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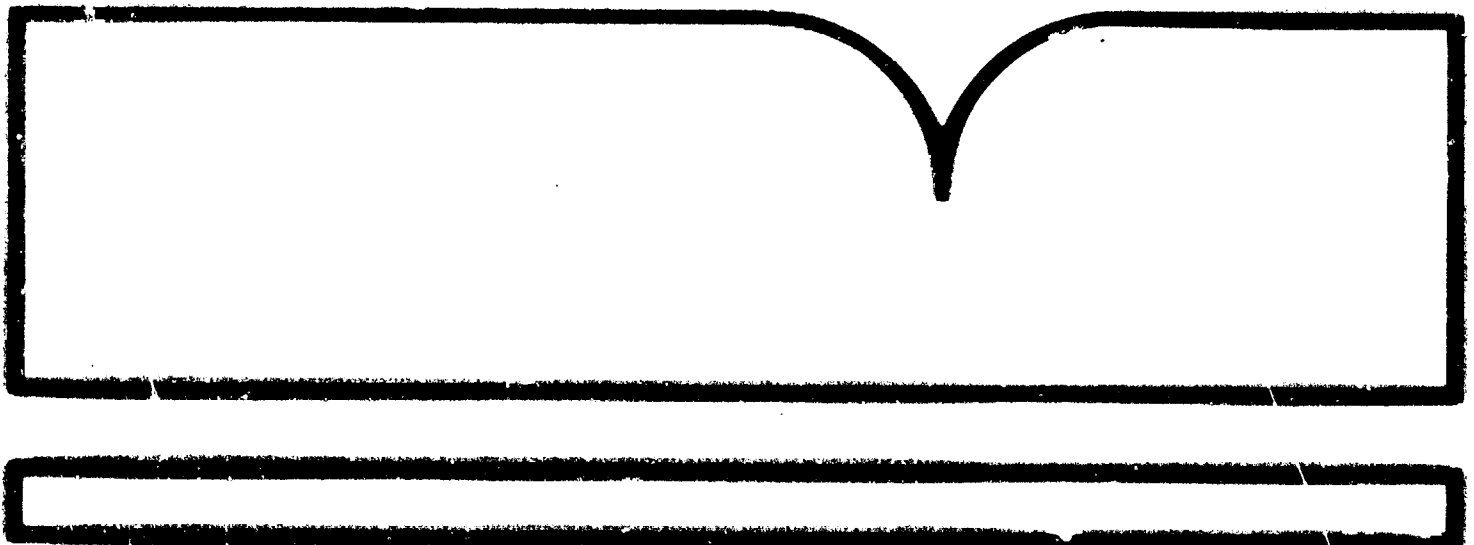
Ergonomic Models of Anthropometry, Human
Biomechanics, and Operator-Equipment
Interfaces: Proceedings of a Workshop

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The Committee on Human Factors was established in October 1980 by the Commission on Behavioral and Social Sciences and Education of the National Research Council. The committee is sponsored by the Office of Naval Research, the Air Force Office of Scientific Research, the Army Research Institute for the Behavioral and Social Sciences, the National Aeronautics and Space Administration, and the National Science Foundation. The principal objectives of the committee are to provide new perspectives on theoretical and methodological issues, to identify basic research needed to expand and strengthen the scientific basis of human factors, and to attract scientists both within and outside the field for interactive communication and to perform needed research. The goal of the committee is to provide a solid foundation of research as a base on which effective human factors practices can build.

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Proceedings of a Workshop

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Ergonomic Models of Anthropometry, Human Biomechanics, and Operator-Equipment Interfaces

Proceedings of a Workshop

Karl H.E. Kroemer, Stover H. Snook,
Susan K. Meadows, and Stanley Deutsch, *editors*

Thomas B. Sheridan, Chair
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Committee on Human Factors
Commission on Behavioral and Social Sciences and Education
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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WORKSHOP ON INTEGRATED ERGONOMIC MODELING

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Foreword

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Preface

In the prospectus for the workshop, co-chairman Kroemer described three major classes of models: *anthropometric*, representations of static body geometry such as body dimensions, reach, position of the body and/or its parts, posture; *biomechanical*, representations of physical activities of the body in motion, using anthropometric data as inputs; and *interface*, specific combinations of anthropometric and biomechanical models for representations of human-machine interactions. These models can all contribute to the system design process. Their integration into a comprehensive ergonomic model of the human operator could provide a valuable tool for researchers, designers, and program planners.

Consequently, the Committee on Human Factors convened a two-day workshop on June 17 and 18, 1985, in Washington, D.C., to assess the feasibility of developing an integrated ergonomic model and, if deemed feasible, to determine how to approach its development. The specific objectives of the workshop were to (1) assess the usefulness of current anthropometric, biomechanical, and interface models; (2) identify critical points of compatibility and disparity among these models; (3) review the feasibility of using these existing models in the development of an integrated ergonomic model; and (4) if feasible, recommend a research approach to the development of an integrated ergonomic model, including studies needed for each of the three major classes of models to provide a basis for an integrated ergonomic model.

Fifteen experts in anthropometry, biomechanics, bioengineering, work physiology, human factors engineering, psychomotor performance, computer modeling, and system design and operation participated in the workshop. Background papers were provided in advance for each of the three modeling domains: anthropometric, biomechanical, and interface. In addition, the participants prepared brief position papers for distribution prior to the workshop. These background and position papers, workshop deliberations, and follow-up materials constitute the basic elements of this project report.

The audience for this report consists primarily of those professionals concerned with ergonomic modeling and system design, both within and outside the human factors community, including those involved in research, training, engineering, system development and acquisition, operations, programming, and maintenance.

We thank the workshop members for their prodigious efforts. We also express our gratitude to a number of persons who contributed extensive additional information following the workshop: Albert I. King and William S. Marras for their research and compilation of the section on biomechanical models, an outstanding table of biomechanical models, and their contributions to development of research needs for biomechanical models; John T. McConville, for his preparation of the section on anthropometric models and for formulating research needs for anthropometric models; Alvah C. Bittner, Jr., who provided much of the information on the BOEMAN, CAPE, and CAR model sections; Joe W. McDaniel, for providing information for the sections on COMBIMAN and CREW CHIEF; and to James L. Lewis, Jeri W. Brown, and Barbara J. Woolford, who provided the discussion of the PLAID-TEMPUS model.

A note of special appreciation is extended to Stanley Deutsch, the former committee study director, who worked with us to plan and organize the workshop, participated in the meeting, and contributed to the editing of this report; Susan K. Meadows, a major editor of this report who augmented, coordinated, and integrated the workshop proceedings into a report format; Michael K. Hayes, freelance editor, who improved the clarity and style of the final report; and Margaret A. Cheng, the committee's former administrative secretary, who provided secretarial and administrative support.

Karl H.E. Kroemer and Stover H. Snook, Cochairs
Workshop on Integrated Ergonomic Models

1

Introduction

The efficient and safe operation of civilian and military systems requires that tasks, equipment, and the work environment be compatible with the users' capabilities. Too often equipment is designed as if it stood alone, and the task is conceived as if it were independent of human characteristics. There are situations in which equipment and system failure are believed to be caused by human error, despite the fact that the equipment or system was developed with little consideration of the capabilities and limitations of the people who operate and maintain it in a field environment. Due to exigencies of time, limited budgets, information gaps, or just lack of consideration, these characteristics of the user are frequently ignored by the designer, engineer, and fabricator of the equipment. Even when people are considered, too often that consideration is incomplete or inaccurate owing to a lack of knowledge or thoroughness. Yet, in many instances, people may be the limiting factor in the effective use of this equipment.

Since the interactions among the person, the equipment, the task, and the environment are complex, many researchers and engineers are concerned with the need for ergonomic models that describe the physical characteristics of people and their interactions with the task and equipment in the work environment. Such models should be representations of real systems designed to describe and predict their essential characteristics and performance. In addition, if feasible, the development of a standard integrated

ergonomic model would provide a means for extrapolating data across a variety of users and increase the data base.

As noted in the following chapters, there have been numerous efforts to develop descriptive physical models of the human body (see especially Table 3-1, Biomechanical Models). In most instances, the development of anthropometric and biodynamic models has not extended beyond the requirements to meet the specific application needs of the moment. Such specialized models may serve their specific purposes well but usually give little help in predicting or solving general human-technology interaction problems outside their specific boundaries. In addition, many of the existing models cannot be joined to form a more general model or be extended into an integrated ergonomic model.

In the past, construction of models that describe people in "the real world" has been limited, due in large part to our inability to capture the versatility and mobility of the human body. In order to develop a universal ergonomic model, comprehensive and accurate representations are required for such factors as physical size, visual field perception, reach capabilities, loadings on muscles and bones, and their responses and strength capabilities.

Precise examination of anthropometric and biodynamic data is facilitated by modern data management techniques such as computer graphics and relational data bases for studying physical interactions. The trend toward the use of common disciplinary (and interdisciplinary) structures, applications software, and data base formats by many researchers helps to provide a larger library of related information. The automation of static and dynamic measurement systems for data acquisition for body mapping, reach, kinematics of motion, and their interactions with independent variables such as work environments provides a wealth of detailed and accurate information. An *integrated ergonomic model* could encompass all three of the more primitive models, i.e., providing anthropometric, biomechanical, and interface information for various populations, under various conditions, for various tasks, in their interactions with various technical components. To have the greatest utility, the integrated ergonomic model should be capable of generalization and contain adequate refinement of detail to be applicable to other design, research, or analytic situations. At the same time, in order to be used it must be user-friendly and time- and cost-effective. Since anthropometric, biomechanical, and interface models provide the basis for the development of

an integrated ergonomic model, any limitations and shortcomings of the former impose restrictions on the usefulness of the latter.

The study group identified current anthropometric, biomechanical, and interface models; determined that they were useful; and provided examples of their applications. Shortcomings of these models were described, and the additional research needed to increase their value was explored for each of these three classes of models. Among the shortcomings are the disparity and incompatibility among the methods used by investigators to collect the data, frequently resulting from the use of samples that are too small to provide reliable data, and the variety of methods used for measurement and data collection.

The workshop members determined that it was feasible to incorporate various models from these three classes into a general integrated ergonomic model or smaller modules and recommended a program of research for their development. The study group further recommended approaches to the collection of additional data using a standardized format and nomenclature and their incorporation into the overall model or modules.

The following chapters describe the current status of development of anthropometric, biomechanical, and interface models, giving limitations and listing research needs specific to each. Approaches to the development of integrated ergonomic models are discussed, and research recommendations are provided for further development of lower-level models.

2

Anthropometric Models

Human body models come in many forms, including two-dimensional drafting board templates, sizing manikins, three-dimensional physical dummies for biodynamic tests, and computer analogs. The discussion of anthropometric models will center largely on computer analogs. Most computer models were developed with a particular purpose in mind—such as biodynamic testing, strength assessment, or human factors evaluations. Whatever their differences, models share a basic need for accurate representation of body size, shape, and proportion in all of their exasperating permutations. Much of this challenge falls in the domain of physical anthropology and engineering anthropometry.

THE ANTHROPOMETRIC DATA BASE

In the United States, formation of an anthropometric data bank was initiated in 1973 by C.E. Clauser of the Harry G. Armstrong Aerospace Medical Research Laboratory (AAMRL). The data bank was meant not only as a repository for information from a variety of sources but also as a facility in which such data would be processed and cast in a comparable format to permit recall and analysis for design purposes using computer routines. Over the years, the data bank has expanded steadily; today it constitutes a unique anthropometric source for designers, engineers, and modelers.

The 1985 holdings of the AAMRL's anthropometric data bank

included 51 separate surveys. Most of the data are based on military rather than civilian populations and on male rather than on both male and female groups. These disproportionalities in coverage are not by design but are due to the limitations of available data. Table 2-1 provides a listing of the current holdings of the data bank for U.S. and foreign military populations. The surveys range in time from 1946 to 1981, with the majority being conducted in the 1960s. In any one survey, as few as 46 body size variables were measured with the largest number of variables (189) being measured in the U.S. Air Force's 1967 survey. In all, more than 300 measured variables, from one or more surveys, are included in the current data bank. A major survey to update the anthropometric data base for the U.S. Army was begun in 1987 and is scheduled for completion in 1988. Data on foreign military populations in general include fewer subjects and variables. For an overview, check the NASA Anthropometric Source Book (National Aeronautics and Space Administration, 1978).

The anthropometric data base for the U.S. civilian population as a whole is rather weak. No comprehensive anthropometric study of the civilian population has ever been undertaken. Our knowledge of U.S. civilian body size variability (see Table 2-2) comes primarily from the various health and nutrition surveys, beginning with the first 1962 Health Examination Survey (HES) (Stoudt et al., 1965).

In these surveys, investigators were concerned with health and nutritional assessment and obtained only limited anthropometric data (primarily on mass-related dimensions, such as girths and skinfolds). In the 1962 HES survey, 12 workspace and 7 nutrition-related dimensions were measured on a nationwide sample ($n = 6,672$) of civilians aged 18-79 years. These data, limited as they are in the description of body size variability and the fact that they are 25 years old, are still the best available for the U.S. civilian population. The sample was sufficiently large, however, to provide adequate descriptors for sex, age, and some racial groups.

Since the utility of military data for civilian populations has often been challenged, McConville et al. (1981) attempted to match military samples with the HES civilian samples on the basis of height and weight. For the males, results were good in that almost 98 percent of the civilians from the HES study were matched with U.S. Army subjects from a single survey. By comparing seven dimensions that were similarly measured in the U.S. Army and

TABLE 2-1

Military Data Contained in the
AAMRL Anthropometric Data Bank

Survey Date	Population	Sample Size	Variables (No.)
<u>U.S. Military Males</u>			
1950	U.S. Air Force pilots	4,000	146
1950	U.S. Army aviators	500	46
1964	U.S. Navy aviators	1,529	98
1965	U.S. Air Force ground personnel	3,869	161
1966	U.S. Army ground personnel	6,682	73
1966	U.S. Navy enlisted	4,095	73
1966	U.S. Marines enlisted	2,008	73
1967	U.S. Air Force fliers	2,420	189
1970	U.S. Army fliers	1,482	88
Total		26,585	
<u>U.S. Military Females</u>			
1946	U.S. Women's Army Corps	7,563	65
1968	U.S. Air Force women	1,905	139
1977	U.S. Army women	1,331	151
Total		10,799	
U.S. military total		37,384	
<u>Foreign Military Populations (Male)</u>			
1960	Turkish armed forces	912	151
1961	Greek armed forces	1,071	151
1961	Italian armed forces	1,342	151
1961	Korean military fliers	264	132
1964	Vietnamese military forces	2,129	51
1967	German air force	1,466	152
1969	Iranian military	9,414	74
1970	Latin-American armed forces	1,985	76
1970	Royal Air Force aircrew	2,000	64
1972	Royal Air Force head study	500	46
1972	Royal Australian Air Force	482	18
1973	French military fliers	174	118
1974	Royal New Zealand Air Force aircrew	238	63
1974	Canadian military forces	565	33
1977	Australian personnel	2,945	32
1975	British Army survey	1,537	61
1975	English Guardsmen	100	61
1976	English Transport Corpsmen	161	61
1976	United Kingdom Gurkhas	36	61
1976	Hong Kong Chinese military	73	47
1981	Israeli aircrewmen	360	63
Foreign military total		27,754	
U.S. and foreign military total		65,138	

SOURCE: Harry G. Armstrong Aerospace Medical Research Laboratory anthropometric data bank (1985).

TABLE 2-2
U.S. Civilian Population Data Contained
in the AAMPL Anthropometric Data Bank

Survey Date		Sample Size	Variables (No.)
<u>Adult Males</u>			
1961	Air traffic controllers	678	65
1962	Health Examination Survey (HES)	3,091	18
1962-1981	Matched Health Examination Survey (HES) (ages 18-65)	2,761	70
1974	Law enforcement officers	2,989	23
1975	Health and Nutrition Examination Survey (HANES) (ages 18-74)	6,563	11
1980	Health and Nutrition Examination Survey (HANES II) (ages 18-75)	5,921	13
1981	U.S. miners	<u>270</u>	44
U.S. civilian males total		22,273	
<u>Adult Females</u>			
1962	Health Examination Survey (HES)	3,581	18
1971	Airline stewardesses	423	73
1975	Health and Nutrition Examination Survey (HANES) (ages 18-74)	10,123	11
1980	Health and Nutrition Examination Survey (HANES II) (ages 18-75)	6,598	13
1981	U.S. miners	<u>86</u>	4
U.S. civilian females total		20,811	
U.S. civilian total		43,084	

SOURCE: Harry G. Armstrong Aerospace Medical Research Laboratory anthropometric data bank (1961-1981).

civilian survey, the authors demonstrated that the matching process provided representative anthropometry for the civilian male sample that was adequate for some design purposes.

Matching proved to be less successful for women. The civilian women were heavier at every increment of stature, on average, than the military women. The matched military sample did not adequately characterize the distribution in the total female civilian population. For those that were successfully matched, however,

the correspondence between other body dimensions for civilian and military women was quite good.

Within limitations, the matching procedure has proven to be a useful technique for estimating the body size variability of a population for whom only limited anthropometric data are available. The procedure is limited, however, to the range of body sizes within the base population from which the matches are drawn.

By and large, all these data have been collected by using traditional anthropometric tools and techniques. What is available, then, is a series of univariate descriptors of body size in terms of heights, lengths, breadths, depths, girths, and surface curvatures (Figure 2-1). The military surveys in particular were designed to satisfy a variety of users, predominantly pattern makers and designers of personal protective equipment. Body dimensions for the layout of workspaces have also received attention, but only a few dimensions have been obtained strictly for human body models. The need for personal protective equipment for the head and face has required a large number of dimensions including surface arcs, breadths, and a series of headboard measurements (Figure 2-2) to relate a series of points in three-dimensional space to a common origin. Using these points and assuming bilateral symmetry, it becomes possible to develop face forms of sizing models for designers based on anthropometric data and the artistic ingenuity of a sculptor. Such forms are then reproduced and provided to designers who are involved in a specific design problem. This has turned out to be an extremely successful mask which is used in newer aircraft in which 6-g forces are common and 9-g forces are not unknown.

The need for anthropometric data translated into a three-dimensional form has extended into other areas as well. The requirements for body forms of 3- and 6-year-old children for crash injury research necessitated the interpretation and integration of data from some six different sources, no one of which could be considered as the principal source. The resultant integrated data were rendered into three-dimensional body forms (Young et al., 1983).

Even when a strong, traditional anthropometric data base exists, it may not be as comprehensive as necessary to develop human body models. The need for sizing of partial pressure suits for U.S. Air Force aircrews led to the translation of the height-weight sizing system into three-dimensional models. The body for

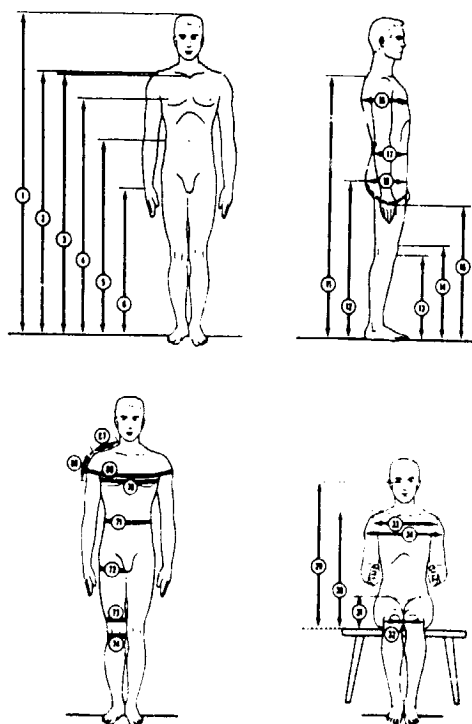


FIGURE 2-1 Typical univariate descriptors of body size. SOURCE: Files of Anthropology Research Project, Inc., Yellow Springs, Ohio.

each size was characterized as a sequence of body girths at specific levels, each girth having a breadth and a depth, with appropriate segment lengths. The development began with an armature to which mesh was affixed to bring the form roughly up to size. Plaster of Paris was applied to bring the forms to final size and shape (McConville et al., 1963). Such body forms were designed specifically for sizing of a particular item of personal protective clothing. Each incorporated a specific statistical breakout of the data. Hence, their use is generally limited. (One exception is the "long regular" body form that was used to provide the body size and shape for the biodynamic analog developed by Payne and Band [1971], called DYNAMIC DAN.)

