COCKPIT DESIGN AND EVALUATION USING INTERACTIVE GRAPHICS

Susan M. Evans

University of Dayton Research Institute

SUMMARY

This report presents a general overview of the characteristics of an interactive graphics system which has been developed to assist cockpit engineers design and evaluate work stations. The manikin used in this COMputerized BIomechanical MAN-model (COMBIMAN) is described, as are provisions for generating work stations and assessing interactions between man and environment. The applications of the present system are explained, and critiques of COMBIMAN are presented. The limitations of the existing programs and the requirements of the designers necessitate future revisions and additions to the biomechanical and ergonomic properties of COMBIMAN. Some of these enhancements are discussed.

INTRODUCTION

During the design and analysis phases of work-station development, it is essential to assess the physical difficulties, inadequacy of conditions, or dangers of the work-station environment with respect to the human operator. The conventional method for accomplishing this has been to build mock-ups and then use an undetermined number of "representative" test pilots to evaluate the work environment and control placement. These mock-ups tend to be costly and time consuming to build, as well as inflexible during testing. The pilot sample size can range from one to 100, depending on pilot availability and the whims of the designers.

In an effort to assist in the design and analysis phases of work-station development, a COMputerized BIomechanical MAN-model (COMBIMAN) is being developed. It will serve as an interactive-graphics-assisted engineering tool to represent geometric, physical, and ergonomic properties of man at his work station. The tool will also aid in assessing interactions between man, equipment, and environment during task performance (reference 1). It will, therefore, eliminate the need for building mock-ups, as the designer can construct his work station in three dimensions on a Cathode Ray Tube (CRT) and can assess interactions by using man-models of various geometries.

18

The man-model used in COMBIMAN is based on a 30-link skeletal system, as shown in figure 1. The dimensions of the skeletal system can be altered by the user/designer. Since the link-lengths are generally internal and unmeasurable dimensions, link-lengths are based on 11 measurable anthropometric surface dimensions. The user can change the proportions of the model by specifying new values for any number of the surface dimensions. Using stored multiplication factors, the new internal link-lengths are then calculated. A similar relationship has been developed between surface dimensions and link-widths and depths to assist in adding volume to the model.

The work stations designed and evaluated through COMBIMAN consist of three-to-six vertice panels, and control points located either on or off a defined panel. The more complicated work-station configurations developed to date consist of as many as 210 panels and well over 150 controls. All of the work stations which have been developed represent aircraft cockpit configurations, but it is possible to construct and display work stations of any type where operator interaction is essential. This would include automobile instrument panels, assembly line setups, and control panels for other types of military vehicles.

METHODS

Program Structure

The programs which comprise COMBIMAN have been written for use on an IBM computer. The machine which is presently used for the development of COMBIMAN is an IBM 370/155. All interaction with the IBM 2250 CRT is accomplished via IBM's FORTRAN-callable Graphic Subroutine Package (GSP). Interactive devices such as the 32 key Program Function Keyboard (PFK), the fiber-optic light pen, and the alphanumeric keyboard are also used. An overlayed structure of all the routines which make up the interactive package requires approximately 200 K bytes of memory.

The entire COMBIMAN system consists of five programs. Four of the programs are preliminary file creation/modification routines. The data generated by these preliminary programs are contained on an initialization data set, and anthropometric, task, and workspace data bases. The initialization data set contains constant link data used in assembling the man-model and the instructional messages displayed on the CRT during execution of program CBM04 (COMBIMAN, Version 4). The anthropometric data base consists of means, standard deviations and percentiles of surface dimensions from selected anthropometric surveys. The workspace data base and a task data base contain work-station configurations and task sequence information, respectively. The contents of these four files are accessed by CBM04, and their creation is essential prior to executing CBM04. A general data flow diagram of program CBM04 is shown in figure 2.

During the execution of the interactive graphics program CBM04, the user has a variety of options available to him through the use of the programmed function keyboard. The functions which have been implemented to date are shown in figure 3.

