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HUMAN ANALOGUE MODELS FOR COMPUTER-AIDED DESIGN AND ENGINEERING APPLICATIONS

BY
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13. ABSTRACT *(Maximum 200 words)*
A review of six computerized human analogue models (SAMMIE, COMBIMAN, CREW CHIEF, CAR, JACK, and SAFEWORK) was conducted to identify the state-of-the-art in ergonomic modeling software. All of the models included here demonstrate some utility as ergonomic design tools and were developed so that materiel designers and engineers can conduct preliminary human factors analysis prior to prototype construction. These human figure models vary widely with respect to primary function and analytical capabilities. However, they essentially fall within one or more of the following categories: anthropometric accommodation analysis, biomechanical/strength modeling, or human-machine interface analysis. This report includes the developmental background of each model, the hardware requirements, and the major functions provided by each system, e.g., reach/clearance analysis, vision analysis, strength modeling, and computer simulation. The underlying anthropometric databases that support model generation are also reviewed. In addition, the techniques used to construct the human figures in terms of skeletal link structure and geometric representation of body segment shape and volume are discussed. Finally, some challenges are presented that confront future refinement of human figure models.

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PREFACE

The Material Systems Human Factors Branch, Behavioral Sciences Division, Soldier Science Directorate (SSD), initiated a program in the fall of 1988 aimed at developing a computerized anthropometric man-model and related three-dimensional modeling software. Once completed, this software system will be used by clothing designers and materiel engineers to create, modify, and evaluate personal protective clothing and equipment systems on dimensionally accurate human figure models. In addition, fully clothed and equipped 3-D man-models will be integrated with solid modeling capabilities to create a comprehensive ergonomic software system.

Since a primary mission at Natick is to develop many functionally diverse clothing and equipment systems for the individual soldier, and since this role demands access to reliable anthropometric data to optimize fit and system compatibility, a strong need exists for a computer-aided design tool that integrates modeling of the materiel system and the human being. This report documents the findings from the first phase of the Anthropometric Models for Computer-Aided Design program which explored the field of human figure modeling and gathered technical information about the nature of existing computerized anthropometric models, and their potential for enhancement to meet the needs of the U.S. Army's design and engineering community.

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HUMAN ANALOGUE MODELS FOR COMPUTER-AIDED DESIGN AND ENGINEERING APPLICATIONS

INTRODUCTION

Computer modeling of the human being for purposes of human factors design and engineering has been conducted since about the mid-1960's. Early models such as FORCE MAN (Chaffin, 1969) and BOEMAN (Ryan, 1969, 1971) were conceived as tools for understanding human-machine interactions, and they are two forerunners of today's most successful modeling programs. These models were developed during a period when the computational resources required to support intense mathematical applications and graphics displays were limited and expensive. With the advent over the last 10-15 years of high-powered, relatively inexpensive computer hardware and sophisticated computer languages such as LISP and C, the technology required to generate accurate realistic images and depict human body movement in real-time (i.e., without a time lapse between command input and command execution indicative of slower computer processors) has become more accessible.

Since the inception of computer models and modeling software, the primary justification for their use has centered around the flexibility they afford to efficiently design, evaluate, and redesign a man-machine interface while the particular item or system is still in the conceptual phase of development. This means it is possible to create virtual worlds and human analogues defined as arrays of three-dimensional points in the computer without ever having to fabricate a single piece of physical materiel or locate human subjects who meet specific body size and shape requirements for evaluation purposes. This approach readily facilitates changes during the design process and increases the user's level of confidence that once a prototype is produced, many of the key human factors concerns have been recognized and, depending upon the trade-offs a designer is willing to make, eliminated.

The present report offers a review of several advanced computer models developed and refined over the past 20 years. All of the models chosen for inclusion in this review achieved a level of development in which their utility as ergonomic design and engineering tools has been successfully demonstrated. The report is based on an in-depth literature search and personal interviews conducted with researchers in the field to identify the current status of three-dimensional man-modeling programs and related computer-aided design software in military and commercial areas. The primary focus of this paper concerns the major features and capabilities of each model. Background information is provided for each model which includes a brief history of its development as well as the computer hardware required to run the model. This section is followed by a description of the major functions of the software and information on the underlying anthropometric and biomechanical data that support model generation. A discussion is also provided which indicates some of the major shortcomings associated with each of the models.

MAN-MODELING BACKGROUND

Before beginning this review of computer man-models, it is first necessary to briefly discuss the term model. Since the term has many different meanings, it is important to provide a logical framework upon which the software presented here can be understood. Kroemer et al. (1988) distinguish between three major types of ergonomic models: anthropometric, biomechanical, and human interface models. Anthropometric models are geared toward representing the wide range of human size and shape variation within the framework of a skeletal link (body segment) system. This rigid link system varies depending upon the purpose and desired accuracy of the model, but most often is used to address questions of reach envelopes, control placements, clearance requirements, and operator visibility. In addition to the link system, anthropometric models generally exhibit some form of geometric surface representation (enfleshment) that is built around the links to provide three-dimensional shape. Strategies for representing human enfleshment also differ substantially among existing anthropometric models.

Biomechanical models tend to be more dynamic than anthropometric models and are used to describe the forces (internal and external), torques, and inertial properties acting on body segments and joints during various types of physical activity such as lifting and walking. Virtually every joint and joint complex in the body has received some attention in this area. Human interface models combine functional aspects of anthropometric and biomechanical models and attempt to arrive at a comprehensive description of the total human being in relation to his/her work environment. No less than 100 different models, predominately biomechanical, have been identified in the literature (Roozbazar, 1973; Kroemer et al., 1988).

Rothwell and Hickey (1986) recognize a slightly different classification scheme for computerized human figure models. They identify three major model types as follows: anthropometric, biodynamic, and animation. In their classification system, the anthropometric and biodynamic (biomechanical) categories are defined similarly to Kroemer et al. (1988) with the addition of an animation group which includes programs using human figure models in real time simulations to provide graphic depiction of body movements. Both of the above classifications systems are easily understood, and either can be used to order the diversity in man-models that exists today. However, it should be recognized that these categories are somewhat flexible as several modeling systems provide a foundation for anthropometric and biomechanical data representation as well as facilities for animation. For purposes of the current discussion, it is important to note the basic difference between anthropometric and biomechanical models and that some programs do provide animation/simulation capabilities. Thus, in the context of this report, the terms model and man-model refer in general to a human figure analogue which may possess one or more of the above attributes.

SYSTEM FOR AIDING MAN-MACHINE INTERACTION EVALUATION (SAMMIE)

Developmental Background and System Requirements

SAMMIE was initially developed at Nottingham University, England under the direction of Maurice Bonney and associates in the late 1960's (see Bonney and Case, 1976; Bonney et al., 1982). In 1977, development was completed and marketing of the software began in England by Compeda, Inc. At this point it became the only commercially available three-dimensional man-modeling tool used in workstation design and evaluation applications. In 1984, Prime Computer originally bought the rights to market the software in North America. The software runs on PRIME's 50-series minicomputers. Although PRIME continues to provide support for SAMMIE users who have purchased the product, in 1989 they ceased marketing the system. The relatively small niche this software occupied in the commercial marketplace was not sufficient to sustain SAMMIE as a viable product.

The developmental rights to the software are presently held by SAMMIE C.A.D. Limited, formerly known as the SAMMIE Research Group, and they have been licensed by the British Technology Group to market the system worldwide (SAMMIE C.A.D. Ltd., 1987). Efforts have been made by this group to enhance the number of computer platforms upon which SAMMIE will run; however, the basic foundation and structure of the software has apparently remained unchanged since its completion in 1977 (Fraar, 1989). SAMMIE is currently available on Apollo and Sun workstations supporting the Programmer's Hierarchical Interactive Graphics Standard (PHIGS) and X-Windows, a common graphics interface standard. Work is also progressing to port SAMMIE to the Silicon Graphics environment and DEC (VAX) machines.

Function

With SAMMIE, a user can build 3-D solid models of equipment and workspaces by controlling the construction of geometric shapes referred to in the system as "primitives." In addition to defining the geometry of a given file, a user can also specify relationships between components of the model using a hierarchical construction scheme (Pye, 1986). This aspect of the software allows functional tasks, such as lever movements and hatch openings, to be executed. SAMMIE is primarily geared toward evaluating the interaction between a human and his environment by permitting the assessment of reach, clearance, and visual field in models exhibiting a wide range of variation in body size (Pye, 1986).

