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Position and Mobility of Skeletal Landmarks of the 50th Percentile Male in an Automotive Seating Posture

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The basis for this project is the use of anthropometric test devices in evaluating injury hazard associated with the various types of motor vehicle occupant protection systems. A rating of injury hazard is obviously only as valid as the level of correlation between the mechanical behavior of the test device and that of the human occupant. Project objectives were to define: 1. the position in space of a human occupant of a car seat; 2. spatial relations between the various parts of the body; and, 3. the relationship between project findings and automotive design tools such as the H-point machine and the "golden shells." The literatures of anthropometry, ergonomics, posture, biomechanics, anatomy, SAE activity, dummy development, and rulemaking activity were reviewed to establish the state of the art and develop plans for future work.

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PART 1. INTRODUCTION

This report presents the results of a research project at the Highway Safety Research Institute entitled, "Position and Mobility of Skeletal Landmarks of the 50th Percentile Male in an Automotive Seating Posture." The basis for this project is the use of crash test dummies in evaluating injury hazard associated with the various types of motor vehicle occupant protection systems. A rating of injury hazard is obviously only as valid as the level of correlation between the mechanical behavior of the dummy and that of the human occupant.

A major determinant of physical response in an impact environment is the geometry, initial configuration, and relative motions possible in the test subject. The overall objectives of the study were to define: 1. the position in space of a human occupant of a car seat; 2. the spatial relationships between the various segments of the human (head, neck, chest, shoulder complex, lumbar spine, pelvis, upper arms, and upper legs); 3. the voluntary motions between these body parts that can be generated by the human; and, 4. the relation between the seated human vehicle occupant and automotive engineering tools such as the H-point machine and the Dummy Master Body Forms, or "golden shells."

The two primary parts of the study consisted of a literature survey and an attempt to satisfy as many of the above-stated objectives as possible. The literature related to the sitting posture of an automobile occupant was found to cover at least the following disciplines and areas of activity: 1. anthropometry; 2. ergonomics; 3. sitting posture and orthopedic considerations; 4. biomechanics; 5. anatomy; 6. SAE committee activity; and, 7. dummy development projects and rulemaking activity. Each of these literatures was found to reflect a particular point of view more or less independent from the others. The review, although it was limited by time and funds, isolated deficiencies in: 1. the ability to locate a human subject in three-dimensional space, based particularly on the data of classical anthropometry; 2. knowledge of the geometry and flexibility of the thoracic skeleton; 3. knowledge of the flexibility of the lumbar spine, pelvic geometry, location of the hip pivot point in the pelvis, and the degree of tilt of the pelvis in a seated person; 4. knowledge of the geometry, flexibility, and range of motion of the various components of the shoulder complex; and, 5. a lack of a list of dummy physical parameters and their comparison with human data.

This report includes four additional parts. Part 2 describes the literature survey while Part 3 attempts to satisfy overall project objectives using available data. Part 4 summarizes the recommendations made within Parts 2 and 3 and outlines a program of research necessary to accomplish overall project objectives. Part 5 is a list of 76 references cited in the text as well as a bibliography with 136 publications related to the work.

PART 2. LITERATURE SURVEY

The literature relating to the sitting position of an automobile occupant covers at least the following disciplines and areas of activity:

1. anthropometry;
2. ergonomics;
3. sitting posture and orthopedic considerations;
4. biomechanics;
5. anatomy;
6. activities of various committees within the Society of Automotive Engineers; and,
7. dummy development projects and rulemaking activity.

Each one of the literatures reflects a particular point of view more or less independent from the others.

The identification of relevant literature proved to be a major task because of the broad range of topics. During the early part of the project, contacts were made with experts in all of the fields for the purpose of identifying the State of the Art in the particular disciplines and activities. Because of the obscure and proprietary nature of some of the reports and documents (some of which are still not available), this activity went on for the duration of the Phase I project. As material became available, it was reviewed.

Anthropometry proved to be one of the easier areas of literature identification as the most extensive surveys are relatively recent and have been conducted either by the U.S. Public Health Service or the U.S. Department of Defense. However, the original documents are, in many cases, difficult to obtain.

The identification of relevant literature of anthropometry led directly to the literature of ergonomics mainly because of the activity in both fields conducted by the Anthropology Section of the Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base, Ohio. Ergonomics applied to seating was found to be largely a European affair with major research findings most often published in Germany or Sweden and difficult to obtain during the time span of the Phase I contract. Seating for motor vehicles produced in the United States is developed in design laboratories with little input from scientific experts in ergonomics or postural orthopedics.

Review of the ergonomics literature led directly into the postural and orthopedic literature which is again primarily a European phenomenon with little research being conducted in the United States. A basic literature review has been conducted, however, a further comprehensive review is recommended.

The literatures of biomechanics and anatomy were combined for this survey. Biomechanics has been the primary source of analytical procedures to locate anatomical segments in space. These procedures, developed in the late 19th century, are found primarily in the publications of the German anatomists. Detailed and extensive studies of motions at joints and motions of one body segment with respect to another have been published by the same school of anatomists over a period from the 1880's through the 1930's. Translations are rare; a complete up-to-date review is needed to supplement modern data, which is much less ambitious and general. This literature is in addition to the well-known works on body segment centers of gravity and mass published by many of the same anatomists.

The committees of the Society of Automotive Engineers (particularly the Crash Test Dummy Subcommittee) are also a source of information. Their deliberations and products (SAE standards, recommended practices, information reports, etc.) are based on corporate needs for improved dynamic test procedures, design manikins, etc. The data base which they use is a meagre collection of readily available documents. Where no data are available in the literature, estimates are made. The committee votes to accept the estimates. It has been difficult to reconstruct the reasoning behind some of the past estimates because of the passage of time and the lack of detailed committee notes.

The final area of activity which was reviewed involved the actual dummy development projects. In each case (e.g., General Motors ATD, Hybrid II, HSRI Repeatable Pete, the Ogle/MIRA series, etc.), the standard military anthropometric data base was used, usually modified by the more recent Public Health Service data. In some cases, parallel research was conducted to better model some segment of the body as physical hardware.

In the following text, each of the disciplines and areas of activity is discussed individually with reference to specific documents. Individual documents referenced in the text are listed in numerical order in Part 5.1, while a more extensive bibliography alphabetized by author is included as Part 5.2.

2.1 ANTHROPOMETRIC DATA

Anthropometric data are gathered and presented primarily to describe populations of subjects. These data are essentially collections of facts describing certain dimensional properties of humans. This reflects a standard methodology of biological scientists -- the collection and manipulation of large masses of data.

Anthropometric data do not describe an average-sized man for design purposes. Man is described in terms of a series of physical dimensions of the various parts of the body. Anthropologists recognize the statistical concept of a 50th-percentile man, but it has been demonstrated by Daniels (1) that no man measured in the 1950 survey exists with all 50th-percentile U.S. Air Force dimensions.

A discourse between Hertzberg (2), who is a classical anthropometrist, and Searle (3) concerning dimensional descriptions of crash test dummies manifests a controversy which arises between the engineer and the anthropologist. This controversy arises necessarily because a crash test dummy requires a unique dimensional description, while anthropometric data provides individual body dimensions in statistical form without providing a geometrical description of the whole body. The greatest controversy arises when attempting to define human sizes other than the 50th-percentile, or average.

The techniques used for presentation of anthropometric data (e.g., measurements of heights, lengths, spans, circumferences, etc.) are insufficient for locating a body in space in the sense of classical mechanics. To adapt anthropometric data to the current problem, it is necessary to employ the concepts of frames of reference (4). Therefore, anthropometric data alone is, at best, only part of the data necessary for determining the location of a 50th-percentile male occupant in an automobile seat.

Much of the literature of anthropometry involves military subject populations. Typical surveys have been conducted by Hertzberg (5), Oberman (6), White (7,8), Churchill (9), and Clauser (10). Surveys of more general populations have been conducted by Stoudt (11) and Hooten (12). The Public Health Service study of Stoudt is the baseline of data for the civilian population. Hooten's limited study is related to seating and is probably obsolete. The adequacy of the Dreyfuss (13) data has been challenged by physical anthropologists, and the Sahley (14) survey has been withdrawn from circulation after its authenticity was questioned.

A different approach has been used by Robbins (15). In attempting to define the shape and dynamic properties of the human body, several non-classical anthropometric measurements were developed to help overcome the limitations of classical anthropometry. In this case, measurements on the individual were important in order to mathematically simulate individual responses to an impact environment and no attempt was made to relate the individual subjects to any population.

Two other documents should be cited. A Collation of Anthropometry by Garrett, et al. (16) reports the results of individual measurements gathered in various surveys and should be regarded as a central source of information. Steinberg (17) proposes development of a National Anthropometric Data Base by the National Bureau of Standards. Interaction with the individuals planning this survey should be vigorous in order to ensure the greatest range of applicability of the resulting data base when and if the survey is conducted.

In conclusion, some discussion of the meaning of the words "anthropometric" and "anthropomorphic" will be helpful. Physical anthropologists, in general, recognize two distinct meanings in these words. The former word,"anthropometric" (anthropometry) is used generically to discuss quantitative measurements of man, and,in some cases, the lower primates. There are many methods and techniques by which one can measure properties of the human body. Anthropometry classically has measured linear surface dimensions; but during the past three decades, with the aid of radiographic and similar techniques, internal measurements of the human body have also been made. "Anthropomorphic" means, on the other hand, simply "man-like" and describes the quality of form rather than the quantity of man's dimensions. Therefore, by definition, an anthropomorphic test device can have only the quality of form of man. An anthropometric test device, which is the necessary result of the various dummy development projects, is the only possibility for duplicating or representing the physical responses of man in an impact environment.

2.2 ERGONOMICS

Ergonomics attempts to relate man to his physical environment. Both man and the environment are described in physical engineering terms (dimensions, forces, motions, etc.). The usual approach of ergonomics is to study the active participation of man, as a machine, in his environment. How much can he lift? What motions are most tiring? How far can he reach? What are optimal definitions of work tasks? etc. Experts in the field of ergonomics are often adept at both biological and engineering approaches to problem solving. Hence, several tools of ergonomics have direct applicability to the present problem. This includes representation of man as a series of links which requires use of well-defined frames of reference. However, the usual application of ergonomics involves the active participation of the subject in his environment. The current application to anthropometric test devices places the subject in a more passive role,where the environment can do him violence. As such, ergonomics provides little or no data on dynamic mass distribution, ranges of motion to the trauma level, action and capability of muscle groups in resisting impact loads, etc.