In all of these sizing models, it was necessary to integrate traditional data from a series of independent studies to produce a usable body model. But the end product was most often a result

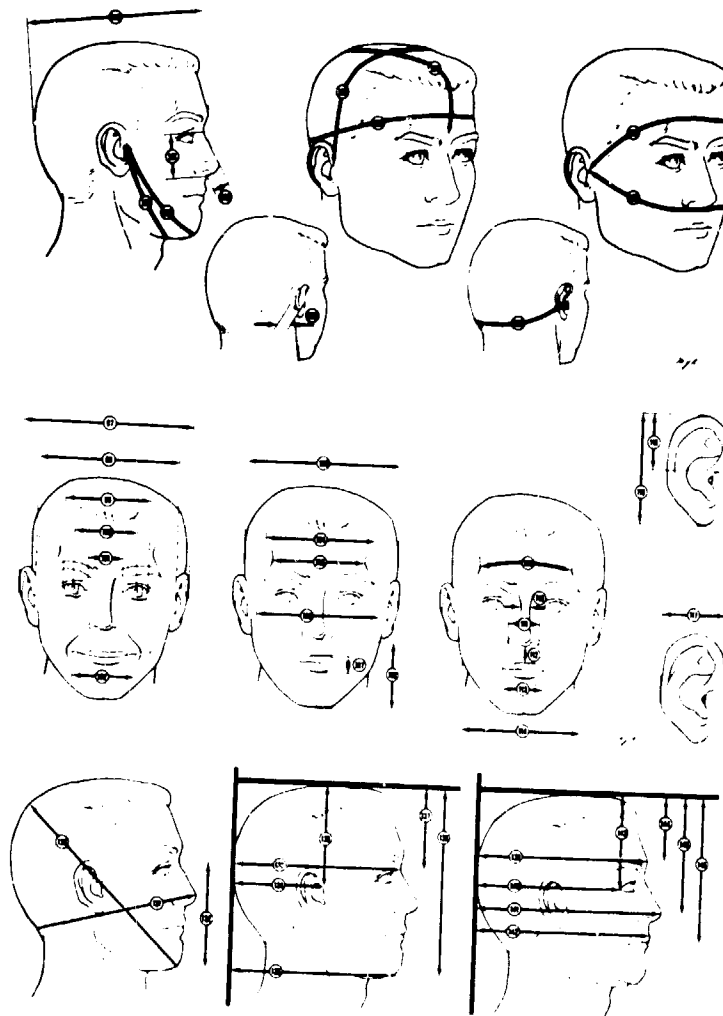


FIGURE 2-2 Head and face measurements. SOURCE: Files of Anthropology Research Project, Inc., Yellow Springs, Ohio.

of the sculptor's skill in providing the final shape by filling in those areas for which no anthropometric data were available.

ANTHROPOMETRIC COMPUTER MODELS

The anthropometric data input to the human engineering evaluation models is far more extensive than the simple lengths, diameters, and circumferences used to specify the size of the geometric forms of the early models. Most of the human engineering evaluation models are based on the simulation concepts of interconnected links, originally outlined by Braune and Fischer (1889) in their classic biomechanical analysis of the German infantryman. This approach was refined and expanded by Dempster (1955), who studied the body as a series of interconnected links that he defined as "straight-line distances between adjacent centers of rotation."

Early geometric modeling (Von Meyer, 1873) reduced the body to a series of ellipsoids and spheres to arrive at estimated mass and centers of gravity of body segments. In 1960, Simons and Gardner developed a man-model by approximating the body segments as uniform geometric shapes. They represented the appendages, neck, and torso by cylinders and the head by a sphere. Using Barter's (1957) equations for the mass of the individual segments, they computed the inertial parameters for the geometric forms and calculated the total-body moments of inertia. This work, elementary in many respects, was the genesis of much of the present biodynamic modeling activity.

In a study of the dynamic response of weightless man, Whitsett (1962) refined the anthropometric model developed by Simons and Gardner (1960) by increasing the number of body segments from 8 to 14 by using additional geometric shapes to approximate more closely the shapes of the various body segments (Figure 2-3). Whitsett's 14 segments include a head, a torso, two upper arms, two lower arms, two hands, two upper legs, two lower legs, and two feet. The head is modeled as an ellipsoid, the hands are spheres, the upper and lower arms and legs are frustums of circular cones, and the feet are rectangular parallelepipeds.

The physical properties incorporated by Whitsett into the model included body size data from Hertzberg et al. (1954), mass properties from the regression equations of Barter (1957), and center-of-mass and segment-density data from Dempster (1955). The equations for the mass moments of inertia were standard for

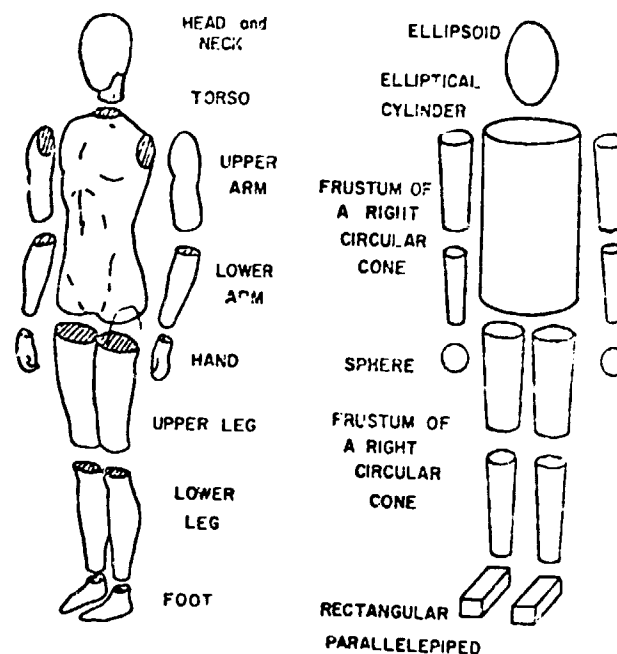


FIGURE 2-3 Segmented human and model. SOURCE: Whitsett (1962).

the particular geometric forms used; only the mass moment of inertia equation for the frustum of a right circular cone needed to be derived. In 1963, Gray refined this basic model.

In 1964, Hanavan published the results of a study intended to (1) design a personalized mathematical man model, (2) analyze the model, (3) prepare a generalized computer routine for calculating the inertial properties of any subject in any body position, and (4) develop a design handbook for a series of percentile body forms in 31 body positions. The model was made up of 15 simple geometric forms hinged at the end of each of the primary segments. While the torso was considered as two linked segments and the head as a third linked segment, they lacked motion. Hanavan, in a manner similar to that used by Gray, defined the body posture by assigning Euler angles to each of the segments and then calculated the inertial dyadic tensor and the center-of-mass locations for a specific body in specific positions. Hanavan used the mass-predictive equations described by Barter (1957) as input. This

technique was then applied by Tieber and Lindemuth (1965) and Robbins et al. (1971) and is still in use. However, with better mass distribution data (McConville et al., 1980, and Young et al., 1983) and the availability of powerful large-scale computers, this approach has become increasingly outmoded.

Most current human body models, such as those incorporated in BOEMAN (Ryan, 1971), SAMMIE (Bonney and Case, 1976), and COMBIMAN (Kroemer, 1973; McDaniel, 1976), begin with a link system, which is simplified from the human skeleton. Modelers assign ranges of joint motion to the primary joints and finish with an enfleshment procedure to give the model its final physical form. Depending on the intended use of the model, additional refinements such as mass distribution properties (Articulated Total Body Model; Kaleps, 1978) or visibility plots (COMBIMAN; Kikta et al., 1982) are added. In every case, an adequate anthropometric data base is required for the construction of these models.

THREE-DIMENSIONAL ANTHROPOMETRY

The existing anthropometric data base does not contain three-dimensional anthropometric data. It has been possible to use the existing univariate anthropometric descriptors to develop three-dimensional models, but such approaches have been compromises at best that are dependent on a series of approximations and assumptions regarding the relationship of individual dimensions. The traditional anthropometric data base lacks a common origin point to which the individual measurements can be related.

In a recent series of studies, stereophotometric techniques were used to obtain mass distribution estimates for a sample of 31 male (McConville et al., 1980) and 46 female (Young et al., 1983) subjects and to relate these mass distribution properties to the anthropometry of the individuals. This procedure, similar to aerial photography, requires paired cameras in front and back of the subject (Figure 2-4) to obtain the stereoplates (McConville et al., 1980). The plates are read, resulting in a "terrain map" of the body (Figure 2-5) from which contours, volumes, and mass distribution estimates can be obtained.

The 31 male subjects were measured for some 75 body dimensions, and the 46 female subjects were measured for a comparable

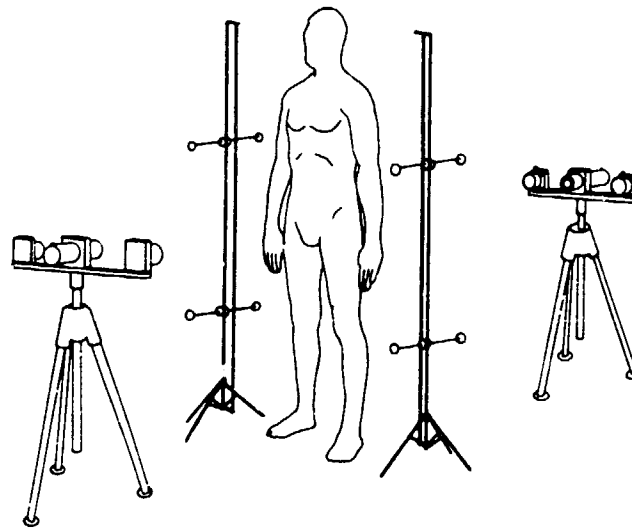


FIGURE 2-4 Stereo camera array. SOURCE: McConville et al. (1980).

but expanded set of 92 body dimensions. After the anthropometry was obtained, some 77 targets were affixed to the body landmarks to facilitate their location during the stereophotometric assessment. Volume, center of volume, and principal volumetric moments and axes of inertia were calculated.

The primary body segments used in these studies were defined by using planes of segmentation similar to those used in previous cadaver studies (Chandler et al., 1975; Clauser et al., 1969). The use of stereophotogrammetry made possible the comparable analytic segmentation of live subjects and facilitated the delineation of additional segments, such as the thorax, abdomen, and pelvis.

An anatomical axis system was established for the total body and for each segment. These were right-hand orthogonal systems based on palpable, largely bony landmarks and were used to provide a consistent reference for the principal axes of inertia for each segment regardless of body and segment position. The axis systems were defined using a minimum of three noncolinear points on each segment located as far apart as was feasible. The anatomical axis system shown in Figure 2-6 for the head segment was established using the right and left trignon landmarks and the right

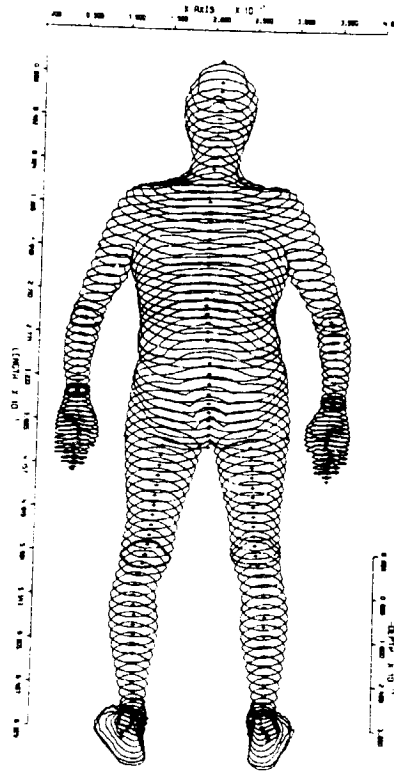


FIGURE 2-5 "Terrain map" of the human body. SOURCE: McConville et al. (1980).

infraorbital landmark. A fourth landmark, sellion, was used to translate the origin of the axis system to the midsagittal plane.

Anthropometric techniques developed for the mass distribution studies may have considerable merit for developing an anthropometric data base for human body models. The anatomical axis system for each segment and for the total body help to define postural orientation in three-dimensional space. Segmental landmarks are related to the segmental axes and to the total body axes, with body mass distribution characteristics predicted through regression equations based on the anthropometry of the model.

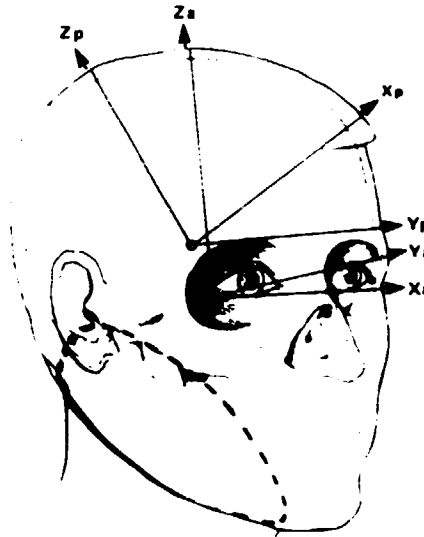


FIGURE 2-6 Anatomical axis system for the head segment. SOURCE: McConville et al. (1980).

DISCUSSION

While there exists a wealth of anthropometric data for a number of populations, and there are methods of extrapolating the data base to other populations, the current data base is deficient for effective human engineering body modeling. Current link systems are largely based on studies by Trotter and Gleser (1958), Dempster (1955), and Snyder et al. (1972). When data bases from several sources are combined with different study samples, interpolations and approximations are required to integrate the data into a functional link system. The traditional anthropometric data base is not as helpful in developing a link system as we would like. Anthropometric landmarks lie on the surface of the body and are often removed from the actual joint centers of rotation by various layers of tissue. Thus, the link length that is sought can only be approximated. In addition, joint centers that define the link lengths are often difficult to locate accurately on living subjects and are even more difficult to locate from photographs. A systematic investigation of a human body link system that incorporates

three-dimensional anthropometry developed specifically for computer simulation is required.

The current anthropometric data base is a collection of univariate body size descriptors that lack a unifying origin to which they may be related in a three-dimensional space. It is desirable to develop a procedure that can supplement and integrate the existing data base to provide the anthropometry necessary for effective three-dimensional models. Reynolds (1977) has coined the term *system anthropometry*, wherein the traditional heights, lengths, and breadths are replaced by three-dimensional coordinates for comparable point locations from a common origin, and the static anthropometric postures of standing and sitting are replaced with postures relating to work and movement.

Before the envisioned system anthropometry can be developed and an effective anthropometric data base created, two basic interrelated problems must be resolved. The first is the selection of an effective data collection system which should be accurate (within required limits) and reproducible, be sparing of subject and observer time, produce immediate digital output, permit rapid transfer to storage for analysis, and be relatively inexpensive.

A wide variety of techniques that can describe points and point relationships in three-dimensional space have been developed over the years. These range from rather simple electromechanical digitizers through stereophotogrammetry to complex systems such as laser imaging. So far none of the existing systems have proven wholly satisfactory.

The second problem is that even if a suitable system were at hand, we would need to develop a method of analysis of the three-dimensional data that the system would generate. In the analysis of traditional anthropometry, we have the solid statistical model of the normal distribution. No comparable analytical model has yet been suggested for summarizing three-dimensional size and shape data for our application.

Even with a complete and realistic anthropometric data base, various "real-life" work factors (e.g., posture, body restraints, clothing) can drastically change the accuracy and validity of the standard data base for many applications, since actual anthropometric characteristics may be quite different from those measured under standardized (laboratory) conditions. Garrett and Kennedy (1971), Roebuck et al. (1975), and Van Cott et al. (1978) compared measuring techniques and anthropometric data from 48 sources

and noted a lack of standardization in definitions and procedures across different studies. Data comparability was also noted as a potential problem in standardization when different instrumentation was used. No systematic study has been attempted to determine whether a number of measurements taken on a large number of participants by different measurement techniques and by different measurers yield equivalent data. The problem is probably most pronounced for measures involving compression of soft body tissue and those requiring a reference to internal skeletal landmarks.

Other limitations of the current anthropometric data base, and hence of models, are the following:

- Data on U.S. civilians are seriously deficient, particularly for females.
- Health Examination Survey (HES) and Health and Nutrition Examination Survey (HANES) data show that the population is taller and heavier than estimated from military data.
- There is insufficient information on special populations that collectively consist of a large portion of the total population, including those over age 65 (about 12 percent of population), those under age 18 (about 26 percent of the population), population extremes (i.e., the tallest, heaviest, shortest, lightest), and disabled persons.
- Most anthropometric data are univariate, which limits their application.
- Neither two- nor three-dimensional data are commonly referenced to a defined reference system.
- There is no standard procedure other than "artistic sculpturing" for arriving at three-dimensional body shape based on the classical anthropometric data.
- Various measurement definitions, measurement techniques, and data processing methods have been used in the different classical anthropometric surveys that constitute the available data base. Therefore, in many cases data are neither interchangeable nor compatible. Furthermore, they cannot be relied on to have the same degree of accuracy.
- Advanced procedures for data collection such as stereophotogrammetry or laser imaging are needed, but they are still in the experimental stages.

3

Biomechanical Models

Interest in the biomechanical properties of the human body has evolved along with mathematical sophistication. The early works of Leonardo da Vinci (O'Malley and Saunders, 1952), Galileo Galilei (1638), and Giovanni Alfonso Borelli (circa 1679) demonstrate man's curiosity and desire to describe the human in quantitative terms. Even though hundreds of years have passed since these early attempts, biomechanical modeling of the human musculoskeletal system remains one of the most challenging tasks known to man.

This chapter evaluates biomechanical modeling knowledge and its significance to ergonomics. Prior to such a review, however, the concept of modeling as used here should be discussed first. A model can be defined as any set of equations that describe physical events or phenomena. Sinclair and Drury (1980) described a model as a paradigm view of science. They proposed two definitions of models. First, they defined a model as "the result of using theoretical understanding to present a particular aspect of the real world." This definition represents a *normative* model, which describes the idealized behavior of the system. Second, they defined another type of descriptive model that used "statistical techniques to relate theoretical variables present in a collection of data." This type of model typically employs regression analysis to describe the dynamic behavior of the human body.

In the context of this review of biomechanical models, only

models according to Sinclair and Drury's first definition will be considered.

Consideration must be given to the objective of a biomechanical model used for ergonomic purposes. A biomechanical model should facilitate the basic understanding of the system. Morris (1967) noted that modeling should be a process of enrichment and enhancement. He pointed out that one should begin with a model that is distinct from reality and, in an evolutionary manner, move toward a more elaborate model that reflects the complexity of the actual situation. Little (1970) stated that the objective of the model should be to provide intuition. It is apparent that these two objectives are complementary. Through a process of understanding the components of a system, the model is expanded and a greater understanding of component interaction is gained.

To achieve these objectives, a model should display several qualities. The model should be robust. It should display the essence of the system under a variety of circumstances. A biomechanical model should also represent reality and have clinical relevance or workplace applications.

The significance of these objectives and requirements applied to ergonomics means that biomechanical models should provide insight into the interaction of people and their environment. Ideally, an ergonomic model should predict both long- and short-term results of human work, and the effects on people, particularly if a risk exists for both traumatic and cumulative injuries.

The discussion on biomechanical models is limited to those models that may be useful to ergonomists. Hence, impact, physiological, and psychophysical models are not included in this review, nor are all existing models of the musculoskeletal system. Instead, examples are presented that concern bones, joints, body segments, and the whole body.

HISTORY OF BIOMECHANICAL MODELS

As noted in Chapter 2, Anthropometric Models, the early models of the 1960s assumed that the body is a series of rigid links. These models were limited in the number of links, usually one, two, or three. Most of the models were two-dimensional, based on kinematic information, with some dynamic data. The objective was to look at the forces, torques, and moments around

the various articulations and then to track the links to determine what type of loading or motion occurs.