While SAMMIE is an interactive system with high resolution graphics capabilities, file processing can also be carried out in batch mode via user-generated macros. The software has a clash detection facility that permits a user to assess the interference between workstation entities and the man-model. The workspace and model are normally viewed as wire frame representations of solid objects so that all edges are visible. However, it is possible to remove hidden lines and obtain a detailed, color-shaded representation of a given workspace and/or model. An image can be viewed in either plane parallel projection or in perspective (from either inside or outside the model) in top, front, and side views (Pye, 1986). User interface with the system is achieved by use of a keyboard or pre-programmed tablet menu and mouse.

Anthropometry and Skeletal Link System

The SAMMIE system employs a combined link and flesh model to depict anthropometric variability in the male and female human figure (Figure 1). Each of the 21-link segment lengths and the joint articulation data are based on data tables reported in Dreyfus (1960), which were compiled primarily from U.S. Army and U.S. Air Force anthropometric surveys. Girth (shape) data originate from an early 1970's Royal Air Force anthropometric survey (Bolton et al., 1973). While these sources of data represent the default values used in construction of a man-model, it is possible for a user to input different anthropometric data. However, problems arise when dimensions are used which are defined differently than those originally used to construct the link and motion algorithms. In addition, while it is possible to change link lengths independently of one another, i.e., construct a 5th percentile right forearm and a 95th percentile right upper arm, it is not possible to independently change body girths. Although girth can be controlled for a given man-model ranging from 1st to 99th percentile values, the choice of a specific girth value is reflected in all of the model's limb segments.

Joint ranges of motion, which include comfort and absolute limits of rotation, can also be modeled in SAMMIE. The source of the range of motion data and the manner in which they were collected is unknown. Given the complex interaction between posture and joint motion which is not accounted for in SAMMIE, these joint range values are somewhat suspect. The joint data table provides angles for each joint in three components, X,Y,and Z, corresponding to flexion-extension, adduction-abduction, and rotation around the joint, respectively. As with the anthropometric data, a user can define new joint limits by inserting the appropriate angles for each plane in the joint tables.

Shortcomings

Overall, the anthropometric data used to generate the man-models in SAMMIE are poorly documented with regard to source and the methods used to transform the external limb dimensions into internal link dimensions. Unfortunately, there is no accompanying information which defines the original measurements used to construct the man-model, the reach and range of motion algorithms, or how to apply new data to the model which may be defined somewhat differently. Other problems more fundamental to use of the software also exist.

In the current version of SAMMIE (release 4.0; Pye, 1986), two hidden links exist in the man-model. The first of these links occurs between the level of the shoulder and the base of the neck link. This vertical distance is not defined by a value in the link data base but by a value in the body size data base that defines the left shoulder breadth. The occurrence of the hidden shoulder link creates problems because it represents a percentage of the model's stature, and without it stature tends to be underestimated. In addition, neck-shoulder separation occurs on a model at certain height and shape percentile values. Secondly, a hidden link exists between the hip joints (transpelvic distance).

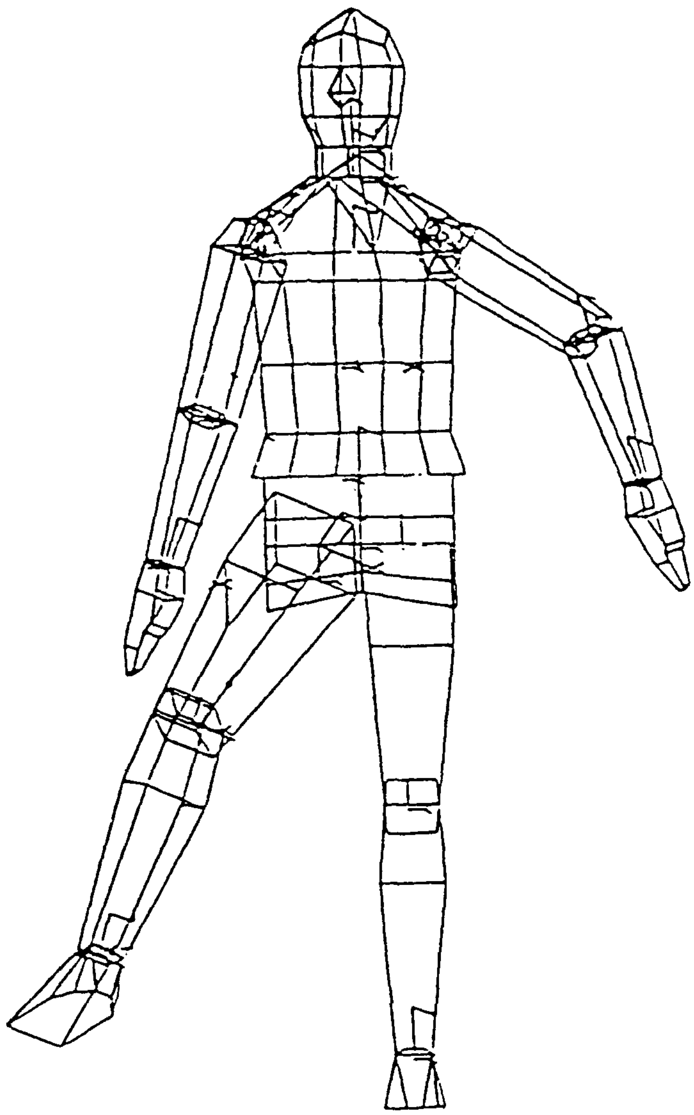

Figure 1. Enfleshed Skeletal Link System of SAMMIE Man-Model (Pye, 1986).

This dimension is controlled by the value for left thigh breadth in the body size table. The hidden pelvic link causes disarticulation between the torso and thighs of a model at various height and shape values (Rothwell, 1989).

Another major problem that exists in the SAMMIE software pertains to positioning of a man-model's eye height. The program automatically positions a model's eye height on a line 58% of the head length above the base of the head. Moreover, the eyes are spaced 25% of head width on each side of the sagittal plane. Thus in order to alter the eye location on a man-model either vertically or horizontally, it is necessary to alter the values for head length and breadth, respectively. While this difficulty can be overcome in situations where the primary area of concern is eye position independent of head size, when head size must be defined in relation to eye location, a serious problem results (Rothwell, 1989).

Additionally, a discrepancy arises when a user defines the stature of a man-model by different methods. When the height of a model is chosen using a standard percentile value (e.g. 95th%) from the existing data base, that percentile value is used to generate the model. However, when that same value is used to set stature using the height command, a model of different height results. Asymmetry of some left and right side links and the inability of a model to successfully reach locations on or near the body which are clearly within range are also problematic (Rothwell, 1989). Finally, there is no seat reference alignment point on the model to aid in properly orienting the model in a seated position. Thus it is necessary to use the bottom edge of the thigh in this process, and this involves some level of geometric computation within the 3-D coordinate system to align a seated model's body in chairs with different seat pan and seat back angles.

COMPUTERIZED BIOMECHANICAL MAN-MODEL (COMBIMAN)

Developmental Background and System Requirements

COMBIMAN (Computerized Biomechanical Man-Model) is a three-dimensional interactive graphics software system initially developed in the early 1970's for aircraft crew station design and evaluation by the University of Dayton Research Institute under contract to the U.S. Air Force (McDaniel, 1976). Dr. Joe McDaniel of the Workload Ergonomics Branch of the U.S. Air Force Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, is the contract monitor and technical advisor for man-modeling research and development. The COMBIMAN software runs within the IBM System/370 environment. It is comprised of five separate programs, four of which are written in FORTRAN IV and a fifth coded in IBM assembler language. Versatec (VERSAPLOT-07), a commercially available plot package, is used to generate on-line plots of COMBIMAN graphics. COMBIMAN has undergone several modifications since its initial development, and it is currently running under Version 7 (Korna and McDaniel, 1985).

Function

Like SAMMIE and other computerized man-models, COMBIMAN is used as an engineering tool to represent the geometry of a workstation/crew station as well as the geometry and physical properties of an individual in that workstation/crew station. Unlike other models, however, the posture of COMBIMAN-generated models is limited to the seated position. Evaluation techniques employed in the COMBIMAN system are designed to permit a user to vary the proportion of a man-model in order to explore a specific compatibility problem, to position a model within a crew station, and to assess performance and placement of controls and panels (Korna and McDaniel, 1985). A crew station may have as many as 250 panels with three to six vertices and 150 separate controls which can be located on defined panels. A crew station and man-model input into the computer exists in three dimensions. Since the CRT display has only two dimensions, a user must rotate the screen image by controlling the roll, pitch, and yaw of the display to suit specific design requirements.

