additivity--is a weakness, for the assumption of approximate linearity in relationships is not always valid. The primary weakness of multiple regression modeling, however, is probably that it does not have an associated, unambiguous definition for size or content of a subpopulation even though the manner in which calculations are done for the subpopulation, defined in terms of specific percentile levels for N independent variables, is clear.

The importance of additivity may not have been appreciated by developers of the first automotive crash test dummies. Papers with descriptions of early midsized crash dummies (Starkey, et al., 1969; Hertzberg, 1969) mention plans for dummies of smaller and larger sizes, and they include data for body part lengths for 5th-percentile females and 95th-percentile males, but they do not suggest that those tabulated data are not useful, since, when added, they will not result in proper overall heights. In a later paper, however, Hertzberg (1970) points out that a term "95th-percentile man" is only a statistical abstraction. Since human beings do not all have the same anthropometric proportions, it is, in fact, impossible for any one person from the entire population to be 95th percentile in every dimension. Searle and Haslegrave also recognized this, and they discuss it in two papers (1969; 1970). A clear discussion of the problem of nonadditivity and the manner in which linear regression resolves the difficulty is given in a paper by Robinette and McConville (1981).

The relevance of regression modeling as a possible tool in designing headforms is now discussed. Again, it is noted that regression methods were *not* used by CTI, but a suitable alternative approach was used instead. A "large" headform might be defined for the purpose of fit studies, for example, as being for "95th-percentile head and face size." This means that values are required for head-face detail dimensions (such as separation between the eyes) that are not *individually* 95th percentile, but, instead, are representative of a head that has "*overall* 95th-percentile size" for head and face. This corresponds to determining, say, lower arm length for 95th-percentile body size as defined by regression on stature and weight. It is not proper or adequate to incorporate all of the individual 95th-percentile head and face dimensions into a headform that is to represent 95th-percentile overall head-face size because those values will produce a head that is far too large--and, in fact, probably larger than any single head in the entire database. Rather, a regression on dimensions that are representive of overall head-face size is required. Examples of such dimensions--independent variables--for an "N=2" model are head circumference and face length. The regression equations determined for every other head and face dimension (the *dependent* variables) will produce values that are additive and which could therefore be incorporated into a 95th-percentile headform design. Only 50th-percentile values for individual dimensions may be added directly to produce a result that is, itself, 50th percentile in size. Regressions are required for all other percentiles unless an altogether different modeling approach is taken.

The fundamental reason for rejection of a multiple regression model for the present project is the primary weakness of multiple regression that is mentioned above--viz., the lack of an associated, unambiguous definition for size or content of a subpopulation. It is essentially meaningless to describe a modeled element of the population as being, say, "overall 95th-percentile size." The number of subjects in the entire population who satisfy the 95th-percentile constraint for each of the N independent variables is vanishingly small as N increases. Further, the proportion of the entire population that satisfies these constraints is not a model input; it must be determined in each instance on the basis of counting. In order to have headforms that represent subpopulation sizes of specific proportions of the entire population, CTI, therefore, selected a method that extracts subpopulations of the desired size and at clearly defined percentile levels.

4.2.4 Selection of Independent Variables. Whatever approach is used for anthropometric modeling, it is necessary to select some small number of variables as *primary*. These variables, the independent variables of the model, are the ones that are used for predicting estimates for all of the other variables--i.e., modeling. In the present study they are also used for segmenting the database into subpopulations.

Variables that are suitable to serve as independent variables must satisfy two basic criteria. First, they should in some way represent specific, *unrelated* but *basic* characteristics of the anthropometry. Second, they need to be related, singly or collectively, to all of the *other* variables--the dependent variables. The independent variables should be unrelated, i.e., not correlated to each other (predictive of each other), so that the model will be as simple as possible. That is, a parsimonious model is desired--one which has a minimal but sufficient number of degrees of freedom. Regarding the need for being *related* to all of the other variables, the model based on a particular set of independent variables has no predictive power if such relationships do not exist--i.e., it is not then really a model at all. The set of independent variables is inadequate if it cannot be used to characterize, in some way, all other variables of the anthropometry.

The best selection of independent variables for any particular application is very much specific to the anthropometry, the database, and the constraints and goals of the study. Nearly all references on anthropometric modeling studies and statistical methods include discussion of pertinence to the selection or identification of independent variables. Several references that were found helpful in the present study are: *Anthropometry in Sizing and Design* (J. T. McConville; 1978); *Statistical Considerations in Man-Machine Designs* (E. Churchill; 1978); *Characterizing the Anthropometric Extremes of the Population*, (C. M. Haslegrave; 1986); *The Use of Bivariate Distributions in Achieving Anthropometric Compatibility in Equipment Design* (W. F. Moroney and M. J. Smith; 1972); *Survey of Head, Helmet and Headform Sizes Related to Motorcycle Helmet Design* (A. Gilchrist, et al.; 1988); and *Anthropometry for Respirator Sizing* (J. T. McConville and M. Alexander; 1972). The following report is also pertinent and should be referenced, although it was obtained only near the end of the present study: *A Multivariate Anthropometric Method of Crewstation Design: Abridged* (G. F. Zehner, et al.; 1993).

Hubbard and McLeod (1973; pg. 130) cite a study by Churchill and Truett (1957) in which it was found that there is very low correlation (r = 0.12) between head length and head breadth. Such primary variables are good candidates for roles as independent variables, assuming that in addition to low correlation to each other, they have relatively higher correlation to a significant number of other variables in the database. Hubbard and McLeod also note that the Churchill-Truett study documents a generally poor correlation between dimensions of the head and face. This is found also by McConville and Alexander (1972; pg. 24) and by Cheverud, et al. (1990; Parts 2-5). It could be anticipated that face length would serve well as an independent variable in an anthropometric model for headforms. This variable was used as a key variable by McConville and Alexander (in a respirator sizing study). Their definition for face length was menton-to-nasal root depression. A definition more appropriate for a model that will be used for masks and NVGs (night vision goggles) is menton-to-sellion (nasion) (Damon and Randall, 1944; pg. 306) (personal communication, H. M. Reynolds).

CTI selected the following variables to serve as four independent variables for the cluster model: (1) head length,

(2) head breadth, (3) head circumference, and (4) the menton-to-sellion distance (face length). The process that resulted in selection of these particular variables is discussed in the CTI report.

A possible alternative approach to designing a headform that is to be used for fit testing of helmets as well as masks, NVGs, etc., is to attempt to model head (skull) features and facial features independently and then to find a way to juxtapose the head and face models properly. (This would be done with each size of headform.) The head model and the face model would each have its own set of independent variables. It might be possible to use the strongest correlations between skull and face points, or dimensions, that can be found from a regression study to establish the best juxtaposition.

5.0 HEAD INERTIAL PROPERTIES

There is an abundance of literature pertinent to the inertial properties of the human head. There is also a large amount of literature pertinent to the inertial properties of anthropomorphic headforms, primarily the Hybrid III dummy. The design values for the headform of the Hybrid III dummy itself represent a compilation of the best available (cadaver) data for midsized human males. Table 3 describes all data found in the literature review of the present study for head mass, head density, and head principal moments of inertia. All Hybrid III data are located at the beginning of the table, and all cadaver data follow.