Among the major ergonomics studies which are relevant to the current study are the work space studies of Dempster (18), the torso linkage developed under Snyder, et al. (19), the general workspace linkage of Luming and Krause (20), the linkages of Chaffin (21, 22), BOEMAN as developed by Ryan et al. (23, 24), and Kilpatrick's workspace model (25),which includes discussions of spinal location and joint centers. All these studies use complex sets of coordinate systems to locate the human body in space. The geometry and physical dynamic body properties are based for the most part on the old anatomical literature on segment mass, joint locations, centers of gravity, etc.

Throughout these documents are strong statements about the lack of physical data on the human body. Assumptions are usually made that joint centers are fixed with respect to adjacent body elements.

Dempster's (18) classic work, "Space Requirements of the Seated Operator," is relevant to the current project and some data can be extracted directly for the anatomical location of joint centers of rotation, ranges of motion, pelvic tilt, etc. The data unfortunately are not presented in a form related to an automotive seat. Furthermore, some of these data were measured on embalmed cadavers which could introduce an inestimable bias in those dimensions dependent upon density and the musculo-skeletal system. However, when it is possible to define with a known probability where the pelvis, spine line (a line representing the orientation of the vertebral column), and head are located in space relative to an automotive seat, then more use of Dempster's results will be possible to define several body joint locations, centers of gravity, ranges of motion (from the seated position), and link lengths.

The Snyder, Chaffin, and Schultz report (19) entitled, "Link System of the Human Torso," concentrates on the spinal linkage, pelvis, and torso-to-elbow linkage. All measurements locate a functional elbow position relative to an Air Force seat configuration where lumbar and thoracic support is removed. As such, this does not relate to the problem of automobile seating. In addition, their subject sample was stratified primarily by stature to match an Air Force male population (see Reference 19, page 266) that may not represent the male civilian population.

A further difficulty occurs when one attempts to construct a complete spinal linkage from the data. One must choose among "most likely" alternative linkages based on the variety of ways possible to implement the regression equations. This is not intended to be a reflection on the quality of the methodology of the link system model. It reflects only the size of the x-ray plates used to measure spinal position and on the different application of the results of that project. The novel procedures used in the "torso link" study could, alone be used to accomplish the objectives of the current project.

2.3 SITTING POSTURE AND ORTHOPEDIC CONSIDERATIONS

Sitting posture and orthopedic variables have rarely been considered in recent anthropometric test device development projects. However, studies of posture and sitting, as published in the orthopedic literature, offer insight on the variety of positions a person can assume in a seat. Intuitively, safety engineers regard posture as an important variable in the design of restraint systems. The combination of anthropometric, ergonomic, and orthopedic research methodology provides most of the tools to define the automotive seated position of a 50th-percentile male.

The orthopedics of spinal posture is almost exclusively a European research subject. Representative and recent work has been published by Åkerblom (26), Andersson (27), Carlsöö (28), Grandjean (29), and Schoberth (30). Three of these authors, Grandjean, Schoberth, and Andersson, deal in depth with automotive seating posture and attempt to develop guidelines for comfortable designs. X-rays defining spine line are commonly used to demonstrate concepts and to develop data. The document edited by Grandjean (29) contains several papers relating to the current project. Medical considerations are presented by the above authors as well as by the Japanese, Kohara (31), and by the American, Keegan (32,33).

The American anthropologist, Hooten (12), conducted a classical study on train seats. Keegan has presented design criteria for good seating and has also compared seating systems for conformance to his criteria. Automotive seating rates low on his comfort scale.

Geoffrey (34) and more recently Kohara (31) both have conducted work relative to automotive seating design manikins. Kohara's manikin incorporates a degree of spinal flexibility and is intended as a comfort design tool. Geoffrey's work has special relevance to the current project in that the H-point, or hip-pivot point, is defined in an automotive seated position using whole-torso x-rays. The H-point, as defined in SAE J826, is therefore, based on documented experimental data, collected from a small group of subjects seated in an automotive seat. Mr. Geoffrey has made available to the project the data gathered during his project, including the whole-torso x-rays. Unfortunately, the subject population is not composed of 50th-percentile males. In addition to the admittedly difficult H-point measurements, many of the x-rays show the spine line, some details of the pelvis, most of the cervical vertebrae, and, in a few cases, the skull. A detailed review of these x-rays is highly recommended, not only to verify the original results, but also to see if additional spinal position data can be extracted.

2.4 BIOMECHANICS AND ANATOMY

Biomechanics, for the present discussion, will be defined as that field of study concerned with the engineering response of the human to dynamic loads. In application to the problem of automotive seating posture, biomechanics draws heavily on the work of functional anatomists who historically have been interested in how the anatomy of the body interacts with a dynamic environment. The biomechanics specialist often concentrates on mathematical models of human motions and experimental procedures for measuring human mechanical properties. The approach is often an engineering one and may involve only minimal input from the biological sciences. The biomechanics specialist is also an experimentalist. He designs procedures to measure static and dynamic strength of the body and its components while worrying about the accuracy of measurements of force, acceleration, velocity, and position. Frames of reference are an implied tool of the trade because all physical vector quantities have a magnitude and a line of action defined in space. Because of the concentration on dynamic response, biomechanics, as defined above, offers a unique input to the development of crash test dummies.

The brief survey conducted for this project grouped available documents into four classes. The first class of documents was developed by 19th century anatomists such as Braune and Fischer (35) and Fick (36). Braune and Fischer determined body segment masses and centers of gravity. A most interesting item in their publication is a figure which shows front and side schematic views of the human body on the background of scaled graph paper. Therefore, using the figures, it is possible to obtain three-dimensional coordinates of joint centers, segment mass centers, etc., for the various standing postures which were considered in their study. It is surprising that it is necessary to re-emphasize the importance of the "coordinate system approach" about 85 years later. The work of Fick builds on the previously laid foundations, with additional details of the mechanisms and ranges of joint motions added.

The second class of documents includes more recent efforts to measure and define human body properties. Clauser et al. (10), Dempster (18), Barter (37), Drillis (38), Becker (39), and Waller (77), among others have contributed to this effort. Bernstein quotes data (40) but the original documentation reporting results does not appear to be available. Recent work conducted at the Civil Aeromedical Institute of the Federal Aviation

Administration (See Reynolds, et al. (78)) with the cooperation of the U.S. Air Force and National Highway Traffic Safety Administration adds substantially to the data base on body segment parameters. These are the first data reporting the inertial tensor for the whole body and its major anatomical segments on male cadavers.

The third class of documents reflects the need for body segment mass, length, gravity centers, and moments of inertia for human subjects not fitting the cadaver populations discussed above. Based mostly on an input consisting of classical anthropometric measurements, researchers such as Hanavan (41), Patten (42), and Robbins (15) have developed simple mathematical formulas which predict these quantities. The accuracy of these predictions has not been established, but results from a modified Hanavan model have been compared with measured data by Chandler. The first results appear to predict the principal moments of inertia within 10% to 20% of the measured values. Hanavan's work related to space applications, while Patten's and Robbins' models are used to develop input data sets for mathematical crash victim simulations.

The fourth class of documents is the work primarily of mathematicians, engineers, and in some cases, anatomists. In this work, attempts are made to describe the dynamics of human body motion in terms of mathematical formulations. All such attempts require well-defined coordinate systems. The most successful attempts usually reflect the greatest insight into body anatomy and anthropometry. One of the early efforts was by Fischer (43), who followed the lead of Euler (44) in describing the human body as a chain of rigid links. The formulation by Grammel (45) uses a more modern notation and appears to be a major "link in the chain" of development between the ancients and the recent work of Bowman (46). All the previous models segment the body into rigid links -- the approach often associated with dummy manufacture. Recent finite element approaches add flexibility within body segments.

Andriacchi (47) has developed one such model. The detail needed for description of the body components in these most recent models is demonstrated in the works of Roberts (48) and Schultz (49), who attempt to define rib and rib cage geometry. This recent work reflects the state of the art in defining the rib cage in three dimensions. The data presented is for cadaver material which is not related to any population data. In a follow-on phase of the present project, it may be possible to relate the work of Roberts to a population and extrapolate it to a seated 50th-percentile male.

The publications listed in the above discussion represent only a small portion of those available. Inclusion of all work in this field would result in a survey far beyond the scope of the present project. However, for purposes of historical research and to isolate and compare all available data, the current investigators believe that a complete review would be highly useful to researchers in many fields.

2.5 SAE, RULEMAKING, AND DUMMY DEVELOPMENT

The Society of Automotive Engineers has been very active in crash test dummy development. Groups such as the Crash Test Dummy Task Force have been active for an extended period and have developed a variety of standards and recommended practices. Committee minutes and documents, where available, have been reviewed as an aid in tracing the history of test device design specifications such as H-point, SAE J963 (Anthropomorphic Test Device for Dynamic Testing), and the "golden shells." In many ways the SAE groups have been at the mercy of admittedly meagre data. At the same time they have been under strict schedules for producing results, based on committee votes, without having the research resources required to assess and document the accuracy of their conclusions. Separate from but parallel to the SAE activity are test device development and evaluation projects sponsored mostly by the U.S. Government in support of rulemaking activity. Where published results are available, they have been reviewed with respect to the objectives of the present contract. For the most part, the same base of anthropometric data has been used in this activity as has been used by SAE committees.

The importance of knowing the seated location of a vehicle occupant is reflected in the number of SAE recommended practices, standards, information reports, etc., which make reference to the eye point or the H-point. The thirteen which have been identified are listed in Table 1. Seven refer to vision while the remainder refer to seat design or the dynamic interaction of an occupant with a vehicle interior.

Dummy development, rulemaking activity, and SAE committee work have been found to be so inter-related that it has been difficult to identify the source of the anthropometric and biomechanical data which was used in designing one dummy at any one time. Rather than the academic exercise of comparing and evaluating numbers used at various times, a chronology of events is presented in Table 2 including selected items in recent dummy development, rulemaking, and SAE activity which are believed relevant to the present study.