Man-Model Generation

In order to display the man-model on the CRT, CBM04 uses information from both the initialization data set and the anthropometric data base, as well as user supplied data on a variable number of anthropometric surface dimensions obtained at run time from the CRT. The ability to make use of user supplied dimension data permits the construction of man-models of variable proportions thus generating a man-model suited to the particular needs of the user. While seated at the CRT, the user can select a survey from the anthropometric data base, and then may choose to input all 11 anthropometric surface dimensions or two key dimensions related to height and weight. These dimensions can be supplied as percentiles, that is 5th, 95th, 50th, etc., or as absolute values. If only two key values were supplied, the balance of the dimensions are calculated based on stored regression equations. To obtain the needed link-lengths, the appropriate anthropometric dimensions are multiplied by predetermined factors stored in the initialization data set. These link-lengths, in conjunction with available link hierarchies and the angular relationship between connecting links, are used to generate the skeletal system of the man-model.

A man-model consisting of solely a link system would provide the user with insufficient information on necessary cockpit dimensions. Volume about the link system is necessary to give the user body support and control placement data. The skeletal system is enfleshed, or supplied with volume, by placing elliptical cylinders about crucial links. The dimensions of the major and minor axes of the proximal and distal ellipses of each link are derived from the multiplication factors stored on the initialization data set and from the relevant anthropometric dimensions used to generate the link lengths. A few special links are enfleshed by ellipsoids, while others, such as those connecting SRP and MID HIP, MID HIP and RIGHT HIP, and MID HIP and LEFT HIP are not enfleshed at all. Third degree polynomial equations have been developed to curve over joint centers, where necessary, to eliminate gaps (reference 2). A view of the enfleshed man-model can be seen in figure 4.

The procedure for generating the enfleshed man-model configuration is to fix to each link L_{I_i}, a local coordinate system C_{I_i}, at the distal joint of the link P_{I_i}, with Z_{I_i} - axis directed along the link in the distal direction. Figure 5 illustrates the local coordinate systems of two links, L_{I_i} and $L_{I_{i-1}}$. The angular relationship between links can be expressed in terms of the transformation between the local coordinate systems. For example, in figure 5, local coordinate system C_{I_i} is related to local coordinate system $C_{I_{i-1}}$ by a constant translation of L_{I_i} and a three-dimensional rotation. Thus, a positional vector $\left\{R_{I_i}\right\}$ in C_{I_i} is transformed to a positional vector $\left\{R_{I_{i-1}}\right\}$ in $C_{I_{i-1}}$ by the matrix equation

$$\left\{R_{I_{i-1}}\right\} = T_{I_i}\left[\left\{R_{I_i}\right\} + \left\{t_{I_i}\right\}\right] \tag{1}$$

Where $\left\{t_{I_i}\right\}$ is constant vector in C_{I_i} with components $[0, 0, L_{I_i}]$ which causes the translation, and T_{I_i} is a rotation transformation matrix which represents the three-dimensional rotation of a local coordinate system. The best means of expressing this transformation is by the Euler angles phi (ϕ), theta (θ), and psi (ψ), which are used commonly in rigid body dynamics. The three Euler angles used correspond to the three rotations of the coordinate axis of the $C_{I_{i-1}}$ system to get to the position of the coordinate axis of the C_{I_i} system. The transformation matrix T_{I_i} for the coordinate system C_{I_i} is shown in figure 6. For the location of the joints, we chose as the reference frame a cartesian coordinate system with its origin at the base point P_0, z-axis directed upward, x-axis directed to the front of the man-model, and y-axis directed to the left side of the man-model. In order to obtain the joint locations, it is necessary to trace the angular relationship from the base point to the joint in question. This may be accomplished conveniently by the transformation matrix T_{I_i}. Instead of considering only the joint locations, we shall consider a more general case of how a position vector $\left\{R_{I_i}\right\}$ in C_{I_i} transforms into a position vector $\left\{R_{I_j}\right\}$ in C_{I_j}, where $j < i$. This is essential when trying to enflesh the link system. The transformation of $\left\{R_{I_i}\right\}$ may be accomplished by the recursive application of equation 1. The general case can be deduced as

$$\left\{R_{I_j}\right\} = \left(\prod_{k=j+1}^{k=i}\right) \left\{R_{I_i}\right\} + \sum_{m=j+1}^{m=i} \left(\prod_{k=j+1}^{k=m} T_{I_k}\right) \left\{t_{I_m}\right\} \tag{3}$$

where $j < i$. Figure 7 shows the preferred transformation angle values for phi, theta and psi, and the link lengths used to position a 50th percentile man-model in seated erect position. The above equations represent the core of the COMBIMAN program designated as CBM04. They are used to assemble the link system of the man-model, to position the enfleshment around it, and to position the enfleshed man-model within a work station. For a more detailed description of the geometry of the model see reference 3.