It is recommended here that, except for the direction angles of the principal axes, the inertial properties of the Hybrid III headform be used as the model for the midsized headform developed in the present study. No data have come from any recent studies that are contradictory to the cadaver data used in determination, over a period of 30 years, of the most appropriate inertial property design specifications for the Hybrid III headform. It is essentially the cadaver data in Table 3 that, collectively, established and corroborated the inertial properties of the current Hybrid III headform. (The following GM ATD 502 and Hybrid III dummy references, among others, are pertinent: Hubbard and McLeod, 1973; Hubbard and McLeod, 1974; Hubbard, 1975; General Motor Corporation, *Hybrid III - An Advanced Anthropomorphic Crash Test Dummy*, 1978/1983; Kaleps, et al., 1988; Kaleps and Whitestone, 1988; Mertz, et al., 1989; Backaitis and Mertz, 1994.)

5.1 Midsized Headform. The headform of the GM ATD 502 crash dummy was designed by Hubbard and McLeod (1974). (Also, see Hubbard, 1975.) That headform was incorporated without change into the Hybrid III dummy (Foster, et al., 1977; pp 977-981). The design specifications of Hubbard and McLeod for inertial properties include a mass value of 10.0 lb (4.54 kg) and a moment of inertia I_{yy} about the lateral principal axis of 238 kg-cm^2 ±

10 kg-cm² (0.207 in-sec²-in ± 0.10 in-sec²-in). The design specifications *do not* include requirements for I_{xx} or I_{zz} or the orientations of their principal axes with respect to an anatomical coordinate system.

The best available inertial property data for the Hybrid III (midsized) headform, as manufactured, are those in the study reported by Kaleps and Whitestone (1988), in which properties of the Hybrid III dummy were experimentally measured. The measured values for mass (9.92 lb) and I_{yy} (240.4 kg-cm²) are in good agreement with the Hubbard-McLeod design specifications. Clarification is needed, however, in regard to other Kaleps-Whitestone data. Some of the data are *apparently* not in good agreement with the widely cited results of McConville, et al. (1980) (and the same study as reported by Kaleps, et al., 1984), for living male subjects as determined by stereophotometric techniques and multiple regression modeling. While head masses are not greatly different--9.92 lb and 9.632 lb, respectively--the reported values for head principal moments of inertia and the orientation of the principal axes are very different. Kaleps and Whitestone determine their principal X-axis, X_p, to be rotated 26.6 degrees ($\cos^{-1}$ 0.89426) *downward* from the head anatomical reference system (i.e., from the Frankfort Plane) while McConville, et al., determine an *upward* rotation of 36.05 degrees--a difference of about 63 degrees. The principal moments of inertia I_{yy} about the lateral principal axis are found to be similar, as shown below, but there is considerable apparent disagreement between the values for the principal X- and Z-axes. In particular, Kaleps and Whitestone report I_{zz} to be much larger than I_{xx} while, conversely, McConville, et al., report I_{xx} to be much larger than I_{zz}. In a personal communication with Dr. Ints Kaleps (October 13, 1994) it was learned that the orientations of the principal axes differ in actuality by about 27 degrees, not 63 degrees, and, further, that the principal moments of inertia are actually in reasonably good agreement since the identifications of X_p and Z_p are transposed in the two studies. Specifically, $-Z_{p,McConville}$ corresponds to $+X_{p,HybIII}$ and $+X_{p,McConville}$ corresponds to $+Z_{p,HybIII}$. Thus, *in terms of McConville's system*, while the human (male) principal X-axis is rotated 36.05 degrees upward from the anatomical X-axis (forward), the Hybrid III "X_p-axis" is rotated 63.4 degrees upward. The Z_p-axes--in terms of McConville's system--are similarly different by about 27 degrees, and both are upward through the back of the crown. In relation to the described transposition of axis definitions, I_{xx} and I_{zz} values in the McConville and Kaleps studies must be interpreted inversely. The two tables below, respectively, show the values of principal moments of inertia as reported in the two studies.

PRINCIPAL MOMENTS OF INERTIA AS REPORTED IN FOR TWO STUDIES

Kaleps and Whitestone (Hybrid III, midsized)	Ixx = 159.1 kg-cm^2	(0.1408 lb-sec^2-in)
	Iyy = 240.4 kg-cm^2	(0.2128 lb-sec^2-in)
	Izz = 221.0 kg-cm^2	(0.1956 lb-sec^2-in)
McConville, et al. (midsized living males)	Ixx = 204.1 kg-cm^2	(0.181 lb-sec^2-in)
	Iyy = 232.9 kg-cm^2	(0.206 lb-sec^2-in)
	Izz = 150.8 kg-cm^2	(0.133 lb-sec^2-in)

PROPERLY COMPARED PRINCIPAL MOMENT OF INERTIA VALUES
FOR THE McCONVILLE AXIS SYSTEM

Kaleps and Whitestone (Hybrid III, midsized) [*transposed values*]	Ixx = *221.0* kg-cm^2	(*0.1956* lb-sec^2-in)
	Iyy = 240.4 kg-cm^2	(0.2128 lb-sec^2-in)
	Izz = *159.1* kg-cm^2	(*0.1408* lb-sec^2-in)
McConville, et al. (midsized living males)	Ixx = 204.1 kg-cm^2	(0.181 lb-sec^2-in)
	Iyy = 232.9 kg-cm^2	(0.206 lb-sec^2-in)
	Izz = 150.8 kg-cm^2	(0.133 lb-sec^2-in)

It may be seen from examination of Table 3 that for some of the major experimental studies in which cadaver head principal moments of inertia are measured, I_{xx} is reported to be much greater than I_{zz} while others show the opposite relative magnitudes. (Note: Major experimental studies with cadavers are italicized in the Tables 3 and 4.) Specifically, Chandler, et al. (1975), and Reynolds, et al. (1975), have $I_{zz} >> I_{xx}$ while Beier, et al. (1980), and Young, et al. (1983), have $I_{xx} >> I_{zz}$, in basic agreement with the values for living male subjects in the McConville study. (Young's values were determined with a regression model from stereophotometric measurements made with living female subjects in the same manner as McConville's for living males.)

Reasons for the relatively large discrepancies between values from different studies for I_{xx} and I_{zz} could not be determined in the present study, except as noted above regarding the seeming, but not actual, discrepancy between Kaleps-Whitestone values for the Hybrid III dummy and the values of McConville, et al., for living human males. Sectioning of cadavers seems to have been done in the same way in the various studies, but small differences in method could have large effect on principal moments of inertia. Further, there is an inherent sensitivity to experimental conditions in the equations for the direction angles of the principal axes that, in fact, increases without bound as the differences between values of the principal moments of inertia approach zero. Additionally, *none* of the authors describe the method used for measuring principal moments of inertia and principal axis orientation--a nontrivial experimental endeavor--so it is not possible to assess the accuracy of reported results. Only the papers of Kaleps and Whitestone (1988) and Kaleps, et al. (1984), include schematics that show the principal axes. (The system used in Kaleps, et al. (1984) is, however, the same as was used for the studies by McConville, et al. (1980), and Young (1983).) Thus, a possible explanation for the two groupings of reported values--$I_{xx} >> I_{zz}$ and $I_{zz} >> I_{xx}$--that seems likely to be correct is that axes are defined oppositely in various studies, as for the Hybrid III and living human male studies described above. If this is true, then if the McConville system is used (see Kaleps, et al. (1984)), it would be correct for each study to use the larger of the reported values, I_{xx} and I_{zz}, for I_{xx} and the smaller for I_{zz}. That is, $I_{xx} >> I_{zz}$, where the X_p axis is approximately through the forehead and the Z_p axis is through the back of the crown.