In COMBIMAN it is also possible to map the visual field (centered on the 3-D eye position) of an operator in a given crew station. The size of the operator, seat adjustment, head position, and visual obstructions, can be controlled to produce realistic visual angles. The degradation of the visual field caused by personal protective equipment worn on the head, such as goggles, masks, and helmets, can also be modelled.

Anthropometry and Skeletal Link System

The man-model generated in COMBIMAN is based on a 35-link skeletal system (Figure 2.). However, two of the links represent the seat reference point, which acts as the starting point for adding links to the model. Each link connects primary points of rotation of the body

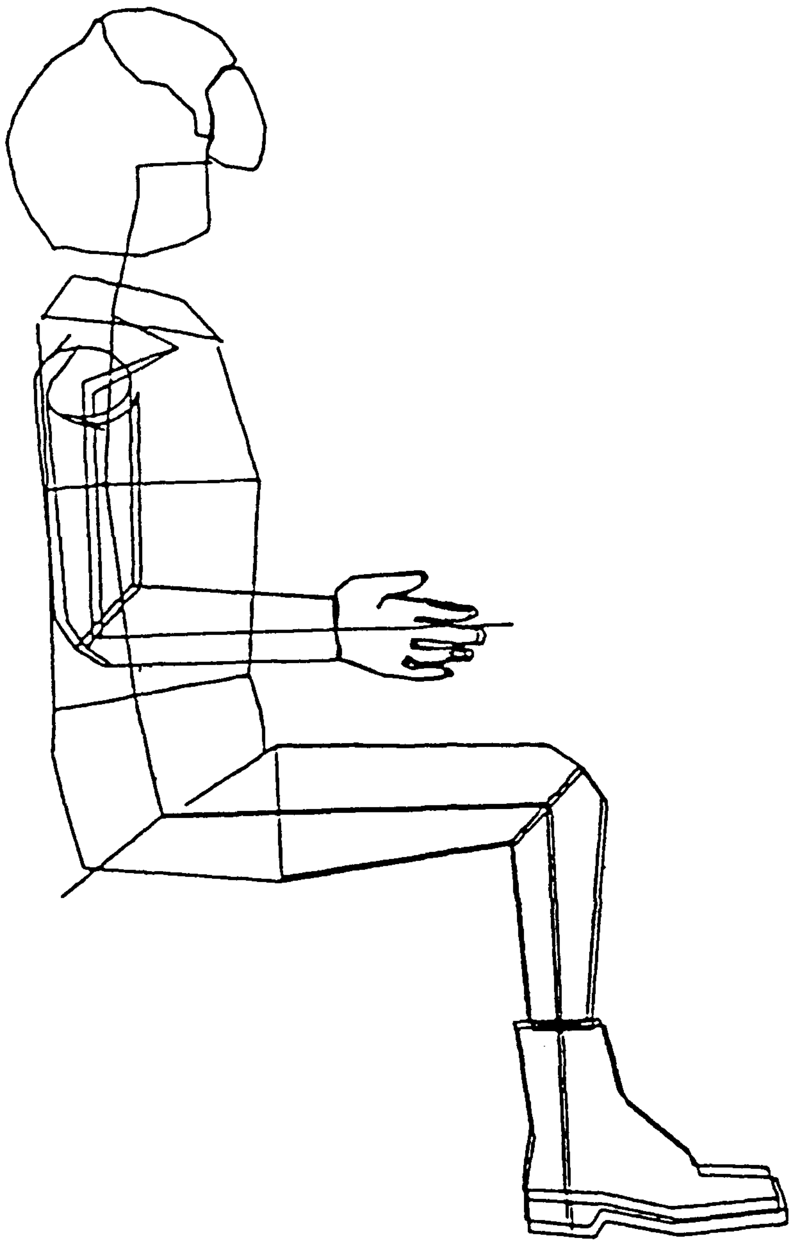

Figure 2. Enfleshed Skeletal Link System of COMBIMAN Man-Model with Helmet and Boots (Korna and McDaniel, 1985).

segments. The lengths of the links, as well as their orientation to adjacent links, can be controlled by the user. In order to generate a man-model on the screen, a user supplies the link dimensions which can be based either on outside anthropometric data entered directly into the model or computed from an on-line data base. The skeletal system of a man-model can be modified to represent anthropometric variability from six different anthropometric survey populations including Army aviators and Army females. Plans are underway by the Air Force to include more recent data on U.S. Army pilots into COMBIMAN collected during the 1988 anthropometric survey of U.S. Army personnel (Donelson and Gordon, 1990).

One method of defining the COMBIMAN model requires that values for the 12 anthropometric variables, which generate the 35 internal link lengths, be provided. These data may be either direct values obtained from individual subjects or percentile values chosen from the COMBIMAN anthropometric data base (Korna and McDaniel, 1985). The second method for generating a man-model requires that a user supply values for one mass-related variable and one length-related variable which are both important for a given compatibility evaluation. The program then calculates the other ten variables using multiple regression equations generated from the larger survey population. Once the link system is constructed, enfleshment ellipsoids are situated around the joint and connected with tangent lines.

The man-model can be positioned in a crew station by directly entering sets of rotational angles used to orient the links of the model, or with the reach analysis function by specifying a point on the display. Positioning can be controlled by keyboard commands or a light pen. Finger tip reach, functional reach, and whole hand reaches can be examined in the reach analysis performed by COMBIMAN. The user also possesses the ability to define the seated posture of the man-model as either standard anthropometric seated (erect), slumped (13 degree seat-back angle and 6 degree seat-pan angle), or a unique user-defined posture. Additional capabilities provided in Version 7 of COMBIMAN include a leg reach function, which permits reach analysis of the left and right legs, and a strength analysis function, which predicts the amount of force available for application on a lever, wheel, or pedal while assuming a seated posture (Korna and McDaniel, 1985). Finally, a printout and plot of the crew station can be generated which provides the dimensions of the man-model as well as the 3-D coordinates of the cockpit geometry.

Shortcomings

While COMBIMAN has served its developers well as an evaluation tool for the U.S. Air Force designers and their aircraft contractors, its applicability to other engineering problems is severely limited due to the seated operator restrictions. Given the diverse needs of designers and engineers to model the human body in a variety of body positions and within a number of different environments, the adoption of COMBIMAN without major modifications for applications other than seated operator modeling is not feasible. In addition, the graphics of COMBIMAN are relatively crude compared to contemporary computer graphics standards, and the wireframe representations of the model and crewstation used in most analysis applications cannot be shaded to improve visual clarity. A lack of portability of the COMBIMAN system outside the IBM environment in which it was developed is also a difficulty. However, efforts are underway to port COMBIMAN to stand-alone workstation platforms which provide high speed processing and high resolution 3-D graphics.

CREW CHIEF

Developmental Background and System Requirements

The CREW CHIEF man-model was also developed by the Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, Ohio, via a contract to the University of Dayton Research Institute. Development began in the mid-1980's and was completed in 1988. The CREW CHIEF system of programs is designed to interface with several commercially available CAD/CAM software packages and it will run on the hardware that supports those packages. Since CREW CHIEF was ultimately intended to support U.S. Air Force aircraft contractors, efforts to provide compatibility for their existing computer equipment (hardware and software) was a driving force behind its development. Therefore, the developmental work on CREW CHIEF (Version 1.0; Korna et al., 1988) has been aimed toward interfacing it with the commercially available CADAM modeling software package (Version 20.0.1 through the Geometry Interface Module) since this software is used by most of the Air Force's major aircraft contractors. A second version of CREW CHIEF runs on the Computervision CDS 4001 system with an Analytical Processing Unit and CADDS 4X software (Revision 5B or later). A third version of CREW CHIEF has been designed as system independent with the ability to run under the operating system of the host computer.

Function

The major function of CREW CHIEF is to optimize the maintainability of an aircraft system during the design process by assessing the interface between the physical characteristics and capabilities of a maintenance technician and his/her work environment. CREW CHIEF is a somewhat more advanced 3-D man-model than COMBIMAN in the sense that it provides analytical capabilities for a wider range of man-machine interactions. The CREW CHIEF man-model simulates an aircraft maintenance technician in a variety of realistic situations using several different types of tools and equipment such as a wrench, screwdriver, hammer, and power drill. Maintenance task analysis (reach interference and work envelope), visibility analysis, and accessibility evaluations are all possible through the CREW CHIEF system. In addition, modelling the strength capabilities of a technician is also integrated into CREW CHIEF. This aspect of the software permits a user to evaluate the amount of torque applied to a tool under a given postural configuration, as well as the materials handling ability of an individual performing tasks such as lifting, pushing, and carrying objects of various weight and resistance.