Work-Station Generation

Two methods are used to generate and display work stations, depending on whether the designer chooses to use an existing configuration, or decides to construct a new one on the CRT using the light pen. Panels and controls for existing configurations are stored on the workspace data base. Prior to running CBM04, the workspace data base maintenance program read in the coordinates of the vertices of each panel as well as the coordinates of each control and converted the points to the right handed coordinate system used throughout the

COMBIMAN system, with the origin located at seat reference point (SRP). Once an existing work station has been retrieved, it and the man-model are rescaled and displayed as two orthogonal views on the CRT.

The second method of generating work stations has the user designing a work station on the CRT with the use of the light pen, alphanumeric keyboard and PFK, following the basic series of steps similar to those used on a drawing board. These steps include locating SRP, specifying back rest and seat pan angles as well as dimensions, and determining line-of-sight and heel rest line of the seated operator. The program CBM04 has been designed to request operator information in a predetermined sequence. As shown in figure 8, three dimensions are projected onto the display area of the screen by using two, two-dimensional views (two orthogonal views) of the man-model and/or work station.

The designer can light pen points on the screen in three dimensions by following the following steps: 1) Position the tracking symbol with the light pen at a point in the left view (normally the X-Z plane of the image) and depress the appropriate PFK; this will signal the program to read the screen coordinates of the light pen. 2) As soon as a horizontal line is displayed on the right side (normally the Y-Z plane) at the Z-level established in the left side, position the tracking symbol with the light pen and again depress the appropriate PFK. This will cause the screen coordinates to be read and will supply the program with a third coordinate for the XYZ triple. Because the screen coordinates are scaled values, the values are converted back to real world units for the benefit of the user and for use in future calculations by the program. This basic sequence of steps is used repeatedly by the designer to construct panels, define controls, and to determine the location of points within the workspace.

Reach Analysis

The key method of assessing interaction between the man-model and work station involves a reach analysis routine which is part of the CBM04 program. The purpose of the reach analysis routine is to determine whether a point in space can be reached by human operators of various anthropometric dimensions. The user light pens the point to be reached, and specifies the link on the man-model where motion is to start. Specifying the latter item allows the designer to restrict motion of certain body segments, as in simulating a restraining cockpit environment where the seated operator is unable to move his back. The routine places the most proximal link of the chain or series of links in a position that brings its distal end closest to the test point. A chain is defined as a series of connected links, such as those links used in the torso-head or right arm systems. This procedure is repeated for the remaining body links of the chain. The specified point is considered to be within reach if the distal point of the most distal link can be placed at that point. The positioning of an individual body link closest to the point to be reached is accomplished by using the IBM-supplied minimization subroutine DFMFP, which is based on the method developed by R. Fletcher and M.J.D. Powell (references 4 and 5). The objective function and gradient vector which are required by the DFMFP routine have been developed by University of Dayton Research Institute (UDRI) personnel (references 2 and 3).

The angular limits of mobility, the minimum and maximum values for each of the transformation angles, are obtained from the initialization data set and are used in calculating the objective function and gradient vector to avoid unrealistic positioning of the man-model.

RESULTS

By using the man-model, work station and reach analysis routines mentioned above, the work-station engineer can gain additional information about the interactions of human operators and work-station environments.

The reach analysis routine explained above, in conjunction with the other elements of COMBIMAN, can assist the designer in determining static body positions of the model. A key element in this procedure is the joint mobility constraints. These angles, when used by the reach routine, prevent the model from assuming a humanly impossible position. Until the model includes data on link weight factors, the resulting static position may not be the position most likely assumed, but it will nonetheless be possible to assume it.

The reach analysis routine can also be used to establish reach envelopes. For this purpose, a point in space is light penned and the reach analysis is initiated. After the first attempt the point can be light penned again, this time at a location just beyond the reach capabilities of the man-model. The most distal point of the displayed man-model will then mark the point of maximum reach in that direction. The point to be reached can then be moved in increments in any desired direction. Each one of these moves results in the determination of another point of maximum reach. Thus reach envelopes can be point wise established on the CRT. By adding the user-initiated option of storing these points, they would be available at the time the user requested hard copy plots of the envelopes. Since changes in body geometries tend to alter the definition of the reach envelopes, the user could obtain envelopes for an infinite number of combinations of body geometries by altering the anthropometric dimensions used in generating the man-model.