As the (transposed) principal moments of inertia measured by Kaleps and Whitestone for the Hybrid III are in good agreement with the living human male values of McConville, et al., either set of values can be recommended for use. *For direction angles of the principal axes, however, it is recommended here that the McConville value (36 degrees) be used for the midsized and large headforms and the Young value (42 degrees) be used for the small ("female") headform.* Support for this recommendation is found in the basic agreement between the cadaver measurement results of Beier, et al. (1980) and the results of McConville, et al., in regard to both the reported direction angles (34 degrees and 36 degrees upward) and the reported relative--and absolute--magnitudes of I_{xx} and I_{zz}.

No values for headform volume for the Hybrid III headform could be found in the literature search of the present study, nor could values for average density be found. Consequently, the average density of the Hybrid III headform could not be established. Average specific gravities of cadaver heads, however, are determined by several researchers. These values are included in Table 3. They range from 1.056 to 1.15. (Specific gravity is called "density" in most of the references.)

5.2 Small and Large Headforms. For small and large headforms, the result of Kaleps and Whitestone for head mass (midsized, 9.92 lb) or the design specification (10.0 lb) should be supplemented with the results of Mertz, et al. (1989). Their values for headforms for the small female and the large male are 8.10 lb and 10.90 lb, respectively, based on the design value for the (midsized) Hybrid III headform and scale factors of 0.808 and 1.093, respectively. *Either set of values, i.e., those based on a mass of 9.92 lb or 10.0 lb for the midsized headform, can be recommended for use for the headforms of the present study.* These values are shown in the following table.

SCALED HYBRID III HEADFORM	Head Mass	
Hybrid III, midsized		
Kaleps-Whitestone measurement	9.92 lb	(4.500 kg)
Mertz, et al., design specification	10.00 lb	(4.536 kg)
SCALE FACTOR = 1.0		
Small female (scaled)		
Scaled Kaleps-Whitestone	8.02 lb	(3.638 kg)
Scaled design specification	8.10 lb	(3.674 kg)
SCALE FACTOR = 0.808		
Large male (scaled)		
Scaled Kaleps-Whitestone	10.84 lb	(4.917 kg)
Scaled design specification	10.90 lb	(4.944 kg)
SCALE FACTOR = 1.093		

Mertz, et al., while providing values for many properties scaled from midsized (Hybrid III) to small and large, do not include values for head principal moments of inertia for even the Hybrid III headform. It may easily be shown that, for geometric similarity and uniform and equal density, moment of inertia scales as the 5/3rd power of the ratio of the masses or, equivalently, as the 5th power of the ratio of the lengths. (See Bowman, et al., 1977; pg. 75.) Mertz, et al., give head length-scale ratios relative to the midsized male of 0.931 for small females and 1.030 for large males. The fifth powers of these values are 0.6994 and 1.1593, respectively. These scale factors can be multiplied by the Hybrid III values for principal moments of inertia to obtain the values below. The I_{xx} and I_{zz} values here are the *transposed* Kaleps-Whitestone Hybrid III values, as described in Section 5.1.

SCALED HYBRID III HEADFORM	Head Principal Moments of Inertia for the McConville Axis System[1]	
Kaleps and Whitestone	Ixx = 221.0 kg-cm^2	(0.1956 lb-sec^2-in)
(transposed values)	Iyy = 240.4 kg-cm^2	(0.2128 lb-sec^2-in)
(Hybrid III, midsized)	Izz = 159.1 kg-cm^2	(0.1408 lb-sec^2-in)
SCALE FACTOR = 1.0		
Scaled Kaleps-Whitestone	Ixx = 154.6 kg-cm^2	(0.1368 lb-sec^2-in)
values (for small female)	Iyy = 168.1 kg-cm^2	(0.1488 lb-sec^2-in)
SCALE FACTOR = 0.6994	Izz = 111.3 kg-cm^2	(0.0985 lb-sec^2-in)
Scaled Kaleps-Whitestone	Ixx = 256.2 kg-cm^2	(0.2268 lb-sec^2-in)
values (for large male)	Iyy = 278.7 kg-cm^2	(0.2467 lb-sec^2-in)
SCALE FACTOR = 1.1593	Izz = 184.4 kg-cm^2	(0.1632 lb-sec^2-in)

[1] The Xp axis is approximately through the forehead and the Zp axis is through the back of the crown. The magnitudes of the direction angles of the principal axes are given in the text.

Note is made here that if the Hybrid III values of Kaleps and Whitestone are adopted for the midsized headform, rather than the results of McConville, et al., scaled data as described above should be used for the small female and large male rather than the results of Robbins (1983b, 1983c) since those data are derived in part from the McConville (and Young) data. Additionally, Robbins' values for principal moments of inertia for small females and large males are in error since, on the assumption of geometric similarity, he scaled moments of inertia in proportion to the square of a characteristic length rather than the fifth power of a characteristic length. His procedure involved scaling only *adjustments* to the values, however, so the size of the errors may not be large.

5.3 Definitions and Other Considerations. All researchers whose data are presented in Table 3 used essentially the same *anatomical coordinate system* for the head. The definition of Kaleps and Whitestone (1988) is as follows: The Y-axis unit vector *Y* is from right tragion to left tragion. The X-axis unit vector *X* is parallel to a vector that is normal to the Y-axis and passes through right infraorbitale. The X-axis itself passes through the midpoint between right and left tragion, and the Z-axis unit vector is $X \times Y$ (upward). *X* and *Y*--or, equivalently, the three points right tragion, left tragion, and right infraorbitale--define the Frankfort Plane. (The head anatomical coordinate system is sometimes called Frankfort Horizontal.) Differences between this definition and ones used by other researchers are negligible in regard to use of data from Table 3 (and Table 4). Those differences include: (1) use of right and left auditory meatus instead of right and left tragion for the *Y* vector; (2) definition of *X* as a normal to *Y* that passes through nasion (sellion).

Two additional points regarding the cadaver data in Table 3 (and Table 4) need to be made. First, no female cadavers were included in any of the studies done with cadavers. Further, no study identifies data from male cadavers as being for "small," "midsized," or "large" males (or heads). That is, average values presented by the authors are from cadaver pools in which small, midsized, and large heads are all included. It is necessary, therefore, that an assumption be made that "midsized" can be equated with "average." Any other definition would reduce already small sample sizes to an extent that results would have greatly reduced statistical significance.