In CREW CHIEF the capability to model standard U.S. Air Force clothing ensembles is also provided. Presently, four different clothing types are available: (1) fatigues, without jacket; (2) fatigues, with jacket; (3) arctic (parka with fur-lined hood, insulated trousers, and mittens added to the standard fatigue ensemble); and (4) chemical protection (CP mask and hood, CP over-garment, CP over-boots, and rubber gloves). The clothing produces limitations in maneuverability and affects the joint mobility limits while performing automated reaches, and during typical maintenance activities and accessibility evaluations.

Anthropometry and Skeletal Link System

The man-model used in CREW CHIEF is based on a 35-link system. See Figure 3 for the graphic representation of CREW CHIEF enfleshed and clothed. These links connect the primary centers of rotation and are used to graphically depict the model in various postures. The lengths of the link segments are computed from regression equations generated from 13 anthropometric dimensions. The regression equations for males were derived from the 1965 survey of U.S. Air Force men (AFARML, 1965). Only subjects who met existing Air Force weight requirements were included in the sample.

Female regressions were computed from data representing a combination of Air Force women measured in 1968 (Clauser et al., 1972) and U.S. Army women measured in 1977 (Churchill et al., 1977) who also fell within prescribed weight limits. Using anthropometric data from a 1981 sample of Air Force Basic Trainees (McDaniel et al., 1983) for input into the regression equations (the best available data representing maintenance technicians), 11 of the 13 dimensions needed to generate the link structure of CREW CHIEF were then estimated. Stature and weight were directly recorded in the 1981 survey (McDaniel et al., 1983).

Enfleshment of the CREW CHIEF model is accomplished by a technique that defines 3-D points of solid objects. These objects are separated into triangular facets with the vertices and edges of the triangles marked for tracking. Sonic digitization is used to define X,Y, and Z coordinates of the vertices. Sorting programs were applied to identify coincidental edges and points, to transfer the 3-D coordinates to the CREW CHIEF reference system, and to determine the display lines used to generate the graphics (Korna, et al. 1988).

Ellipses located around major joint centers were connected and a modelling technique that defines the 3-D points of solid objects was then used to determine the display lines for the body enfleshment. At joints characterized by high compressibility, such as the knees and shoulder, multiple ellipses are used. These ellipses can be modified to represent the dimensional changes in body size that occur under the four different clothed conditions.

In accordance with MIL-STD-1472C (1981) (Human Engineering Design Criteria for Military Systems, Equipment, and Facilities), CREW CHIEF is designed to model human variation for the purposes of accommodating individuals ranging from the 5th percentile female to 95th percentile male for critical body dimensions. However, the program also includes the 1st, 50th, and 99th percentile dimensions for males and females.

Shortcomings

Since the CREW CHIEF software system and databases which support the system are strongly focused on the dimensions, posture, and performance of an aircraft maintenance technician, the system's applicability to other design problems is somewhat limited. While the overall foundation of the

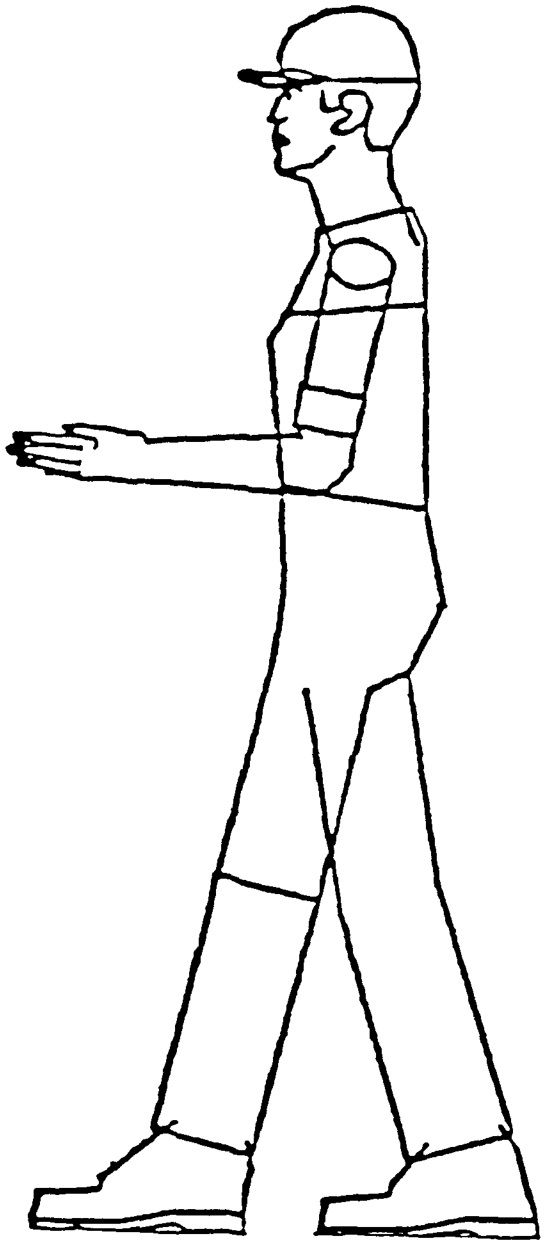

Figure 3. Enfleshed Skeletal Link System of CREW CHIEF Man-Model with Clothing (Korna et al., 1988).

program could be adapted with modifications for other workspace design and evaluation applications, and while the ability to represent the dimensional changes in body size due to clothing and equipment items is an attractive feature of the software, the level of surface detail needed to do detailed clothing design and evaluation on a 3-D man-model is lacking. In any use of the CREW CHIEF model outside U.S. Air Force maintenance technician applications, the anthropometric, strength, performance, and clothed data bases would need to be revised to reflect other user populations. Current limitations on the range of anthropometric variability that can be modelled in CREW CHIEF (i.e., 1st, 5th, 50th, 95th, and 99th male and female) need to be addressed to allow greater control over the dimensioning of individual body segments.

CREWSTATION ASSESSMENT OF REACH (CAR)

Developmental Background and System Requirements

The CAR model was originally developed for the Naval Air Development Center (NADC), Warminster, PA, by the Boeing Aerospace Corporation in 1976 (Edwards, 1976). CAR is a derivative of the BOEMAN (Ryan, 1969) man-model developed by Boeing in 1969 for aircraft cockpit design. Modifications to the BOEMAN model, which resulted in the first version of CAR (CAR-I), include the addition of a third link in the hand to provide a full range of reach/grips, restrictions on some joint limits on the arm, and the incorporation of a head-helmet link to provide for an over the head clearance check. Processing speed of the program was increased and an interactive user interface was added. Development of CAR-I was also strongly influenced by the work on the Computerized Accommodated Percentage Evaluation (CAPE) model developed by Bittner (1976). In the CAPE approach, a model is used to estimate the effects of imposed limits on the percentage of a population that is accommodated under specific design limits.

In 1979 Analytics Incorporated initiated an evaluation of CAR-I under contract to NADC in order to determine areas for improvement. The results of this study indicated a need for modifications in the overall efficiency of the program, the user interface, and the link transformation algorithms. CAR-II-A was released in 1980 (Harris et al., 1980) incorporating the changes outlined above. Since that time, two other versions were developed finally resulting in CAR-IV (Harris and Iavecchia, 1984). CAR was originally written in FORTRAN to run on a CDC 6600 mainframe computer. CAR-IV has been modified to run on an IBM PC-compatible computer and it can be easily converted to run under other operating systems.

Function

The CAR model is a non-graphic, interactive program used in design evaluations for determining the percentage of a population that can be accommodated by a particular crewstation layout. Reach analysis and determination of reach envelopes are the primary functions of CAR. All program functions are menu driven; however, the crewstation parameters and the anthropometric data can be input via cards. Once a user defines the geometry of the crewstation under evaluation, a population of users is selected by one of two available methods. A population can be either an actual survey population or a sample generated by a Monte Carlo simulation technique. This technique uses the means, standard deviations, and intercorrelation of anthropometric dimensions for a population to define the proportion of individuals that will be accommodated within given workspace/crewstation parameters.

The CAR crewstation is specifically defined by an anchorage point, design eye point (DEP), the line of sight (LOS), seat parameters, head clearance data, and a set of hand and/or foot controls. Each individual in the sample is oriented to the user-determined anchorage point (the location in space to which a specific body part is attached) and then evaluated for the ability to position the design eye point along the line of sight, the minimum head clearance, and the ability to reach the controls (Harris et al., 1980).

