COMPUTERIZED BIOMECHANICAL MAN-MODEL

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ABSTRACT

The COMputerized BIomechanical MAN-Model (called COMBIMAN) is a computer interactive graphics technique for workplace design. This model allows a designer, sitting at a CRT, to manipulate a three-dimensional male form of variable anthropometry and to design a workplace around him by means of a lightpen. While originally intended for aircraft design and evaluation, the general format of the model is suitable for consideration of virtually any workplace configuration and can be used to evaluate existing or theoretical workplaces with equal ease and precision.

INTRODUCTION

With the ever-accelerating advancement of technological progress, the human engineer, or ergonomist, has become a recognized member of the engineering design team. His newfound recognition however, will not endure in the industrial environment unless the quantity and quality of his effort can keep pace with industry's proliferating demands. If a human engineer's contribution is not submitted early in the design cycle, it has no impact on the ultimate product. If the contribution is deficient in quality, it may actually degrade the operator's performance at the workplace and even threaten his safety.

The use of mock-ups for biomechanical evaluation has long been a tool of the human engineer. Recently, however, limited money, manpower, and time make extensive use of mock-ups for biomechanical evaluation unfeasible. As a result, human engineers, like their colleagues in the more traditional engineering fields, are turning to computer-aided simulation techniques to design for and evaluate man's interaction with his working environment.

In the Crew Station Integration Branch of the Aerospace Medical Research Laboratory, we are developing a computerized biomechanical man-model called COMBIMAN. This on-line interactive computer model was conceived as a three-dimensional manikin for workplace design and evaluation. Kroemer (1973) described the program concept and established the goals and general philosophy of the model. Since the beginning of the COMBIMAN program, there have been many changes, such as the evolution of the new body segment/link system, a simplified enfleshment, a redefinition of anthropometric variables, and new interactive graphics techniques.

COMBIMAN has important applications in the evaluation of existing workplaces, design of new workplaces, selection of criteria for personnel to fit workplaces, and mapping visibility plots.

In attempting to simulate the geometry and actions of a human operator, we have discovered many loopholes in the anthropometric and human performance data bases heretofore in use, and have justified several research programs to supplement or improve the data base of human engineering. Perhaps of greatest significance, the COMBIMAN is now being applied to the solution of design problems.

Because a worker functions in three-dimensions, it is impossible to evaluate adequately a workplace from a two-dimensional drawing. Prior to COMBIMAN, the only effective way to evaluate a workplace concept was to build a mock-up which permitted the designer to visualize the three-dimensional aspects of the design for the first time. While the mock-up does provide a three-dimensional representation, construction of a good one is both time consuming and costly. The mock-up evaluation is also limited, because it is difficult to find subject operators who adequately represent the anthropometric variability of the user population, a limitation which has led to erroneous conclusions. A mock-up is hardware, and requires some cost and effort to modify. Thus, it can become an obstacle to design change.

COMBIMAN does not share these handicaps. It is truly a three-dimensional model which may be viewed from any angle. Since the man-model and workplace design exist only on a CRT display and in a computer memory, there is no significant investment of time or materials in effecting modifications. Because the user can modify the design easily while sitting at the display, the resistance to change is eliminated and experimentation is encouraged. Alternative designs may be thoroughly evaluated and then permanently recorded by means of a pictorial plot or tabular printout of the workplace data and man-model.

The variable geometry of the COMBIMAN allows the user to define quickly a series of man-models which represent the entire anthropometric range of a given user population. A variety of special problems can be evaluated by generating realistic

ranges of certain body segments, while proportioning the remaining segments to achieve a reasonable configuration. The sophisticated manipulation of anthropometric data is probably COMBIMAN's greatest asset. We are all aware that each individual's body proportions are unique. If a person has an average sitting eye height, for example, his arms and legs will not necessarily be of average length. This variability in proportions is what ordinarily makes anthropometric data so difficult to apply to workplace design. With one of the options available in COMBIMAN, the operator can specify a certain sitting eye height and the program will generate a man-model with realistic proportions. The user is prevented from selecting an unrealistic combination of body-segment dimensions by constraining equations which are derived from the actual anthropometric data base of the population being considered.