Some of the models were then extended, but none predicted any of the internal loadings on the body. Most of the early models worked in some way with the external loadings, based primarily on kinematic types of information and characteristics of torque and force generated by the link motions. Some models, like that of Sloté-Stone (1963), were used in predicting power and some, like that of Ayoub et al. (1974), were used in predicting position during work. These models provided the basic context of understanding in the programs.

Many of the later models are based on the work of Chaffin (1969), who joined seven or eight different links of the body. Extending the previous principles, he calculated torques and forces around the joint, and then tracked the whole body in a kinetic chain. Most of the later models are two-dimensional static models that represent, to a limited extent, forces and moments acting at each particular articulation to generate internal loading information. More recent versions of this model are built on the same basic logic but use dynamic data and three dimensions.

Ayoub and El-Bassoussi (1976) used optimization to predict a lifting model, and in the early 1980s, Schultz and Andersson (1981) and Schultz et al. (1982) developed a different type of model that no longer considered the body as a set of rigid links. This was a three-dimensional model that represented active analysis of the stresses imposed on the body under working conditions. This two-part analysis can be used to analyze the net reaction which must be resisted by the internal forces of the body. Several methods have been used for this type of analysis. One is to assume that the antagonist muscles are silent (which may or may not be a correct assumption, depending on the circumstances), and another is to use optimization, particularly linear programming with upper and lower bounds.

Another class of new models is that described by Hatze (1976, 1977). This is a complex model that accurately predicts forces in the leg when a person takes a step with a weight tied onto the leg. It represents advanced techniques that may be useful for future ergonomic modeling.

REVIEW OF BIOMECHANICAL MODELS

One of the more basic evaluations that occur in biomechanical modeling is the analysis of moments and forces that act on a body segment in a work environment. Chaffin (1982) performed an analysis of such forces for single- and two-body segments under static planar conditions. In these cases Newtonian mechanics were applied to the segments and the system was evaluated in a state of static equilibrium. When multiple body segments were involved, each body segment was evaluated as a separate link in a kinetic chain system. A two-link model of the arm was developed by Pearson et al. (1961, 1963). It computed the forces and torques present at the elbow and shoulder caused by the motion of arm, forearm, and hand in the sagittal plane. This analysis required data obtained from stroboscopic photography to calculate the instantaneous position, velocity, and acceleration of the arm, forearm, and hand system. Together with the known values of mass and length of the body segments, these data were used to compute the forces and torque present caused by the motion. Extensions of this model were developed by Plagenhoef (1966), who modeled whole-body motion based on kinematics.

Predictive equations for hand motion in workspace design have been developed by Kattan and Nadler (1969), and Slote and Stone (1963) modeled acceleration patterns of the upper extremity. Ayoub et al. (1974) also developed a two-segment, three-dimensional motion model of the upper extremity. This model was unique, however, in that it used optimization (dynamic programming) for a solution to perform a movement. It predicted hand position in space during certain movements. However, Ayoub and coworkers (1974) stressed the need for more detailed evaluation of model assumptions. This work demonstrated the feasibility of using optimization techniques to model the external loading factors of a biomechanical system.

Several biomechanical models that evaluate stress caused by external loads during lifting have been presented in the literature. Models by Chaffin (1967) and Chaffin and Baker (1970) are static, sagittal plane extensions of the major body segments and were expanded to predict the compressive forces sustained by the lumbar spine. They demonstrated how predicted moments generated about the body articulations could be compared with human strength characteristics, and suggested that this method be used

to evaluate the physical strength capability and requirements of manual materials-handling activities. This model assumed that lifting occurs slowly and smoothly, so that the effects of acceleration are negligible. This approach has been adopted by the National Institute for Occupational Safety and Health (NIOSH, 1981) for evaluation of the workplace.

A three-dimensional static strength evaluation analysis was described by Garg and Chaffin (1975). Chaffin and Andersson (1984) also discussed how multiple-link static models could be used to evaluate reactive moments of the body in both coplanar and nonplanar analyses, how modeling techniques assess the moments experienced by joints during motion, single- and multiple-segment dynamic modeling techniques, and how biodynamic analysis techniques could be used to assess pushing tasks. Amis et al. (1980) developed a method to estimate moments about the elbow during maximum flexion. These techniques employed high-speed photographic techniques to predict angular velocities and acceleration. Inertial forces and resistance moments that must be produced by the muscles could then be calculated. Freivalds et al. (1984) used this technique to study dynamic lifting.

The models that have been described take into account the stresses and loads caused by an external load or motion imposed on the body. Some of these models also evaluate internal forces. These assumed that the body is composed of several rigid links which are joined by articulations. The analyses usually consist of evaluations of the motions and loads imposed on these structures via traditional Newtonian mechanics. Recently, some optimization techniques have been used and represent a promising area of endeavor. Chaffin (1969) developed a seven-link, two-dimensional static model to calculate joint forces and moments during material-handling activities. The model also computed the spinal compression force during lifting. This model was later expanded to include three-dimensional static strength prediction (Chaffin et al., 1977; Garg and Chaffin, 1975). Freivalds et al. (1984) also expanded this model to evaluate the sagittal plane kinematic activity. All of these models consider the effects of both external and internal loading when considering the compressive forces on the spine.

El-Bassoussi (1974) and Ayoub and El-Bassoussi (1976) developed a model which predicts stresses on the musculoskeletal system by infrequent tasks in the sagittal plane. The model used predicted movement dynamics based on the findings of Slote and

Stone (1963). This model is dynamic and considers subject movement and the forces that are generated because of these movements. Ayoub et al. (1980) compared the virtues of these lifting models. They pointed out that the limitation of most lifting models for ergonomic purposes is that they only estimate stresses within the body when work is performed in the sagittal plane and few of them consider motion. Gruver et al. (1979) developed a five-link, two-dimensional model of the human body to simulate manual lifting tasks.

These models just described are limited by the fact that most are two-dimensional planar models. These models help us to understand the loading of the body in sagittally symmetric exertions. Many of the more challenging ergonomic concerns, however, involve loading of the body in three dimensions. For many tasks the body is loaded in a torsional fashion. Assessment techniques are required to evaluate these situations.

Another limitation of existing models concerns the ability to assess the consequences of motion. Many of the analysis techniques are static and do not consider the effects of velocity or acceleration of the body part or load when assessing the biomechanical cost to the system. Some models have been reported in the literature that consider motion; however, the motion assessment is usually limited to the sagittal plane, and often, the effects of load weight are not considered.

Basic research is required which addresses the question of whether a kinetic link system portrayal of the biomechanical system is appropriate. Some assumptions regarding the shape and length of link elements are necessary for simplification purposes. Freivalds et al. (1984) pointed out that the spine could be better represented by some semiflexible arrangement. Thus, a rigid beam link analogy may not be the best method of modeling the human system. This is also evident from the previous discussion regarding bone modeling.

The models described in this section describe techniques for assessing the reactive moments and forces at each articulation that must be exerted by the muscles. These reactive moments and forces are necessary to overcome the forces imposed on the biomechanical system by external loads and body weights. These models have been used successfully to match worker capabilities to the demand of the task. They provide insight into worker selection rationale.

Ergonomic models should be capable of assessing the traumatic effects as well as the cumulative effects of the work. To achieve this objective, ergonomic models should be able to evaluate the loading of the articulation and skeletal structures caused by the external and internal loadings. Internal loading refers to the forces supplied by the muscles and ligaments that react to the external loads; thus, both external and internal forces load the body. The significance of internal forces to the loading of the body has been discussed by Cailliet (1968) and Tichauer (1978). Knowledge of the effects of internal and external forces is necessary to predict the instantaneous loading of the body articulations and skeletal structures. Models that include internal forces are usually much more difficult to use since there are often more unknown muscle forces than there are independent equations available to solve the problem. Thus, a unique solution is not possible, and the problem becomes statically indeterminate.

Models of Bones

Work on the biomechanics of bone and load-bearing capability of bone dates back over three centuries to Galileo Galilei (1638) and has progressed to modern stress analysis techniques (Burstein et al., 1970; Minns et al., 1977; Piotrowski and Wilcox, 1971; Toridis, 1969). Others (Brown et al., 1980; Hayes et al., 1978; Huiskes et al., 1981; Olofsson, 1976; Piziali et al., 1976; Rohlmann et al., 1982; Rybicki et al., 1972; Scholten et al., 1978; Valliappan et al., 1977, 1980) used finite-element models of the femur which assume that bone is an isotropic and homogeneous material, even though it is nonhomogeneous and is described as being transversely isotropic. The femoral model described by Valliappan et al. (1977, 1980) used a finite-element analysis to compare the stress distribution in the femur for both a prosthesis model and a normal femur. The stresses were computed both with and without the anisotropic assumption of transverse isotropy, and two loading conditions were used, walking and one-legged stance. The stress distribution was found to change significantly when the anisotropic assumption was used for cortical bone; however, no validation of results was mentioned. Others (Goel et al., 1978; Hayes et al., 1982; Oonishi et al., 1983; Snyder et al., 1983; Williams and Lewis, 1982) developed finite-element models for other bones, such as the pelvis, patella, and trabecular bone. A summary of

the merits of many of the finite-element models used in orthopedic biomechanics was prepared by Huiskes and Chao (1983) and elaborates on the details of the models. It does not include a discussion of a finite-element model of a lumbar vertebra.

Hakim and King (1979) subjected a bilaterally symmetric finite-element model of a lumbar vertebra to static and dynamic loads. The cortex and plates and spongy bone of the vertebral body were modeled with thin plate and shell elements and three-dimensional isoparametric elements. The pedicle, lamina, and articular facets were represented with brick elements, and the facets were modeled to provide articulation such as that in a true facet joint. Plate elements were used to represent the processes. Material properties data from the literature were used, and input load distribution was taken from experimental data (Hakim and King, 1976). Validation efforts showed a favorable comparison between computed and measured strains. Balasubramanian et al. (1979) extended this model to simulate a unilateral laminectomy and bilateral asymmetric loading.

Vibration data have been used to determine in vivo elastic properties of long bones, another area of bone modeling. Jurist and Kianian (1973), Orne (1974), Orne and Mandke (1975), Orne and Young (1976), and Viano et al. (1976) have all studied the elastic property of bone in this manner.

Models of Single Joints

In vivo internal forces and moments at a joint are both difficult to measure and calculate, largely because of the involvement of many muscles and ligaments, which results in more unknowns than there are equations. Electromyogram (EMG) data, minimum total muscular force and/or moment, and minimum total mechanical or metabolic energy are used to reduce the number of unknowns.

Equations in dynamic models are usually nonlinear differential equations. They are reduced to algebraic equations by electing to solve the "inverse dynamic problem" in which kinematic data are supplied as input to eliminate the derivatives.

Models of the Hip and Knee Joints

The knee has been modeled in various ways by Bresler and Frankel (1950); Kettelkamp and Chao (1972), Engin and Korde

(1974), Crowninshield et al. (1976), Harrington (1976), Andriacchi et al. (1977), Hight et al. (1979), Chand et al. (1976), Wismans (1980), Wismans et al. (1980), and Minns (1981).

Morrison (1968, 1969) computed muscle and ligament forces for a normal gait, while eliminating forces in muscles with quiescent EMG data and eliminating ligament forces that become slack during the specific phases of gait. Experimental force plate data were used along with photographic identification of the hip, knee, ankle, and foot to provide joint displacement and rotation data. EMG data of principal muscle groups were acquired from bipolar surface electrodes.

Six equations of motion were used to determine the net reaction force and moment at the knee. When solving for bone contact force components and the muscle and ligament forces, the problem became indeterminate. Use of EMG data eliminated the antagonistic muscle forces and ligament functions and allowed calculations of bone contact or joint force. The results were comparable for repeated tests of the same subject but varied from subject to subject.

Another method of reducing indeterminacy is to compute the forces in the ligaments across the knee joint as a function of knee flexion angle. A ligament model developed by Wismans et al. (1980) assigned stiffness values to the ligaments. This model also considered three-dimensional kinematics of the knee joint and articular surface geometry, which established the conditions of contact on medial and lateral surfaces. With this information, 16 unknowns were calculated, including relative joint location, contact points and forces medially and laterally, relative abduction and rotation, and the magnitude of the joint constraint moment. The results were principally kinematic and did not provide kinetic data, which would have been helpful. In a more complete work by Wismans (1980), kinetic data were also not provided. Rheological models of the knee by Moffatt et al. (1976) and Pope et al. (1976) were based on oscillatory tests that described the knee as a Maxwell fluid or a Kelvin solid.

Hip joint models were developed in much the same way as those for the knee (Crowninshield et al., 1978; Goel and Svensson, 1977; Williams and Svensson, 1968). Paul (1967) assumed that the hip joint transmitted a contact force and that no more than two muscles were active at any instant of gait. Kinematic and force plate data were required by this model.

For the ankle, two-dimensional models were developed by Brewster et al. (1974), Stauffer et al. (1977) and Wynarsky and Greenwald (1983); and a three-dimensional model was developed by Procter and Paul (1982).

Models of Joints of the Upper Extremity

With assumptions of a hinge joint with three major flexors, the elbow becomes simple to simulate. Based on the work of MacConaill (1967), Yeo (1976) used linear programming to compute the total forces generated in the muscles. Because the model results contradicted experimental data that show that all three muscles are active during flexion, Yeo claimed that the "minimum principle" was not valid. Crowninshield (1978) defined maximum allowable tensile stress in each of three muscles, and his objective function was minimum total tensile stress. The model correlated well with experimental data for both isometric and isokinetic contractions. This approach was extended by An et al. (1983) to compute joint contact forces.

Modeling efforts for the shoulder include the work of DeLuca and Forrest (1973), who used isometric abduction.

Models of Intervertebral Joints

Schultz and Andersson (1981) developed a practical three-dimensional, statically indeterminate model which calculated loads placed on a lumbar vertebra during physical activity. This model functioned in two parts, similar to the knee model, and considered the action of both the spinal musculature and the abdominal muscles. The net reaction across a lumbar vertebra, derived from equilibrium considerations, formed the determinate portion of the problem. Linear programming was used to determine the resultant spinal loads and muscle forces while minimizing spinal compression. Large spinal compression forces were predicted for minor activities and were validated with myoelectric activity indicating muscular tension. This model was later modified by Schultz et al. (1982), who changed the objective function to specify minimum intensity or stress.

Other researchers developed models of a single intervertebral joint (Belytschko et al., 1974; Kulak et al., 1976; Lin et al., 1978). They were able to determine the responses of the intervertebral

disc. The claim that such a model could be used to predict material properties of the joint using optimization was a new concept. These disc models were loaded axisymmetrically, which is a physiologically incorrect assumption.

Redundancy and validation continue to be the major problems encountered in the modeling of joints. The use of optimization to solve the redundancy problems is now acceptable; however, the choice of an objective function remains an unresolved problem. This difficulty is linked to the inability to validate the predictions of the models. Reliable methods and transducers have not been developed at this time to achieve the goal. Pedotti et al. (1978) proposed the use of nonlinear optimization schemes that had closer correlations with EMG data than did linear schemes, and Crowninshield and Brand (1981) proposed a model that required a minimum muscle stress and that correlated with EMG activity. These approaches, however, did not reduce the difficulty in the choice of an objective function. An et al. (1983) opined that linear optimization with inequality constraints was superior to a nonlinear scheme.

Models of Multiple Body Segments and the Whole Body

This class of models can be divided functionally into models of five groups: (1) the fingers and thumb; (2) the lower extremities, including gait; (3) the spinal column; (4) the thorax; and (5) the whole body, excluding gait.

Models of Fingers and the Thumb

Many researchers have developed models of the fingers and thumb, from kinematic models (Landsmeer, 1961) to two-dimensional models (Hirsch et al., 1974; Smith et al., 1964) to three-dimensional thumb models (Cooney and Chao, 1977; Toft and Berme, 1980). Other models were developed by Chao et al. (1976), Spoor and Landsmeer (1976), Berme et al. (1977), Chao and An (1978a,b), and An et al. (1974).

There are many problems encountered in the modeling of a finger, as discussed in a series of papers by Chao et al. (1976), Chao and An (1978a,b), and An et al. (1974). These models were three-dimensional and were indeterminate because of the large

number of tendons and intrinsic muscles that could be active during a given activity. Before a mechanical analysis could begin, all unknowns had to be identified and simplifying assumptions had to be made to determine the degree of indeterminacy. In many cases, antagonistic muscles were assumed to be inactive, yet in the isometric function of the finger, they participated in the stabilization of the joints, which is known as the pylon concept. Thus, other justifications were needed to determine simplifying assumptions. A frictionless cable and pulley system for tendons and tendon sheaths enables the tensile force in the tendons to be transmitted undiminished across joints. Other anatomic reasons have been used to yield constraint equations that reduce the number of unknowns. The equations for the model are obtained from a free-body analysis of all joints of the finger. The problem was solved by linear programming with a variety of objective functions that determined joint forces caused by a unit pinch force between the tips of two fingers or between finger and thumb. One objective function was the minimization of the sum of muscle forces or the sum of constraint moments.

An et al. (1974) developed a three-dimensional kinematic model of the human hand based on cadaver measurements. These measurements included tendon location and orientation for all four fingers in a neutral position expressed in coordinate systems normalized against the middle phalanx of each specific finger. Tendon geometry was computed from a force and moment potential.

Models of the Lower Extremities

Models of the lower extremities take on many forms, from a one-legged comprehensive static model (Seireg and Arvikar, 1973) to human gait models of the lower limbs (Cappello et al., 1975; Beckett and Chang, 1968; Gehl et al., 1975; Hardt, 1978; Seireg and Arvikar, 1975).

The most comprehensive dynamic lower limb model was developed by Hatze (1976), who verified it experimentally. This two-dimensional model tracked the motion of a weighted foot as it attempted to hit a target on the floor in minimum time. The action was fully voluntary with no ground interaction. The results compared well with volunteer data.

Models of human gait involving the head, arms, and torso (HAT), in general, try to determine joint reactions and moments

during gait. If the kinematic variables of displacement, velocity, and acceleration are not independent of each other, the number of unknowns exceeds the number of equations by the number of joint moments, thus rendering the problem indeterminate. By assuming known ground reactions and specifying kinematic variables, the problem can become determinate and can be solved as an inverse dynamic problem (IDP). The kinematic variables are assumed to be functions of time, reducing the differential equations of motion to algebraic equations. A direct approach can be taken if the differential equations are solved for unknown kinematic variables and/or joint loads. The problem is generally indeterminate, requiring an optimization scheme with identification of an objective function to create extra equations.

HAT models of the IDP type have been proposed by Townsend and Seireg (1972), Chao and Rim (1973), Cappozo and Pedotti (1973), Townsend and Tsai (1976), Aleshinsky and Zatsiorsky (1978), and Hardt and Mann (1980). Direct solutions of the motion equations include a model by Nubar and Contini (1961), who pioneered the optimization approach by proposing a minimum energy principle for muscular effort. This generated a dynamic two-dimensional, five-link model of the skeleton. However, only a static stance solution was provided. It was then extended to an optimal control model (Chow and Jacobson, 1971). Hatze (1977), likewise, extended his earlier lower-limb model (1976) into a whole-body musculoskeletal control model.

An IDP model developed to solve for ground reactions during bipedal gait was formulated by Thornton-Trump and Daher (1975). This model generated seemingly reasonable ground forces, but did not account for a period of double support and therefore had questionable validity (Paul, 1978). A model by Hardt and Mann (1980) corrected this deficiency. Autogeneration models of gait were proposed by Onyshko and Winter (1980) and Nakhla and King (1983). The autogeneration models were two-dimensional HAT models which applied appropriate muscle moments to the ankles, knees, and hips, enabling the linkage system to move over level surfaces at different speeds and cadences. The models also accounted for double support. Recently, Nakhla and King (1985) formulated a three-dimensional model for the autogeneration of human gait. Limb kinematics were computed from joint moment inputs, 18 of which were required for a seven-segment HAT model. Experimental gait data were used to compute the moment time

histories to ensure that the input was realistic. Gait was then generated by solving the differential equations of motion by using an existing three-dimensional human link model which was developed originally by Calspan Corporation for the simulation of occupant kinematics in an automobile crash. It is also known as the articulated total body (ATB) model, a more complete description of which can be found in the section by that title in Chapter 4. The ATB model was modified to accept joint moments as input.