CAR analyzes the ability of each operator in the population to reach controls by adding links in sequential order beginning at the lumbar joint in the direction of each control. The links have built-in constraints for nude range of motions with the ability to modify constraints for limited clothing ensembles. Three types of reaches can be evaluated in CAR: (1) Zone 1- the shoulder harness is locked and the pilot is not free to strain against it; (2) Zone 2- the shoulder harness is locked, but the pilot is free to strain against it; and (3) Zone 3- the shoulder harness is unlocked. Output from the accommodation analysis indicates the percentage of the sample group that obtain visual accommodation and the percentage that successfully reaches each control. Reports are also generated that provide information on control placement modification (i.e., direction and distance of movement required to accommodate portions of the user populations who could not complete specific reach tasks).

Anthropometry and Skeletal Link Structure

The CAR man-model is comprised of 31 links (Figure 4) based on the skeletal structure of its forerunner BOEMAN. Note that the body contours depicted around the skeletal link system in Figure 4 are for visual clarity only. Link lengths are derived from regression equations used to estimate internal lengths from 12 external anthropometric dimensions. The link transformations are based on the work of Dempster (1955). The CAR program uses anthropometric data from the 1964 survey of U.S. Navy aviators (Gifford et al., 1964); however, it is possible to insert data from other user populations provided that the body dimensions are defined as in the 1964 Navy survey. As discussed above, a Monte Carlo estimation technique is used to generate accommodation percentages based on specified anthropometric and crewstation parameters.

Shortcomings

One of the major drawbacks of the CAR modelling system is that it is non-graphic. All evaluations are conducted by entering the desired information into the program and receiving printed output of the results. This limits the user's interaction with the modeling process in terms of positioning the model and its limb segments, evaluating the overall orientation of an operator within the crewstation, and conducting collision detection. As Rothwell (1989) noted, CAR is a good preliminary assessment tool but its function as a useful design tool is limited. Since it is heavily structured as an aircraft crewstation evaluation program for determining reach envelopes, it has limited utility for a broader range of workstation design problems.

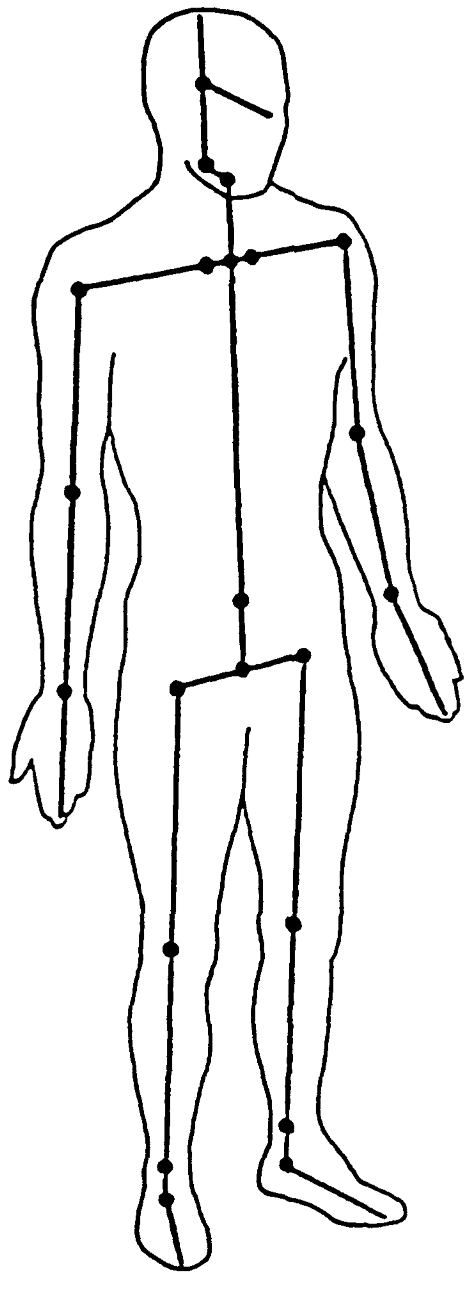

Figure 4. Skeletal Link System of CAR Man-Model (Harris and Iavecchia, 1984).

JACK

Developmental Background and System Requirements

The Jack software system represents the latest advance of computerized man-model research and development initiated at the University of Pennsylvania (Computer Graphics Research Laboratory) in the early 1980's under the direction of Dr. Norman Badler. Jack is an outgrowth of the TEMPUS (Badler et al. 1985) software originally developed for NASA for the design and evaluation of the space shuttle and space station programs. The compilation of software programs known as Jack (Phillips and Badler, 1988; Badler, 1989; Phillips, 1990) has existed since 1986. Jack (4.7) is the most recent version of the software (Phillips, 1990).

Financial support for modifications and enhancements to Jack over the last several years has come from several sources including: Lockheed Engineering, Pacific Northwest Laboratories, NASA Grants (Johnson Space Center and NASA-Ames Research Center), NSF Grants, and Army Research Office Grants which include participation from the Human Engineering Laboratory. Work on the software is generally guided by supporting agencies who request that specific applications be integrated into the overall Jack program. Graduate and undergraduate students at the University of Pennsylvania undertake research projects to fulfill these requests as part of their scholastic training (i.e., M.A. and Ph.D. thesis requirements). As new applications are developed and added to the Jack program, all sponsoring agencies receive an updated version of the software. Jack is written in the C programming language and runs under the UNIX Version 5.0 operating system. It runs exclusively on Silicon Graphics 4D series computer workstations.

Function

Jack is a comprehensive menu-driven software system which graphically displays and manipulates articulated geometric figures in three-dimensional space. Within the structure of the software exist many different facilities for creating, positioning, describing motion, and analyzing human figure models. The geometric objects defined in Jack are displayed in graphics windows and represented by the peabody language system (Phillips, 1990). A peabody environment is comprised of several individual figures which are a collection of segments. Each segment has a specific geometric configuration and it represents a single object or part of an object (e.g., the limb of a human figure). Segments are connected by joints that are rotated along predefined axes with upper and lower limits.

Jack is designed to be a highly interactive system with strong reliance upon graphic representation of the man-model and its 3-D environment. The interface between Jack and a user is accomplished primarily through a three-button mouse which permits a user to pick commands from on-screen menus and to specify geometric transformations. Commands may also be directed to the system from a keyboard. With Jack, a user can create and manipulate one or more anthropometrically variable man-models in a given environment. Orthographic projections are used to provide visual alignment cues to the user. Real time positioning of a human figure model is facilitated through the use of kinematic constraints. In order to execute a reach, for example, algorithms in Jack automatically determine joint angles along the joint chain that place a specified end effector on its intended goal. Joint limits associated with each degree of freedom are obeyed during this process. Interactive positioning of a model's limb segments is also provided in Jack. This is accomplished by allowing a user to define an end effector and the joint chain involved in the movement of the end effector, and then positioning the end effector at the desired reach site (Zhao and Badler, 1989).

In addition to manipulating and positioning human figures, Jack offers several tools for analyzing human visual fields. One such tool permits a user to fix a model's eyes on a given point or object in the environment, and then trace movement of the eyes and head as the object is moved until limits of the eyes and neck are reached. View cones representing a central region of visibility can also be projected from a model's eyes which allow a user to graphically view a model's line of sight. Using two graphics windows it is also possible to interactively position a model's head and eyes in one window and simultaneously see the model's field of view in the second.

Animation facilities are also a major component of the Jack software system (Badler, 1989). This function provides graphic feedback on the interaction between a human model and the environment as it executes a series of movements or tasks. A user is required to construct several key frames which depict the model's global position and postural alignment, and the computer automatically interpolates body and joint position between frames. This facility provides a method of creating animated sequences of model-machine interactions for ergonomic analysis without having to physically describe every detail of the model's movement.

A strength data base and query system have also been implemented in Jack. This model uses data on maximum strength at each joint to compute end effector strength. Since maximum strength is a function of joint angle, strength values (modeled as muscle groups acting on a joint) at the upper and lower limits of joint movement for each degree of freedom are used. An interpolation algorithm computes strength values for intermediate joint positions (Schanne, 1972). Individual or populational strength values can be input into the database, and at present most of the strength data used with Jack are from NASA (1987). The strength query function allows a user to obtain information about available strength at a joint based on variables such as gender, body posture, age, handedness, and fatigue level (Wei, 1989). Graphic strength data displays (icons) are being developed along with the strength model to aid a user in visualizing the effects of various parameters on strength, such as the available torque at each joint and the changes in available torque as body posture changes. In addition, a strength guided motion function (Lee et al., 1990) is being developed in Jack that computes the path of an end effector under loading conditions. The current focus is on one- and two-handed lifting tasks. The strength guided motion algorithm incorporates parameters such as the weight of the load, figure geometry, desired goal, and model strength.