Table 3. Head Mass, Density, and Principal Moments of Inertia

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Reference	Year	Pg	M/I/dens	Description/Values
Foster, et al.	1977	1006	M	Hyb III "desired" head mass: 4.5 kg (9.92 lb)
Kaleps and Whitestone	1988	16	M,I	Hyb III: head weight is 9.92 lb; anatomical axes: *Y* is vector from right tragion toward left tragion, *X* is normal from Y axis to right infraorbitale, *Z* is *X* x *Y*, origin is the midpoint in Y between right tragion and left tragion; *X* and *Y* define the Frankfort Plane; transformation from principal to local reference axes: $\begin{matrix} 0.89426 & 0.00018 & 0.44750 \\ -0.00010 & -1.00000 & 0.00065 \\ 0.44745 & -0.00061 & -0.89426 \end{matrix}$ [rotation from X anatomical axis to principal axis is *63.4 degrees upward; see text*]; the principal moments of inertia (*see text*) are: *Ixx = 221.0 kg-cm^2 (0.1956 lb-sec^2-in)*, Iyy = 240.4 kg-cm^2 (0.2128 lb-sec^2-in), *Izz = 159.1 kg-cm^2 (0.1408 lb-sec^2-in)* [See text for values for small/large.]
Mertz, et al.	1989	134-136	M,I	"Hyb III" (actually, average-sized adult male cadaver) and 5th and 95th: head weights are 10.0, 8.10, and 10.90 lb (5th and 95th calculated from 50th on the basis of equal density and anthropometry study values for circumference, width, and length, which were used to calculate characteristic lengths d=C+W+L for scaling) 50th-percentile length values from Hubbard and McLeod, 1974; 5th and 95th length values from Schneider, et al., 1983: 50th: C = 22.60 in, W = 6.06 in, L = 7.75 in 5th: C = 21.00 in, W = 5.71 in, L = 7.20 in 95th: C = 23.40 in, W = 6.14 in, L = 7.95 in

Table 3. Head Mass, Density, and Principal Moments of Inertia

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Reference	Year	Pg	M/I/dens	Description/Values
Deng	1989	93	M,I	Hyb III (values used for simulation model): head mass = 4.545 kg (10.02 lb); I_{xx} = 257 kg-cm^2 (0.227 lb-sec^2-in), I_{yy} = 300 kg-cm^2 (0.266 lb-sec^2-in), I_{zz} = 192 kg-cm^2 (0.170 lb-sec^2-in)
Perl, et al.	1989	30	M,I	Hyb III: head weight = 10.0 lb, I_{yy} = 0.27 lb-sec^2-in, head length = 7.7 in, head circumference = 22.5 in, head breadth = 6.1 in
Spittle, et al.	1992	121	M	Hyb III: head weight = 9.921 lb
Mertz	1967	115, 116	M,dens	two cadavers: average head weight = 10.8 lb; average head specific gravity = 1.15
Clauser, et al.	1969	46	M	average head mass for 13 cadavers was 4.729 kg (10.43 lb)
Hodgson and Thomas	1971	9-11	M,I	average head weight for 38 cadavers was 10.52 lb; average I_{yy} for seven cadavers was 0.22 lb-sec^2-in
Mertz and Patrick	1971a	18	M,I	averages for four cadavers: head wt = 10.35 lb; I_{yy} = 0.202 lb-sec^2-in
Mertz and Patrick	1971b	223	M,I	same as Mertz and Patrick, 1971a
Ewing and Thomas	1973	314	M,I	cadaver data (same as Walker): average head mass is 4.38 kg (9.656 lb); avg I_{yy} = 233 kg-cm^2 (0.206 lb-sec^2-in)
Walker, et al.	1973	533	M,I	cadaver data, 18 cadavers: average head mass is 4.376 kg (9.647 lb); average I_{yy} = 233 kg-cm^2 (0.206 lb-sec^2-in)
Walker, et al.	1973	14, 15	M,I, density	cadaver data, 18 cadavers: average head mass is 4.376 kg (9.647 lb); average head volume is 3947 ml; average specific gravity (density) is 1.108; average I_{yy} = 233 kg-cm^2 (0.206 lb-sec^2-in)

Table 3. Head Mass, Density, and Principal Moments of Inertia

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Reference	Year	Pg	M/I/dens	Description/Values
Hubbard and McLeod	1974	606	M,I	GM ATD 502 head, design based on cadaver data: wt = 10 lb (4.54 kg); Iyy = 0.207 lb-s^2-in ± 0.01 lb-s^2-in) (238 kg-cm^2 ± 10 kg-cm^2)
Hubbard	1975	5	M,I	same values as in Hubbard-McLeod, 1974
Chandler, et al.	1975	68	M,I, density	cadaver data, 6 cadavers: average head mass is 3.988 kg (8.792 lb); average head volume is 3785 ml; average specific gravity (density) is 1.056 Ixx = 170.8 kg-cm^2 (0.151 lb-sec^2-in), Iyy = 164.0 kg-cm^2 (0.145 lb-sec^2-in), Izz = 200.8 kg-cm^2 (0.178 lb-sec^2-in) [*Ixx & Izz may be reversed; see text*]
Reynolds, et al.	1975	12, 17	M,I	cadaver data, 6 cadavers: average head mass is 3.976 kg (8.765 lb); Ixx = 174.0 kg-cm^2 (0.154 lb-sec^2-in), Iyy = 164.4 kg-cm^2 (0.146 lb-sec^2-in), Izz = 202.9 kg-cm^2 (0.180 lb-sec^2-in) [*Ixx & Izz may be reversed; see text*]
Huston	1975	95, 97	M,I	cadavers (Walker data): 4376 gm (9.647 lb); Iyy = 23300 gm-cm^2 (0.206 lb-sec^2-in)
McConville	1980	32	M,I, density	31 living male subjects: stereophotometric techniques were used to determine surface point coordinates and immersion was used to determine volume; computer processing of data determined the following (average values): volume = 4369 ml; mass = 4.369 kg (9.632 lb) [specific gravity of 1.0 was assumed, but the author cites a value for head density found by Clauser, et al., 1969, as 1.071]; head height = 16.65 cm (6.56 in); head length = 19.93 cm (7.85 in); head breadth = 15.32 cm (6.03 in); head circumference = 57.27 cm (22.55 in); upward rotation of anatomical X-axis to principal axis = 36.05 deg; principal moments of inertia found from regression equations:

Table 3. Head Mass, Density, and Principal Moments of Inertia

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Reference	Year	Pg	M/I/dens	Description/Values
				Ixx = 204.1 kg-cm^2 (0.181 lb-sec^2-in), Iyy = 232.9 kg-cm^2 (0.206 lb-sec^2-in), Izz = 150.8 kg-cm^2 (0.133 lb-sec^2-in) [uniform mass distribution was assumed]
Beier, et al.	1980	222, 225	M	values for 21 cadavers: average head mass is 4.305 kg (9.49 lb), ranging from 3.676 kg to 5.257 kg (s.d. is 0.402 kg); average upward rotation of X anatomical axis to X principal axis is 34 degrees;
				Ixx = 206 kg-cm^2 (0.182 lb-sec^2-in) Iyy = 223 kg-cm^2 (0.197 lb-sec^2-in) Izz = 148 kg-cm^2 (0.131 lb-sec^2-in) (Ixx range: 136-274 kg-cm^2), (Iyy range: 167-298 kg-cm^2), (Izz range: 110-198 kg-cm^2)
Bowman and Schneider	1980	27	M,I	cadaver data: head weight = 8.65 lb; Iyy = 0.136 lb-sec^2-in; principal X-axis is 36 degrees upward from the anatomical X-axis
Robbins	1983a	69, 74, 78	M,I	midsized male (Vol. 2), McConville living subject data: head mass (assuming density = 1.0) is 4.137 kg (9.120 lb); principal X-axis is 36 degrees upward from the anatomical X-axis
				Ixx = 200.3 kg-cm^2 (0.177 lb-sec^2-in), Iyy = 221.5 kg-cm^2 (0.196 lb-sec^2-in), Izz = 144.6 kg-cm^2 (0.128 lb-sec^2-in) [uniform mass distribution was assumed]
	1983b	49, 55, 56	M,I	small female (and large male) (Vol. 3), living female (Young) and living male (McConville) data small female: head mass (assuming density = 1.0) is 3.697 kg (8.150 lb); principal X-axis is 42 degrees upward from the anatomical X-axis
			* Probably in error. See note in text.	*Ixx = 146.2 kg-cm^2 (0.129 lb-sec^2-in), *Iyy = 172.9 kg-cm^2 (0.153 lb-sec^2-in), *Izz = 131.7 kg-cm^2 (0.117 lb-sec^2-in) [uniform mass distribution; 50th scaled]