By combining the above mentioned applications, the designer can analyze the present placement of major controls within the displayed work station with respect to the reach envelope of the seated operator, and he can determine their optimum location. He can also analyze the dimensions of the work station with respect to the body geometry of the operator. Controls and panels of predefined, as well as newly developed, work stations can be deleted and then redefined by following the same sequence of steps using PFK and light pen as used to design a new work station. The geometry of the man-model can be varied to fully evaluate the particular area being tested.

In assessing control placement, for example, man-models of the 5th, 50th and 95th percentiles of a particular survey may be displayed within a work station, one after another, and instructed to reach to a particular control. A printed message on the CRT, as well as the repositioned model, will assist the user in determining the correct control placement for this range of the population. In another example, when evaluating ejection seat clearance, a key anthropometric dimension involved is Butt-Knee Length. The designer may change this dimension alone, or this along with Shoulder Breadth or any number of others, generating as many combinations of dimensions as he needs to fully analyze the clearance dimension requirements.

The standard COMBIMAN CRT display area consists of a prompting area, an informational area, and a display area, similar to that shown in figure 9. At any time during the design and analysis phases of COMBIMAN, the contents of the display area can be rotated and/or magnified to gain a more detailed and accurate view of the man-work-station combination. Both views may be rotated, or just one of the two can be enlarged to occupy the entire 12" screen, rather than the normal 6" square. Rotation of the display to any plane will provide the user with a complete three-dimensional composite of the configuration. To further assist the user, hard copy plots of the present configuration can be requested, as well as a printed copy of man-model and work-station coordinates. At termination of the program CBM04, a detailed activity log is printed.

FUTURE RESEARCH

Additional research and redesign efforts are underway to eliminate the limitations of the present system. One of such limitations is the lack of interference handling. The mobility constraints of the man-model prohibit it from reaching through itself but there is no provision for avoiding interference of the work station itself. This includes control sticks, instrument panels or back rests. Another limitation was mentioned before. The static body positions as derived and displayed are humanly possible to assume, but in some cases, they would not be the position the majority of human operators would assume. Within the next few months, the body positioning of COMBIMAN will be improved to achieve a more realistic simulation of static body positions and to simulate dynamic body motions on the CRT. This incorporation of kinematic reach with typical movement patterns will be based on pertinent available experimental results, as well as segment mass distribution and moment of inertia data.

Enhancement of the ergonomic properties of COMBIMAN will enable the user to better assess man, equipment and environment interactions during actual task sequences. In addition to the incorporation of kinematic reach, scheduled additions include incorporation of ground visibility plots and the effects of personal-protective equipment and acceleration fields. These additions, when used in conjunction with the COMBIMAN model, will allow the user to specify a task sequence contained on the task data base, a specific G-force, encumbering equipment, and body supports, and then allow the user to watch as the model performs within the specified environmental conditions. This capability will provide the designer with information on safety, comfort and performance not easily measurable in real life.

CONCLUDING REMARKS

With the COMBIMAN system in its present state of development, the designer can display an existing work station from the workspace data base, or can generate one from scratch, or even combine parts of existing work stations with newly designed ones. He can add a man-model with dimensions to suit his needs. He can then vary the position of the model and the configuration of the work station as many times as necessary to obtain the best possible work-station environment. To attempt to obtain this variability in man and work station with any other method than a computer drawing board would be impossible.

As the anthropometric, biomechanical and ergonomic analogs of COMBIMAN advance in development, COMBIMAN, as an engineering tool will increase in power. COMBIMAN, as an anthropomorphic dynamic analog of the man-cockpit interface, will be a powerful engineering tool in the evaluation of existing, or the planning and design of new manned systems. Its flexibility and power will serve the engineers' needs directly and will accelerate or eliminate the manual phases of design work.

REFERENCES

1. Kroemer, K.H.E.: COMBIMAN-Computerized Biomechanical Man-Model. AMRL-TR-72-16, 1973.

2. Dillhoff, K.J., Evans, S.M., and Krause, H.E.: Incorporation of Reach, Dynamic and Operational Capabilities in an Improved COMBIMAN Man-Model. UDRI-TR-74-50, 1974.