Anthropometry and Skeletal Link Structure

Like its forerunner TEMPUS, Jack is based on a 31-link skeletal system (Figure 5.) which is essentially derived from the link structure of the CAR man-model (Grosso et al., 1989). Two geometrically distinct man-models are presented in Figure 5. The polybody representation tends to exhibit more realistic enfleshment values. For each body segment, three measurements are used to define its geometry. These correspond to the length, width, and depth of that segment. A polyhedral surface (psurf), which describes the vertices, edges, and faces of each segment, is used to graphically represent segments in 3-D space. Each psurf is stored in a normalized format where the z (length) dimension ranges from 0 to +1, and the X (depth) and Y (width) dimensions range from -1 to +1. The psurfs are scaled in order to be displayed on the computer screen, and the scaling factors for each dimension can be specified by the user. This process is accomplished within the peabody language system discussed above. A peabody file contains information which defines the relationship between each psurf, the location of joints, joint limits, segment masses, and other information relevant to construction of the human figure (Phillips, 1990).

Anthropometric data which are used to define the individual dimensions of a man-model are stored in a separate program, the Spreadsheet Anthropometry Scaling System (SASS). The spreadsheet can be modified to contain data which represent population percentile values for a given dimension or values from single individuals. With Jack it is possible to isolate all the anthropometric data from the spreadsheet into a graphics window, change any or all of the data which describe the current man-model, and visualize the actual changes in body size that result in the displayed model. Strength data are also stored in SASS.

Since the work on this software has been primarily geared toward meeting the needs of NASA designers and engineers, and since NASA personnel have worked closely with the computer graphics research laboratory over the history of TEMPUS/Jack development, the anthropometric data currently incorporated into Jack are compiled from NASA references. These include the Anthropometry Source Book, Volume II (Churchill et al., 1978) and the NASA Man-Systems Integration Manual (NASA, 1987). However, both of these documents contain compilations of anthropometric data from a variety of civilian and military surveys, and it is not known specifically what survey populations or segments of those populations are represented in the SASS. It is known that in situations where necessary data values were unavailable for a population, values were taken for similar measurements from a different population or were estimated using regression equations. All of the joint range of motion data used in the most recent version of Jack were taken from NASA (1987).

Shortcomings

One of the major deficiencies inherent in the Jack man-model is the derivation of its link structure. Currently, most link-lengths in Jack are defined on the basis of external (surface) dimensions with no use of

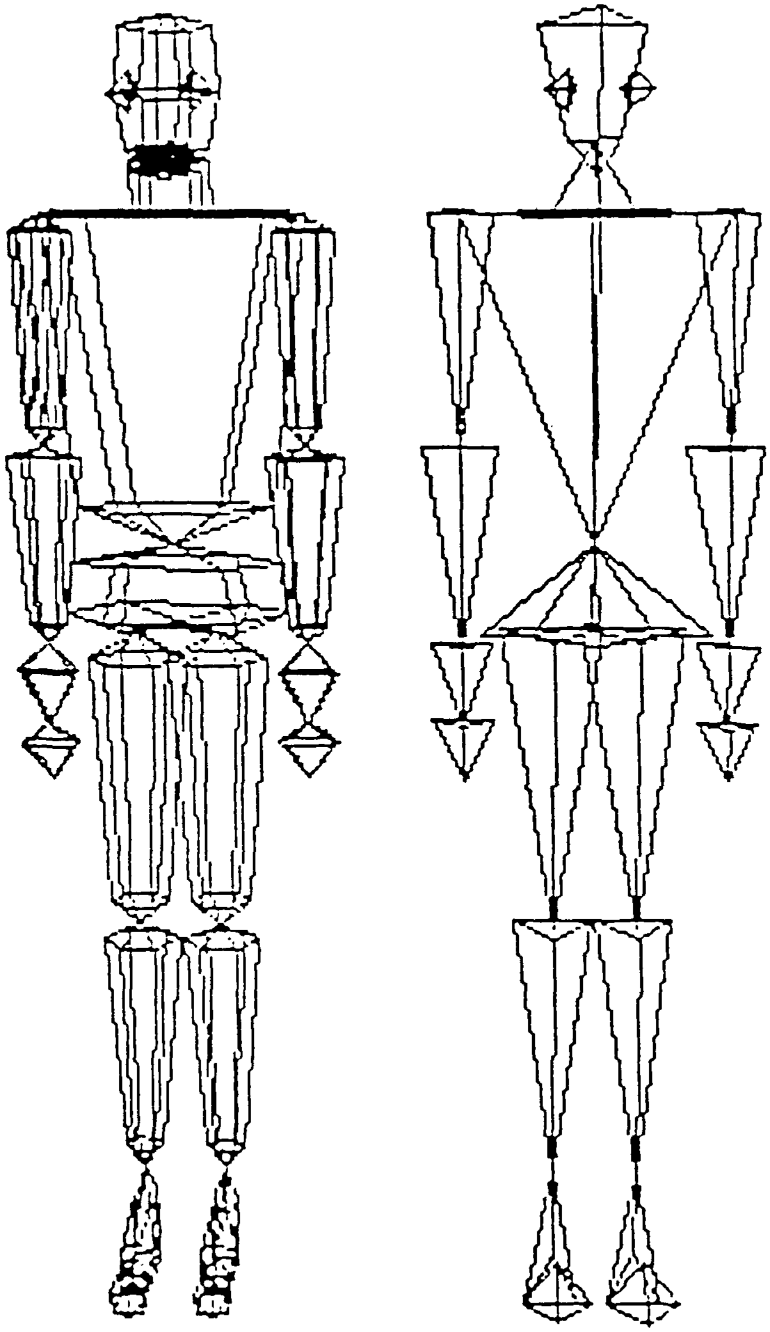

Figure 5. Enfleshed Skeletal Link System of Jack Man-Model (Grosso et al., 1989); Polybody Representation-Left; Skinnybody Representation-Right.

internal link transformations. This yields link-lengths which do not approximate actual bone lengths between adjacent joint centers of rotation. Depending upon the specific segment lengths in question, underestimation or overestimation of the actual value results.

While the anthropometric and joint range of motion data currently used in Jack meet NASA's design and engineering requirements, as well as many other sponsors of the software, they must be updated if they are to meet the needs of a wider user community. Unfortunately, with Jack as with other computer models, an absence of appropriate data imposes many limitations on users of the software. While the structure of the anthropometric spreadsheet used in Jack is designed for ease in inputting percentile based anthropometric data to generate a man-model, the overall representation of models based on percentile values is somewhat problematic as discussed previously. Given the numerous problems associated with creating models in which all body size data are based on a single percentile value (i.e. 5th, 50th, and 95th), efforts are underway by the developers of Jack to improve size and shape representations approaching accurately proportioned human figures.

Another problem with Jack involves the geometric representation of the man-model's body segments independent of the link system. Use of polyhedral surfaces to display the human figure is appropriate and desirable for many modeling applications, but for detailed modeling of clothing and equipment the dimensional accuracy of the man-model's surface representation (enfleshment) requires improvement. Recent work on Jack has focused on improving the shape and dimensionality of the man-model. Stereophotogrammetric data were acquired from the U.S. Air Force in an attempt to replace the polybody figures with accurate 3-D human body data. While the overall shape of the figure is much more realistic, problems also exist with this approach. The joint locations must be estimated and the degree of accuracy in their placement is questionable.

SAFEWORK

Developmental Background and System Requirements

SAFEWORK (Version 1.0) is a graphically based man-modeling system that incorporates anthropometric and biomechanical capabilities for human factors design and analysis applications. Development of this software began in 1984 by GENICOM Consultants, Montreal, in cooperation with the Department of Industrial Engineering, Polytechnic School of Montreal and the Department of Kinanthropology, University of Quebec at Montreal (Fortin et al., 1990). Various modular enhancements to the basic software package are still ongoing. The SAFEWORK model is marketed as a general purpose workstation design system primarily intended for users evaluating human-machine incompatibilities, including safety and health concerns.

The software is written in the Microsoft C programming language and operates in the Microsoft "Windows" environment. It will run on an IBM AT (80286 CPU) microcomputer or compatible PC-DOS environment with an enhanced graphics adapter (EGA) card. However, an 80386 computer with arithmetic coprocessor is recommended for optimal processing performance. All data accessed by the main series of modeling programs is stored in dBase III data files. Any output device supported by "Windows" can be used to obtain hardcopy of results displayed during analysis performed with SAFEWORK.