Table 3. Head Mass, Density, and Principal Moments of Inertia

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Reference	Year	Pg	M/I/dens	Description/Values
	1983b	50, 55, 58	M,I	large male (and small female) (Vol. 3), scaled McConville living male data: large male: head mass (assuming density = 1.0) is 4.511 kg (9.945 lb); principal X-axis is 36 degrees upward from the anatomical X-axis *Ixx = 225.9 kg-cm^2 (0.200 lb-sec^2-in), *Iyy = 263.1 kg-cm^2 (0.263 lb-sec^2-in), *Izz = 168.7 kg-cm^2 (0.169 lb-sec^2-in) [uniform mass distribution; 50th scaled] * Probably in error. See note in text.
Young, et al.	1983	18, 19	M,I	46 living female subjects: parallel to males study above (see McConville, 1980) with identical methodology; average values determined were as follows: volume = 3894 ml; mass = 3.894 kg (8.585 lb) [specific gravity of 1.0 was assumed]; head height = 15.59 cm (6.14 in); head length = 18.69 cm (7.36 in); head breadth = 14.58 cm (5.74 in); head circumference = 54.78 cm (21.7 in); upward rotation of anatomical X-axis to principal axis = 42.18 deg; principal moments of inertia from regression equations: Ixx = 160.2 kg-cm^2 (0.142 lb-sec^2-in), Iyy = 189.9 kg-cm^2 (0.168 lb-sec^2-in), Izz = 140.4 kg-cm^2 (0.124 lb-sec^2-in) [uniform mass distribution; modeled]
Kaleps, et al.	1984	1232	I	living male data (McConville): head principal X-axis is 36.13 degrees upward from the Frankfort Plane Ixx = 204.1 kg-cm^2 (0.181 lb-sec^2-in), Iyy = 232.9 kg-cm^2 (0.206 lb-sec^2-in), Izz = 150.8 kg-cm^2 (0.133 lb-sec^2-in)
Goldsmith, et al.	1984	93	M,I	cadavers: skull wt.=3.53 kg (7.78 lb); Ixx = 0.0353 kg-m^2 (0.312 lb-sec^2-in), Iyy = 0.0516 kg-m^2 (0.457 lb-sec^2-in), Izz = 0.0516 kg-m^2 (0.457 lb-sec^2-in) [*Ixx & Izz may be reversed; see text*]

Table 3. Head Mass, Density, and Principal Moments of Inertia

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Reference	Year	Pg	M/I/dens	Description/Values
SAE J1460 MAR85	1985	34.245	M,I	cadaver data, recommended for use in anthropomorphic dummies: head mass = 4.69 kg (10.34 lb); principal moments of inertia Ixx = 0.0226 kg-m^2 (0.200 lb-sec^2-in), Iyy = 0.0213 kg-m^2 (0.189 lb-sec^2-in), Izz = 0.0263 kg-m^2 (0.234 lb-sec^2-in) [*Ixx & Izz may be reversed; see text*]
Hayes, et al.	1986	1203	M,I	cadaver-based data for "the 50th percentile standard military aviator for male human analogue" (draft military standard): head mass = 4.24 kg (9.348 lb); principal moments of inertia: Ixx = 198 kg-cm^2 (0.175 lb-sec^2-in), Iyy = 226 kg-cm^2 (0.200 lb-sec^2-in), Izz = 147 kg-cm^2 (0.130 lb-sec^2-in)
Hoen and Wismans	1986	5,6	M,I	cadavers, proposed head/neck model: head principal X-axis is 36 degrees upward from Frankfort Plane; the Y-axis is tragion-to-tragion; head mass is 4.28 kg (9.44 lb); principal moments of inertia: Ixx = 0.0230 kg-m^2 (0.204 lb-sec^2-in), Iyy = 0.0238 kg-m^2 (0.211 lb-sec^2-in), Izz = 0.0124 kg-m^2 (0.110 lb-sec^2-in)
Howe, et al.	1991	293	M,I	cadaver study summaries (except for McConville@); adult midsized males:

Ref.	Mass (kg)	Ixx&	Iyy (kg-cm^2)	Izz&	No. of Subjects
Walker	4.46	-	233	-	16
Hubbard	4.54	-	-	-	11
&Reynolds	4.69	226	212	263	6
Beier	4.32	207	226	149	19
@McConville	4.55	224	255	166	31
@Robbins	4.54	220	243	159	25
Wismans	4.45	-	-	-	15
AVERAGE*	4.51 (9.94 lb)	219	234	184**	--
WT. AVG.#	4.49 (9.90 lb)	218	242	166**	123

Table 3. Head Mass, Density, and Principal Moments of Inertia

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Reference	Year	Pg	M/I/dens	Description/Values
				NOTE: 1 kg = 2.2046 lb 1 kg-cm^2 = 8.8511E-4 lb-sec^2-in * - principal moment of inertia values based on four studies: Reynolds, Beier, McConville, and Robbins ** - includes greatly different I_{zz} value from Reynolds study # - based on number of subjects in each study @ - living male subjects, not cadavers & - I_{xx} and I_{zz} should possibly be reversed for studies in which $I_{xx} < I_{zz}$ if the principal axis system of McConville, et al. (1980) [Kaleps, et al., 1984] is used; see Sections 5.1 and 5.2

NOTES:

1. All cadavers used in all cited studies are males.
2. Major experimental measurement studies with cadavers are italicized.

6.0 LOCATIONS OF THE HEAD CENTER OF GRAVITY AND THE OCCIPITAL CONDYLES PIVOT

Locating the head center of gravity (CG) properly for the small, midsized, and large headforms is important for dynamics studies, including helmet retention studies. In order that the head of the manikin be able to replicate human response reasonably well, this means that its CG location with respect to the head-neck pivot should be reasonably accurate. For static fit studies the location of neither the CG nor the head-neck pivot is of significance.

Numerous references have been found that contain data pertinent to properly locating the head center of gravity and the occipital pivot in the headforms designed in the present study. Those data are given in Table 4. Many of the references are ones included in Table 3 for inertial properties. As in Table 3, the references in Table 4 begin with ones pertinent to the Hybrid III dummy headform, and references for cadaver studies, or studies in which cadaver data were used, follow. *As for inertial properties, it is recommended that Hybrid III headform data for the center of gravity and the occipital pivot be used for the midsized headform designed in the present study.* Here, as for inertial properties, the data presented from cadaver studies are the very data that were used, collectively, to establish and corroborate the design of the current Hybrid III headform. A reanalysis of the available cadaver data would not produce results for the locations of the CG or the occipital condyles that are significantly different from the values adopted for the Hybrid III headform. (Note: Major experimental measurement studies with cadavers are italicized in the Tables 3 and 4.)