TABLE 1. SAE DOCUMENTS

Identification	Title	Reference No.
J100	Passenger Car Glazing Shade Bands	50
J198	Windshield Wiper Systems-Trucks, Busses, and Multipurpose Vehicles	51
J338	Motor Vehicle Instrument Panel Laboratory Impact Test Procedure-Knee-Leg Area	52
J382	Windshield Defrosting Systems Performance Requirements - Trucks, Busses, and Multipurpose Vehicles	53
J787b	Motor Vehicle Seat Belt Anchorage	54
J826b	Devices for Use in Defining and Measuring Motor Vehicle Seating Accommodations	55
J834a	Passenger Car Rear Vision	56
J879b	Motor Vehicle Seating Systems	57
J902b	Passenger Car Windshield Defrosting Systems	58
J903b	Passenger Car Windshield Wiper Systems	59
J941c	Motor Vehicle Driver's Eye Range	60
J944a	Steering Wheel Assembly Laboratory Test Procedure	61
J963	Anthropomorphic Test Device for Use in Dynamic Testing of Motor Vehicles	62

TABLE 2. CRASH TEST DUMMY DEVELOPMENT FOR AUTOMOTIVE APPLICATIONS

Date	Item
Pre-1967	Early generation dummies
1968	J963 published
May 2, 1969	Proposal submitted by Sierra Engineering to build body forms.
Jan. 1970	Three golden shells completed by Sierra Engineering.
Feb. 1970	New Public Health Service data (63) released which made some features of golden shells, J963, etc. candidates for revision.
end 1970	A kit was provided to modify the Sierra with a retrofit detailed pelvis in order to prevent belt submarining. This activity was precipitated by General Motors which provided Sierra with human pelvis data to model.
mid 1971	Hybrid I dummy in use. This consisted of Sierra 1050 head, VIP50A torso and limbs, and a GM Proving Ground rubber neck. A major purpose was improved belt test results.
July 1971	MVMA initiated a dummy neck development project at HSRI.
Aug. 1971	NBS issued a draft report detailing restraint system dynamic tests using Sierra 1050 and modified 850 dummies.
Jan. 1972	Alderson presented a report on dimensional and mass distribution data for golden shells with reference to the new Public Health Service data.
Apr. 15, 1972	MVMA initiated dummy development project at HSRI.
mid 1972	Hybrid II dummy in use. This was developed to obtain improved airbag test results. Problems with Hybrid I, such as chin-chest interaction, were eliminated.
July 1972	NHTSA issued dummy purchase description. Its specifications were similar to Hybrid II.
Nov. 13, 1972	A dummy procurement was issued by NHTSA to GM. This was based on a GM counterproposal to the July dummy purchase description. The contract began Dec. 1, 1972 and continued through most of 1973.
Nov. 27- Dec. 1, 1972	Williamsburg meeting on the Vehicle Research Institute

TABLE 2. CRASH TEST DUMMY DEVELOPMENT FOR AUTOMOTIVE APPLICATIONS (cont.)

Date	Item
Dec. 5, 1972	The court ruling on dummy performance was issued.
Dec. 1972	General Motors issued a request for proposal on the anthropometric measurements of a seated vehicle occupant to supplement the work in developing the GM-ATD-502.
Feb. 7, 1973	HSRI proposal on the above modified and presented to VRI.
Apr. 2, 1973	NHTSA recognized Hybrid II as the "most satisfactory design which is currently commercially available."
June 1973	Repeatable Pete, the HSRI dummy, was delivered.
Aug. 1, 1973	Part 572 (Hybrid II) written into Motor Vehicle Safety Standard 208.
Oct. 15, 1973	VRI Seating Posture Anthropometry project initiated at HSRI.
Dec. 1973	GM-ATD-502 delivered to NHTSA.
Apr. 15, 1974	Planned completion date for VRI Seating Posture Anthropometry project.

PART 3. SATISFACTION OF PROGRAM OBJECTIVES

PHASE I EFFORT

The seven sections of Part 3 describe work done during this project and the data available from the literature survey relative to the seven program objectives listed in the statement of work. The degree to which the Phase I effort satisfies each of these objectives is indicated.

3.1 ANTHROPOMETRIC LANDMARKS AND REFERENCE FRAMES

The objective is to determine anthropometric landmarks and reference frames on or within the skeletal structures of the head, thorax, and pelvis, and on the external body surfaces associated with these structures. Candidate coordinate systems have been proposed for the head by Ewing (68) and Hubbard (69). The directions of the coordinate axes are the same in the two cases and are based on the Frankfort plane and a vertical perpendicular. The origins are different, with Hubbard's located at the nasion of the skull and Ewing's located at the midpoint of a line connecting the superior edges of the left and right auditory meatus. Neither of the origins is located at the center of gravity of the head. Either coordinate system offers a sufficient framework for studying kinematics and dynamics of the head when it is viewed as a rigid body. Hubbard's has the possible advantage of being located on the external surface of the structure.

The thorax presents a considerable problem because of its flexibility, the lack of classical landmarks which may be related to the thoracic skeleton, and the difficulty of using x-ray procedures to quantify the position of the thoracic skeleton at any point in time. The only known coordinate system associated with the thoracic skeleton other than those used for mathematical modeling procedures,where each bone of the thorax is defined in terms of one or more coordinate systems, has been developed by Ewing (68). This coordinate system is capable of following the motions of the first thoracic vertebra as a rigid body. Its origin is at the anterior superior corner of the vertebral body. A +X axis is defined by connecting the midpoint of a line between the superior and inferior corners of a posterior spinous process to the anterior superior corner. A +Z axis is set perpendicular in a superior direction. To account for flexibility, the current authors recommend that a similar coordinate system be developed for each of the thoracic vertebrae. In addition, to be able to monitor motions at the front of the chest, it is recommended that additional coordinate systems be developed for the sternum, possibly based on suprasternale and substernale. If it is thought necessary to define the thorax as a rigid body or as a flexible body with a single coordinate system, the authors recommend the following procedure: 1. connect the first and twelfth thoracic vertebra coordinate origins with a line; 2. connect the substernale and suprasternale with a line; 3. connect the centers of the two lines with a new line directed toward the front of the chest to define the directions of a +x axis; 4. construct a perpendicular in the superior directions to define +z-direction and a +y-direction to the left; and, 5. choose as the origin the center of gravity of the thorax as measured in a 50th percentile seated male automotive driver in the middle of the breathing cycle.

The pelvis is sufficiently rigid to warrant the use of a single coordinate system. Difficulties arise in that sufficient soft tissue, often of considerable delicacy, surrounds the structure to mask most bony landmarks. X-ray examination of the pelvic region is also difficult for the present purpose. Candidate landmarks (all palpable and accessible by x-ray) are symphysion and the right and left anterior-superior iliac spines. A possible reference frame could be constructed as follows: 1. connect the two anterior-superior iliac spines with a line; 2. specify as the origin the center of the line; 3. define a +X-axis as the line from the origin to the symphysion; and 4. construct an upward normal to define the +z-axis and a leftward normal to define the +y-axis.

3.2 SHAPE OF THE THORACIC SKELETON

The objective is to determine the shape of the thoracic skeleton for the 50th percentile American male. It has not been possible to satisfy this objective based on the literature survey or manipulations of the data in the literature survey. A primary reason for this has been the insufficiency of available anthropometric data for locating the thorax in space. Circumferences, breadths and depths, etc., have been measured, but the height at which the measurement is taken is usually not available. (It should be noted that nipple height is not well-correlated with measurements of bony landmarks.) In addition, chest measurements are usually made on a subject standing erect with a spine-line and thoracic mass distribution different than for an automotive-seated subject. Breadths and depths are also not useful unless they are oriented with respect to a coordinate system such as the thoracic system proposed in Section 3.1. The only known cases where the position in space of the elements of thoracic skeletons have been quantified are reported by Andriacchi (47), Roberts (48), and Schultz (49). Unfortunately, the data presented in these papers have not been related to populations but rather to specific skeletal material for the purpose of deductive mathematical analysis.

It is recommended that a procedure be developed specifically for the purpose of defining the thoracic shape of the seated automobile occupant. The optimal procedure would probably make use of stereophotographic techniques to define external contours, x-ray procedures to define interior thoracic geometry and coordinate systems, and also special anthropometric measurements which could be related to classical measurements. The new procedure should be correlated with standard anthropometric procedures and populations using a minimum of test subjects measured in standard seated and standing anthropometric positions.

3.3. SEATED POSITION OF 50TH PERCENTILE MALE

The objectives are to determine for the 50th-percentile male in a representative automotive seated position the location of: 1. the shoulder joint centers and skull relative to the thoracic skeleton; 2. the thoracic skeleton and femora relative to the pelvis; and, 3. the location of the shoulder joint centers, skull, thoracic skeleton, pelvis and femora relative to appropriate external body contours. To accomplish this objective, it is necessary to present all the required data in one coordinate system. The first of these objectives can be accomplished for the special case of a hard Air Force seat (6° seat pan, 15° lumbar support, no upper seat back) using procedures set forth in Snyder and Chaffin's torso-link study (19). Results of a similar exercise have been reported by General Motors Corporation (65) in connection with their development of the GM-ATD-502 dummy. References on the thorax are limited to the thoracic spine, however. Relative to the second objective, the thoracic spine can be related to the pelvis using the same procedures and seating configuration. The angular position of the femora in a representative automotive configuration is not known to the authors. It may be more desirable to establish a range of positions for the femora based on the vehicle occupant task, whether it be resting, braking, accelerating, feet on floor, feet on toeboard, etc. Data are not available to satisfy the third objective. Again, we recommend as an optimal procedure the use of stereophotographic techniques to define external contours and x-ray procedures to define interior thoracic geometry and coordinate systems. Sections 3.3.1 and 3.3.2 present the available data and procedures that have been reviewed and relate to this task. Section 3.3.1 contains anthropometric data modified for presentation in a three-dimensional coordinate system. The shortcomings and limitations of this procedure are discussed. All measurements have been taken in the erect seated position. Section 3.3.2 uses the torso-link procedures and regression equations of Chaffin (19) to extrapolate to a seated posture not much different from the automotive case. Because the torso-link study relates to workspace requirements and elbow reach, the normal seated position is not a standard position. This may lead to inaccuracies in the results presented here. These results are included primarily to demonstrate the power and potential of this technique in accomplishing overall project objectives. Part 3.3 is concluded by Section 3.3.3, which is a general discussion of the errors encountered in anthropometric measurements.