Models of the Spinal Column

An early three-dimensional static model of the spine proposed by Schultz and Galante (1970) generated complex equations that were not solved. A geometric model resulted from the use of fixed-length elements. This was followed by work by Panjabi (1973), who developed a general formulation for a three-dimensional discrete parameter model of the spine that could simulate responses to static and dynamic loading. No specific model was proposed. Belytschko et al. (1973), however, developed a three-dimensional structural model of the entire spinal column with responses to three loading cases. This model simulated vertebrae, ligaments, and soft tissue and provided resistance against axial, torsional, bending, and shear loads. The results were validated against experimental data. Panjabi (1978) has since proposed a model of a functional spinal unit which could simulate coupled motion. The disc and soft tissue were represented by a deformable element such as a viscoelastic body, but because of the lack of material properties, no model of either a spinal segment or the spinal column was proposed. Koogler et al. (1979), attempted a three-dimensional finite-element model of the lumbar spine based on the mesh developed by Balasubramanian et al. (1979), with no conclusive results. Preliminary results, however, from a finite-element model of a functional spinal unit formulated by Yang and King (1984) indicate that it is able to accurately predict intradisc pressures.

Models of the Thorax

A three-dimensional, bilaterally symmetric, elastostatic, and finite-element model of the human thorax, developed by Roberts and Chen (1977), was able to reasonably predict rib displacement

under loading conditions. The ribs were simulated by beam elements, and geometric and physical rib properties were included.

Sundaram and Feng (1977) developed both a full thoracic and a skeletal finite-element model of the thorax. The former models simulated the soft tissues and organs of the rib cage, the thoracolumbar spine, the sacrum, the coccyx, the ribs, and the sternum. The results of stresses and displacements from 11 static loading conditions compared favorably with experimental data.

Models of the Whole Body

While several investigators have proposed whole-body models of human motion not involving gait, many were inspired by the simulation of movements in space. Kane and Scher (1970) and Passerello and Huston (1971) formulated models of people in space and simulated yaw, pitch, and roll maneuvers. Huston and Passerello (1971) went further to simulate lifting, swimming, and kicking with one leg.

A lumped-parameter model of a seated human (Muskian and Nash, 1974) simulated the head and torso, which were subjected to sinusoidal excitation at the seat level. Heart and diaphragm activity was also simulated; and responses of the head, back, torso, and other masses as a function of frequency was given for 0-30 Hertz (Hz). Muskian and Nash (1976) proposed a simpler three-mass model which simulated dual load paths from the head to the pelvis, the spinal column, and the abdominal viscera. Non-linear frequency-dependent damping was used to simulate actual responses.

DISCUSSION

King and Marras prepared an extensive table of biomechanical models for this study (Table 3-1) that presents an extensive overview and summary of the specific variables and parameters of existing models. They listed the model type, input and output variables, model characteristics, and the assumptions made in model development. This table is a unique contribution to the literature and should prove valuable to those who do research on biomechanical models.

The ultimate goal of biomechanical models should be to create

Table 3-1

TABLE OF BIOMECHANICAL MODELS

AUTHOR(S)	JOINT OR SEGMENT	D.O.F.	INPUT VARIABLES	MODEL OUTPUT		CHARACTERISTICS	ASSUMPTIONS
				EXTERNAL	INTERNAL		
THORNTON, 1969	FEMUR	3	5 JT. & MUSCLE LOADS		STRESSES	BEAM THEORY	LINEARLY ELASTIC
PIOTROWSKI & WILCOX, 1971	FEMUR	3	5 JT. & MUSCLE LOADS		STRESSES	BEAM THEORY	LINEARLY ELASTIC
AMSTERDAM ET AL., 1970	FEMUR	2	5 COMBINED LOADS		STRESSES	BEAM THEORY	LINEARLY ELASTIC, FEMORAL CONDYLES ONLY
HUBBS ET AL., 1977	TIBIA	3	5 JT. & MUSCLE LOADS		STRESSES	BEAM THEORY	LINEARLY ELASTIC
PRATT ET AL., 1972	FEMUR	2	5 JT. & MUSCLE LOADS		STRESSES	BEAM THEORY & FEM	LINEARLY ELASTIC, PROX FEMUR
BRANN ET AL., 1980	FEMUR	2	5 JT. & MUSCLE LOADS		STRESSES	FEM	LINEARLY ELASTIC, PLANE STRAIN, FEMORAL HEAD MODEL
PITTLAI ET AL., 1976	TIBIA	3	5 JT. & MUSCLE LOADS		STRESSES	FEM	LINEARLY ELASTIC, ANISOTROPIC, TIBIAL PLATEAU
HAYES ET AL., 1978	TIBIA	2	5 JT. & MUSCLE LOADS		STRESSES	FEM	LINEARLY ELASTIC
OLSSON, 1976	FEMUR	3	5 JT. & MUSCLE LOADS		STRESSES	FEM	LINEARLY ELASTIC
SCHULTEN ET AL., 1978	FEMUR	3	5 JT. & MUSCLE LOADS		STRESSES	FEM	LINEARLY ELASTIC
DOUGLASS ET AL., 1982	FEMUR	3	5 JT. & MUSCLE LOADS		STRESSES	FEM	LINEARLY ELASTIC
MITSSES ET AL., 1981	FEMUR	3	5 JT. & MUSCLE LOADS		STRESSES	FEM	LINEARLY ELASTIC
WALLINGRA ET AL., 1977	FEMUR	3	5 JT. & MUSCLE LOADS		STRESSES	FEM	LINEARLY ELASTIC
CHIEL ET AL., 1978	PELVIS	3	5 JT. & MUSCLE LOADS		STRESSES	FEM	LINEARLY ELASTIC, TRANSVERSELY ISOTROPIC
GOLDSHET ET AL., 1983	PELVIS	3	5 JT. & MUSCLE LOADS		STRESSES	FEM	LINEARLY ELASTIC, TRANSVERSELY ISOTROPIC
HAYES ET AL., 1982	PATELLA	2	5 JT. & MUSCLE LOADS		STRESSES & TRAJECTORIES	FEM	LINEARLY ELASTIC
SWYDER ET AL., 1983	PATELLA	2	5 JT. & MUSCLE LOADS		STRESSES & TRAJECTORIES	FEM	LINEARLY ELASTIC, ANISOTROPIC
WILLIAMS & LEWIS, 1982	FEAR BONE	2	5 JT. & MUSCLE LOADS		STRESSES	FEM	STRICT OPT TECH USED TO MATCH FEM STRESS TO TRAB ARCHITECTURE
RAJIN & KING, 1979	VERTEBRA	3	5/D COMP. & BENDING		STRESSES	FEM	LINEARLY ELASTIC, ANISOTROPIC
BALASUBRAMANIAN ET AL., 1979	VERTEBRA	3	5/D COMP. & BENDING		STRESSES	FEM	LINEARLY ELASTIC, BILATERALLY SYMMETRIC
JONSSON & RYLAND, 1973	ULNA	1	1 D RESONANT FREQ.		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
ONE, 1974	ULNA	1	1 D RESONANT FREQ.		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
ONE & HARRIS, 1975	ULNA	1	1 D RESONANT FREQ.		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
ONE & YOUNG, 1976	ULNA	1	1 D RESONANT FREQ.		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
VIHARI ET AL., 1976	FEMUR	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
ROE-JER & FRANKEL, 1956	FEMUR	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
PHILLIPS, 1968	FEMUR	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
HARRINGTON, 1976	FEMUR	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
REILLY & CHAO, 1972	FEMUR	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
ENGEL & LOOSE, 1974	FEMUR	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
CHAMBERS ET AL., 1976	FEMUR	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
AMERSON ET AL., 1977	FEMUR	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
STEWART ET AL., 1979	LEG	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
CHAMP ET AL., 1976	LEG	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
STEWART ET AL., 1980	LEG	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
HARRIS, 1961	FEMUR	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
NOFAT ET AL., 1976	FEMUR	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
NOFAT ET AL., 1976	FEMUR	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
PAUL, 1967	HIP	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC
WILLIAMS & STEVENSON, 1968	HIP	2	2 D ELASTIC PROPERTIES		ELASTIC PROPERTIES	BEAM THEORY	LINEARLY ELASTIC, BILATERALLY ASYMMETRIC

[illegible]

BY A. L. KING AND W. S. HARRAS

TABLE OF BIOMECHANICAL MODELS

AUTHOR(S)	JOINT OR # OF SEGMENT	DIM	MOD TYPE	INPUT VARIABLES		MODEL OUTPUT		CHARACTERISTICS	ASSUMPTIONS
				EXTERNAL	INTERNAL	EXTERNAL	INTERNAL		
SCHEITZ & GILBERT, 1970	SPINE	3	S	KINEMATIC VALUES	SPINAL COMF	SPINAL COMF	3T FORCES AND MOMENTS	STAT EQUIL	RESULTS ON LATERAL BENDING, AXIAL ROT & FLEX OF ENTIRE SPINE
PARIZZI, 1973	SPINE	3	D	FORCES AND MOMENTS	SPINAL COMF	SPINAL COMF	3T FORCES AND MOMENTS	DYN EQUIL	NO EXAMPLES GIVEN, A GENERAL FORMULATION ONLY
MELTZSCHEID ET AL., 1973	SPINE	3	S	EXTERNAL FORCES	SPINAL COMF	SPINAL COMF	3T FORCES AND MOMENTS	STAT EQUIL	INCREMENTAL METHOD FOR LARGE DEF., SCOLIOtic SPINE APPLICATION
PARIZZI, 1976	SPINE	3	D	FORCES AND MOMENTS	SPINAL COMF	SPINAL COMF	3T FORCES AND MOMENTS	DYN EQUIL	NO EXAMPLES GIVEN, A GENERAL FORMULATION ONLY
DOUGLE ET AL., 1979	LUM SPINE	3	D	NOT AVAILABLE	NOT AVAILABLE	NOT AVAILABLE	NOT AVAILABLE	DYN EQUIL	NO SOLUTION, BASIC FE MODEL OF VERTEB BY HARRIS & KING (REF 29)
YANG ET AL., 1984	LUM SPINE	3	S	AXIAL FORCE & MOMENT	VERT BODY KIN	VERT BODY KIN	STRESSES & PRESSURES	STAT EQUIL	FE BILAT SIM MODEL OF FIVE SP UNIT, LUM PROPS, FALL LOAD SIM
ROBERTS & CHEN, 1977	THORAX	3	S	EXTERNAL LOAD	THOR KIN	THOR KIN	RIB & CARI STRESSES	STAT EQUIL	FE MODEL: BILAT STP, NO SOFT TISSUE SIM
UNICARAN & FERG, 1977	THORAX	3	S	EXTERNAL LOAD	THOR KIN	THOR KIN	RIB STRESSES	STAT EQUIL	2 FE MODELS, 1 W/ SOFT TISSUE, LUM PROPS, EXFAL VERIF
KANE & SCHER, 1977	WHOLE BODY	3	D	LIMB MOTION	BODY MOTION	BODY MOTION	BODY MOTION	DYN EQUIL	SELF-ROT 3-LINE MOD FOR MANEUVERS IN SPACE, FETCH & YAN SIM
PASSELLO & HUSTON, 1971	WHOLE BODY	3	D	LIMB MOTION	BODY MOTION	BODY MOTION	BODY MOTION	DYN EQUIL	SELF-ROT 3-LINE MOD FOR MANEUVERS IN SPACE, FETCH & YAN SIM
HARRIS & PASSELLO, 1971	WHOLE BODY	3	D	LIMB MOTION	BODY MOTION	BODY MOTION	BODY MOTION	DYN EQUIL	EXT OF REF 139 TO LIFTING, SWIMMING & KICKING WHILE SUSPENDED
HARRIS & WASH, 1974	WHOLE BODY	3	D	SEAT DISPLACEMENT	HEAD & TORSO MOTION	HEAD & TORSO MOTION	HEAD & TORSO MOTION	DYN EQUIL	VIB RESP W/ NON-LIN DAMP, LUMBER PARAM MOD
HARRIS & WASH, 1976	WHOLE BODY	3	D	SEAT DISPLACEMENT	HEAD & TORSO MOTION	HEAD & TORSO MOTION	HEAD & TORSO MOTION	DYN EQUIL	VIB RESP W/ NON-LIN DAMP, LUMBER PARAM MOD
HARRIS & KING, 1985	H-T	3	D	3T MOMENTS	LIMB KIN, GRD REACT FORCE	LIMB KIN, GRD REACT FORCE	LIMB KIN, GRD REACT FORCE	DYN EQUIL	3-D AUTOMAT OF GAIT, 3T MOMS CALC FROM GAIT DATA

LEGEND FOR TABLE OF BIOMECHANICAL MODELS

ABD	ABDUCTION OR ABDOMINAL
ANISOTROPIC	THE MATERIAL DOES NOT HAVE THE SAME RESPONSE TO LOADS FROM DIFFERENT DIRECTIONS
ANNULUS	THE FIBROUS OUTER RING OF AN INTERVERTEBRAL DISK
ANTAGON	ANTAGONISTIC
AUTO GEN	AUTO-GENERATION
AVAIL	AVAILABLE
AX	AXIAL
AXISYM	AXIAL SYMMETRY IS ASSUMED
BEAM THEORY	SIMPLIFIED THEORY OF ELASTICITY APPLIED TO ONE DIMENSIONAL PROBLEMS, SUCH AS BEAMS
BILAT	BILATERAL
CALC	CALCULATE OR CALCULATED
CART	CARTILAGE
CLOSED SOLUTION	SOLUTION TO A SET OF DIFFERENTIAL EQUATIONS CARRIED OUT ANALYTICALLY IN TERMS OF A MATHEMATICAL EXPRESSION
COMB	COMBINED OR COMBINATION
COMB/PERM	COMBINATION/PERMUTATION
COMP	COMPRESSION OR COMPRESSIVE
COND	CONDITION
CONF OR CONFIG	CONFIGURATION
CONST M OF I	THE MASS MOMENT OF INERTIA OF BODY SEGMENTS IS ASSUMED TO REMAIN CONSTANT DURING LOCOMOTION
CONTACT MODEL	A TECHNIQUE IN ELASTICITY TO COMPUTE CONTACT STRESSES BETWEEN TWO BODIES IN CONTACT
CORT	CORTICAL
D	DYNAMIC
DAMP	DAMPING
DEFL	DEFLECTION
DIFF EQS	DIFFERENTIAL EQUATIONS
DOF	DEGREES OF FREEDOM
DYN EQUIL	PRINCIPLES OF DYNAMIC EQUILIBRIUM WERE USED TO FORMULATE MODEL
ELASTIC PROPERTIES	THE PROPERTIES OF A MATERIAL ASSOCIATED WITH ITS ELASTIC RESPONSE, SUCH AS MODULUS OF ELASTICITY
EMG	ELECTROMYOGRAPHY - THE TECHNIQUE OF MONITORING ELECTRICAL ACTIVITIES OF MUSCLES
EQUIL	EQUILIBRIUM
EXT	EXTREMITY OR EXTENSION
FEM OR FE	FINITE ELEMENT METHODS OR FINITE ELEMENT
FLEX	FLEXION
FUNC SP UNIT	FUNCTIONAL SPINAL UNIT
INDET	INDETERMINATE
INDIV	INDIVIDUAL
INIT	INITIAL
INV DYN PROB	INVERSE DYNAMIC PROBLEM
GRD REACT	GROUND REACTION
H-A-T	MODEL OF A HUMAN BODY IN WHICH THE HEAD, ARMS AND TORSO CONSIDERED AS A SINGLE MASS

IMPED	IMPEDANCE
INCOMP	INCOMPRESSIBLE
INEXT. JTS	THE JOINTS BETWEEN BODY SEGMENTS ARE ASSUMED TO BE INEXTENSIBLE. BODY SEGMENTS CAN ONLY ROTATE WITH RESPECT TO EACH OTHER
JT	JOINT
KELVIN MODEL	A VISCOELASTIC MODEL WHICH HAS A MORE SOLID LIKE BEHAVIOR
KIN	KINEMATICS
LAT	LATERAL
LIG	LIGAMENT OR LIGAMENOUS
LIN	LINEAR
LINEAR ELASTIC	THE MODEL ASSUMES THE BIOLOGICAL MATERIAL TO BEHAVE IN A LINEARLY ELASTIC MANNER
LINEAR PROG SOLN	SOLUTION TO A SET OF LINEAR ALGEBRAIC EQUATIONS WHICH ARE REDUNDANT, USING THE LINEAR PROGRAMMING METHOD
LINEARLY ORTHOTROPIC	A MATERIAL WHICH HAS A LINEAR RESPONSE TO STRESS BUT HAS 9 TO 12 MATERIAL CONSTANTS
LOC	LOCATION
LUM	LUMER
L. M	LUMBAR
MAX	MAXIMUM
MAXWELL MODEL	A VISCOELASTIC MODEL WHICH HAS A MORE FLUID LIKE BEHAVIOR
MEF	MECHANICAL
MECH	MECHANICAL
MEU	MEDIAL
MIN	MINIMUM
MOE	MODULUS
MOD	MODULUS
MUSC	MUSCLE OR MUSCULAR
NON LIN	NON LINEAR
OBJ FUN	OBJECTIVE FUNCTION USED IN OPTIMIZATION TO MINIMIZE
PARAM	PARAMETER
PHYSIOLOGICAL	PHYSIOLOGICAL CROSS SECTION
PLANE STRAIN	A 2-DIMENSIONAL STRAIN ASSUMPTION IN WHICH THE PARTICLES DEFORM IN ONE PLANE AND REMAIN THAT PLANE
PROB	PROBLEM
PRON	PRONATION
PROF	PROFESSOR
PROX	PROXIMAL
REDUNDANT MODEL	A MATHEMATICAL MODEL WHICH HAS MORE UNKNOWN THAN EQUATIONS TO SOLVE FOR THESE UNKNOWN
RESONANT FREQUENCY	THE FREQUENCY AT WHICH A SYSTEM RESONATES OR HAS LARGE AMPLITUDE OF DISPLACEMENT
RESP	RESPONSE
RHEO	RHEOLOGICAL
RIGID BODY	AN ASSUMPTION TO MAKE THAT THE BODY SEGMENT IS RIGID OR NON DEFORMABLE

ROT	ROTATION
S	STATIC
SEG	SEGMENT
SIM	SIMULATION
STA:	STATIC OR STATICALLY
STAT EQUIL	PRINCIPLES OF STATIC EQUILIBRIUM WERE USED TO FORMULATE THE MODEL
STRUCT OPT TECH	STRUCTURAL OPTIMIZATION TECHNIQUES
SUP	SUPINATION
SUPP	SUPPORT
SYM	SYMMETRIC OR SYMMETRY
TEND	TENDON
THOR	THORAX OR THORACIC
T-M	TEMPORAL-MANDIBULAR
TRAB	TRABECULAR
TRANSVERSELY ISOTROPIC OR TRANS ISOT	ONE FORM OF ANISOTROPY FOR WHICH 5 TO 6 DIFFERENT MATERIAL CONSTANTS ARE NEEDED TO DESCRIBE THE RESPONSE OF THE MATERIAL
VAR	VARIATION
VERT	VERTICAL
VERTEB	VERTEBRAL
W/	WITH

a universal model that is applicable in a variety of situations. This model should accurately predict the loading on the body caused by both internal and external forces and should be capable of evaluating "wear and tear" of the body under realistic (static as well as dynamic three-dimensional) conditions. Such a model should be adaptable to a variety of situations. The same model should be able to simulate gait and weight lifting and perform a variety of human tasks.

To achieve such a goal, several areas of model improvement and development are needed. More data are needed to describe the material and functional properties of body tissues. These findings should be incorporated into analyses that investigate the aging as well as the time- and frequency-dependent repetitive loading effects of loads exerted on the body. The properties of bone must also be incorporated into models that are used for ergonomic purposes. More specifically, for spinal models, investigation of the load-bearing role of the articular facets is needed to understand low back pain etiology.

For bone stress analysis, the most promising model is finite-element analysis, which can model the irregular geometry and the composite nature of bone. Validation against experimental data continues to present problems. Rohlmann et al. (1982), Huiskes et al. (1981) and Hakim and King (1979), however, have attempted such a validation. There continues to be a lack of data on material properties and a large variation in such properties for biological materials. The problem is made more complex because of anisotropy, inhomogeneity, and nonlinearity. Experimental research and clinical application of the models are needed to further advance the modeling effort. One area for further research is that of developing a capability for a variation of model geometry without a complete respecification of nodal coordinates. Lewis et al. (1980) proposed such a scaling method for femoral models.