In nearly all listed references the same anatomical coordinate system defined in Section 5.0 was used, viz., one in which X and Y define the Frankfort Plane and Z is normal to the Frankfort Plane at the midpoint of the Y-axis between right and left tragion. The definition of Kaleps and Whitestone (1988) from Section 5.0 is repeated in the footnote.[1]

The center of gravity of the head is assumed, or measured, to be on the midsagittal plane--i.e., at Y=0--by all researchers. Nonzero Y_{CG}, whenever measured, is small enough to be negligible. The coordinates of the CG are in nearly every instance given relative to the origin of the anatomical coordinate system. The most common exception to this is identification of the X and Z separations between the CG and the occipital condyles (along the anatomical X- and Z-axes) without accompanying values that locate either the CG or the occipital conyles with respect to the anatomical coordinate system.

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[1] The Kaleps and Whitestone (1988) definition of the anatomical coordinate system of the head: The Y-axis unit vector is from right tragion toward left tragion. The X-axis unit vector is parallel to a vector that is normal to the Y-axis and passes through right infraorbitale. The X-axis itself passes through the midpoint between right and left tragion, and the Z-axis unit vector is $X \times Y$ (upward). X and Y define the "Frankfort Plane." NOTE: Differences between this definition and ones used by other researchers are negligible in regard to use of data from Tables 3 and 4. Those differences include: (1) use of right and left auditory meatus instead of right and left tragion for the Y vector; (2) definition of X as a normal to Y that passes through nasion (sellion).

The occipital condyles location has been selected as the best for the head-neck pivot for headforms designed in the present study. This is in accordance with the design of the Hybrid III headform. There are two occipital condyles in the human head, separated symmetrically to the left and right of the midsagittal plane. As there is essentially no lateral articulation at this "joint," however--i.e., only pivoting in the midsagittal plane--it is unnecessary to determine Y coordinates for the occipital condyles. Rather, only the X and Z coordinates of the axis of rotation at the occipital condyles need be established. The occipital condyles (and the CG) can be located with respect to any point on the head if the coordinates of that point and the coordinates of the condyles are both known with respect to the anatomical coordinate system (which can be defined absolutely if the laboratory frame (X,Y,Z) coordinates of left and right tragion and right infraorbitale are known).

6.1 Midsized Headform. The design of the Hybrid III headform--originally developed for the GM ATD 502 crash dummy--locates the CG and the head-neck ("occipital condyles") pivot relative to each other and relative to head and face landmarks. (See Table 4: Hubbard and McLeod, 1974; Hubbard, 1975.) In the anatomical (Frankfort Plane) coordinate system the CG is 1.9 inches above and 0.7 inches forward from the occipital condyles.

There is good agreement between the various authors in regard to the relative locations of the CG and the head-neck pivot in the actual Hybrid III (midsized) headform. In the head anatomical coordinate system the CG is 2.00 inches above and 0.55 inches forward from the head-neck pivot according to Kaleps and Whitestone (1988), Spittle, et al. (1992), and Grewal, et al. (1994). These values are *not* in agreement with the design specifications of Hubbard and McLeod. Denton and Morgan (1988) give a value of 1.9 inches for the superior-inferior (Z) separation and a value of 0.7 inches for the anterior-posterior (X) separation. It is probably not of consequence which of these two sets of values is used for the midsized headform.

All values for midsized males tabulated in Mertz, et al. (1989) are identified as being for the Hybrid III dummy. However, these values are, in fact, all taken from from cadaver studies and therefore represent midsized males rather than the actual Hybrid III dummy. Mertz, et al., give a value of 1.9 inches for the superior-inferior separation between the head CG and the occipital condyles--viz., the *design* value of Hubbard and McLeod. Mertz, et al., do not give a value for the anterior-posterior separation, but the Hubbard-McLeod specification for the anterior-posterior separation is 0.7 inches.

6.2 Small and Large Headforms. If the Mertz (Hubbard-McLeod) values are used for the midsized headform and if the anterior-posterior separation is scaled in the same manner that Mertz, et al., scale the superior-inferior separation between CG and occipital condyles--viz., on the basis of characteristic dimensions for the skull--the values below are obtained for small females and large males. The Mertz head-dimension scale factors for the large male and small female are 1.030 and 0.931, respectively.

CADAVER DATA (SCALED)	CG-to-Occipital-Condyles Separation	
	Superior-Inferior	Anterior-Posterior
Mertz/Hubbard & McLeod (midsized male, "Hybrid III") SCALE FACTOR = 1.0	1.9 in	0.7 in
Mertz/Hubbard & McLeod (small female) SCALE FACTOR = 0.931	1.8 in	0.65 in
Mertz/Hubbard & McLeod (large male) SCALE FACTOR = 1.030	2.0 in	0.72 in

If the Hybrid III values, 2.0 inches and 0.55 inches, are used instead of the cadaver-based design values (1.9 inches and 0.7 inches), similar scaling would be reasonable. The results, shown below, are not greatly different from those above from scaling of midsized-male cadaver data.

HYBRID III DATA (SCALED)	CG-to-Occipital-Condyles Separation	
	Superior-Inferior	Anterior-Posterior
Hybrid III (midsized male) SCALE FACTOR = 1.0	2.0 in	0.55 in
Small female (using Mertz scale factor) SCALE FACTOR = 0.931	1.9 in	0.51 in
Large male (using Mertz scale factor) SCALE FACTOR = 1.030	2.1 in	0.57 in

Table 4. Head Center of Gravity and Occipital Condyles Locations

(Page 1 of 5)

Reference	Year	Pg	CG/Condyles	Description/Values
Hubbard and McLeod	1974	605-607	CG,con	GM ATD 502 head: occipital condyles is 3.7 in rearward and 2.4 in downward from nasion [sellion]; CG is 3.0 in rearward and 0.5 in downward from nasion; the CG is therefore 0.7 in forward and 1.9 in above the condyles in the head anatomical coordinate system
Hubbard	1975	2	con	GM ATD 502 dummy head specifications from cadaver data: pupil to crown (Z), 4.1 in (104 mm); pupil to back of head (X), 7.0 in (178 mm); crown to occipital condyles (Z), 6.0 in (152 mm); back of head to occipital condyles (X), 3.6 in (91 mm)
Bishop and Wells	1986	133	--	Hyb III: moment origin for the upper neck is not at the nodding pin
Denton and Morgan	1988	355	CG	Hyb III: CG is forward of condyles pivot (i.e., nodding pivot) by 2.50-1.80=0.70 in; CG above condyles pivot by 1.000+0.90=1.90 in; condyles pivot is at bottom-center of a Denton Model 1716 Neck Load Cell, which measures the forces along three orthogonal axes and the moments about these axes
Kaleps and Whitestone	1988	16	CG	Hyb III: CG is forward of condyles (nodding pivot) by 0.55 in and upward by 2.00 in
Mertz, et al.	1989	136	CG,con	"Hyb III" (actually, average-sized adult male cadaver) and 5th and 95th: inferior-superior components of distances from CG to occipital condyles are 1.9 in, 1.8 in, and 2.0 in, respectively (see Hubbard and McLeod, 1974); distances from vertex to occipital condyles are 6.0 in, 5.6 in, and 6.2 in, respectively; values for 5th and 95th were calculated by multiplying cadaver-based values for 50th by head scale factors