Construction of the Man-Model

The man-model itself is constructed in three stages (see also Evans, 1975). The first stage is the generation of the link system consisting of 33 segments which correspond functionally to the human skeletal system. Each of these links connects major points of rotation of the body segments, see Figure 1. Two of the links are actually not part of the man-model, but serve to provide a reference to the "seat reference point." The link system is constructed by adding links sequentially from the reference point. The dimensions of the links are based on data entered directly by the user or computed from anthropometric survey data. As each link is added to the model, it is assigned a three-dimensional Euler-type angle which relates the angular coordinates of each new link to that of the previous link. Thus each link has a local coordinate system attached to its distal end. The advantages of this construction technique are that it places realistic limitations on the range of mobility of each joint and permits the repositioning of a distal link by movement of a proximal link. This system allows each link to move with up to six degrees of freedom with respect to the external coordinate system.

The second stage of man-model generation is the definition of the enfleshment ellipsoids (a three-dimensional ellipse) about the link system joints as shown in Figure 2. The dimensions of each of these ellipsoids are derived from a complex combination of body surface dimensions and body mass. Each ellipsoid has a height, width, and breadth which is consistent with the surface dimensions at that joint. In addition, each ellipsoid is offset some distance from the joint itself, since the center of rotation of a joint is not in the center of the external surface dimension. This offset is most noticeable in Figure 2 in the case of the elbow joint and the trunk ellipsoids. The accuracy of the enfleshment equations is currently being validated against actual subject data gethered through use of a photogrammetry technique.

There are three orthogonal viewing planes available to the user: X-Z, X-Y, and Y-Z. The user may look at any two of these projections simultaneously (see also Bates, et al., 1973).
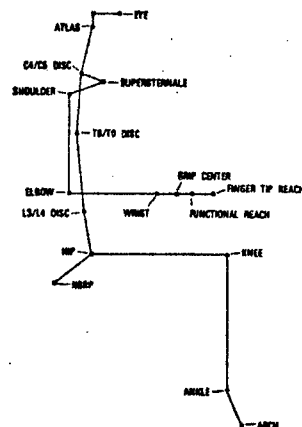

Figure 1. First stage of man-model construction - side view of COMBIMAN link system showing major axes of rotation.
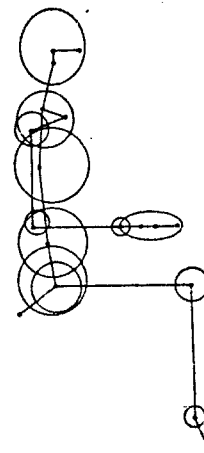

Figure 2. Second stage of man-model construction - side view of link system with projected silhouettes of enfleshment ellipsoids.
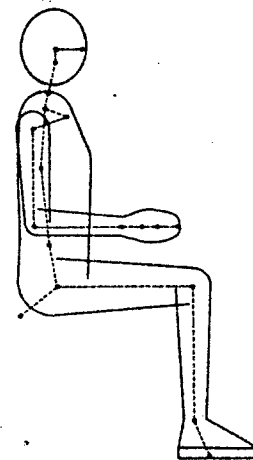

Figure 3. Third stage of man-model construction - side view of completed model. Dashed lines indicate link system.

The model need not be parallel to these viewing planes however, as he is in Figures 1 to 3. The man-model may be, and frequently is, rotated at some acute angle to the viewing plane.

One of the major shortcomings of the original COMBIMAN was that the enfleshment consisted of rectangular solids. Not only were these rectangles unnatural in appearance, but they were difficult to interpret. The enfleshment alone was nearly 400 lines, and it became difficult to determine which lines were part of the man-model and which lines were part of the workplace.

With the new enfleshment technique, only the silhouette of the man-model is projected. This corresponds more accurately to the human form and is much easier to interpret.