The analogy of the rigid beam link should be investigated. Instead of viewing the body as a set of rigid links, perhaps a semiflexible spinal column can provide more accurate assessments of the lifting of loads on the body.

The modeling of joints and human locomotion (single and multiple joints) is aimed primarily at predicting forces in muscles, ligaments, and bone contact. This can serve a variety of needs, such as prosthesis design, treatment and diagnosis of musculoskeletal diseases, rehabilitation, and quantification of normal

function. There is very little evidence, however, that current models are able to calculate these forces accurately. The measurement of these forces in vivo is extremely difficult, and therefore, the need exists to develop experimental techniques and transducers to verify the analytical results. Inferences from time domain correlations of muscle forces with EMG activity are at best a crude indication of validity. One of the major problems with this area of research is the choice of appropriate objective functions to solve a redundant problem. It does not fall within the deterministic realm of mechanics and requires physiological data that are, as yet, unavailable. The hypothesis that an objective function indeed exists needs to be proven before further advances can be made. A secondary problem concerns the use of linear optimization techniques. The limitations of a linear analysis are implicit in their use and should be recognized.

Whole-body models can now incorporate three-dimensional activity as well as motion. The development of these models over the years has progressed from those based on pure Newtonian mechanics to optimization theory to control theory. The control theory model by Hatze (1977) appears to simulate the rate and recruitment coding of the muscles during the performance of a task. Unfortunately, when the predictive power of the models increases, the complexity of the model also increases dramatically. Hence, a trade-off must occur between model complexity and the degree of accuracy that is needed to model a situation for ergonomic purposes.

An area which remains untouched by biomechanical modelers is that of modeling the cognitive link. People, as information processors, possess the ability to modify the interaction with the musculoskeletal system. Under circumstances of great stress or during life-threatening situations, people can short-circuit internal protective mechanisms and are capable of exhibiting nearly "superhuman" traits. There is also an awareness that the "psychological factor" can become dominant in times of illness, as shown by treatment with a placebo. Additional experimental research is needed on these issues so that the cognitive control process can be evaluated and eventually included in biomechanical models. Pope et al. (1980) have begun to explore such a link between personality traits and biomechanics.

It is clear that much research is needed to achieve the goal of producing a universal biomechanical model. Progress has been

slow over the years. Basically, it appears that progress in the area of biomechanical modeling is now limited by a basic understanding of the body rather than by computational ability. The current state of modeling will advance when advances in basic understanding are achieved and better validation methods are developed.

In addition, many of the limitations in existing biomechanical models are related to incomplete or unrealistic data inputs into the model. The problems include nonrigid or nonuniform links, effects of dynamic action, internal loading including antagonistic muscle action, comparison data for cumulative trauma limits, and cognitive links.

Furthermore, models based on motion kinetics alone provide an inadequate description of a person who is operating equipment in a real-world environment. The human operator's need and ability to adapt the dynamic behavior of the limbs is not included in current models. A model of the biomechanical system that uses single values for its dynamic parameters such as muscle stiffness or viscosity is unrealistic. A fixed-parameter model cannot be applied reliably in situations other than those for which it was calibrated.

Determination of the difference between the net reaction forces at a given body joint and the actual internal loads (e.g., those generated by the antagonistic muscle groups that are involved) is essential to a complete biomechanical analysis of a strain that has an impact on the system. Predictions of internal loads usually incorporate simplistic optimizing assumptions, for example, that minimal antagonistic muscle activity is used in performing a task. If the performance is not governed by the assumptions, the actual internal loads can be much higher than the predicted values.

Finally, existing biomechanical models do not address the problem of repeated activities over a period of time, and hence, physiological aspects such as fatigue are not considered.

4

Human-Machine Interface Models

Information generated by anthropometric and dynamic biomechanical models is needed to build the next level of model in the hierarchical structure, that is, the interface model. Interface models describe the interactions among the anthropometric and the biomechanical models in a symbiotic relationship with the equipment used in system operation.

Typical applications of these quantitative anthropometric and biomechanical models are their use in the development of interface models as COMRIMAN (*computerized biomechanical man model*), CAPE (*computerized accommodated percentage evaluation*), CAR (*crewstation assessment of reach*), SAMMIE (*system for aiding man-machine interaction evaluation*), CREW CHIEF (*computer-aided design model of an aircraft maintenance technician*), and PLAID-TEMPUS (*three-dimensional model of an interactive environment for the design and evaluation of system design and operation*). Each of these interface models relies on anthropometric and biomechanical data to model the relationships among people, tasks, equipment, and the workplace.

Early approaches to the development of interface models and their characteristics are shown in Table 4-1 (Kroemer, 1973). In 1967, Popdimitrov (Popdimitrov et al., 1969) reported on one of the first interface models, BULGAR, which was used for calculating the positions of certain parts of the body related to a person's posture. Other approaches, such as DYNASTICK (Wartluft,

Table 4-1
Early Interface Model Characteristics

MODEL	CONFIGURATION				MECHANICS			ERGONOMICS				OUTPUT			
	Dimensions	Links	Joints	Volumes	Mass	Static	Kinematic	Actively Dynamic	Displacement	Strength	Work		Power	Equipment	Environment
BH CAR 1967	3	14	11	-	-	x	-	-	-	-	-	-	-	-	Location of body joints depending on posture
DYNASTICK 1970	3	13	12	-	x	x	-	-	-	-	-	-	-	-	Mass distribution depending on anthropometric parameters and posture
TORQUE MAN 1968	2	7	6	-	x	x	-	-	-	x	-	-	-	-	Chain of static force vectors through joints
LIFT MAN 1969	3	18	17	-	x	x	-	-	-	y	-	-	-	-	Static lift capabilities at 1g
FORCE MAN 1971	3	18	17	-	x	x	-	-	-	x	-	-	x	-	Static force capabilities depending on equipment and gravity
MTM MAN 1970	3	8	7	-	-	x	-	-	x	x	-	-	x	-	Body segment positions depending on hand location
SABOTIE 1969	3	18	17	x	-	x	-	-	x	-	-	-	x	-	Body position in relation to equipment and hand location
ARM MODEL 1971	3	2	1	x	x	x	x	x	-	-	-	x	-	-	Arm motions depending on power expenditure
BOEYAN 1971	3	23	22	x	x	x (x)	-	-	x (x)	-	-	-	x	x	Fit of equipment to man in related body positions
CINCI KID 1971	3	15	16	x	x	x	x	x	-	-	-	-	-	x	Attitude control and motions in force fields
COMBATMAN 1971	3	x	x	x	x	x	x	x	x	x	x	x	x	x	Kroemer 1971

SOURCE: Kroemer (1973).

1971) and TORQUE MAN, LIFT MAN, and FORCE MAN (Chaffin, 1969), were based on link-joint "stick man models"; they represented mass properties and capabilities for exerting forces. MTM MAN (Patrick, 1970) incorporated elementary motion times from tables used by industrial engineers. The ARM MODEL (Ayoub, 1971) simulated two-link arm movements, using power as an optimization algorithm. CINCI KID (Huston and Passerello, 1971) incorporated kinematic and kinetic aspects of the human body and the effects of gravity. BOEMAN (Boeing Company, 1970; Ryan, 1971) was a complex model of a pilot sitting in an aircraft cockpit. This model was intended for use in the evaluation of the geometry of aircraft cockpits with respect to their suitability for the aviator. COMBIMAN (Krause and Bogner, 1987; Kroemer, 1973; McDaniel, 1976) was developed based largely on the experience of the Boeing Company, hence it has been called "son of BOEMAN."

Since 1973, several other interface models have been developed. They include CAR (Edwards, 1976), CAPE (Bittner, 1975), ATB (Fleck and Butler, 1975; Butler and Fleck, 1980), PLAID-TEMPUS (Lewis 1979 a, b) and, currently under development, CREW CHIEF (Korna and McDaniel, 1985). These models and their interrelationships are discussed in the following text.

BOEMAN

BOEMAN is a computer-based model that was developed for the design and evaluation of cockpit and other crewstations (Ryan, 1970, 1971). Although it provided a broad conceptual framework for the study of diverse variables, its primary reason for development was aimed at the assessment of the seated operator's ability to move toward and reach controls.

The operator model is made up of a system of 31 links that are constrained by hard angular limits at each body joint. In addition, a time-cost function is associated with each joint. Mathematical programming is used to minimize the total time as the operator reaches from one point to another.

The links are typically en fleshed by truncated cones. Cockpit boundary surfaces are defined. Model reaches are made within the boundaries imposed by en fleshment and cockpit surfaces. The result of exercising the model is a description of the effort and time required to reach the controls and provides indications of the points

of contact between limbs and cockpit surfaces. This model has proven complicated to implement because of the volume of data required and the complexity of the cost of movement algorithms. Consequently, it was typically employed late in the design process.

BOEMAN provided the conceptual bases and motivation for other workplace assessment models, for example, CAPE, CAR, and COMBIMAN.

COMPUTERIZED ACCOMMODATED PERCENTAGE EVALUATION (CAPE) MODEL

The CAPE model was developed as a design tool for the assessment of cockpit crewstation design in terms of the percentage of the aircrew population that could be accommodated by that design (Bittner, 1975, 1979). The CAPE program used a multivariate Monte Carlo simulation to create a typical sample, based on 2,500 "pilots" that matched the means, standard deviations, and correlations of 13 anthropometric variables that are critical for the design of cockpits, that must fit a target population (Gifford et al., 1965). The Monte Carlo simulation component of this model was tested in a series of investigations that compared actual and Monte Carlo estimates of the proportion of a population accommodated as various anthropometric exclusions were applied (Bittner, 1974). The Monte Carlo component was found to be valid based on the results of four evaluation studies (Bittner, 1976).

The CAPE pilot link system component was selected to augment arm and leg reach models in the design standard for military aircraft (Department of Defense, 1969). This link system was viewed only as a baseline; the development of a later model based on the BOEMAN (Ryan, 1970, 1971) link system was proposed (Bittner and Moroney, 1975). This proposal was implemented subsequently in the CAR model (Edwards, 1976; Harris et al., 1980), which replaced CAPE.

CREWSTATION ASSESSMENT OF REACH (CAR) MODEL

The CAR model is a design evaluation tool for determining the population percentage that can be accommodated by a particular crewstation design (Edwards, 1976; Harris and Iavecchia, 1984; Harris et al., 1980).

The CAR model allows the user to define the geometry of

the crewstation and to select an operator sample to evaluate the crewstation design. The CAR model consists of an anchorage point, the design eye point (DEP), the line of sight (LOS), seat characteristics, head clearance data, and a set of hand and/or foot controls. The anchorage point is the fixed location in space to which the operator must position a specific body part. Anchorage options include:

- seated, positioned to DEP (similar to BOEMAN);
- seated, positioned to a foot control;
- seated in a nonadjustable seat;
- standing in a fixed position;
- shoulder positioning; and
- hip positioning.

The operator's seat consists of a seat back, seat pan, seat adjustment, and harness. The seat adjustment is defined by the seat reference point (i.e., the center of the line segment formed by the intersection of the seat back and the seat pan), the furthest-down forward position of the seat, and the furthest-upward back position of the seat. The user defines the harness by specifying the position along the horizontal shoulder line where the harness meets the shoulder. A maximum of 50 controls can be specified for the crewstation. Controls are defined in terms of body part (hand or foot), the grip that is appropriate for the control (clenched palm open; fingertip; thumb; or pinch, extended, or point), the harness condition (locked or unlocked), and the control location. An additional point representing the limit of the linear range of movement is specified for adjustable controls.

The sample population can be generated either by a Monte Carlo process based on the means, standard deviations, and correlation coefficients of standard anthropometric measurements following the procedure developed by Bittner (1975) or by using direct inputs based on the actual measurements of test individuals. In either case, body measurements for the sample population are transformed into links, a modification of the procedure used in BOEMAN (Ryan, 1970, 1971). The 19 links in the CAR link-person model (Figure 4-1) represent a simplification of the human skeletal structure from the 31 links used for BOEMAN (Harris and Iavecchia, 1984; Harris, et al., 1980; Zachary, 1979).

The CAR model analyzes the ability of an operator in the sample to reach a control by starting at the lumbar joint and

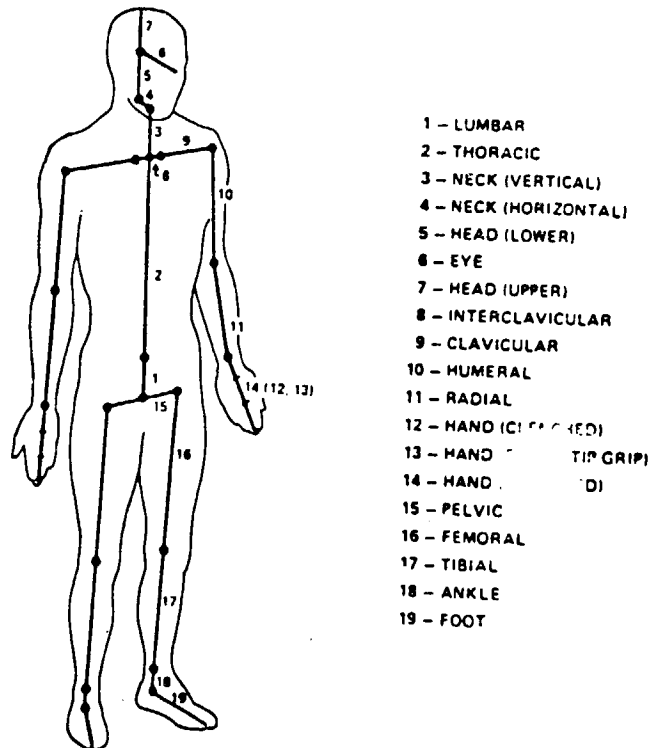


FIGURE 4-1 CAR Link-person model. SOURCE: Harris and Iavecchia (1984).

adding links in succession in the direction of that control. The links are constrained by angular limits of motion associated with each link joint, the harness conditions, and the type of clothing. Since the link lengths calculated for the operator sample are for an unclad operator, CAR allows the user to specify whether the operator is wearing either summer or winter flight clothing. The clothing specification modifies the appropriate link lengths and the angular limits of motion.

Three types of reaches can be incorporated into the CAR model:

Zone 1: The shoulder harness is locked, and the operator does

not strain against the harness. The lumbar, thoracic, interclavicular, and clavicular links are immobile. The remaining links are allowed to move within their angular limits.

Zone 2: The shoulder harness is locked, and the operator strains against the harness. The lumbar, thoracic, and interclavicular links are immobile. The clavicular link is allowed to move within the confines of the harness. The remaining links are allowed to move within their angular limits.

Zone 3: The shoulder harness is unlocked. All links are allowed to move within the bounds of their angular limits. Zone 1 and zone 2 reaches are performed for all hand controls, where the shoulder harness is specified as locked by the user. Zone 3 reach is performed for foot controls and hand controls, where the shoulder harness is specified as unlocked.

CAR evaluates each operator in the sample to determine the ability to place himself adequately (i.e., with respect to anchorage point, DEP, LOS, and head clearance) and the ability to reach controls for zones 1, 2, and/or 3 reach as appropriate.

The results indicate the percentage of the population that can achieve visual accommodation and the percentage that is capable of reaching each control. Guidance in changing control positions for improved accommodation is given in the form of reports detailing the distance and direction of control location alteration to accommodate additional portions of the population.

The flexibility of a model such as CAR was illustrated in a recent program for flight deck design (Stone and McCauley, 1984). In that study, data input was based on the anthropometric measurement of a broad range of aviation personnel in the U.S. Air Force, Army, and Navy. Stone and McCauley observed that, using the standard numerical link-person analysis provided by CAR, an accurate analysis of reach could be performed. Complete fit and function analyses required both graphic output and enfleshment (Figure 4-2). The resulting figures are three-dimensional and possess the dimensional characteristics of the people created by the CAR program in terms of both link and body dimensions.

For flight deck design, the CAR model generates full reach envelopes in various planes, along with eye and seat reference point locations. All the components are then integrated to allow evaluation of alternative designs for placement of controls, displays, and other equipment as a function of operational task requirements.

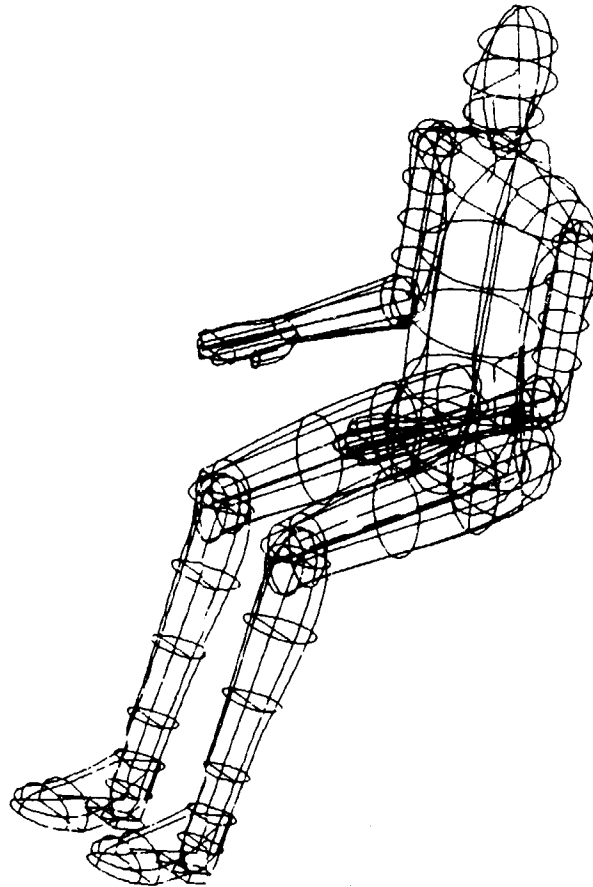


FIGURE 4-2 CAR three-dimensional anthropometrically variable crew member. SOURCE: Stone and McCauley (1984: 11). Reprinted with permission © 1984 Society of Automotive Engineers, Inc.

The resulting three-dimensional models of the operator, the equipment, and the environment can be viewed on the screen in front, top, and side elevations; in isometric projection; or in perspective from any viewpoint. This capability enables the user to enter and walk around inside the model.

The scale of the model can be changed and hidden lines can be removed. All objects within the model can be repositioned and regrouped. Further development of the CAR model will provide

a building block concept for systematic design and evaluation of various workstations.

Efforts are under way to validate the CAR model. For example, based on the CAPE model (Bittner, 1975), the Monte Carlo component has been evaluated by four accommodation studies, which have been summarized by Bittner (1976). In addition, the anthropometric measurements and reach envelopes for individual subjects are being directly compared with model estimates under typical seat, restraint, and workplace conditions. Finally, CAR has been tested for the congruence of model reach data and experimentally derived anthropometric reach envelopes (Bennett et al., 1982; Kennedy, 1978).

SYSTEM FOR AIDING MAN-MACHINE INTERACTION EVALUATION (SAMMIE)

SAMMIE, developed by a team of investigators at the University of Nottingham, England, under the leadership of Maurice Bonney, was produced to evaluate the design of simple workstation layouts (Bonney et al., 1969). With SAMMIE three-dimensional models of equipment and environments can be built by specifying and assembling geometrical shapes. The anthropometric model is preprogrammed to represent a male of average height and weight based on data developed by Dempster (1955), but can be modified to represent other anthropometric data.

SAMMIE consists of two independent modules:

- *Three-dimensional modeling functions:* This component builds models of equipment or workplaces by assembling primitive geometric shapes or general shape definitions, as shown in Figure 4-3.
- *Man-model:* The human model consists of 19 connected links representing a schematic skeleton around which three-dimensional solids such as boxes, cones, and cylinders are placed to denote outer contours of the human body.