3.3.1 Seated Position Using Anthropometric Techniques

A partial description of an erect seated 50th-percentile male has been made using anthropometric measurements. The first step in this process was to review the literature and assemble relevant data from several surveys. These surveys present data collected from living civilian and military populations. There are, therefore, obvious statistical and measurement technique considerations which make the reported average values of questionable use. The thirty-one measurements are listed in Table 3, including the data source and the overall average value. As the second step, these measurements were manipulated to form a three-dimensional description of the relation between head, pelvis, hip joint, shoulder joint, and a limited number of spinal points. This information is presented in Table 4. Similar procedures could be developed to define the position of the occupant in an automotive seat, including landmarks

TABLE 3. BASIC ANTHROPOMETRIC DATA (50th PERCENTILE)

Measurement	No.	1950 Survey Hertzberg(5)	1000 Aviators 1965 Oberman (6)	HEW-PHS 1965 Stoudt (11)	Soldier Body Size 1966 White(7)	Army Aviators 1970 Churchill(9)	Air Traffic Controllers 1965 Snow (70)	Army Aviators 1961 White (8)	Holloman Subjects Robbins(15)	Link Study 1972 Snyder(19)	Hooten 1945(12)	Average
Number of Subjects		4000+	675	3091	6682	1482	678	500	6	28	1959	
Age of Subjects		18 - 45		18 - 79		17 - 40+	21 - 50	20 - 47				
Population		USAF		US Civil.		US Army		US Army	USAF	College Students		
Statistical Basis		50th Percen.	50th Percen.	50 Percen.	50 Percen.	50th Percen.	50th Percen.	Mean	Median	Mean	50th Percen.	
STANDING												
Weight (lbs)	1	161.9		166	156.28	170.53	158.7		167	174.61		165
Stature (in)	2	69.1		68.3	68.67	68.73	69.5	69.497	69.6	70.26		69.2
Tragion H.	3	64.0					64.0					64.0
Cervicale H.	4	59.2			58.85	58.93	59.0		59.5	60.13		59.3
Acromial H.	5	56.6			56.66	56.32	57.8		57.9	57.95		57.2
Iliocristale H.	6				41.87			41.655		42.69		42.1
A.S.I.S. H.	7									40.41		40.4
Penale H.	8	34.5					34.1					34.3
Biacromial B.	9	15.8		15.7					15.9	15.67		15.8
Shoulder B.	10	17.9			17.81	18.66	18.3	18.268	18.0			18.2
Chest B.	11				11.98	13.5	12.7		12.9			12.8
Chest D.	12	9.0			9.06	9.46	9.4		9.2			9.2
Waist D.	13	7.9					8.1		8.9			8.3
Bi-Iliac B.	14		11.46									11.5
Bispinous B.	15									10.21		10.2
Buttock D.	16	8.8					9.3		9.1			9.1
SITTING												
Sitting H.	17	36.0		36.0	35.73	35.79	36.1	35.608	35.8	36.66		36.0
Cervicale H.	18								25.5	26.55		26.0
Eye H.	19	31.5			31.0	31.02	32.0	30.904	31.0			31.2
Back H.	20										28.6	28.6
Waist H.	21	9.3							8.5			8.9
Thigh Clearance	22	5.6		5.7		5.79	5.08		6.3			5.7
Trochanterion H.	23									3.48		3.5
Troch. - Seat Back	24									5.54		5.5
Knee-Knee Back	25	7.9										7.9
HEAD (SITTING)												
Tragion-vertex	26	5.1			5.21	5.23		4.986				5.1
Tragion-occiput	27	4.0			4.01	4.06						4.0
Nasal root-occiput	28	7.8			7.52	7.87						7.7
Ext. Canthus-occiput	29	6.8			6.78	6.81						6.8
Bitragion	30	5.6			5.31	5.58						5.5
Interpupillary B.	31	2.49			2.41							2.5

TABLE 4. ERECT SEATED GEOMETRY BY ANTHROPOMETRY

ITEM	X-Position	Computation	Note. No.	Y-Position	Computation	Note No.	Z-Position	Computation	Note No.
Vertex (Sitting)	?	-	1	0	-	-	36.0	17	2
Tragion (R)	4.0	27	-	-2.7	30/2.0	-	30.9	17-26	3
Tragion (L)	4.0	27	-	2.7	30/2.0	-	30.9	17-26	3
Infraorbitale (R)	6.8	29	-	-1.3	31/2.0	-	30.9	17-26	3
Infraorbitale (L)	6.8	29	-	1.3	31/2.0	-	30.9	17-26	3
C2	?	-	-	0	-	-	28.6	20	-
C7	1.0	-	4	0	-	-	26.1	17-(2-4)or 18	-
ASIS (R)	5.1	See Text(p.33)	-	-5.1	15	-	7.9	[(16-(2-6)) + (19-1")]/2.0	5
ASIS (L)	5.1	See Text(p.33)	-	5.1	15	-	7.9	[(16-(2-6)) + (19-1")/2.0	5
Symphysion	9.1	16	-	0	-	-	3.4	[17-(2-8)+22]/2.0	-
Hip Joint Center (R)	5.5	24	-	-4.1	(25/2.0) + 14	-	3.9	See Ref. 18 p. 116	-
Hip Joint Center (L)	5.5	24	-	4.1	(25/2.0) +14	-	3.9	See Ref. 18 p. 116	-
Shoulder Joint Center (R)	4.6	12/2.0	-	-7.9	See Ref. 18 p. 125	-	22.0	17-(2-5)-2"	6
Shoulder Joint Center (L)	4.6	12/2.0	-	7.9	See Ref. 18 p. 125	-	22.0	17-(2-5)-2"	6

NOTES:

1. All measurements are in inches. The origin of coordinates is set at the intersection of seat bottom and seat back. Positive X is forward; Positive Y is left; Positive Z is upward.

2. Numbers in each computation refer to Measurement Numbers from Table 3.

3. The Frankfort plane is assumed (longitudinal).

4. Two subjects were used.

5. This computation agrees reasonably well with data presented in text, 7.9 inches.

6. See Ref. 19, p. 111.

on the thorax. The greatest shortcomings of this procedure are the lack of information concerning the spine and external body contours. Procedures such as x-rays (See Section 3.3.2) and stereo-photography could be used to obtain this additional data. The text which follows discusses each of the quantities presented in Table 4 with particular details concerning the pelvis.

Vertex

X-Axis

No data have been located.

Y-Axis

The vertex is assumed to lie in the mid-sagittal plane of symmetry. This is a functional definition and is a reasonable assumption for modeling purposes.

Z-Axis

This height is taken using an anthropometer with the subject in the classical erect seated position.

Tragion, Right and Left (Assume bilateral symmetry).

X-Axis

The measurement of this dimension is often taken on the seated subject with his head visually aligned in the Frankfort Plane. The occiput rests against a back board and the vertex is touching a perpendicular "head board." The dimension is thus taken with a modified anthropometer as the perpendicular distance from the back board (on occiput) to tragion.

Y-Axis

This dimension is measured with spreading calipers on the seated subject as the distance between the right and left tragion (Bitragion Diameter).

Z-Axis

This dimension has not been measured in the seated position and is therefore a derived length in the Z-Axis. Tragion height in the standing position has been reported in two of the referenced studies. This dimension when subtracted from stature is 5.2 inches, which corresponds to the more direct measure (No. 26) of 5.1 inches, which is the distance from tragion to vertex. Tragion height for the present seated position was derived by subtracting 5.1 inches from sitting height (measurement 17).

Infraorbitale, Right and Left (Assume bilateral symmetry)

X-Axis

This point is one of two points used by anthropologists to align the head in the Frankfort Plane. For the purposes of this report, four points (Tragion, R & L and Infraorbitale, R & L) will be used to define the Frankfort Plane. Infraorbitale, the lowest point on the inferior surface of the bony orbit of the eye, has not been measured on a living population relative to the head or floor. It was assumed that this point would be approximately the same distance from the occiput as the lateral corner of the eye. Thus, measurement 29 of Table 3 was used to define this quantity.

Y-Axis

There is also no measure of the distance between right and left infraorbitales. Therefore, as an estimate using available anthropometric data, the distance between the pupils of the eyes was used. Measurement 31 from Table 3 was divided by 2.

Z-Axis

Since the Tragion and Infraorbitale landmarks are being used to establish the Frankfort Plane which is parallel to the floor (perpendicular to the gravity vector), this dimension is the same as that given for the right and left Tragion.

C2 Surface Landmark

X-Axis

No data have been located.

Y-Axis

It is assumed to lie on the plane of symmetry and is equal to 0.

Z-Axis

This is an approximate location of an area defined by Hooten (12). He measured back height as the perpendicular distance from the seat to the "... point of junction between the head and neck," which is approximately the height of the 1st and 2nd cervical vertebrae. This measurement was taken using a special measuring chair with 6° seat pan and 13° seat back pitch.

C7 Surface Landmark

X-Axis

There are no data locating the distance of the tip of the spinous process of the seventh cervical vertebrae with respect to the plane of the back in the erect seated position. Therefore, based on measurement at HSRI of two subjects, a distance of 1 inch has been chosen.

Y-Axis

The point is assumed to lie in the plane of symmetry and is therefore equal to 0.

Z-Axis

The height of cervicale has been measured primarily in the standing position (4 studies based on over 10,000 military male subjects). Two studies (34 male civilians) measured it in the seated position. Deriving the height of cervicale from the standing data gives a seated height .1 inch greater than the seated data. The height of cervicale was derived by subtracting the standing cervical height (No. 4) from stature (No. 2) and then subtracting the result from sitting height (No. 17).

The Pelvis

Before discussing the means of estimating five points (right and left anterior-superior iliac spines, symphysion, right and left hip joint centers) on the pelvis in three-dimensional space, a brief review of the motion and position of the pelvis in the seating and seated subject should be given.

First, the pelvis can be defined as rotating about the L5/S1 (lumbo-sacral) joint. According to Dempster (18), the pelvis rotates approximately 46° (p. 113) from "normal standing position" when the subject sits with legs completely extended (i.e., sitting on the floor with torso approx. 90° to floor plane). His data are presented as an angle between a hard seat pan ("wooden replica of the pilot cockpit") and a plane formed by the right and left anterior superior iliac spine and symphysion. The angle is related to seat-pan height in increments of 3 inches from 0 inches to 30 inches. Dempster states that he adjusted the reference line on his pelvic-tilt measuring device to make it equal to 0° (vertical) but he fails to give data recording the amount of adjustment. Thus one must assume that the anatomical plane is parallel to the reference plane when the subject is in the standing position.