Function

The SAFEWORK Software System consists of three primary modules: anthropometric, workstation, and analysis/animation. The anthropometric module provides for the creation of human figure models that can represent body dimensions of specific individuals or selected samples derived from larger population data. Using statistical procedures such as the Monte Carlo method, a man-model's dimensions can be constructed using individuals who correspond to a particular linear combination of anthropometric dimensions that are critical for a given analysis. These multivariate techniques allow selection of samples representative of specific accommodation ranges within the larger population. Once the choice of a set of dimensions is complete, a generation function within the anthropometric module is used to construct a model using additional data such as age, sex, and ethnicity (Fortin et al., 1990). Any missing anthropometric information is estimated by the program. The vast majority of anthropometric data used by SAFEWORK is derived from U.S. military sources (NASA, 1978).

The workstation module is used to construct the 3-D geometry of the environment to be evaluated. A number of commercially available CAD systems such as AUTOCAD can be used and transported into SAFEWORK for this purpose. Finally, the anthropometric and workstation modules are integrated with one-another via the analysis and animation module. Animation is a somewhat misleading term in this context since the program does not provide for pre-defined simulation routines of operators performing tasks within a prescribed environment. Instead, the primary function of this module is to provide a user with the ability to bring a man-model into an environment and interactively position its body segments for task analyses.

A zoom facility exists for accurately positioning the model's limb segments and adjusting posture for reach analysis and other mobility tasks. Using a mouse, a user can manually input target reach coordinates or select a body segment and change the proximal angle by dragging the segment to its desired location. The program then displays the angle and the population percentile capable of accomplishing the reach. A collision detection algorithm is intended to be implemented in SAFEWORK in the near future. Other basic operating features of SAFEWORK include 2-D orthographic and 3-D projections of the workplace with user visualization possible from any point in the environment. The mouse is used to control the size of the window and move objects around the screen. Hidden line removal for enhanced visibility is also provided.

A biomechanical sub-module composed of 14 mathematical models allows a user to perform a variety of biomechanical analyses within a given human-machine environment. This sub-module is imbedded in a low-level expert system. For a given postural configuration, this sub-module calculates the equilibrium, sliding moment, forces, and torques for every joint in the model. Once the stability of a specific posture has been determined, a user can obtain stress and torque information for any joint. The expert system allows a user to specifically define various parameters of a given task such as the existence of pulling or pushing forces, the number of hands involved in the action, and specific points of support for the body (Fortin et al., 1990). The program then automatically chooses the best of the available 14 biomechanical models for the situation. The biomechanical data and mathematical models used in SAFEWORK have been compiled from a number of published sources. These include: Drillis et al. (1966); Dempster (1955); Dubois et al. (1964); and Brozek et al. (1963). Vision analysis and natural movement capabilities are two enhancements planned for the SAFEWORK software; however, they have not yet been implemented.

Anthropometry and Skeletal Link System

The SAFEWORK man-model is based on a 35 link skeletal system (Figure 6.). The link lengths for the body segments are derived by using two sets of transformations. Initially the external anthropometric dimensions of each segment are used to estimate segment bone lengths. The bone lengths are then used to estimate actual link lengths. Equations used in these transformations are derived from basically the same sources used in other models (Dempster, 1955; Dempster et al., 1964). Enfleshment of the links is achieved through the use of Bezier equations which yield approximations of body segment volumes (Fortin et al., 1990). It is also possible tc refine the volumetric representation of the individual body segments by using a set of predefined morphological sub-types (somatotypes) contained within the program. Once the data for a particular individual or statistically derived sample has been obtained, a man-model is generated as previously discussed.

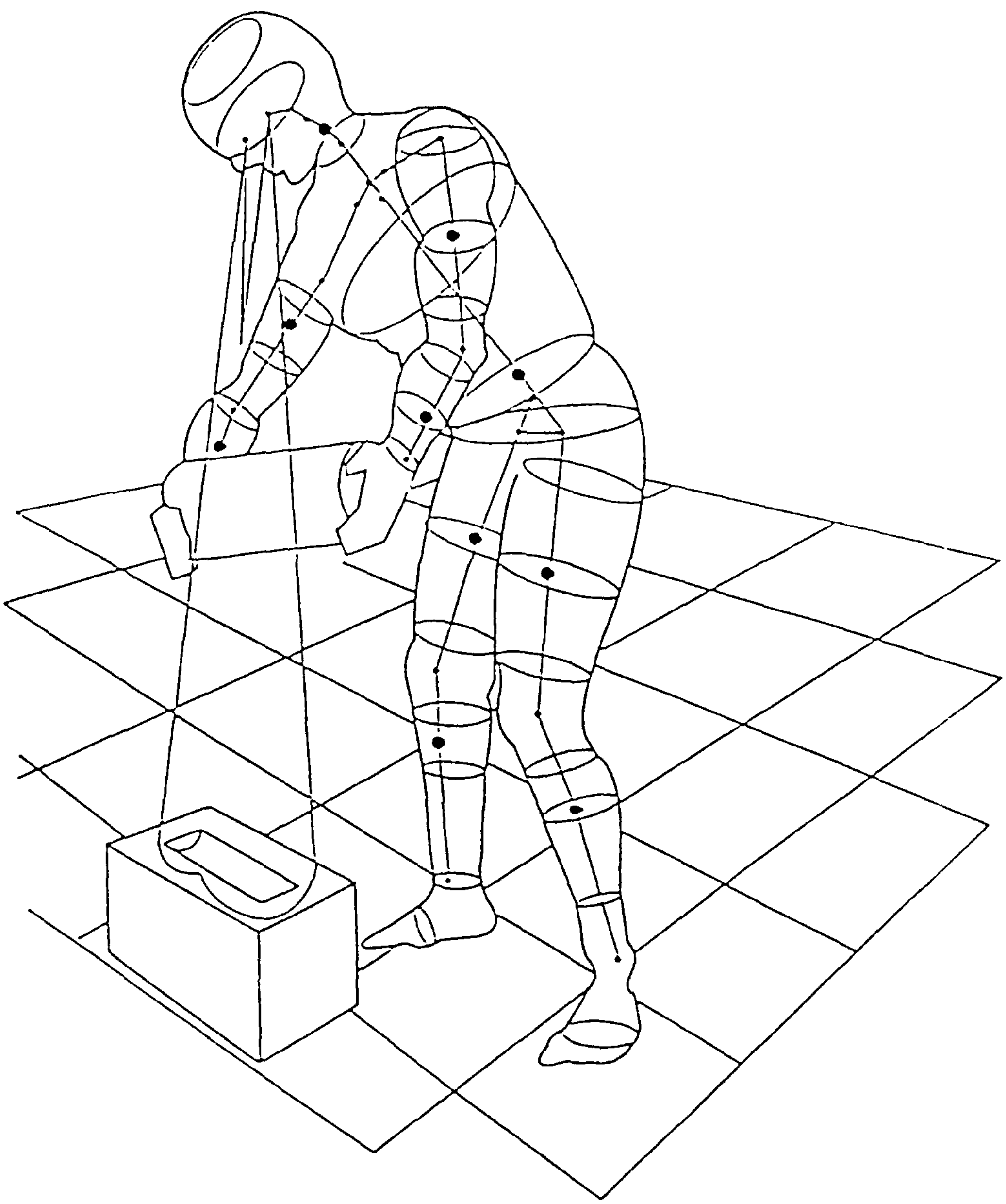

Figure 6. Enfleshed Skeletal Link System of SAFEWORK Man-Model; (Genicom Consultants, 1990).

The developers of SAFEWORK are currently working on improving the accuracy of the surface representation and volume estimates of the body segments using a modeling technique known as dual krigeage. Krigeage is a statistical interpolation method that is being adapted to represent complex surface and shape information in a simple analytical equation (Genicom Inc., 1989; Fortin et al., 1990; Gilbert et al., 1990). This method requires fewer data points than other available methods to determine the exact equation of a given object; thus making it faster and more practical for real-time modeling applications.

Shortcomings

While the SAFEWORK software program currently offers a broad range of applications related to basic anthropometric and biomechanical modeling of the human-machine interface, extensive research and development still remain for it to become the design tool envisioned by its founders. Important features such as vision analysis and animation of models within a workstation are not yet provided. However, as indicated earlier, both of these applications are planned for future implementation. Since SAFEWORK is a relatively new tool with limited information available about its use in actual design and engineering applications, the fundamental accuracy of its model's predictions are somewhat uncertain. Until formal validation of its anthropometric and biomechanical models is conducted and published, the full utility of SAFEWORK as a comprehensive modeling tool remains to be demonstrated. As with most other current human analogue models, the anthropometric and joint range of motion data which support the generation of SAFEWORK's man-model are taken from sources which were not intended to serve complex 3-D anthropometric modeling applications. This necessarily leads to problems in constructing the link system and other physical parameters of the model.