Table 4. Head Center of Gravity and Occipital Condyles Locations

(Page 2 of 5)

Reference	Year	Pg	CG/Condyles	Description/Values
Perl, et al.	1989	30	CG	Hyb III: CG is 3.00 in posterior from nasion [sellion] and 0.50 inches inferior
Spittle, et al.	1992	7, 121	CG	Hyb III: CG is forward of condyles (nodding pivot) by 14.0 mm (0.55 in) and upward by 50.8 mm (2.0 in)
Grewal, et al.	1994	80	CG	BioSID: CG is forward of condyles (nodding pivot) by 14.0 mm (0.55 in) and upward by 50.8 mm (2.0 in)
Dempster	1955	191	CG	cadavers (avg): CG at a point in the sphenoid sinus 4 mm beyond the antero-inferior margin of the sella; on the surface, its projections lay over the temporal fossa on or near the nasion-inion line at a point about 32 percent back from the nasion; it is equally distant above the zygomatic arch and behind the malar fronto-sphenoid process
Mertz and Patrick	1967	176-179	CG	cadavers: CG is 0.75 in forward and 2.44 in upward from occipital condyles
Mertz	1967	109	CG	average distance from CG to condyles for two cadavers = 2.1 inches
Clauser, et al.	1969	46	CG	cadaver data, 13 cadavers: ratio (CG-to-top of head)/(head height) = 0.4642; ratio (CG-to-back of head)/(head length) = 0.3996
Mertz and Patrick	1971a	18	CG	average distance from CG to condyles for four cadavers = 2.745 in
Mertz and Patrick	1971b	223	CG	same as Mertz and Patrick, 1971a
Ewing and Thomas	1972	54	CG	cadaver data, five cadavers (NAMRL, *Becker*): CG is 1.33 cm (0.52 in) forward and 2.09 cm (0.82 in) upward from the origin of the head anatomical coordinated system

Table 4. Head Center of Gravity and Occipital Condyles Locations

(Page 3 of 5)

Reference	Year	Pg	CG/Condyles	Description/Values
				cadaver data, 16 cadavers (*Tulane*): CG is 0.883 cm (0.35 in) forward and 2.145 cm (0.84 in) upward from the anatomical origin
Ewing and Thomas	1973	314	CG	cadaver data, 18 cadavers (*Walker* data) CG is 0.88 cm (0.35 in) forward and 2.14 cm (0.84 in) above the origin of the head anatomical coordinate system
Huston	1973,5	97	CG	cadavers: CG is 1.17 cm (0.46 in) forward and 7.0 cm (2.76 in) above the *atlanto-occipital* joint (Walker data)
Thurston and Fay	1974	25	CG	distance from CG to condyles: 3.0 in
Reynolds, et al.	1975	13	CG	cadaver data, 6 cadavers: CG is 0.02 cm (0.01 in) forward and 2.67 cm (1.05 in) above L/R tragion
Schneider, et al.	1976	43	CG	cadaver data reported by Ewing, et al.; CG is 1.3 cm (0.51 in) forward and 2.1 cm (0.83 in) above L/R tragion [notation: 0.88 cm forward is a better value]
Beier, et al.	1980	224	CG	CG is 0.83 cm (0.33 in) forward and 3.12 cm (1.23 in) upward from auditory meatus; these values are the average for 21 cadavers; corresponding measures from Walker are 1.42 cm (0.56 in) and 2.41 cm (0.95 in)
Bowman and Schneider	1980	27	CG	cadaver data: in a coordinate frame aligned with a principal axis system that is rotated 36 degrees upward and rearward from the Frankfort Plane, the CG is 0.988 in forward and 1.66 in upward from the occipital condyles
Williams & Belytschko	1981	69	CG	(values not reconstructed from tabular data)
Chandler and Young	1981	7	CG	McConville, CG is 0.85 cm *behind* L/R tragion; Beier, CG is 0.83 cm *forward from* auditory meatus [These results are discrepant.]

Table 4. Head Center of Gravity and Occipital Condyles Locations

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Reference	Year	Pg	CG/Condyles	Description/Values
Robbins	1983a	71, 91	CG,con	living male subjects (Vol. 2): occipital condyles is 1.1 cm (0.43 in) rearward from anatomical origin and 2.6 cm (1.02 in) below; CG is 1.94 cm (0.76 in forward from occipital condyles and 5.7 cm (2.24 in) upward
	1983b	15, 52	CG,con	living female subjects (and large male) (Vol. 3): small female: occipital condyles is 1.1 cm (0.43 in) rearward from anatomical origin and 2.5 cm (0.98 in) below; CG is 0.9 cm (0.35 in forward from occipital condyles and 5.8 cm (2.28 in) upward [Note: CG is behind anatomical origin and Z component of CG-to-condyles separation is greater than for midsized male; data may be incorrect]
	1983b	15, 52	CG,con	living male subjects, large male (and small female) (Vol. 3): large male: occipital condyles is 1.1 cm (0.43 in) rearward from anatomical origin and 2.6 cm (1.02 in) below; CG is 1.96 cm (0.77 in forward from occipital condyles and 5.73 cm (2.26 in) upward
Bowman, et al.	1984	175	CG,con	cadaver data: CG is 0.83 cm (0.33 in) forward and 3.12 cm (1.23 in) above the origin of the head anatomical coordinate system; the origin of the anatomical frame is 1.10 cm (0.43 in) forward and 2.63 cm (1.04 in) upward from the occipital condyles; thus, the CG is 1.93 cm (0.76 in) forward and 5.75 cm (2.26 in) upward from the occipital condyles [All values are in the anatomical system frame of reference.]
Hayes, et al.	1986	1203	CG,con	cadaver-based data for "the 50th percentile standard military aviator for male human analogue" (draft

Table 4. Head Center of Gravity and Occipital Condyles Locations

(Page 5 of 5)

Reference	Year	Pg	CG/Condyles	Description/Values
				military standard): CG is 2.4 cm (0.94 in) forward and 15.2 cm (5.98 in) above the C7/T1 junction; occipital condyles is 2.0 cm (0.79 in) forward and 11.0 cm (4.33 in) above the C7/T1 junction; CG is therefore 0.4 cm (0.16 in) forward and 4.2 cm (1.65 in) upward from the occipital condyles
Hoen and Wismans	1986	3,5	CG,con	cadavers, proposed head/neck model: head principal X-axis is rotated 36 degrees upward from Frankfort Plane (infraorbitale); the Y-axis is tragion-to-tragion; in the anatomical coordinate system (Frankfort Plane), the occipital condyles is 1.1 cm (0.43 in) rearward of the origin and 2.6 cm (1.02 in) downward; the CG is 1.2 cm (0.47 in) forward and 2.9 cm (1.14 in) upward; thus, the CG is 2.3 cm (0.91 in) forward and 5.5 cm (2.17 in) upward from the condyles
Howe, et al.	1991	290	CG	cadaver data: CG is 93 mm (0.37 in) rearward from glabella and 100 mm (0.39 in) downward from vertex

NOTES:

1. All cadavers used in all cited studies are males.
2. Major experimental measurement studies with cadavers are italicized.