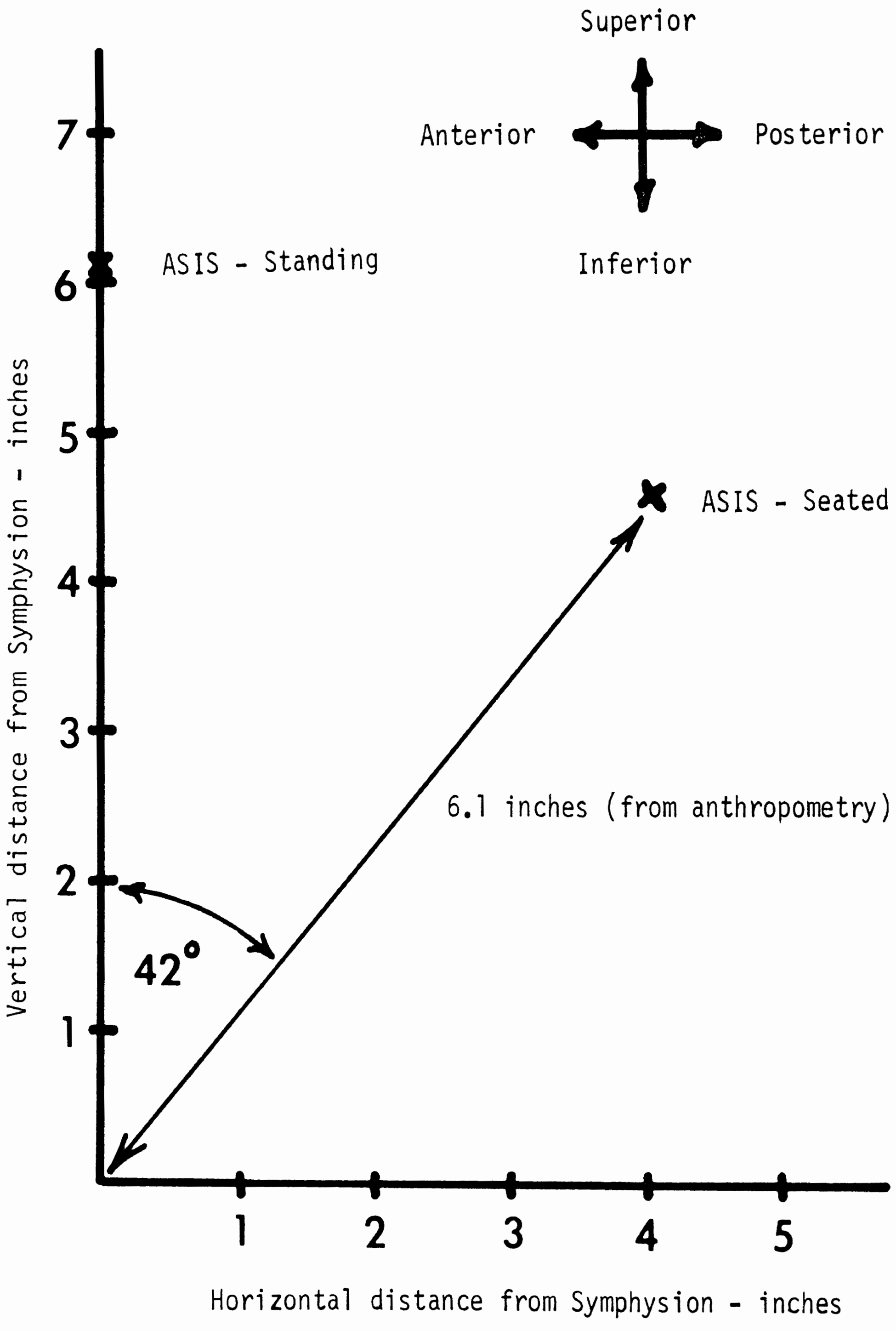
In addition, there is some confusion regarding the actual seat and subject position which Dempster employed. It appears that he used blocks to elevate the subject in 3-inch increments and had the subject remain in a legs-extended position from 0 inches to 30 inches seat height. The seat pan, seat back,and thigh orientation contribute significantly to pelvic orientation, and these variables are not discussed by Dempster.

If Dempster's pelvic rotation data are accurate (and they are the only data known outside of European literature that has not yet been completely reviewed), one then needs to know the location of one or more of the points on the pelvis relative to the L5/S1 joint center. The present authors do not believe that there are 46° degrees of angular rotation in one spinal column joint--this is probably achieved through movement in the whole lumbar region. The link study of Snyder and Chaffin (19) concludes that there is 20% more mobility in the L5/S1 to L3/L4 levels than in the L3/L4 to L1/L2 levels. However, they suggest that biokinematic models may use a single vector to represent the lumbar region. This could be questioned by the pelvic tilt implications for the lumbar spinal column found in Dempster. Furthermore, the link study does not appear to provide any data on pelvic rotation in the subjects. There are no data available at present which describe the pelvic geometry in three-dimensional space.

Thus, it appears that there are two problem areas. First, all of the preceding head and torso points need to be adjusted in the Z-axis,(possibly the X-axis as well) for a given degree of pelvic tilt. For example, the height of those points above the pelvis could be reduced in the seated position by as much as 1.5 inches in a representative automobile seat with a compressed seat pan height of 6 inches if it can be assumed that measurements taken across soft and hard tissue are linearly related to those measurements made on the skeleton above. See Figure 1 and Reference 71.

Second, the pelvis must be located relative to the seat pan-seat back configuration. The anatomical landmarks as well as the hip-joint center will rotate above the L5/S1 joint center through unknown paths. At present, one must assume a standing position as the position from which to start rotating, and that position has not been defined by any bony landmark locations in the X-axis.

Dempster (18) proposes that the hip joint center can be approximated by half the distance from the anterior superior iliac spine to the seat surface. The means by which he arrived at this derivation of Z-axis location of hip joint center is questionable as to applicability over a wide range of seating configuration problems. Furthermore, he defines the tolerance level in his last two paragraphs on p. 117,which are worth quoting:



NOTE: ASIS = Anterior Superior Iliac Spine

Figure 1. Pelvic rotation from standing to sitting with a 6-inch seat pan height from floor.

> "The earlier study of instantaneous axes for joint movement pointed out that centers of rotation shift about over an appreciable range. The cluster of center locations varied somewhat from one cadaver joint specimen to another. A "mean center" position for the hip is surrounded by a circle of probability of joint-center position with a 1-cm radius. This factor, added to the range of variability of the mid-acetabular position in relation to the seated position of the pelvis, could very well be double the 0.75 inch circle mentioned above; this variability in position would be further augmented for forward movments of a subject in the seat.
>
> Thus, our analysis on pelves has only confirmed that made on femora, suggesting the joint center could at best be predicted only within a 1.2- to 1.5 inch ellipse. For the subject seated with the reference plane at 40° to the vertical, a line dropped vertically from the anterior superior spine becomes the best estimate. This prediction, however, is a nominal location that may be modified by forward displacement of the trunk, forward or backward rotation of the pelvis, oblique orientations of the pelvis, and variable amounts of fat padding or padding caused by clothing."

Thus, the location of the pelvis and the hip joint center is tenuous at best with available data. The measurements used are for the most part approximations on the part of the authors as to which anthropometric dimensions best describe the position of the desired bony landmarks.

Furthermore, these data are presented as if the subject were seated in a hard seat pan -- parallel to the floor -- 6" from the floor. The pelvis has been rotated 42° relative to the vertical plane perpendicular to the floor and thus assumes a 0° rotation as starting point. In addition, some of the data are based on the hard seat-pan seat-back configuration modeled after the Air Force seat angle standards.

The remaining data have been collected on subjects in an erect sitting posture with thighs positioned parallel to the plane of the floor,thereby ignoring "design seat height" and standardizing "anatomical sitting position."

Symphysion

X-Axis

The standing measurement of buttock depth is taken at approximately the level of the pubic symphysis. Thus, this dimension has been used to locate the x-axis for the symphysion.

Y-Axis

Symphysion is assumed to lie in the plane of symmetry and is therefore chosen to be equal to 0.

Z-Axis

Since the pelvis is assumed to rotate about the L5/S1 joint center in the seated configuration, the standing location of penale height (junction of penis and abdomen) - which approximately locates symphysion -- will be used to define its lowest possible height. Furthermore, it is felt that the superior border of the pubic symphysis will not rotate above the uppermost level of the thigh (thigh clearance No. 22). Therefore, the average of penale height in the seated position (No. 17 - (No. 2 - No. 8)) and thigh clearance has been used as the location of symphysion in the seated position.

Anterior-Superior Iliac Spines, (ASIS), Right and Left (Assume Bilateral Symmetry)

X-Axis

Since location of L5/S1 joint center of rotation is unknown, the pelvis will be assumed to rotate around symphysion (see Figure 1). Thus, with a 42° rotation (6" seat pan height) the ASIS, in the mid-sagittal plane, moves posteriorly from symphysion approximately 4 inches. Therefore, Measurement No. 16 minus 4 inches has been chosen for the x-coordinate.

Y-Axis

Assume bilateral symmetry and divide Measurement No. 15 by 2.

Z-Axis

See Figure 1 for inferior-posterior movement of ASIS in the XZ plane. The spinous process is approximately 4.5 inches above symphysion in the seated position. Therefore, 4.5 inches is added to the Z-axis dimension for symphysion. This agrees reasonably well with the computation presented in Table 4.

Hip Joint Center (Assume Bilateral Symmetry)

These dimensions are dependent upon where and how the joint center is defined. Dempster (17) is the only person known to have defined its location but the definition on page 125 of his report is made with the subject in the classical anatomical position. Thus, one must follow his assumptions on pages 114-117 which were briefly discussed in the section on the pelvis. The following assumptions have been made based on Dempster's work:

1) The greater trochanter of the femur is the best anthropometric location of the joint center projected on the mid-sagittal plane.

2) The joint center lies approximately half the distance between the ASIS and the seat pan.

3) The human body is bilaterally symmetrical.

X-Axis

The distance from seat back to greater trochanter has been measured in one study (19).

Y-Axis

The knee-to-knee breadth plus 30 mm has been taken as the trans-pelvic link diameter. See Dempster (18), p. 128.

Z-Axis

Half the height of ASIS from the seat pan. See Dempster (18), p. 116.

The Shoulder

The shoulder is the most complex link mechanism in the body. It is comprised of the sterno-clavicular, acromio-clavicular, coraco-clavicular, and humero-scapular joints through all of which pass a shoulder "linkage." Thus, the location of either acromion or the shoulder joint center becomes a function of the position of several links with respect to each other as well as the position of the humerus relative to these joints.

Shoulder Joint Center (Assume Bilateral Symmetry)

X-Axis

There are no data locating the joint center, or any landmark(acromion or ball of humerus) with respect to the back plane. Therefore, it is assumed that this dimension could be grossly approximated by half of chest depth. Measurement 12 is divided by 2. (It should be noted that this point is more accurately determined using the x-ray procedures discussed in Section 3.3.2).

Y-Axis

There is some inconsistency here: Dempster (18) - p. 125

> "Glenohumeral joint center -- Midregion of the palpable bony mass of the head and tuberosities of the humerus; with the arm abducted about 45° relative to the vertebral margin of the scapula; a line dropped perpendicular to the long axis of the arm from the outermost margin of the acromion will approximately bisect the joint."

Paragraph 3 in letter from Chaffin to Hubbard 7/24/73 (72).