The microcomputer-based platform upon which SAFEWORK was developed, the IBM AT, also creates a potential problem. Although this hardware is both affordable and accessible to most potential users, limitations are inherent in the processing power of the 80386 CPU. The ability to do real-time simulation and analysis is somewhat hampered in this environment as is the ability to implement advanced graphics routines such as color shading, hidden line removal, and ray tracing. However, SAFEWORK has been ported to the Silicon Graphics IRIS Platform, and in this reduced instruction set (RISC) based environment, the increased processing power needed to run the complex mathematical models is readily available.

One of the most promising aspects of the SAFEWORK software is the current research being conducted on Krigeage theory and dual Krigeage techniques used for man-model enfleshment and volumetric representation of body segment surfaces. If this approach fulfils the expectations of the SAFEWORK developers, one major payoff will be the ability to accurately represent the complex surface features of body segments for the intricate modeling and design of personal clothing and equipment.

ANTHROPOMETRIC COMPUTER AIDED DESIGN SYSTEM (ACADS)

The U.S. Navy has currently abandoned work on computerized man-models in the belief that they cannot provide the degree of accuracy needed for the Navy's design and engineering requirements. As an alternative to CAR and other Navy sponsored modeling research, the U.S. Naval Air Test Center, Patuxent River, MD has been working on a program known as the Anthropometric Computer Aided Design System (ACADS) (Dunn, 1989). This program is intended to replace human figure models with digitized images of living human subjects.

ACADS is essentially a data recording system which uses stereoscopic video inputs (two specially configured video cameras) to create an image which is transferrable to a 3-D graphics workstation. The resulting image is not dynamic in the sense that individual limbs of a subject or controls in a cockpit cannot be modified or manipulated independently of one another for modelling purposes. The fixed image can be inserted into a CAD drawing package for purposes such as compatibility testing. The 3-D image produced during this process can be rotated in any plane along the X,Y, and Z axes and analyzed for information such as linear and angular measures at any location (Dunn, 1989). Modifications of lighting and shading of the 3-D computer image is also possible. The ACADS software is written in LISP. The program is currently running on a Symbolics 3675 computer which is networked with a Silicon Graphics IRIS (4D-70GT) workstation.

To date, the primary use of ACADS has involved modeling seated pilots/crewmen inside a cockpit as well as modelling various aspects of interior cockpit surfaces. Once development is completed on ACADS, it will be used to evaluate the utility of cockpit designs and cockpit geometry issues such as fit, reach envelopes, ingress/egress, and ejection pathway analysis early in the conceptual phase of aircraft design. In addition, the effects of seating, restraint devices, and protective clothing on eye and body position will also be examined using ACADS technology. Vision envelopes and the effects of body position on task performance will also be investigated.

The major benefit of this technology is that <u>actual human subjects</u> instead of multiple link-segment computer generated human figures will be used to test man-materiel systems in a 3-D CAD environment. The anthropometric dimensions of the human subjects chosen for ACADS applications could represent any segment of the population but they will ideally reflect worst case scenarios under a given set of cockpit geometry conditions. One disadvantage of this system is that since the postural alignment of an ACADS generated model is essentially fixed in 3-D space, it is necessary to position subjects according to specific design contraints before image generation. Thus if the image of a seated pilot is desired, a mock-up seat configuration incorporating variables such as the seat back and seat pan angles, arm rests, and harnesses must exist before conducting reach and clearance evaluations with respect to the overall cockpit geometry.

The extent to which anthropometric modeling will benefit from ACADS technology depends on the ability to further develop dynamic applications into the software such as body segment movement and real time manipulation of the computer image. ACADS has completed proof-of-concept demonstrations and it has entered testing phases such as accuracy determinations and system validation.

Summary and Conclusion

The ergonomic modeling systems examined in this review encompass a wide range of strategies for generating human figure representations. The differences in skeletal link structure and approaches to enfleshment evident among these models indicate there is no single method for using computers to model human size and shape variability (Table 1). Depending upon the dimensional accuracy required to evaluate a human-machine interface, it may be appropriate to use a simple stick figure without enfleshment, or the need may exist for great detail about body shape and volume. If clothing and equipment design capabilities are sought from computer models, an even greater degree of surface contour and shape detail is required. All of the models presented here provide the ability to model basic link lengths and approximate body segment volumes. However, Jack, with its use of 3-D stereophotogrametric data, and SAFEWORK, with an emphasis on improved enfleshment techniques, provide the greatest potential for implementing clothing and equipment design applications.

In addition to variability in the underlying structure of these human analogue models, they exhibit diverse human-machine interface design and analysis functions. (See Table 1 for a comparative list of model parameters). Some of the major distinctions among them include: CAR emphasizes non-graphic cockpit accommodation evaluation; COMBIMAN is limited to seated aircraft operators; CREW CHIEF focuses on Air Force maintenance technicians; SAMMIE is a general purpose model but limited to graphic anthropometric analysis; SAFEWORK is centered upon human factors concerns related to health and safety; and Jack provides a foundation for broad applications as well as the most advanced vision analysis and strength modeling functions. In fact, Jack is the only modeling system that currently offers well developed capabilities in each of the major modeling areas: anthropometric, biomechanical, and animation. However, it should be emphasized that no single model presently possesses all the attributes required for a universal design and analysis system. Data enhancement, algorithm refinement, and improved functionality are ongoing processes in successful modeling efforts. While research and development on CAR, SAMMIE, and COMBIMAN has essentially been abandoned, innovative work is continuing on CREW CHIEF, SAFEWORK, and Jack.

One of the most pressing problems that impacts the future development and refinement of ergonomic models is the need for accurate anthropometric and biomechanical (strength and joint range of motion) data that lie at the foundation of any modeling system. While traditional anthropometric data have been used to generate human figure models, these data bases were not conceived with the aim of developing man-models and they do not contain link length approximations of the human body. The 1988 anthropometric survey of U.S. Army personnel (Gordon et al., 1990) is the only existing database that includes measurements taken as approximations of segment link lengths. However, in no instance are true link length dimensions available. Therefore, it has traditionally been necessary to estimate internal link lengths based on external surface dimensions primarily using transformation equations provided by Dempster (1955).

Table 1. Comparative List of Computerized Man-Model Attributes.

	SAMMIE	COMBIMAN	CREW CHIEF	CAR	JACK	SAFEWORK
Primary Function	General Purpose Eval.	Seated Cockpit Eval.	Maint. Techn. Eval.	Cockpit Eval.	General Purpose Eval.	Safety & Health Eval.
Skeletal Link System	19-rigid 2-hidden	35-links	35-links	31-links	31-links	35-links
Enfleshment Technique	Geometric Prim. Cones, Cylinders	Ellipses	3-D Facets	None	Geometric Prim. Polyhedrons	Bezier Curves
Primary Anthropometric Database	Dreyfus; Royal AF	USAF US Army	USAF	USN	NASA	USAF US Army
Visibility Analysis	Yes	Yes	Yes	Yes	Yes	Yes
Strength Analysis	No	Yes	Yes	No	Yes	Yes
Animation Capabilities	No	No	No	No	Yes	No
Graphical User Interface	Mouse; Keyboard	Light Pen; Keyboard	Light Pen; Keyboard	Keyboard; Cards	Mouse; Keyboard	Mouse; Keyboard
Computer Platform	PRIME 50 Series Minicomp.	IBM 370 Mainframe	IBM CADAM; Comp.Vision CDS 4001	CDC 660 IBM-PC	Silicon Graphics 4D Series	IBM-PC 80386 CPU
Model Developer	Nottingham University	USAF	USAF	USN	Univ. of Penn.	Genicom Inc.

Creating realistic representations of the complexities of human size and shape variation is another challenge. Until it is technologically possible to collect three-dimensional anthropometric data that unite all body landmarks to a common origin, and until statistical techniques that permit summarization of 3-D populational data emerge, serious limitations on the dimensional accuracy of human models will exist. Ironically, advances in computer hardware and software that permit complex human model generation, computationally intensive real time analysis, and development of sophisticated graphics techniques for interactive design, have far exceeded the quality of available ergonomic data on human beings. This does not mean the future of computer modeling is bleak. It simply suggests that a stronger emphasis needs to be placed on anthropometric and biomechanical data collection efforts that can provide the foundation required for a comprehensive human modeling system.

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