7.0 SKIN PROPERTIES

The literature search found there to be a paucity of useful published, relevant, research data for skin properties of the human head. Specifically, it has not been possible to determine the friction properties of the scalp, with or without hair, and, further, it has not been possible to establish force-deflection properties of the face and scalp as a function of position on the head. (Frangible face forms are not relevant to the present study.) Information is available, however, for the thickness and composition of skin on the Hybrid III headform. The headform skin specifications for the Hybrid III were established to meet requirements of durability and proper head-acceleration response in drop tests with impact to the forehead. *It is recommended that Hybrid III headform skin be used for headforms developed in the present study.*

7.1 Friction Properties. Prasad, et al. (1988, *Advanced Anthropomorphic Test Device (AATD) development program, Phase 1 reports: concept definition*; Chap. 1, pg. 1) describe the scalp as follows:

> The scalp is 5 to 7 mm (0.20 to 0.28 in) in thickness and consists not only of the hair-bearing skin but also of layered soft tissues between the skin and the skull. When a traction force is applied to the scalp, its outer three layers (the hair-and-skin layer, a subcutaneous connective tissue layer, and a muscle and fascial layer) move together as one. Next there is a loose connective tissue layer plus the fibrous membrane that covers bone (periosteum). The thickness, firmness, and mobility of the outer three layers of scalp as well as the rounded contour of the cranium function as protective features.

Prasad, et al., note the looseness of the scalp on the skull. Neither they nor (apparently) any other researchers have attempted to quantify this looseness, however, nor do they give any measure of the friction between the scalp's hair, or the skin of the face, and any contacting surface. Neither these authors nor any others quantify the force-deflection characteristics of the scalp (except in the form of constitutive properties, e.g., McElhaney, et al., 1969, and Melvin and Evans, 1971).

Webster and Newman (1976; pp. 233-235) describe qualitative properties, however; viz., that surface friction should be *small* and the coupling of the scalp to the cast aluminum skull of the headform should be *weak*. In a comparison of force-time history responses for impacts to cadaver heads and anthropomorphic headforms, they found that the headform force responses that most nearly replicated cadaver head force responses were for headforms with smooth, low-friction "skin" surfaces and skin that is not fastened to the skull--i.e., skin that is free to slide over the headform surface. Hodgson (1990) also conducted friction (skid) tests for anthropomorphic headforms, but he did not include cadaver tests in his study.

The apparent absence of quantitative data for the friction properties of the scalp, and hair, is probably not serious, provided that the guidelines of Webster and Newman are followed. Adequate representation of human-hair friction characteristics in manikin headforms is probably most important for helmet retention tests. However, proper helmet fit and the design and fit of retention straps are much more important factors than friction between the helmet and the hair. Even if quantitative data for hair friction properties could be found, it would then still be necessary to design the headform scalps in such a way as to replicate these properties. Probably the only ways to accomplish this would be (1) to use a headform covering that has numerous hair plugs or else to put a wig made from human hair, or a suitable substitute, over the headform covering, or (2) to use a smooth, relative slick headform covering. The latter method is clearly easier, and it is probably adequate.

7.2 Force-Deflection Properties. Head force-deflection properties may be important for impact studies with Army manikins (or the headforms and necks alone), but the importance in impact studies relevant to helmeted personnel would certainly be much less than in studies for which no helmet is present. Since studies in which impacts of the unhelmeted Army headforms occur are unlikely to be of interest, it is probably not important to have more humanlike head force-deflection properties than in the Hybrid III. In any case, no force-deflection specifications more representative of a human than those for the Hybrid III headform were determined in the present study.

Early work done by Thurlow (1963) established that the shock-absorption properties of the living human scalp may be simulated in anthropomorphic dummies by covering the heads with a 5/32-inch thick layer of cellular silicone rubber. Research conducted since Thurlow's work has determined the best formulation for the skin to be ARL Vinyl Formulation No. PT-4. This is used for the current Hybrid III headform (Howe, et al., 1991; Benson, et al., 1991). Skin thickness for the Hybrid III varies at positions over the face. It is 1.55 cm at nasion, 1.09 cm at zygoma, and 1.13 cm at maxilla (Gallup, et al., 1988; pg. 332). Gallup, et al. (ibid), recommend 1.00 cm at nasion, 1.10 cm at zygoma, 1.10 at maxilla, 1.05 cm at subnasale, and 1.10 for the nose. Corresponding specifications for the Hybrid III 5th-percentile female and 95th-percentile male crash dummies were not found in the present study, but it may well be that they should be different from the 50th-percentile dummy specifications in order to satisfy drop-test acceleration requirements. (See the discussion of results of Mertz, et al., 1989, below.)

Only very limited head force-deflection data (except for frangible faces: Newman and Gallup, 1984; Allsop, 1993) is available for even the Hybrid III dummy, which is used routinely for impact studies involving automobile occupants, which are unhelmeted. In particular, the forehead covering of the Hybrid III headform is of such composition and stiffness as to allow replication of head acceleration responses in cadaver head (forehead) drop tests. Possibly the first work on cadaver head drop tests was done by Hodgson and Thomas (1972). Prasad, et al. (ibid; pp. 12-13), report results derived from the work of Hodgson and Thomas, and they find, specifically, that the peak acceleration of the center of gravity of the head should be within a corridor defined by corner points of 230 ± 42 G for free-fall drops of 330 mm and and 293 ± 42 G for drops of 1060 mm. (Also see 1991, SAE Information Report, SAE J1460 MAR85.) The requirement in Federal Motor Vehicle Safety Standard (FMVSS) Part 572.102 is for a single drop height, viz., 14.8 inches (376 mm), rather than a corridor. The peak acceleration must be between 225 G and 275 G, i.e., 250 ± 25 G. (1991, *Vehicle Occupant Restraint Systems and Components, Second Edition. A Compilation of SAE, ASTM and FMVSS Standards, Recommended Practices, and Test Methods*) The headform and headform covering of the Hybrid III dummy satisfy these test criteria.

Mertz, et al. (1989) scaled the FMVSS acceleration values for the above described response range to obtain values appropriate for small female and large male headforms. Dividing the Hybrid III acceleration values by a scale factor of 1.030 for large male and 0.931 for small female and rounding to the nearest 5 G, they obtain lower limit, midpoint, and upper limit values, for drop heights of 14.8 inches, as follows: large male - 220 G, 245 G, and 265 G; small female - 240 G, 270 G, and 295 G.

Two final observations regarding force-deflection properties of the head are made here. First, Hodgson and Thomas (1971) state that impact force for direct impacts to the heads of bushy-haired individuals can be distributed sufficiently to raise the fracture force level by a significant amount. This would not be a factor for impacts to the helmeted manikin headforms. Secondly, Sakurai, et al. (1993), have demonstrated in headform impact tests, with and without skin, that the influence of headform skin on the maximum acceleration and the HIC value is insignificant, although the presence of the headskin does serve as a low-pass filter on high-frequency elements.

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