> "When the gleno-humeral joint center is used as a center-of-rotation, the distance between the centers of the shoulders is approximately 12.94 inches for an average stature man. This is based on the following. First, the x-ray study disclosed a mean distance from the C7/T1 disc center to the humeral head center of 6.47 inches with the arm raised horizontally and slightly forward. This same arm position disclosed a suprasternale to acromio-clavicular junction mean distance of 6.5 + 1.13 = 7.63 inches. A check of this latter dimension with the over-body data (page 103) disclosed a mean distance of 8.00 inches with the arm down. The difference is the fact that the over-the body measurement was to the lateral border of acromion, and the acromion rotates inward as the arm is raised (Inman, et al.). Consensual validity for the shoulder-to-shoulder joint centers being correct is given by the close agreement with Dempster's data ("Properties of Body Segments...", Am. J. Anat., vol. 120, 1967), who disclosed a mean of 12.89 inches for an average size man."

Biacromial breadth has been presented in Table 4. This measure needs further development.

Z-Axis

The height of the shoulder joint center has been derived by estimating sitting acromial height and subtracting 2 inches (See Dempster (18), p. 111).

3.3.2 Seated Position Using X-Ray Procedures

The objectives of this procedure were to: 1. evaluate the capabilities of the techniques developed by Snyder, Chaffin, and Schutz in the torso-link study (19); 2. define insofar as is possible the geometric relations between body landmarks, joint centers, head, thorax and pelvis for a seated position; and, 3. develop more data concerning the location of the vertebrae in space to define a trial spinal geometry. The next few paragraphs describe the techniques used, present the results, and make recommendations to use similar procedures to accomplish the overall objectives of this project.

In order to locate head, external spinal landmarks, internal vertebral joint locations, pelvic orientation, etc.,it was necessary to use a two-step process. The first step was to use regression equations developed by Chaffin to locate the following external landmarks: 1. right acromion; 2. supersternale; 3. seventh cervical vertebra (C7); 4. eighth thoracic vertebra (T8); 5. twelfth thoracic vertebra (T12); 6. second lumbar vertebra (L2); 7. fifth lumbar vertebra (L5); and 8. the right anterior-superior iliac spine. The general regression equations were implemented as a simple computer program requiring as input the position of the elbow in space. An alternate set of regression equations was implemented which use several anthropometric parameters to more closely predict the eight surface marker locations for specific subjects. The elbow position chosen for the predictions represented the upper arm aligned with a vertical axis close to the torso. This was not a position used in gathering the original data for generation of the regression equations and represents somewhat of an extrapolation. Within the time framework of this project it was not possible to determine the effect of this on the accuracy of the results. The location of C7 was predicted for additional elbow positions 8 and 12 inches in front of the L5 surface marker which may be a more representative position of an automobile occupant. Figure 2 shows the location of the eight surface points as predicted using the general regression model and includes three positions for C7. Predictions using the regression equations modified for anthropometric data did not appear to be realistic in the case where numerical values derived from SAE J963 were used. Conversations with Dr. Chaffin indicated that possible future refinements of the anthropometric model were necessary to improve its accuracy.

The second step was to use the torso-link x-ray data to predict the location in three dimensions of the remainder of the landmarks, including: 1. nasion; 2. C2/C3 junction; 3. C3/C4 junction; 4. C4/C5 junction; 5. C5/C6 junction; 6. C6/C7 junction; 7. C7/T1 junction; 8. T4/T5 junction; 9. T8/T9 junction; 10. T12/L1 junction; 11. L2/L3 junction; 12. L3/L4 junction; 13. L4/L5 junction; 14. L5/S1 junction; 15. acromio-clavicular junction; 16. humeral head; 17. humeral mark; 18. sterno-clavicular junction; and 19. supersternale. These locations are shown in three dimensions in Figures 2, 3, 4. Visual comparison of the relative locations of these points with skeletal material indicates that they are realistic.

Four additional points have been added to Figure 2. The first is the hip pivot point as estimated by Dempster (18). It is located directly below the anterior-superior iliac spines, one-half the distance to the surface of the seat. The second point is the H-point as defined in SAE J 826a. It should be noted that the hard seat pan allows direct application of the dimensions of the H-point machine or two-dimensional drafting template. The H-point is located 5.28 inches in front of the seat back and 3.84 inches above the seat pan. Both of these hip joint pivots are based on human data. It was not possible to resolve the differences within the framework of this project.

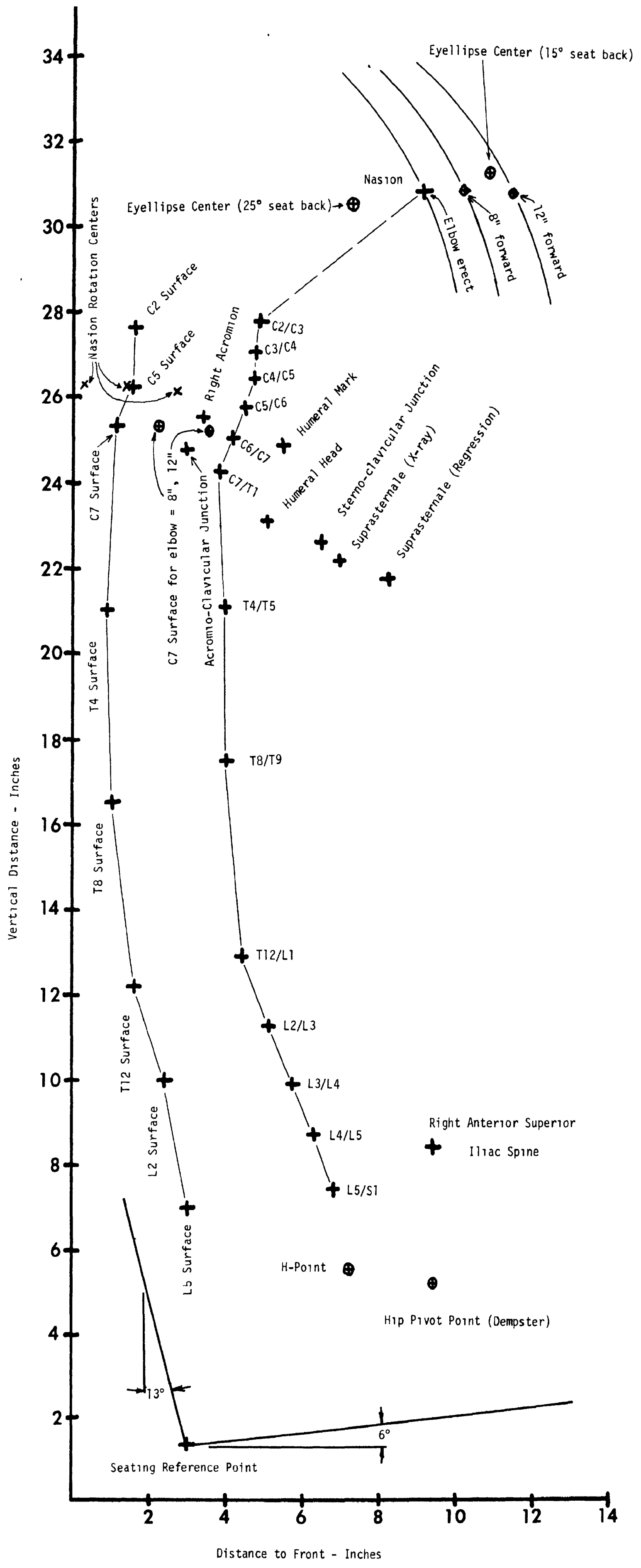


Figure 2. Location of Body Landmarks Using Torso-Linkage Concepts (Side View)

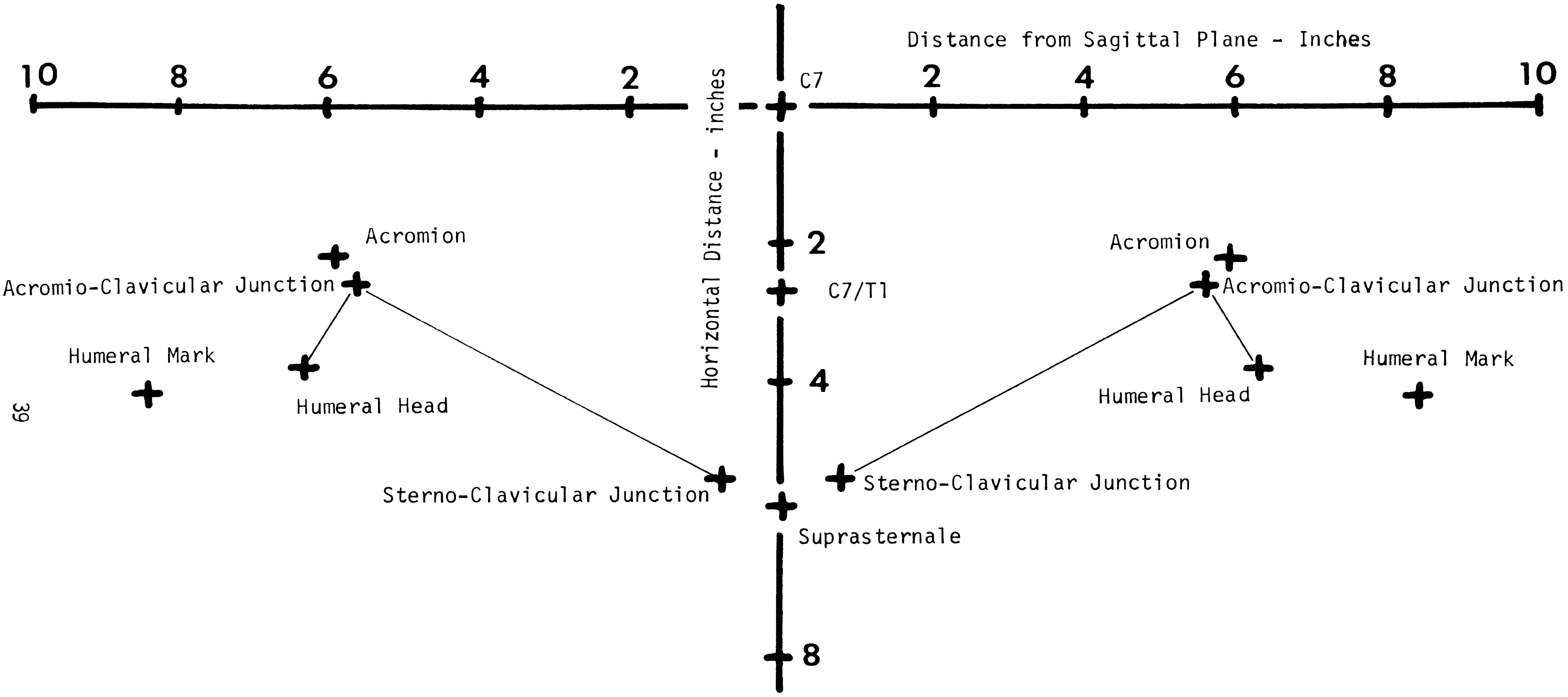


Figure 3. Location of Body Landmarks Using Torso-Linkage Concepts (Top View)