3. Bates, F.J., Evans, S.M., Krause, H.E., and Luming, H.: Three Dimensional Display of the COMBIMAN Man-Model and Workspace. UDRI-TR-73-47, 1973.

4. Fletcher, R. and Powell, M.J.D.: A Rapidly Convergent Descent Method for Minimization. Computer Journal, June 1963, pp. 163-168.

5. Fletcher, R. and Powell, M.J.D.: Function Minimization by Conjugate Gradients. Computer Journal, July 1974, pp. 149-154.

ACKNOWLEDGMENTS

Research for COMBIMAN by the University of Dayton Research Institute is sponsored by the Crew Station Integration Branch, Human Engineering Division, 6570th Aerospace Medical Research Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The current effort is funded by Contract No. F33615-75-C-5092.

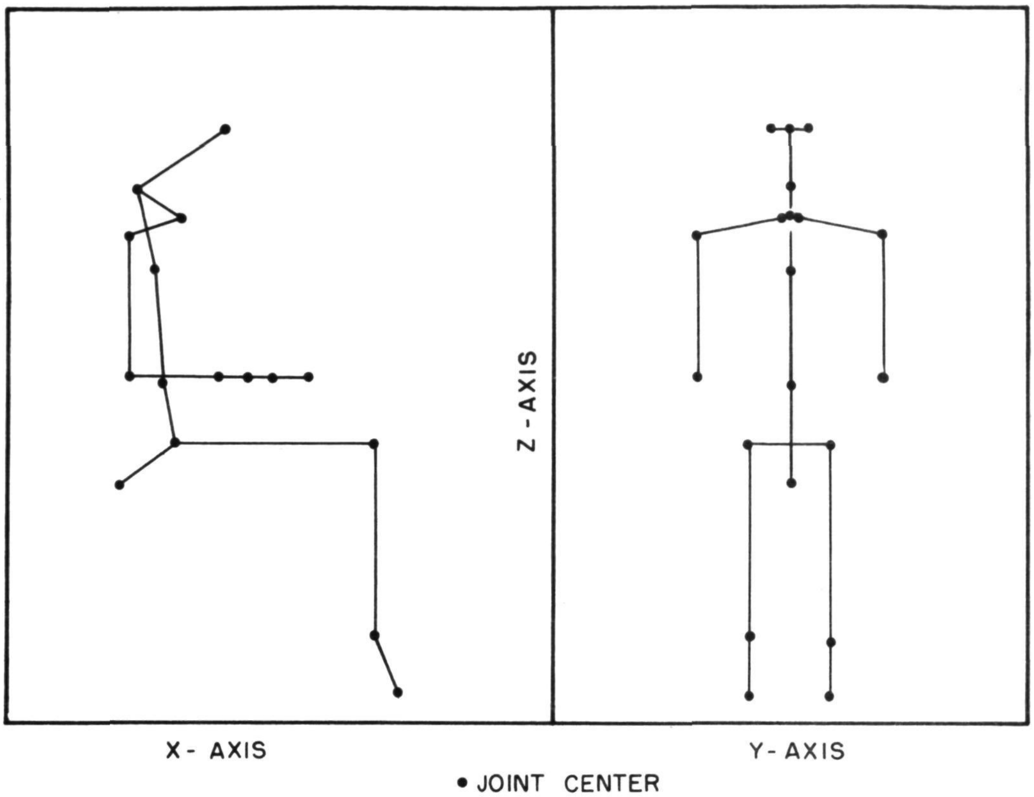

Figure 1.- Link system of present COMBIMAN man-model.