The idealized flesh contours can be varied to simulate body builds from slim to rotund (Sheldon, 1940). Each link length can be varied to create different body proportions and can be adjusted to any feasible body position. Extreme limits of joint movements and comfort can be included in the model. The body segments are connected by pin joints at the shoulders, hips, neck, knees,

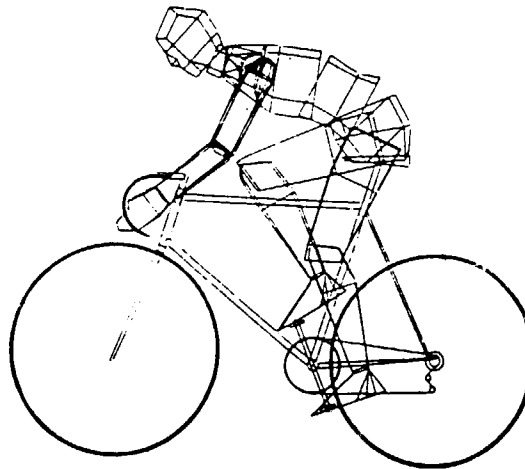


FIGURE 4-3 Example of a SAMMIE geometrical model. SOURCE: SAMMIE Human Factors 3-D Design System (1985).

and other articulations. Logical relationships are included so that when an upper arm moves, the lower arm and wrist also move in the expected direction, representing normal human movement, as specified in a user-definable joint constraints table. The limbs can only extend as far as human limbs can reach. It is also possible to model factors that limit movement, such as clothing.

SAMMIE has the capability to create concave, convex, or plane mirrors superimposed on any surface in the workplace and can then examine the reflections found from any vantage point. Another module is used to assess visibility encompassing 360 degrees of view horizontally and 180 degrees vertically.

The following evaluations can be performed by SAMMIE:

- ability to reach;
- fit of a person in a confined workspace, including operator size and shapes, clearances, and access aperture sizes and positions;
- working postures (e.g., seated, standing, bending);
- visibility, including head and eye movement constraint, production of two-dimensional vision maps, and three-dimensional vision charts;
- field of vision;
- blind spots; and

- mirror views.

The environmental component of SAMMIE consists of geometrical information defining solid objects, location and orientation data, and relationships between objects and humans.

The model can be viewed in plane parallel projection or in perspective (from either outside or within the model) in front, top, and side elevations or a combination of views. The model can be viewed from a specific internal center of interest or from a position that represents the subject's visual view of the environment. The scale can be changed and hidden lines can be removed.

The model, once constructed, can be repositioned and regrouped as needed. It lends itself to the modeling of human interactions with control panels and workplace ergonomic evaluations. Movement can be simulated frame by frame to evaluate reach, fit, strength, balance, comfort, or vision for candidate postures.

ARTICULATED TOTAL BODY (ATB) MODEL

The ATB model is a modified version of the crash victim simulator program developed by Calspan Corporation for the National Highway Traffic Safety Administration (NHTSA) to study human response during automobile crashes (Fleck et al., 1975). The U.S. Air Force's Armstrong Aerospace Medical Research Laboratory modified this model for application to the study of human body dynamics during ejection from high-performance aircraft, developed a three-dimensional projected graphics display capability, and applied the name articulated total body (ATB) model to this modified software program (Butler and Fleck, 1980; Butler et al., 1983; Fleck and Butler, 1975).

The three-dimensional ATB model is formulated in terms of rigid body equations of motion. The body segments do not deform during motion; all body deformation occurs only at the joints that connect the body segments. The standard configuration consists of 15 segments, but the actual number that can be specified is limited only by the computer memory.

The body segments are coupled at joints, the centers of which are specified by three-dimensional coordinates within each segment and with respect to landmarks on that segment. Each segment has its own coordinate system defined with respect to bony anatomical landmarks on that segment. Coordinate systems are also defined

for each segment for each of the joint centers to provide for the application of resistive torques in the joints and to limit the range of motion as a function of joint position.

The segment masses can be specified, as can the rotational principal moments of inertia. The principal axes are specified with respect to the segment anatomical landmark coordinating systems.

Motion or dynamic response of the body is induced by specification of the motion of a body segment or an external configuration or force that interacts with the body. In the most common application, motion is defined by seat displacement. The body interacts with the seat by contact forces between planes that describe the seat geometry and planes and ellipsoidal contact surfaces that are attached to each segment. In addition, harnesses, air bags, wind pressure, gravity, and prescribed forces and torques can act on body segments. For most applications the body is assumed to respond passively; however, the model formulation does allow for active muscle elements (Freivalds, 1984).

The output from the model consists of time histories of linear and angular displacement, velocity and acceleration for each segment, the location on each segment of the point of contact with the external configuration or any other body segment, and the force of contact; restraint harness forces and the forces that the harness applies to the body surface; the joint orientations and the forces and moments across each of the body joints; the wind forces on each segment; and the total body center of mass location, momentum, and kinetic energy. In addition, by using the complementary program VIEW (Leetch and Bowman, 1983a,b), body graphics can be displayed in the form of three-dimensional projected images. The program also allows arbitrary selection of the viewpoint.

The standard 15-segment configuration establishes a body structure, but individual data bases determine dimensions and inertial properties. A program (GEBOD) was developed to generate various percentile data sets for adult males and females as well as for 3- and 6-year-old children (Baughman, 1983). Also, data sets have been developed for flying personnel based on a 1967 survey of U.S. Air Force male aviators (Grunhofer and Kroh, 1975) and for manikins used in acceleration and impact testing (Chestnut et al., 1985; DeLeys, 1981; Hubbard and McLeod, 1977). Various methods for the determination of human body segment inertial

properties have been developed, ranging from the use of approximating geometric shapes (Baughman, 1982) and measurement of cadaver segment properties (Chandler et al., 1975) to the use of stereophotometric methods to map the three-dimensional surface of the human body (McConville et al., 1980; Young et al., 1983). The last method has provided the most comprehensive body segment inertial property data for both males and females that is currently available, and presents the data with respect to precisely defined bony anatomical landmark segments and coordinate systems based on these landmarks.

Because of the common technical interests of the U.S. Air Force and NHTSA in biodynamics, particularly regarding tolerance criteria to mechanical forces, related model enhancements have been shared by both agencies and integrated into one common code (Kaleps, 1978; Kaleps and Marcus, 1982). This code is used by aerospace and automotive companies, universities, and government agencies.

COMPUTERIZED BIOMECHANICAL MAN-MODEL (COMBIMAN)

COMBIMAN is a three-dimensional computerized interactive graphics technique originally developed for workplace design and evaluation (Bates et al., 1973; Korna and McDaniel, 1985; Kroemer, 1973; McDaniel, 1976, 1982). It is also used for selecting persons who fit workplaces and for mapping visibility plots.

The man-model is constructed in three stages (Evans, 1975; McDaniel, 1976). A 33-segment link system which corresponds functionally to the human skeletal system is generated. Each link connects major points of rotation of the body segments. Two of the links represent the seat reference point, which serves as a starting point to add links sequentially to form the man-model. The link dimensions are based on anthropometric data that are entered directly or computed from anthropometric survey data. Each link is assigned a three-dimensional Euler-type angle that relates the angular coordinates of each new link to that of the previous link. This coordinate system places realistic limitations on the range of mobility of a joint and permits the repositioning of a distal link by moving a proximal link. Each link has up to 6 degrees of freedom with respect to the external coordinate system.

Version 7 of COMBIMAN (Korna and McDaniel, 1985) uses

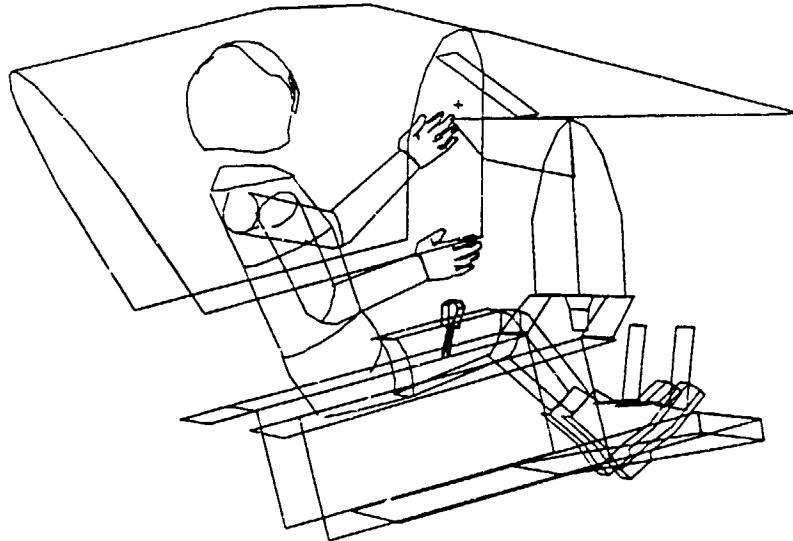


FIGURE 4-4 COMBIMAN man-model. "Reach Successful" is displayed after the reach is successfully performed. SOURCE: Korna and McDaniel (1985).

an entirely new enfleshment technique to represent the irregular surface necessary to depict clothing and personal protective equipment. A surface is created by an array of small triangles, similar to the technique used in finite-element analysis. An algorithm determines those lines that are on the profile view (from any view direction) and also those lines that are essential (such as facial features) and eliminates all other lines before the displayed image is generated. The result is a high-fidelity profile view of an irregular figure (Figure 4-4).

In workplace design, the control and display panels are defined by cornerpoints around the man-model. Predetermined panel dimensions, restrictions, and constraints are entered by light pen, keyboard, punched cards, magnetic tape storage, or disc storage. The user has the option of displaying all or a few of the characteristics of the workplace at one time.

The workplace is evaluated by interaction with the three dimensional human model. Although the cathode-ray tube is a

two-dimensional display, two orthogonal views are projected simultaneously and can be rotated for viewing at any angle and can be magnified. In the model, however, algorithms exist in three dimensions.

The evaluation techniques consist of defining the dimensions of the man-model and simulating intended tasks within the workplace.

The man-model dimensions can be defined in several ways:

- *Direct Measure*: Specific measurements are entered from the keyboard or punched cards.
- *Data Base Summary Statistics*: Percentiles computed from large samples are used to define the man-model. Individual segments may be modeled for groups with different percentiles.
- *User Population*: Several anthropometric surveys are incorporated in the COMBIMAN model. A utility program allows the user to define which survey to use or to add data from other surveys.
- *Computer-Aided Dimensioning*: Abstract human models can be generated from anthropometric survey data. A critical body characteristic relevant to the evaluation of a task can be called up and used to construct a proportioned man-model based on a series of regression equations.

Once the man-model is built, it can be positioned by commands from a light pen or keyboard.

The COMBIMAN hand is made up of three links originating from the wrist: (1) grip center (for whole-hand grasp); (2) functional reach (e.g., finger grip, knobs); and (3) fingertip reach (e.g., pushing a button).

The program evaluates reach capability as a function of clothing and restraints (harness) in two ways. First, the user can select a control handle or pedal, or even an arbitrary point in space, and the COMBIMAN simulates the process of reaching to that point. Second, the user can select a control panel, and the model will compute the maximum reach envelope in the plane of that panel.

If a point or control can be reached, the user can evaluate the force which the COMBIMAN can exert in that control location, in a defined direction, and to a specific control.

The reach routine applies to the arms, legs, and head. Movements can be limited or confined, such as arm-shoulder movement only or arm-shoulder-trunk movement.

A printout and plot of the workplace providing detailed body dimensions of the man-model and coordinates of the workplace in any scale can be generated at any design or evaluation stage.

For mapping the visual field of a workplace, COMBIMAN defines a range of three-dimensional head and eye positions with coordinates. The size of the operator, seat adjustment, head position, and visual restrictions can all be varied. This generates realistic visual angles.

Other features of the COMBIMAN include the following:

- *Change View*: Views the model and crewstation from any angle.
- *Identify Object*: Shows the name and three-dimensional coordinates of any characteristic of the crewstation.
- *Omit Object*: Declutters the display.
- *Retrieve Crewstation*: Calls up any of the crewstations stored in the library.
- *Visibility Plot*: Plots the crewstation as seen by COMBIMAN.
- *Display Anthropometry*: Displays the values of sizes of the body segments.
- *Display Links*: Displays the dimensions and angles of the skeletal link system of COMBIMAN.
- *Design Panel*: Allows the user to add a new characteristic of modification to an existing crewstation.
- *Modify Posture*: Permits the user to manually change the posture of the model.
- *Seat Adjust*: Allows the user to reposition the seat.
- *Zoom*: Causes a portion of the image to be magnified to fill the entire screen.
- *Plot*: Produces paper a plot of the crewstation and COMBIMAN in any scale.
- *Add Crewstation*: A utility program that allows a user to define a new crewstation and add it to the library.

CREW CHIEF

The U.S. Air Force Armstrong Aerospace Medical Research Laboratory and the U.S. Air Force Human Resources Laboratory are jointly developing a computer-aided design (CAD) model of an aircraft maintenance technician (McDaniel, 1985; McDaniel and

Askren, 1985). This three-dimensional interactive graphics model would have an interface with existing commercial CAD systems. The developers expect to have an initial version available for use in 1988.

The CREW CHIEF model will give the CAD designer the ability to use the computer drawing board to simulate maintenance and related human operator interactions with a system. It will represent the correct body size and proportions of the maintenance technician, the encumbrance of clothing and personal protective equipment, mobility limitations for simulating working postures, physical access for reaching into confined areas (with hands, tools, and objects), visual access (seeing around obstructions), and strength capability (for using hand tools and manual material-handling tasks).

The CREW CHIEF model user will be able to select data from a range of body sizes of both male and female maintenance technicians.

The initial model will have four types of standard clothing to choose from: fatigues, cold weather, arctic, and chemical defense. The clothing interacts with the joint mobility limits for strength and posture to model accessibility.

The CREW CHIEF model will display the visual accessibility of maintenance personnel. For example, inserting a screwdriver into a screw head requires that the technician simultaneously see and reach the screw head. The CREW CHIEF model allows the designer to see the task from the maintenance technician's viewpoint and to determine whether it can be physically accomplished.

The 12 CREW CHIEF model postures include standing, sitting, kneeling on one knee, kneeling on both knees, stooping, squatting, prone, supine, lying on the side, walking, crawling, and climbing. Some of these postures reduce the mobility of the limbs and the strength available to perform the task. These are only starting postures, however, and the designer can manipulate all the body segments as required to achieve the desired posture. Posturing will be automated for accessibility, reach, and strength analyses.

The CREW CHIEF model will have a realistic simulation of the strength capabilities of a maintenance technician. AAMRL has recently gathered strength data relative to the manual handling task (lifting, pushing, and pulling) for the postures described

above. Another major data base includes torque strength with various hand tools.

The CREW CHIEF model itself will be three-dimensional. To accurately represent the clothing, the model will have a surface of facets (triangles) attached to the 35 links which make up the skeletal link system. A simplified three-dimensional model will be available whenever the designer wishes to rotate the model, and a hidden line two-dimensional model will be available for high-resolution views and plots.

PLAID AND TEMPUS

PLAID and TEMPUS are modeling programs created specifically for the Man-Systems Division, Lyndon B. Johnson Space Center (JSC), National Aeronautics and Space Administration, for use in man-machine interface design and evaluation for the space shuttle and the initial space station configuration. The earliest concept of PLAID was an interactive graphics software system for the design of instrumentation panel layouts (Lewis, 1979a; PLAID Preliminary Specifications, 1977). PLAID is currently housed in a VAX 11/785 computer. PLAID will also be used with an automated anthropometric measurement system being developed for JSC (Lewis, 1979b).

PLAID is a system for analyzing the crew interaction with crewstations and spacecraft systems and components (Brown, 1982). It is based on full-scale, three-dimensional, solid-geometry computer software models that are created interactively by the user. The program can represent humans in shirtsleeves and space-suits, crew workstations, spacecraft, and virtually any structure the user desires to build. These elements, called primitives, are assembled in the computer and viewed on the computer monitor. PLAID provides flexibility in achieving the desired renderings and evaluation products, while the model data base stores created primitives and assemblies for subsequent use (Brown, 1981).

The user begins the modeling process by defining the end product. If a primitive that is required for the activity is in the data base, the user can assess its appropriateness for the particular analysis.

All primitives are constructed in BUILD, the first major module of PLAID, from planar polygons created interactively by the user. The polygon can be built either graphically or numerically in

one of six standard orthographic views (front, back, top, bottom, left, or right). Once polygons are created, the user can combine them, either by translation along one, two, or three axes or by rotation about some axis. Hence, a square can be translated along the nonrepresented axis for conversion to a rectangular box, a half-circle can be rotated about its base to create a sphere; and a circle can be rotated about an offset axis to form a torus.

A contour function allows the creation of a solid object by joining planar polygons, essentially creating a surface between the edges of two planes. This function is particularly useful for building objects with complex contours, such as the human body, human reach envelopes, and the space shuttle orbiter. For example, by using cross-sectional plots (reduced from digitized body mapping data in PLAID's REACH module), a shirtsleeved crew member can be created graphically.

A second major module of PLAID, COG (composite object generator), is the basis for grouping constructed primitives. The COG file contains primitive parts, COG file (subassembly) parts, or some combinations of primitives and subassemblies. Versatility can be achieved by careful selection of parts and by the COG file structure itself. The use of subassemblies facilitates stop-action articulation or motion in assembly since a subassembly has both its own local coordinate system and a second one in a global coordinate system of the assembly achieved via translation and rotation. By layering subassemblies and parts, a human arm, for example, can attach to the shoulder, yet when rotated, the upper arm primitive and lower arm subassembly move as a unit. At the next level, the lower arm, attached at the elbow, moves itself (a primitive) and the hand assembly attached at the wrist. Each element of the arm has its own local origin and coordinate system to enhance motion commands but can be translated and rotated to attach it to the next element in the tree.

Final viewing and conflict checking is performed with a third major PLAID module, DISPLAY. Here, the user identifies the object (i.e., target file) of interest and specifies the other parameters that are required to produce the desired end product.

Several alternatives for the final renderings are available, including a wire frame, in which all assembly lines are visible. This common-form rendition is often satisfactory for simple objects, but interpretation usually suffers from ambiguity. In another rendition, hidden lines are automatically removed or shown as dashed if

behind-the-scene viewing is required. A conflict detector is another user option in which collisions of parts are defined numerically and graphically for ready identification. The PLAID program also calculates between-vertex clearance. While these line drawings are appropriate for most applications, PLAID shaded renderings are also available.

The REACH module of PLAID serves as the interface with the anthropometric data to render crew reach and body mapping contours and contours from other digitized data.

By using PLAID for interface ergonomic models, human body models of various sizes can be built and articulated with respect to workstation layouts. Improvements are sought, however, in the complementary software package TEMPUS to create a basic man-model that will interact with the PLAID program and data base elements. The TEMPUS user interfaces allow for a user-specified body to be constructed and more easily manipulated in the desired environment. For example, the PLAID person is articulated by the user on a joint-by-joint basis, with the user being responsible for body size parameters and joint limits. In TEMPUS, the user selects a specific crew member from the data base, one or more anthropometric measurements, or a random body. The internal anthropometric data base governs the constraints for size, range of motion, sex, and other parameters. Thus, the computer can avoid the use of a trial-and-error positioning schema.

The body modeling is accomplished by using the data in the CAR model (Harris et al., 1980). Following CAR, TEMPUS calculates the body segments by using regression equations. These segments are then used to build a link person. One graphic procedure that provides a realistic approach is the use of "bubble people" (Badler et al., 1980), which are composed of hundreds of small spheres. Enfleshment of the link is proportional to link length; girth measurements are not used. Other graphics models include stickmen (no thickness) and "polybodies" built of polyhedrons. In each case, the three-dimensional body is generated by the computer and displayed graphically in the workstation. (For a detailed review of this technique, see Woolford and Lewis [1981] and Stramler and Woolford [1982]).

Knowledge of the positions of the arms, legs, head, and torso as well as their velocities and vectors are required to specify a body in motion. Specifications of forces requires knowledge of accelerations as well. Data storage and access requires extensive effort, however.

In the initial stages of the study of the biomechanics of astronaut extravehicular activity (EVA), a dictionary of units of motion is constructed. The dictionary entries are isolated motions that can be combined to describe complex tasks. For planning new tasks, the components can be extracted from the dictionary and combined to describe the activity. Information regarding time, forces, restraints, and aids that are required to perform the tasks can be deduced.