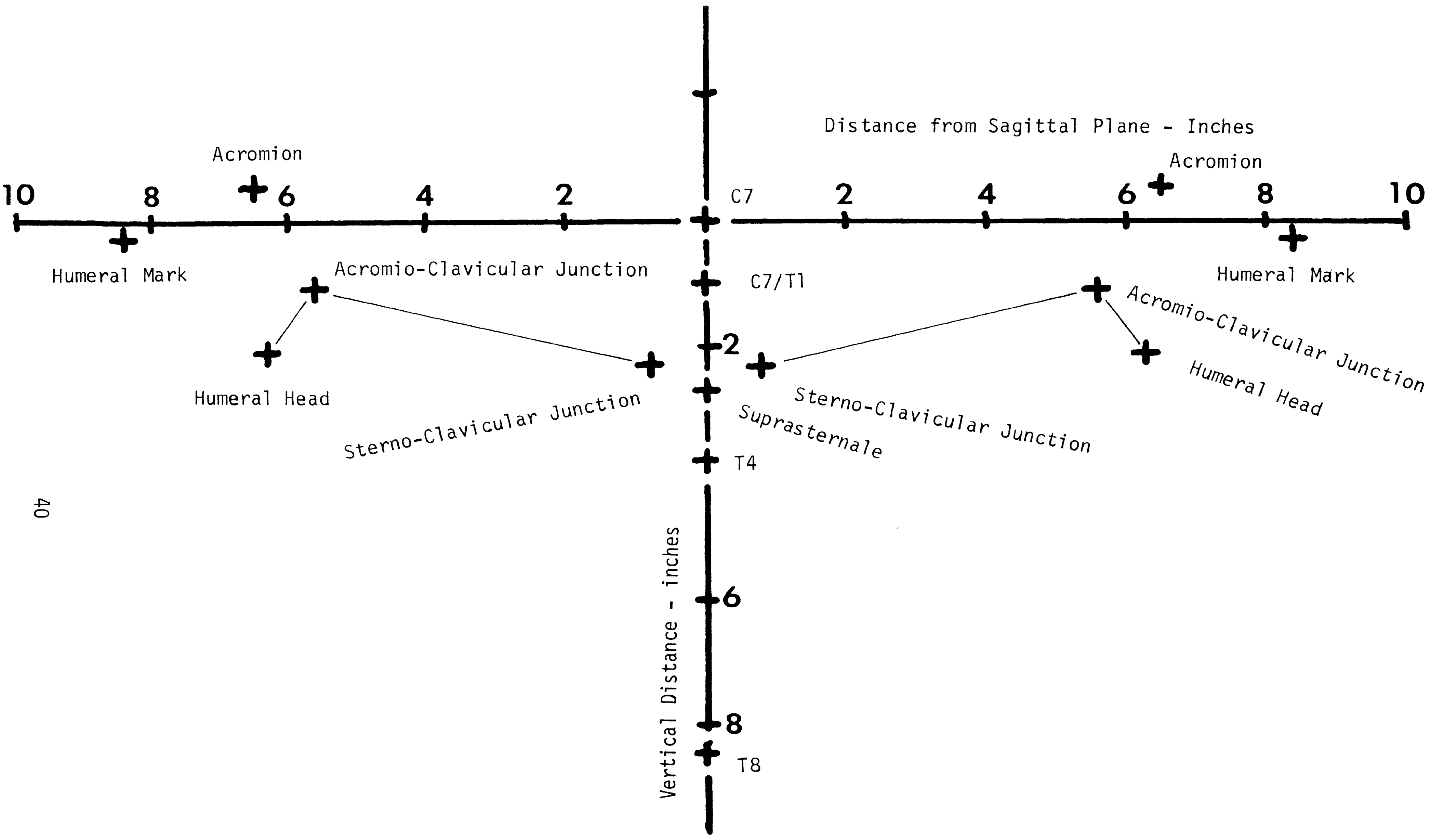


Figure 4. Location of Body Landmarks Using Torso-Linkage Concepts (Front View)

The third and fourth points are derived using the eyellipse data from SAE J941. The eyellipse center for a 15° seat back falls between the 8-inch and 12-inch elbow positions, which appears to be realistic for a driver. The eyellipse center for a 25° seat back is, as would be expected, farther back.

This sample study of seated position landmarks and joint centers demonstrates the power and scope of the procedures developed by Snyder, Chaffin, and Schutz (19). It is recommended that this work be expanded to: 1. define a more complete set of skeletal and surface landmarks using anthropometric information; 2. locate coordinate systems in the head, thorax, and pelvis based on the combined data; and, 3. redefine the torso-linkage for the automotive seated position using whole body x-rays (if medically possible) to decrease errors associated with an analysis of multiple x-rays, or possibly reanalyzing Chaffin's data to provide a set of regression equations more closely related to the objectives of the current project.

3.3.3 Anthropometric error

Errors in anthropometric data originate from three sources in addition to possible equipment or data handling errors:

1. the observer
2. the measurement
3. the point

Anthropometric measurements are made and recorded according to what the anthropometrist observes. Objective errors (See Kemper and Pieters (73) and Jamison and Zegura (74)) occur between two or more observers and reliability errors occur for one observer. In both cases, observer error is dependent upon perception of the same anthropometric model for each subject. The model in this case is three dimensional, dynamic, and highly variable, and must be described precisely by static dimensions.

Every anthropometrist further recognizes the geometric nature of his measurements. The instruments when constantly calibrated are accurate within a millimeter tolerance. Thus, the second source of error - the measurement - is the ability of the anthropometrist to measure precisely: 1. a perpendicular distance of one point to a floor or seat plane; 2. the magnitude of a vector distance between two abstruse points; or 3. the circumference of an irregular, compressible body. These measurements are usually made with reference to undefined axis systems. For example, stature, sitting height, chest depth and breadth are measurements taken parallel and perpendicular to the gravity vector. Coordinate directions are partially specified. These measurements assume an inertial axis system whose point of origin remains unspecified. In addition, hand length, hand breadth, shoulder-elbow length, and upper arm circumference (relaxed) are measurements taken parallel and perpendicular to a segment axis system. This latter axis system is constructed by the observer as he takes the measurement, and it is basically some longitudinal axis on the segment. In this case, the segment axis system is unspecified as to its point of origin and the direction of coordinates.

The accuracy of the measurement, therefore, depends on subject position, instrument alignment and position, as well as correct reading and recording of the measured quantity. Subject position is often the most difficult variable to control, particularly when the measurement is made across several joints as in the case of biacromial diameter. The acromion landmark on the acromion process of the scapula is at the lateral and superior edge of the shoulder. Dempster (18) approximates the movement of the complex linkage system in the shoulder by stating that the acromion moves on a hemispherical surface. This conclusion was based on the early work of Fick (36) and others who devised globographic descriptions of joint motions. The distance between the two acromion landmarks - biacromial diameter - is therefore dependent both on the position of the human body and the definition of the surface landmarks. In the International Biological Program Handbook, No. 9 (1969), the maximum biacromial diameter is defined for a subject when he "...stands with his shoulders relaxed to the point of slumping forward" (p. 10). Other studies define this position differently. For example, in the Anthropometry of Flying Personnel - 1950 (Hertzberg (5)), the subject sits in an erect "anthropometric seated position" (i.e., head in Frankfort Plane, torso erect, upper arms hanging at sides with lower arms flexed 90° and hands extended). The United States Public Health Survey 1960 - 1962 (Stoudt (63)), used a slightly different seated subject position. The anthropometrist "...placed his hands on the examinee's shoulder, asked him to roll his shoulders slightly forward, and assisted him to do so" (p. 4). Another position was used in the link system of the human torso study by Snyder, Chaffin, and Schutz (19), where the subject stands in an erect posture with his "arms hanging at his side..." (p. 105). Thus, in four reports concerning anthropometry, four positions were described which could give four different dimensions for biacromial diameter. Data available in the literature are confounded by variables (population, equipment, observers, etc.) which do not permit a quantitative evaluation of these problems. Thus, physical anthropologists consider the above problems to produce significant error.

The definition of the measurement points - the third source of error - is also critical and variable for items such as biacromial diameter. Most of the definitions used by anthropometrists have been noted by Garrett (16). In summary, acromion is defined as a point on the "external borders," the "lateral edge," and the "superior edge of the lateral border" of the scapula. All of these definitions refer to a rounded bony protuberance that moves relative to the examinee and the examiner. Furthermore, the acromion landmark is the "bony point" by which the shoulder joint center is located as indicated by Dempster (18) and Snyder (19).

The acromion landmark and biacromial diameter have served to illustrate problems in interpreting the anthropometric literature. Other landmarks (e.g., trochanterion, which is equally important for locating the hip joint center) could have been chosen because they each present the same problems in even greater complexity for the anthropometrist. These problems, however, along with claims that everything has been measured, do not conclude the role of anthropometry in workspace design.

All three sources of error cannot be avoided entirely by the most highly trained and experienced physical anthropologist specializing in anthropometry. Unfortunately, much anthropometric data are taken by non-professionals. In most cases, the measurers are trained by professionals, but occasionally data will be collected by non-trained personnel thereby magnifying all of the above errors.

Traditional anthropometric techniques are limited by anthropometric errors but these techniques provide adequate data on static dimensions with which one can define populations. These data have been useful also for limited workspace applications; but, with the advent of modern high speed transportation where split-second timing can make the difference between life or death, the old techniques must be replaced with new techniques and new forms of data which precisely define man in his three-dimensional workspace. The human body is not a disjointed collection of dimensional parts but an integrated three-dimensional system which functions precisely in three dimensions. It is apparent that present-day anthropometric descriptions of the human body underestimate and grossly define the precision with which the human body can perform within an exactly defined dynamic workspace.

3.4 HIP PIVOT POINT VERSUS 3-D H-POINT MACHINE

The objective is to compare the findings of the literature review with seating reference positions given by the SAE 3-dimensional H-point machine. Figure 2 shows a direct comparison between H-point and estimates made by Dempster (18). The application of Dempster's estimate for this study depends on the work of Snyder, Chaffin, and Schutz (19) for a correct location of the right anterior superior iliac spine. It should be recalled that the H-point is based upon the x-ray study conducted by Geoffrey (34) of Ford Motor Company. It has not been possible to resolve the differences within the scope of this contract; both points seem to be based on reasonable data and assumptions. The accurate location of a hip pivot point, because of its potentially large effect on occupant dynamics, is a primary research topic which should be included in any further attempts to meet the overall objectives of this project.