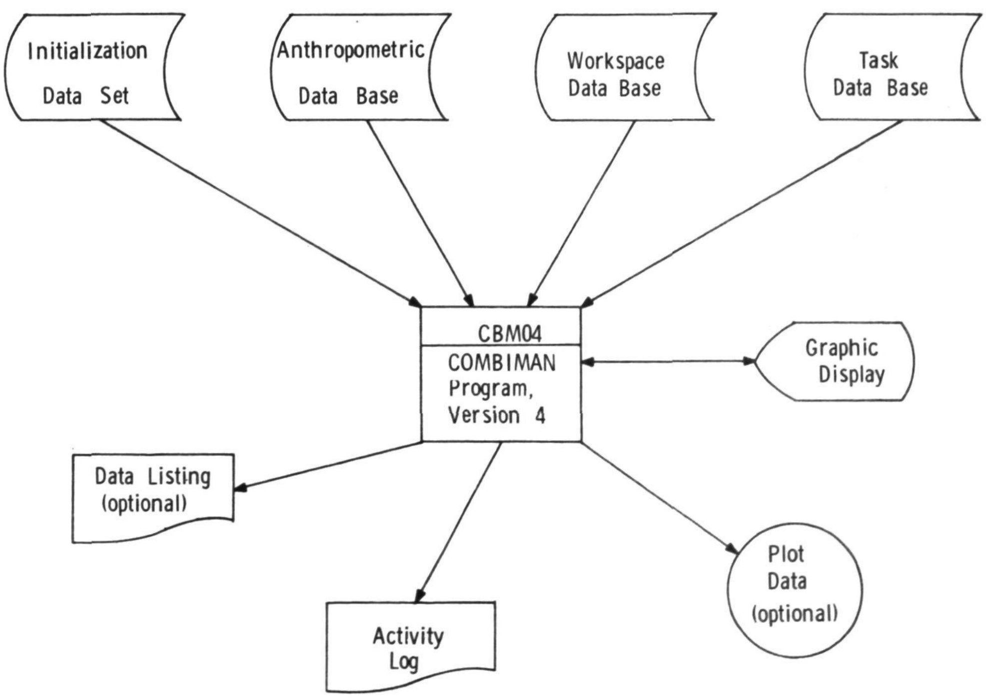

Figure 2.- Data flow in the COMBIMAN interactive graphics program CBM04.

ANTHROPOMETRY-RELATED	WORKSPACE-RELATED	DISPLAY-RELATED
Retrieve Anthropometry	Retrieve Workspace	Change View
Enter Link Dimensions	Design Panel	Identify Object
Enter Two Key Dimensions	Define Control	Omit Object
Display Link Table	Delete Panel	Include Object
	Delete Control	Note Light-Pen Location
	Change Panel	
	Change Control	

MAN-MACHINE-INTERACTION-RELATED	PRINTER/PLOTTER-RELATED	PROGRAM-EXECUTION-RELATED
Perform Task	Print Data	Set Sense Switch
Perform Reach	Plot COMBIMAN	Restart Program
		End Program

Figure 3.- Program function keys implemented to date.