A major requirement for these models of human performance is realistic motion data. Some rules of motion can be extracted from the viewing of films of human motion. However, more precise data can be obtained by digitizing data derived from points on the arms, legs, and torso as the subjects move. Automation can play a large role in this regard (O'Rourke, 1980).

TEMPUS has an associated animation capability in which the movements of subjects and objects in the picture can be coordinated with each other and with a soundtrack. The animation is dependent on the operator drawing key frames in which the stages of motion are displayed. For example, while reaching for a switch the body might be portrayed in the rest position with the arm partly raised and the hand on the switch. The animation facility then generates intermediate frames between these key frames to interpolate motion.

One approach to the analyses of changes in body position and force vectors during the performance of a task is the use of models rather than traditional tables. For example, the body can be modeled as rigid links connected with rotary motors capable of exerting known forces or moving at known velocities. The kinematics and dynamics of the body can then be modeled by using trigonometry, differential equations, and linear algebra.

Digitized film data taken of astronauts are used to develop models of forces applied in EVA tasks. (See Bowden [1981] for a description of some of the pioneering efforts in this area.) This effort results in equations of motion that can be integrated numerically to provide position and orientation information for the body segments. In turn, these data can be used to drive graphic displays of motion to permit assessment of proposed EVA procedures.

DISCUSSION

Table 4-2 summarizes many of the important features of these models. The following points describe the state of the art in the development of interface models.

- Current interface models are specific to given designs, purposes, or characteristics.
- The usefulness of interface models is limited by the anthropometric and/or biomechanical data input.
- The workstation and the operator need to be accurately modeled.
- Predictive models of the effects of the dynamics of "platforms" (e.g., ships, spacecraft, airplanes) on tasks are not available.
- There is a paucity of dynamic interface models.
- Effects of stress and motivation have not been adequately quantified or modeled.
- Effects of fatigue, trauma, and other injuries have not been adequately quantified or modeled.
- The effects of environmental factors on human performance are largely unquantified.
- The impact of complex aspects of vision, audition, and the speed and accuracy of responses to other sensory inputs and signals need to be explored for their impact on human-machine interface modeling.
- Sociological factors such as habitability that have an effect on human performance are largely unquantified.
- Model validation is a largely unresolved issue.

COMPARISON TABLE OF INTERFACE MODELS

Table 4-2

TABLE OF COMPARATIVE MODELS

MODELS	2-D 3-D	LINE/OTHER	SHAPE	DYNAMIC/STATIC	LIMITS JOINTS	STRENGTH	VISION
CAR (BLOG, BLOCK SYSTEM)	3-D	-31 LINES VARIED BY MONTE CARLO SIMULATION FROM DATA	-EMBEDMENT AROUND LINES (GEOMETRICAL PRIMITIVES & CIRCLES) ONLY IN THE SCENE & MECHANICAL CAD/CAM INTERFACE VERSION	STATIC -VARIOUS POSITIONS	-JOINT ANGLE CONSTRAINTS CLOTHING, RESTRAINT SYSTEM	NO	-EYE REFERENCE POINT AND LINE OF SIGHT
SAMPLE	3-D	-RIGID -19 LINES	-GEOMETRICAL PRIMITIVES (CONES, CYLINDERS CIRCLES)	STATIC -VARIOUS POSITIONS -CAN BE SEQUENCED	-LOGICAL RELATIONSHIPS -INITIATION OF MOVEMENT -JOINT CONSTRAINT -CLOTHING	NO	-HEAD & EYE MOVEMENT CONSTRAINT -2-D VISION MAPS -3-D VISION CHARTS -FIELD OF VISION
ATD	3-D	-15 OR MORE -RIGID -SEGMENTS	-ELLIPSOIDAL FOR CONTACTS, ANY SHAPE FOR GRAPHICAL DISPLAY	-3-DIMENSIONAL BODY DYNAMICS	-PIN, EULER AND GEOGRAPHIC JOINTS WITH RANGE OF MOTION AND MOTION RESISTANCE PROPERTIES	NO	NO
COMBIMAN (Computerized Biomechanical MAN-model)	3-D	-35 VARIABLE LINES, DEFINED MANUALLY OR FROM DATA BASE	-IRREGULAR 3-D FACETED SURFACE W/ NONESSENTIAL ESSENTIAL LINES LINES REMOVED	-STATIC WITH AUTOMATED LIMB REACH CAPABILITY, ALL LINES REMOVED	-ALL JOINTS MOVABLE W/ 4 DEGREES OF FREEDOM, HUMAN AND CLOTHING MOBILITY -LIMITS WITH AUTOMATED LIMB REACH	-PREDICTS 1,5,50, 95 AND 99TH PERCENTILE MALE & FEMALE STRENGTH IN FORWARD REACH- HEMISPHERE	-PLOTS VIEW TO CREWSTATION +100 DEGREES AZIMUTH, +90 DEGREES ELEVATION WITH VISION LIMIT OVERLAYS, -MOBILE HEAD
CREW CHIEF	3-D	-35 VARIABLE LINES DEFINED FROM DATA BASE	-IRREGULAR 3-D FACETED SURFACE W/ NONESSENTIAL LINES REMOVED	-STATIC WITH AUTOMATED LIMB REACH CAPABILITY, ALL LINES REMOVED	-RESTRICTION BY CLOTHING OR PROTECTIVE EQUIPMENT MOBILITY LIMITATIONS -RESTRICTED REACH BY 4 DEGREES OF FREEDOM	-PREDICTS 1,5,50, 95 & 99TH STILE MALE & FEMALE STRENGTH FOR MAINTENANCE ACTIVITIES	-PLOTS VIEW OF WORKPLACE +100 AZIMUTH, +90 DEGREES ELEVATION WITH VISION LIMIT OVERLAYS -MOBILE HEAD
PLATO/TENPUS	3-D	-MULTI-LINE BODY MODEL -MAN-MODEL SAME AS CAR -STICKMAN -POLYEDRONS/ BUBBLE PEOPLE/ SPHERES	-GEOMETRIC MODELS-SPHERES -3-D SURFACE MAPPING SYSTEM (LANS) -LASER BASED COORDINATES	-STATIC, BUT SIMULATES MOTION W/ USE OF GEO ANIMATED SEQUENCE -GLOBAL TRANSLATION OR ROTATION OF LIMB OR BODY	-ROM CONSTRAINTS -CONSTRAINT BY CLOTHING	-COLLECTING DATA -MODELING FORCES FOR TASKS	-DEFINITION OF VIEWING COORDINATES -CAMERA FUNCTION VISUAL ACCESS

COGNITIVE	WORKSTATION	FORCES APPLIED	ANTHROPOMETRIC DATA BASE	DATA	SCALE/CHANGE	VIEW
NO	-CONTROLS, DISPLAYS SEAT, RESTRAINT SYSTEM	NONE	-ANY POPULATION DATA BASE WHICH INCLUDES MEANS, RESTRICTIONS, CREW STANDARD DEVIATIONS, AND STATION GEOMETRY BIVARIATE CORRELATION COEFFICIENTS OR ACTUAL OPERATOR MEASUREMENTS	-BODY SIZE, CLOTHING BASE WHICH INCLUDES MEANS, RESTRICTIONS, CREW STANDARD DEVIATIONS, AND STATION GEOMETRY	-YES (IN STONE AND MCCABEY VERSION)	-ANY VIEW IN STONE AND MCCABEY VERSION
NO	-EQUIP OR WORKSPACES OF GEOMETRIC SHAPES LOCATION DATA RELATIONSHIP DATA				YES	-MIRROR -PLANE PARALLEL PERSPECTIVE -FRONT -PLAN ELEVATIONS -PLAN -SIDE COMBINATION CENTER OF INTEREST VIEWING POINT
NO	-DEFINABLE IN TERMS OF FORCE INTERACTIVE PLANES AND ELLIPSOIDS	-CONTACT FORCES ON AND BETWEEN BODY SEGMENTS -NORMAL PRESSURE ON SURFACE OF ELLIPSOIDS -RESTRAINT SYSTEM INTERACTION -GRAVITATIONAL FORCES -PRESCRIBED FORCE OR TORQUE ON ANY SEGMENT	-USAF FLYING PERSONNEL -VARIOUS MALE & FEMALE POPULATIONS -3 AND 6 YEAR OLD CHILDREN -VARIOUS TEST DUMMIES	-JOINT CENTERS -SEGMENT INERTIAL PROPERTIES -SEGMENT FORCE- DEFLECTION CHARACTERISTICS -JOINT MOTION RESISTANCE PROPERTIES	DETERMINED BY DATA BASE	-BODY DEFINED BY ELLIPSOIDS OR OTHER USER SPECIFIED SHAPE FOR SEGMENTS AND DISPLAYED IN 3-DIMENSIONS PROJECTED VIEW FROM ANY VIEWPOINT
NO	-ANY SEATED WORKSTATION DEFINED BY THE USER	NONE	-1ST-99TH PERCENTILE AIR FORCE MALE & FEMALE PILOTS -ARMY & NAVY MALE PILOTS -AIR FORCE WOMEN -ARMY WOMEN -OTHERS AS DEFINED BY USER	-BODY SIZE -BODY MOBILITY -CLOTHING RESTRICTION -STRENGTH -VISION LIMITS -CREWSTATIONS	YES -200X ON C.R.T. -PAPER PLOTS TO ANY SCALE	-MAY BE VIEWED FROM ANY ANGLE: 3 ORTHOGONAL VIEWING PLANES -MAY VIEW 2 SIMULTANEOUSLY -MAY BE ROTATED & ACUTE ANGLES TO THE VIEWING PLANE -MAGNIFIED -2-D C.R.T. DISPLAY
NONE	-ANY WORKSTATION DEFINED BY THE USER	-GRAVITY FOR BALANCE COMPUTATIONS	-U.S. 50-95 & 99TH RILE AIR FORCE MALE & FEMALE MAINTENANCE TECHNICIANS, -OTHERS AS DEFINED BY USER	-BODY SIZE -BODY MOBILITY -CLOTHING RESTRICTION -STRENGTH -VISION LIMITS	ACCURATE SCALE REPRESENTATION ANY SCALE ON CRT	CAN BE VIEWED FROM ANY ANGLE
	-CREATED BY POLYDROM TRANSLATED OR ROTATED -PUNCH" CREATES HOLES -HILL" ADD'S OR SUBTRACT'S -CHARACTERS/LETTERS -CONTOUR: CREATES SURFACE BETWEEN SPHERES -CAG-GROUPS PRIMITIVE		-NASA ASTRONAUT FILES			FRONT & BACK TOP & BOTTOM LEFT & RIGHT AXES: HORIZONTAL VERTICAL IN/OUT SCREEN DIMETRIC & ISOMETRIC ORTHOGONAL & PERSPECTIVE

COMPARISON TABLE OF INTERFACE MODELS

TABLE OF COMPARATIVE MODELS

MODELS	MOVING LINES REMOVED	OUTPUT	CONTROLLED BY	FEATURES	ASSUMPTIONS	COMPUTER
AM PLS (BLOCK SYSTEM)	YES, IN SOME MCCABREY VERSION	PROPORTION OF CREW ACCOMMODATED IN VISION AND REACH, REACH ENVELOPES	KEYBOARD CARDS DISK TAPE THE STORE/ MCCABREY VERSION REQUIRES INTER- ACTIVE GAB/CAN TERMINAL	REQUIRES SPECIFIC ANTHROPOMETRIC DATA FROM DATA BASE OR ACTUAL OPERATORS	MINIMALLY REQUIRES ESTIMATES OF INDIVIDUALS, STANDARD DEVIATIONS, AND CORRELATIONS	FORTRAN 77 MAINFRAME OR LARGE MINI UNIVAC
SAMITE	YES	REACH CLEARANCES VISIBILITY ASSESSMENTS COCKPIT DESIGNS				PRIME 50 SERIES 32 BIT COMPUTER PRIMS OPERATING SYSTEM "PRIMNET" SOFTWARE 1-25 PACKET SWITCHING PROTOCOL REMOTE JOB ENTRY EMULATION PROGRAMS
ATR	YES	SEGMENT LINEAR AND ANGULAR DISPLACEMENTS, VELOCITIES AND ACCELERATIONS, JOINT ORIENTATIONS, FORCES AND TORQUES CONTACT POINTS AND FORCES, AND OTHER FORCES BODY CENTER OF GRAVITY, MOMENTUM AND KINETIC ENERGY GRAPHICAL DISPLAY SHOWING BODY POSITION IN TIME	BATCH INPUT			REQUIRES MAINFRAME OR MINICOMPUTER CODE IN FORTRAN 77 KNOWN IMPLEMENTATION INCLUDE: PERIM-ELMER REC-VAX IBN CBC
CONTRAM (COMBINED PIONEER/CHIEF MAN-MODE)	AUTOMATED HIDDEN LINE REMOVAL IN MAN MODEL; MANUALLY REMOVED AT WORKPLACE	PAPER PLOTS PAPER TABLES OF ALL ACTIVITIES AND DATA TAP FILES OF PLOTS AND DATA	LIGHT PEN (ON MOUSE ON SOME DISPLAYS) ALPHANUMERIC KEYBOARD FUNCTION KEYBOARD	HIGH RESOLUTION BODY SIZE AND PROPORTION, STRENGTH, VISION, PEACH	SEATED OPERATOR	IBM MAINFRAME (OR EQUIVALENT) VECTOR GRAPHICS GRAPHICS SUBROUTINE PACKAGE
CREW CHIEF	AUTOMATED HIDDEN LINE REMOVAL IN MAN MODEL; MANUALLY REMOVED IN WORKPLACE, OR OTHER AS PROVIDED BY CAD SOFTWARE	SIMULATE MAINTENANCE AS PROVIDED BY CAD SOFTWARE/HARDWARE	GRAPHICS DISPLAY CRT LIGHTPEN (OR MOUSE) KEYBOARD ALPHANUMERIC FUNCTION	VARIABLE BODY SIZE & PROPORTION, STRENGTH, VISION, REACH, ACCESSIBILITY, INTER- ACTION W/ HAND TOOLS & OBJECTS, 12 STARTING POSTURES ADJUSTED BY USER	WILL BE AVAILABLE IN 1980	FOLLOWS CAD SOFTWARE OR SYSTEMS: CADAM (IBN)
FLATO/TERPHIS	YES	CREW REACH CONTIGUOUS ANIMATED MOTIONS CREATES WORKSTATION		COLOR AVAILABLE DATA ADJUSTED FOR BODY DIMENSION CHANGES IN GRAVITY RETENTION IN MULTIPLE COPIES DISPLAYS REACH DATA		VAX 11/780 INPUTS TERTRONIX TERMINALS

5 General Discussion

CONCLUSIONS

As a result of the workshop, the members arrived at the following three major conclusions.

1. *There is a need for an integrated model of the human body, its performance characteristics and limitations, and its interactions with technological systems.* An integrated ergonomic model would provide a valuable tool for the development of specifications for the physical parameters of the work site based on the anthropometric, biomechanical, and interface characteristics of the operators. A valid model of the performance of people in technological systems in the early conceptual and design stages could result in substantial savings in terms of effort, time, and money. The development of an integrated computer model that describes human traits and limitations could prove useful to those who research basic human qualities as well. Thus, the need has both theoretical and practical implications.

2. *The development of such a model appears to be feasible.* Advances in research methods and instrumentation, many of which are associated with the increasing sophistication in the use of computerized systems, have made research feasible on the many anthropometric, biomechanical, and interface details, as well as their interactions regarding human performance capabilities and limitations. The establishment of a standard protocol and nomenclature is essential to the integration effort.

3. *An integrated ergonomic model would be useful for guidance for research, development, and engineering applications.* While current models indicate the usefulness of the approach, they also reflect many of the shortcomings of the diverse approaches identified earlier. The approaches provide solutions to specific problems but contribute little to a generalizable model. Typical examples in which an integrated ergonomic model would be very useful is in applications to computer-aided design (CAD) and engineering, which are fast evolving as major design tools.

Requirements

A study of the requirements for the development of a standard ergonomic reference data system (SERDS) was prepared by the National Bureau of Standards (Van Cott et al., 1978). Although this system was never implemented, the study provides information relevant to the development of an integrated ergonomic model. The following were some of the major findings of this study: (1) A definitive survey of user needs and priorities is necessary in order to define the scope of the system. (2) Standards must be developed for the definition of units, measures, measurement methods, and data reporting. (3) An assessment of alternate technologies for capturing, storing, and processing ergonomic data is needed to identify a cost-effective approach. (4) Data derived from the published ergonomics literature and from the national ergonomics survey (discussed in the SERDS report) must be evaluated critically.

A preliminary survey of potential users at that time identified several important areas of needed research. These areas are shown in Table 5-1.

Similar findings were identified at a conference on the theory and application of anthropometry and biomechanics in 1980 (Easterby et al., 1982) and at a conference on space workstation human factors in 1987 (Montemerlo and Cron, 1982).

Criteria for the Development of an Integrated Ergonomic Model

Several general major criteria that should guide the development of an integrated ergonomic model require that the model have the following characteristics (this list does not imply a ranking by importance):

TABLE 5-1

Data Requirements of Potential SERDS Users

Area of Need	Specific Data Needed	Date Application
Static anthropometry	Basic human body dimensions as function of age/sex, etc.	Design of tools and other hard goods; development of clothing sizing and tariffs
Dynamic anthropometry	Bending and stooping capabilities; reach dimensions	Control location and operation; workspace design
Strength characteristics	Static and dynamic force measurements; lifting; pushing and pulling capabilities	Equipment and job design for industrial workers; product portability design
Physiological characteristics	Aerobic and anaerobic capacity; maximal heart rate; expiratory volume	Environmental design; job specifications; toxicity levels
Sensory/perceptual processes	Measures of visual and auditory acuity, color vision	Design of controls; digital displays; visual and auditory warning signals
Tolerance to environmental conditions	Exposure tolerance to physical and chemical agents, e.g., tolerance to high-intensity light, noise, temperature, radiation	Protection of workers and environmental design
Reaction time	Simple and complex reaction time to a variety of stimuli	Display-control relationships; blade stopping time
Information processing/cognitive functions	Interpretation of symbols, learning processes, memory	Design of displays, signals, instructional materials, training devices
Capabilities of special populations	Anthropometric, sensory, physiological measures of children, the aged, the handicapped	Product and environmental design

SOURCE: Van Cott et al. (1978).

- be dynamic,
- use a common notation system,
- incorporate or simulate the real world,
- have three-dimensional structure,
- be predictive,
- be capable of being validated,
- be user-friendly,
- be time- and cost-effective,
- be flexible,
- permit rapid analysis,
- permit on-line documentation,
- be written in a standard language for transportability (use on different systems),
- have standardized segment and whole-body coordinate systems, and
- have graphical display capability.

Standardization

Standardization is a basic requirement for any kind of integrating ergonomic model. Such standardization is particularly important in two key areas: common format of the input data and standard language to make models and submodels compatible, including their use on different computer systems.

If this is not the case, each model or module needs a "translator" that allows data exchange by software modulation. Graphics input and output should be in accordance with the International Graphics Exchange Standard Format (IGES). If certain assumptions are made for the various data bases of submodels, these must be known to the user to make the system usable and reliable.

Given the conclusions that an integrated ergonomic model and its submodels, that is, anthropometric, biomechanical, and interface models, are needed, feasible, and useful, methods for accomplishing the modeling goals need to be determined.

APPROACHES TO THE DEVELOPMENT OF AN INTEGRATED MODEL

Two approaches to integrated ergonomic modeling evolved from the discussions at the workshop on which this report is based. The first approach is to develop one "supermodel" that integrates

the best qualities of all or most other models, while the second is a "modular" approach, which would incorporate various existing models or submodels to develop an integrated ergonomic modeling system. The pros and cons of each approach were reviewed.

Supermodel Approach

Some current interface models such as PLAID-TEMPUS, CAR, COMBIMAN, and Crew Chief appear to be moving in the direction of a supermodel approach. These models have been developed individually and, as a rule, are not compatible (e.g., there is no interface between COMBIMAN and SAMMIE). This incompatibility is usually a result of different data formats, degrees of modeling complexity, technically different computers, and different modeling theories or techniques. Furthermore, the data and assumptions in data collection may not be appropriate for specific models or sets of data.