3.5 RELATIVE BODY SEGMENT TRAJECTORIES

The objective for the seated configuration is to determine the possible trajectories and extreme configurations which can be obtained without voluntary muscular hindrance for: 1. humeri relative to shoulder joint centers; 2. shoulder joint centers relative to the thoracic skeleton; 3. skull relative to thoracic skeleton; 4. thoracic skeleton relative to pelvis; and, 5. femora relative to the pelvis. The standard presentation of humerus range of motion is relative to the thorax without considering the shoulder linkage and the movement in space of the shoulder joint. Authors such as Dempster (18) and Fick (36) use a globographic approximation to locate the range of the shoulder pivot point. Standard data from SAE J963 represents the combined motion. It is possible that a combination of the Dempster data with that from SAE J963 could be used to uncouple the two types of motion.

The data then could be presented for the seated posture. None of the range-of-motion data has been gathered for the seated posture, necessitating a new method of presenting data.

A more complex and accurate alternative is to use the procedures of the torso-link study of Snyder, Chaffin and Schutz (19) to generate the limits of motion. Their procedures define elbow point, humeral head, acromio-clavicular junction, and sterno-clavicular junction in space. A new experiment would have to be conducted, however, in that their tests allowed motion of the torso for the purpose of establishing maximum reach rather than a range of motion.

Considerable data is already available describing the motions of the skull relative to the thorax. Again, however, much of the data show only an angle of the head relative to some line defining the torso. To the best of the knowledge of the current authors, no data are available for describing the motion of a coordinate system attached to the skull, relative to a coordinate system attached to elements of the upper thoracic skeleton. At least two research projects which are currently in progress should yield this type of data. One, which is nearing completion, is sponsored by the Insurance Institute for Highway Safety at The University of Michigan and is under the direction of R. G. Snyder. Another, also at The University of Michigan, is sponsored by the U.S. Department of Health, Education, and Welfare, and is under the direction of J. W. Melvin. Current research by Ewing at the Naval Aerospace Medical Research Laboratory should also produce data of this general type. The output from these projects should satisfy this objective of the current project.

Only limited data are available concerning motion of the torso relative to the pelvis. The data in J963 show angles of bending the torso forward, backward, sideward, as well as twist, which, in a limited sense, describes the subject motion. Using these data, it is not possible to relate the possible ranges of motion of a coordinate system in the torso with respect to a pelvic coordinate system. In addition to tracking the pelvis, it is necessary to define thoracic flexibility in order to relate the two coordinate systems. Another approach would relate the motions of a coordinate system attached to the L1/T12 interspace to the L5/S1 interspace and finally to the pelvic system. This approach has the advantage of avoiding thoracic problems and isolating lumbar flexibility. No known research definitely studies this problem. Any further research project attempting to reach the overall objectives should assign the pelvis-thorax range-of-motion study a high priority.

There are considerable data defining the motion of the femora relative to the general area of the body containing buttocks, pelvis, and lumbar spine. (See J963). However, as is usual, the data are not presented and cannot be presented in terms of coordinate systems. It is recommended that this subject be considered in an overall project dealing with flexibility of the lower body elements from T12/L1 to the femora.

3.6 DUMMY MASTER BODY FORMS

The objective of this task is to critically review the Dummy Master Body Forms," golden shells," and specify the degree of compatibility between the findings of the present project and these forms. It has been noted in Section 3.3 that the data are inadequate to define the seated position or any other position relative to external body contours. In the past, body shape has been judged by overall appearance -- an anthropomorphic evaluation. This procedure cannot yield a quantification of the body contours relative to coordinate systems attached to the body skeletal structure.

It is possible, however, to compare the anthropometric measurements of SAE J963 with stereometric measurements made on the golden shells by Radovich and Herron (75). There is close agreement between the two sets of data. When a relation is established between the anthropometric data and body coordinate systems, then it will be possible to complete the analysis based on Herron's work. If there is close compatibility, it may be possible to use much of Herron's data to establish quantified external body contours. If the compatibility is poor, it would be recommended that the golden shells be modified.

In conclusion, recommendations for further work are as follows:

1. Develop procedures to present Herron's data for the various body segments in terms of internal skeletal-related coordinate systems.

2. Compare the Herron data as related to seated occupant coordinate systems with the new data to be gathered during continuations of this project.

3. Revise the golden shells, establish new body contours using stereometric procedures, and reanalyze the new forms using the procedures referred to in Recommendation 1.

3.7 SEATED GEOMETRY FOR OTHER PERCENTILES

The objective of this task is to specify a valid scheme by which the results of this program for the 50th-percentile male can be extended to other percentiles. To the knowledge of the authors, no completely satisfactory scaling laws have been developed for use in specifying occupants with sizes other than the 50th percentile. One of the most promising procedures has been developed at Calspan Corporation by Bartz and Gianotti (76). However, their work has limited relevance to the present problem, for two reasons: 1. the data they are using are based on classical standing and seated anthropometric measurements which have not yet been related to the motor vehicle seated posture; and, 2. the output from the computer program is in a form useful primarily as input to computerized mathematical crash victim simulations.

The basic problem in developing scaling laws relates to the necessity of combining a set of independent measurements to represent a complete man. For example, there are many individual measurements defining the 95th-percentile, but attempts to construct a dummy using only 95th-percentile measurements have failed to produce realistic results. If 95th-percentile limb lengths for lower leg, upper leg, torso length, and head-neck length are added together, the total length will sum up to be 3 to 4 inches greater than 95th-percentile stature. As mentioned in a previous section of this report, the most interesting interchange of thoughts in the literature on this topic is reflected in a series of papers by Hertzberg (2) and Searle (3).

The authors of this report recommend that a team consisting of a physical anthropologist, a statistician, and an engineer be assembled to develop the scaling laws. The physical anthropologist can define the various descriptors of the human. The statistician can validate data populations and develop valid procedures to manipulate and/or combine the data. The engineer can make the necessary judgments of which physical measurements describing man are important to his dynamic response or workspace geometry, and, therefore, which measurements must be included in the scaling laws governing eventual dummy designs.

PART 4. RECOMMENDATIONS

This part of the report collects recommendations made throughout the text into one place (4.1) and consolidates these into recommendations for further research (4.2).

4.1 SUMMARY OF RECOMMENDATIONS

The first three recommendations are based on the literature survey presented in Part 2.

1. The literature of Ergonomics should be subjected to further review with an emphasis on the European literature, much of which is not published in the English language.

2. A further and more detailed review should be conducted on the older anatomical and biomechanical literatures covering the period from about 1840 to 1945. Much of this literature has also not been published in English.

3. A list should be compiled of all parameters needed for dummy design and construction. A table of values for these parameters should then be prepared, including data from the golden shells, the Public Health Service anthropometric surveys, the various military surveys, the H-point machine, and the four most widely used crash test dummies.

The remaining seven recommendations are related to completion of the seven overall objectives of this project.

4. Using the data presented in this report, graphical presentations should be made of coordinate systems based in the head, thorax, and pelvis.

5. A procedure should be developed to define external and skeletal geometry of the thorax for the 50th-percentile automotive seated male, and correlations made with standard anthropometric measurements. An approximate short-

range solution to this problem is to scale the skeletal data of Andriacchi (47) and Roberts (48) to the population used in the torso-link study of Snyder et al. (19) and present the thoracic data superimposed upon Figure 2 of this report. The flexibility of the thorax should be investigated under both static and dynamic conditions.

6. With respect to the pelvis, a thorough study of pelvic tilt in various seating configurations should be conducted. The location of the pelvis should be defined in three-dimensional space with respect to a coordinate system attached to non-deformable seat structural members and relative to adjacent body structures such as the lumbar spine, the thorax, and the femur. One procedure for accomplishing these recommendations is to adopt the previously discussed x-ray and photographic procedures of the torso-link study developed by Snyder, et al. (19). The range of motion of the pelvis relative to the thorax and femurs should also be determined by the procedures.

7. The differences between the H-point (as measured by the H-point machine) and Dempster's method for prediction of hip pivot point as presented in Figure 2 should be resolved.

8. Range of motion data should be developed as follows:
a. the shoulder mobility data of SAE J963 should be uncoupled into motions at the sterno-clavicular junction and at the gleno-humeral joint possibly using the data of Dempster (18) and Fick (36); b. shoulder mobility should be evaluated, using procedures of the torso-link study; c. procedures should be developed to define range of motion and flexibility of the human body from the T12/L1 junction down to the femora.

9. Procedures should be developed to present geometrical data describing the golden shells in terms of skeletal-related coordinate systems. These data should then be modified and presented in terms of an automotive-seated coor-

dinate system for correlation with eventual studies using human subjects in an automotive seated posture.

10. An interdisciplinary team should be established to develop laws to scale 50th percentile data to other occupant sizes. Anthropological inputs will define human descriptors; statistical inputs will develop and validate the scaling laws; engineering inputs will determine relevancy of physical quantities which are proposed for inclusion in the scaling laws.

4.2 SUGGESTED FUTURE RESEARCH PROJECTS

Within the context of the above recommendations, follow-on research in three phases is suggested. With the present work defined as Phase I, the Phase II effort should: 1. attempt to tie together the data collected during Phase I; 2. develop experimental procedures to obtain needed data; and 3. test the procedures on small populations of approximately ten subjects.

The tasks which are recommended for inclusion in Phase II follow directly from the present work:

1. Develop a list of dummy design parameters and all related data describing human populations and existing dummy designs.

2. Develop a thoracic shape based on existing data and a test program to define thoracic flexibility.

3. Define pelvic geometry, orientation in space (seated pelvic tilt), and the flexibility of the human subject from the T12/L1 junction to the femora.

4. Define shoulder linkage geometry for the seated occupant, the constraints to motion, the voluntary range of motion, and estimates of the mass of tissues involved in these motions.

5. Develop scaling laws to other percentiles from the 50th-percentile seated occupant data.

The purposes of Phase III are to establish the seated position of the 50th percentile male subject, based on a valid population and on valid test procedures, and also to define research programs to consider dynamic properties of the human. The two tasks are:

1. Conduct population studies for geometry, range of motion, and body flexibility as outlined in the original Phase-I proposal developed by HSRI.

2. Develop recommendations for research programs to define dynamic human parameters such as body segment masses and centers of gravity, dynamic range of motion, dynamic mass distribution, and dynamic strength (all relevant to future dummy design).

Phase IV would concentrate on obtaining the dynamic human descriptions. From the practical point of view a primary objective of this final phase would be to understand the parameters describing the occupant to such an extent that rational simplifications in dummy design can be recommended, executed in hardware, and verified by test.

PART 5. REFERENCES AND BIBLIOGRAPHY

This part of the report is divided into two parts. Part 5.1 is a list in numerical order of the references included in the text. Part 5.2 is a more extensive bibliography in alphabetical order by author including all items of Part 5.1 plus additional relevant material.

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