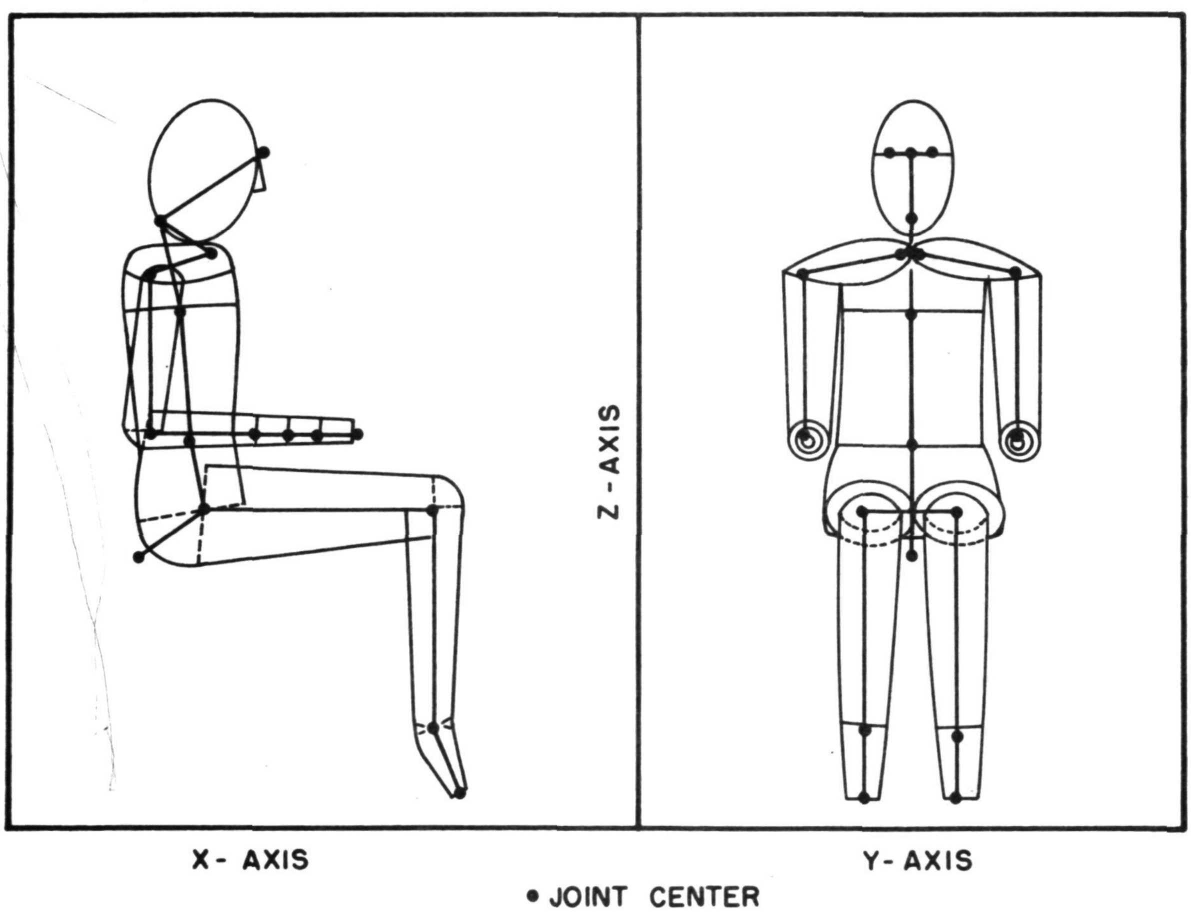

Figure 4.- Enfleshed COMBIMAN man-model.

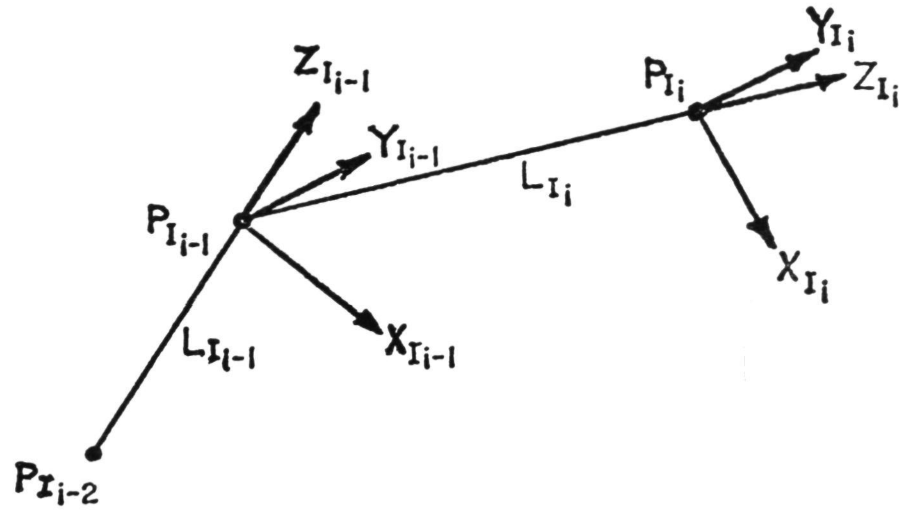

Figure 5.- Typical local coordinate systems affixed to links.

$$T_{I_i} = \left[\begin{array}{c|c|c} \cos\theta_{I_i}\cos\phi_{I_i}\cos\psi_{I_i} - \sin\phi_{I_i}\sin\psi_{I_i} & -\cos\theta_{I_i}\cos\phi_{I_i}\sin\psi_{I_i} - \sin\phi_{I_i}\cos\psi_{I_i} & +\sin\theta_{I_i}\cos\phi_{I_i} \\ \hline \cos\theta_{I_i}\sin\phi_{I_i}\cos\psi_{I_i} + \cos\phi_{I_i}\sin\psi_{I_i} & -\cos\theta_{I_i}\sin\phi_{I_i}\sin\psi_{I_i} + \cos\phi_{I_i}\cos\psi_{I_i} & \sin\theta_{I_i}\sin\phi_{I_i} \\ \hline -\sin\theta_{I_i}\cos\psi_{I_i} & \sin\theta_{I_i}\sin\psi_{I_i} & \cos\theta_{I_i} \end{array}\right]$$

Figure 6.- Transformation matrix T_{I_i} for coordinate system C_{I_i}.