These models are similar in many of the respects that meet the criteria for integrated ergonomic models. An evaluation of these existing models regarding their potential for integration into a supermodel is needed.

Modular Approach

A modular approach to an integrated ergonomic modeling system is a building block process of joining compatible modules with a standard structure. This allows flexibility for the user to incorporate those aspects of the ergonomic model or its component modules into as simple or complex a system as desired. For example, an engineer interested in fixed base activities on the ground might have no interest in a module that describes characteristics of reduced gravity or a module that incorporates platform motions and dynamics and their effects on the human operator.

The modular approach requires that the modules fit together. They need to be designed and structured according to common principles and nomenclature. A modular approach thus requires a superstructure to make each module a true component of the general system. Thus, even a modular approach constitutes one form of an integrated ergonomic model.

A flow chart illustrating a process for integrated ergonomic

models was provided by Joe W. McDaniel (Figure 5-1). It contains the following features:

1. Data bases are structured in a standardized protocol so that a new model could retrieve a data base or a subset of a data base. This minimizes the number of data bases required to be maintained on a system and makes it easier to update the data bases. (Researchers and model users could develop data to use with the model without having to be programmers or model developers.)

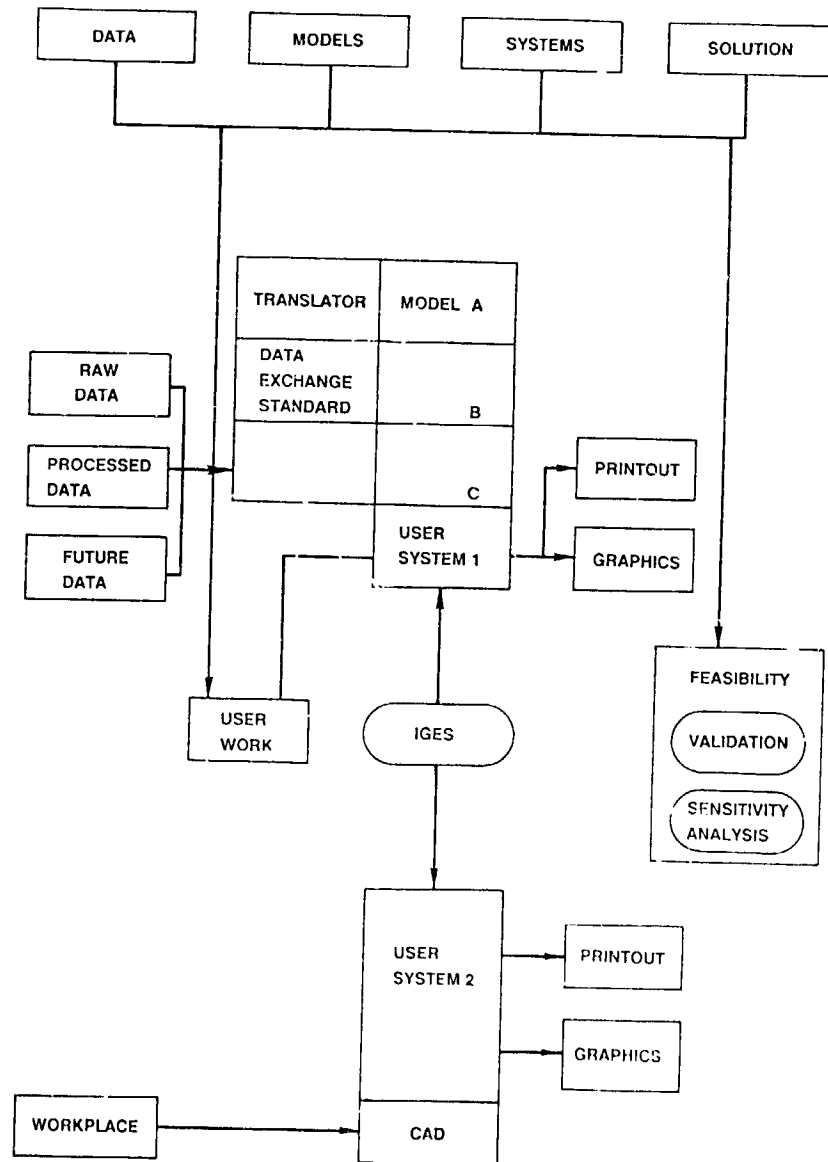
2. Each model has a translator or data exchange standard on the front end to access the required data. This feature would make the model less system dependent.

3. Model users have a library of programs to use in their specific designs that communicate indirectly through shared data bases, permitting the use of smaller computers. This also prevents obsolescence by allowing individual models or data bases to be acquired, replaced, or upgraded individually and as needed. In this concept the user can select items specific to a particular modeling analysis. Data and computer graphics systems should be standardized to allow interchange among systems. This approach is similar in concept to the workspace design analysis system proposed by Evans (1985).

One approach to the development of an integrated workspace design system based on the modular approach is shown in Figure 5-2. This system may be suitable to integrate operator analyses with existing computer design models (Evans, 1985). The system components, outlined in Table 5-2, provide a more detailed explanation of the data requirements (Evans, 1985).

DATA REQUIREMENTS

Users of anthropometric and biomechanical data have tended to rely on existing data bases, adapting, inferring, and making assumptions to meet their needs. For the most part, these are limited to the measurements made on the male U.S. soldier. The civilian anthropometric data base, particularly that for women, is extremely weak. For other subsets of the population (e.g., the aging and the handicapped), the data are virtually nonexistent. Yet,



(*) - International Graphic Exchange Standard
or Data Exchange Standard

FIGURE 5-1 Graphic display of an integrated ergonomic modeling system.
SOURCE: Joe McDaniel (unpublished data).

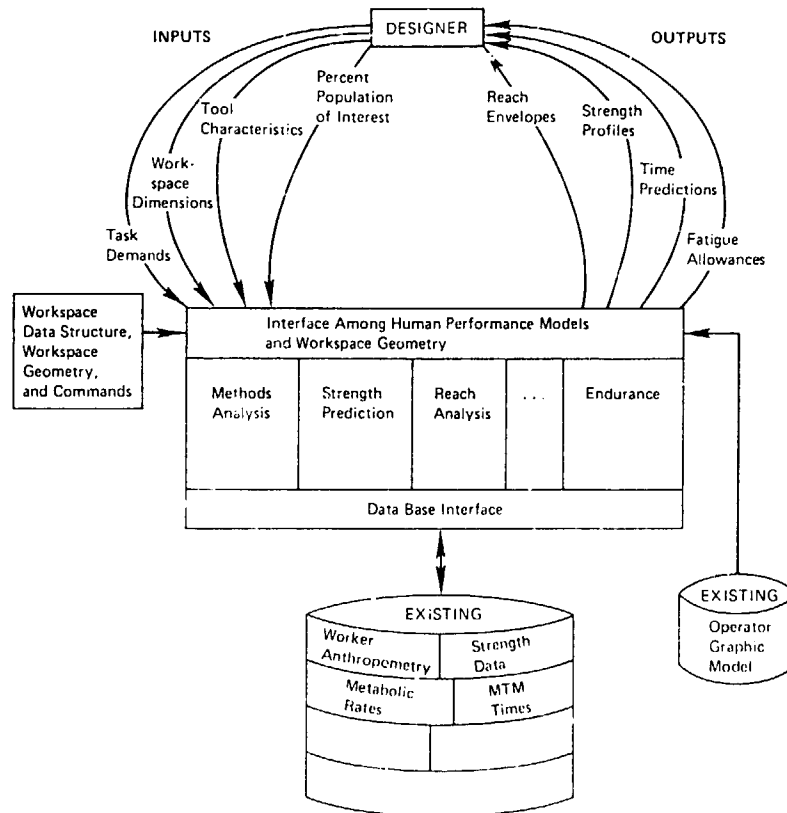


FIGURE 5-2 System structure for an integrated computer-aided workspace design system. SOURCE: Evans (1985). Reproduced with permission.

TABLE 5-2

System Components for a CAD Approach
to the Design of Manual Workspaces

System Components	Implementation Approaches
User dialogue interface	Menu-based command language Display windows showing parameters and options
System modes (states)	Default--task entry Options--workspace entry, object definition, operator definition, task evaluation
Design modes	Preliminary design--provides design guidelines with incomplete workspace or task information
Operator performance prediction models	Single exertion, posture prediction and biomechanical analysis Repeated trials--biomechanical and physiological effects on lifting Time prediction based on MTM-2 get and place elements
Design data bases	Static data bases--system files of generic operator, workspace, or task data Dynamic data bases--user defined files, which vary with the application, and the stage of design
System input and output	System defaults for posture, gender, and analysis modes Task input syntax similar to current process descriptions Output in graphic format--workspace and operator three-dimensional graphics; two-dimensional graphs and charts of analysis results Output formatted to comply with designer-stated preferences

SOURCE: Evans (1985).

these populations must be accommodated in the design of hundreds of products and workspaces. For example, clothiers, pattern makers, and other product designers have a need for anthropometric and biodynamic models.

It is difficult to determine whether data from different sources are comparable. The names used for the same dimension can vary from study to study, and measurements with the same name can be entirely different as a result of the use of differing landmarks or measuring techniques (Garrett and Kennedy, 1971).

In general, anthropometric measurements are static and posture-dependent. While a static subject facilitates measurement, the technique creates a data set that describes the body only in relatively artificial poses and provides no direct information on how body size and shape change with motion. Changes in size and shape of the proximal ends of body segments are particularly pronounced as a result of muscle dynamics. In addition, body shape data have generally been inferred from traditional anthropometric body size data and have not been quantified. Most body dimensions are measured independently of each other. While traditional anthropometric analysis has a solid statistical foundation based on normally distributed variables, a comparable statistical methodology must be established for three-dimensional models. When a person is viewed in the lateral plane, for example, measurements for stature, shoulder height, and length of leg are all taken from different measurement positions, with no established relationships among them. Therefore, it is difficult to generate a three-dimensional model from these isolated measurements in a systematic manner without making artistic assumptions regarding these relationships.

Loadings on internal structures in the body change significantly under dynamic conditions (Marras et al., 1984). There is a need to measure the dynamic loadings in vivo, however, since most models involving ergonomic analysis of activities have been based on static conditions. Three-dimensional models are needed that describe the acute as well as cumulative wear and tear in a joint caused by the dynamic motion of the body and the synergistic action of internal forces (e.g., muscles, ligaments, and pressures). Current methods such as electromyography and disc pressure measurements are questionable under true dynamic conditions.

New transducers are needed based on noninvasive measurements such as ultrasound to identify this wear and tear. These devices must be capable of producing quantitative data regarding the load components. Dynamic biomechanical models are needed that do more than simply describe the position of the body or the body components. Optimization techniques may provide a useful approach.

Analysis of Muscle and Joint Dynamics

Three-dimensional models of the body are useful for accurate descriptions of joint loadings. Therefore, more information regarding the position and the line of action of agonist-antagonist pairs of muscles is needed. Several model approaches using these data have been described by Schultz and Andersson (1981). These models determine the compression and lateral and anterior shear components of stress on joints and replace the simple compression estimates that are currently used.

Current methods for determining the strain in muscles and joints measure the net output of all actions involved. This net output, however, is the sum total of a number of individual muscle efforts. For example, in elbow flexion, in which both extensors and flexors are active, the combined torques around the elbow joint partially nullify each other. The result shows the net joint loading, but does not measure the forces that are contributed by the individual muscles. The problem involved is of practical importance because under the combined torques, for example, those created by concurrent contraction of flexor and extensor muscles, the intermediate body joint may be overloaded. This cannot be predicted from the net result, which is the only information that current methodologies yield.

In addition, gross estimations are required for the lever arms of muscles acting around body articulations. The geometry of these muscle attachments with respect to their lever arms may be quite different for different people. This produces uncertainty about the actual torques developed around joints, the strength to be exerted by the muscles involved, and the loading on the intermediate joints.

Most information about human muscle strength capabilities assumes a 1-g constant force field condition. We know little about the effects of higher or lower constant and transitory force fields on the ability to exert muscle strength. It is difficult to determine the muscle strength that is available, for example, in the reduced gravity of space or in an airplane that flies a path that generates accelerations on the pilot. While there have been a few isolated experiments (e.g., Kroemer, 1974), there have been no systematic measurements made under controlled laboratory conditions.

There is a need to evaluate existing systems for measuring the properties of the biomechanical system and to develop a system

for measuring the mechanical impedance of the body during the performance of normal activities. Then it is necessary to measure the extent of impedance modulation as a function of the task being performed and to correlate these data with other measurable variables such as the electromyogram activity of antagonist muscles.

Body Segments and Effects of Trauma

Data are needed to develop models of specific body segments such as head and neck, arm and hand, and leg and foot, beyond those required for a total body model. An example, a total body model describing the behavior in an impact situation does not usually require specific information about the biodynamic characteristics of the wrist-finger subsystem. This specific information also would be useful for the design of controls to be operated with small motions of the wrist and fingers, as in high-performance aircraft under loading in excess of normal gravity.

Available information on the susceptibility of the body to single (acute) or cumulative trauma is limited. Individual excursions or positions in body articulation that occur in activities such as force exertion or the direction of certain motions may not produce immediate trauma, but the injuries may be cumulative. We know that accompanying conditions such as temperature may influence the occurrence of certain cumulative trauma items. It is not known, however, how the combination of these, that is, the magnitude of excursion, directions of excursions, and accompanying force or torque generations, together may generate cumulative trauma injuries to tendons or tendon sheaths or impingement on nerves. Although the phenomenon is known, the conditions under which it may occur are not fully understood.

Bone and Link Dynamics

Stressed bones behave differently when anisotropic assumptions are made. The knowledge gained from bone models will apply to link models of the human body. The geometrically complex features of bone should be included in these link models since stress within a joint would most certainly change as the geometric characteristics of interacting bone surface areas change. Studies of human body linkages, which are basic to the majority of human

body analogs, require the precise location of specific skeletal landmarks. Current methods in anthropometry can only approximate the location of these landmarks in a three-dimensional system because of the varying thickness of overlying tissue. Finally, link models of the human body cannot assume that the spine is a rigid link, but must acknowledge its flexibility.

Finite-element models of the anisotropic features of bone may provide useful data for the development of a complete index of bone characteristics of the body. Typically, models are needed to describe the characteristics of the spinal column and of body joints in general (Hakim and King, 1979).

Motivation and Fatigue

Factors such as motivation and fatigue play important roles in human biomechanical actions. The control that the operator exerts over muscles because of transitory motivation or fatigue are biasing factors that have been largely ignored in biomechanical modeling. We know that when motivation is present, people are capable of exerting force which far exceeds that predicted by most biomechanical models. The effects of fatigue on muscular performance have not been quantified. Some of the recent literature has also indicated that when workers are subjected to unexpected loadings they are at a greater risk of musculoskeletal injury. There is a lack of suitable theory and experimental data regarding internal nervous control with respect to feed-forward generated in the brain and to the rearrangement of CNS motor signals according to the feedback that is received (Kroemer et al., 1986). Consequently, quantification of the effects of learning and adaptation and of psychomotor behavior while a person is fatigued is difficult since the internal processes in the central nervous system are not readily accessible. However, much of this adaptive behavior manifests itself in changes in the mechanical parameters of the biological system, specifically the impedance (i.e., mechanical stiffness and effective viscosity) about the joints. These quantities are under voluntary control (e.g., elbow stiffness may be changed by a factor of 100 or more) and dramatically influence the behavior of the biomechanical system and its response to external loads.

6

Research Recommendations

The workshop members determined that an integrated ergonomic model is needed, feasible, and useful. Whether a "supermodel" or a "modular approach," either constitutes a general model encompassing all elements in its infrastructure. The structure of such a general model can provide a standard protocol and common nomenclature for the collection of data and the rationale for prioritizing the following research recommendations.

Recommendation 1: Establish the objectives, procedures, and outline for the development of a general integrated ergonomic model.

In this report we have identified many useful anthropometric, biomechanical, and interface models. These models have been developed independently by researchers, engineers, and organizations for specific purposes and use special procedures. In most cases, it is not possible to combine them. No common taxonomy exists that can classify these models in terms of an orderly system, and no common notation system exists that can describe the types, functions, and components of these models.

Prepare detailed requirements and criteria for the development of a common conceptual framework for an integrated ergonomic model. These requirements should include the development of a common taxonomy and language that would permit standardization and compatibility in collection, analysis, and collation of data from a variety of sources. Compile an annotated list

of assumptions and measurement techniques suitable for use by modelers (See Hertzberg, 1968; Roebuck et al., 1975).

Recommendation 2: Review and integrate existing anthropometric and biomechanical data bases.

Review and assess existing anthropometric and biomechanical data bases for their suitability for inclusion in a common data base using the criteria developed in Recommendation 1 (e.g., Garrett and Kennedy, 1971). If appropriate, these data bases should be consolidated into a basic set of anthropometric and biomechanical descriptors. Determine whether the relationships between independent body descriptors can be applied to the development of three-dimensional models.

Identify data requirements for additional population groups, such as civilians, women, the elderly, children, and the physically handicapped, for whom insufficient data currently exist. The result should be a list of reliable and usable modeling data, including correlation coefficients and prediction equations that would allow the calculation of data subsets that were not originally measured.

Examine the assumptions and methodology employed in current data collection procedures, including the development of a standard reference system for the body and body segments; the development or refinement of methods for obtaining three-dimensional data, such as locating three-dimensional subsurface landmarks from the surface of the body; and quantifying human body shape and contour while incorporating consideration of the effects of body motion on body size and shape.

Determine whether the relationships between independent body descriptors can be established for the development of three dimensional models.

Evaluate the current measurement methods, such as stereophotography, to provide information for the development of techniques that will make it possible to relate all landmarks and body dimensions to a common origin.

Recommendation 3: Develop methods for the analysis of muscular action and joint loads as a result of dynamic actions.

Assess the use of noninvasive systems, such as magnetic resonance imaging (cineradiography, computerized axial tomography (CAT) scan, and ultrasound to establish the locations of subsurface features with respect to stable, identifiable surface landmarks.

Measure the muscle attachment geometry either directly on cadavers or indirectly by stimulating muscle tension under controlled conditions. Determine the resultant torques that are dependent on the geometry of the muscle attachments. Develop techniques to measure the involvement of the related muscles and the loading on the joints. For example, consider the use of electromyograms to indicate the activity of the muscles involved under normal conditions and while fatigued (see Basmajian and DeLuca, 1985; Chaffin and Anderson, 1984; Kroemer et al., 1986). Techniques are needed that allow measurements of the actual loading on the joint.

Collect data on muscle and joint dynamics in a simulator under conditions of constant force fields and transitory changes in the force fields.

Use the data collected by these methods to initiate the development of models of single and cumulative trauma and bone and body segment link dynamics.

Identify and evaluate existing theories on feed-forward and feedback signals within the body leading to the development of a suitable model of central nervous system control over muscle actions and human body motions.

Recommendation 4: Develop submodels and modular groups.

Develop elemental models to provide for the development of modular groups. These include:

- models of specific body segments that function in coordination with each other such as head and neck, lower arm and hand, lower and upper arm, upper arm and shoulder, foot and lower leg, lower and upper leg;
- models of bones under stress under various anisotropic assumptions;
- models that describe the effects of motivation on the mechanical impedance of muscles and joints; these should include sudden bursts and sustained action; and
- models that describe cognitive and neural functions.

Recommendation 5: Develop a model for the generic interface between human models and workstation models.

Describe the major elements in the interactions between humans and equipment in general terms. An annotated listing of

these elements should cover all important interfaces that place demands on the human user physically (e.g., posture, position, reach), physiologically (e.g., strength, endurance, fatigue), and psychologically (e.g., vision, audition). Consider gross environmental factors (e.g., reduced or increased gravity, acceleration, atmospheric conditions). Develop a generic taxonomy of descriptors of the interfaces between machines and the human operator.

Generic descriptors should include: descriptions of human-machine interfaces, task requirements, specifically requirements on the human, and a definition of the interchange of information between the technical systems and the human.

Recommendation 6: Develop methods and criteria for the validation of ergonomic models.

Reliable and accurate models that can be validated are needed so that trust in their use can be developed and so that their transferability can be enhanced. Determine the feasibility and approach for the validation of integrated computer ergonomic models, including the development of external criteria.

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