The third stage of man-model construction is connection of the ellipsoid silhouettes by tangent lines. This is done separately for each viewing plane to keep the number of lines in each projection to as few as possible. The resulting man-model is similar to that shown in Figure 3. Sections of ellipsoid projections are retained to curve over the joints. The link system itself, shown as a series of broken lines in Figure 3, may or may not be displayed at the option of the user. At the present time, hidden lines in the man-model and workplace may be individually eliminated by the user with the lightpen or keyboard commands. A subprogram is currently planned which will automatically eliminate the hidden lines although this will remain optional because there are many instances in design and evaluation which require the projection of all the parts.

The two most important applications of COMBIMAN are in (1) the design of workplaces and (2) the evaluation of workplaces. The other features of the model (variable anthropometry, reach envelopes, visibility plots, etc.) are used in support of these two primary applications.

Workplace Design

The COMBIMAN is a valuable and powerful tool for assisting the engineer in the design of workplaces. Starting with a list of requirements for a workplace, the designer can call up the man-model to which he has assigned dimensions representative of the population of intended operators. The designer can then quickly define the various control/display panels around the man-model indicating the cornerpoints with the lightpen. These are then connected by lines to indicate the panels which are not only created on the display, but are also entered in the three-dimensional storage arrays and can be printed for future use. The designer can cause the coordinates of a point to be displayed simply by pointing the lightpen and pressing a button. The displayed coordinates are in inches, full scale with respect to a meaningful reference point rather than in arbitrary units which would have to be scaled or converted in order to be understood.

Frequently, the area available for the workplace is predetermined or at least constrained by some maximum dimensions. The size and location of

some control panels may also be known. If workplace constraints are known in advance, they may be entered from one or any combination of these input devices:

1. Lightpen (on CRT)
2. Keyboard (on CRT)
3. Punched cards
4. Magnetic tape storage
5. Disc storage

The user can temporarily prevent certain characteristics of the workplace from being displayed, without removing them from the workplace storage arrays. To eliminate the projection of a particular control panel, the user simply points the lightpen at the panel and presses a button. This technique allows the operator to unclutter a very complex workplace. After the workplace has been designed around the man-model, the designer may evaluate the workplace by the following method.

Workplace Evaluation

A major feature of the COMBIMAN is its utility in evaluating workplaces. These generally fall into three categories:

A. Existing workplaces.

B. Conceptual workplaces (which have not been constructed, but exist as an engineering drawing).

C. Workplaces generated with the lightpen in on-line design operations.

Once a workplace has been entered into the program, it exists in three dimensions and can be made to interact with the man-model. Although the CRT is a two-dimensional display, two orthogonal views are simultaneously projected and can be rotated for viewing at any angle. If the user wants to take a closer look at some feature of the display, that feature can be magnified to the desired size. Regardless of the scale of the display, all coordinates and dimensions are stored in full scale.

There are several evaluation techniques available to the user and others are presently under development or in planning stages. These techniques are chiefly designed to define the dimensions of the man-model and move the man-model within the workplace to simulate the intended task.

Dimensioning the Man-Model

Presently the operator has several options in defining the body segment dimensions for the man-model:

A. Direct Measure: specific individuals are entered into the model from the keyboard or punched cards. Although this method is rarely used in designing workplaces, it is very useful for the validation of the model, which is in progress.

B. Stored Individual Data: data from

anthropometric surveys are stored on computer tapes. Dimensions of a selected individual can be recalled and used to dimension the man-model.

C. Data Base Summary Statistics: percentiles computed from large samples are used to define the man-model. Because a 5th percentile man is not an assemblage of 5th percentile body segments, the user must select a separate percentile value for each of the critical variables by selecting the desired value from a list of displayed percentile values. The lightpen is used to check off the desired percentile value as each critical dimension is successively underlined.

D. Computer-Aided Dimensioning: assists the user in generating abstract, but realistic man-models from anthropometric survey data.

This last method is most useful for workplace evaluation. The user starts by defining the body characteristic most relevant to the evaluation. This characteristic may be a dimension (such as sitting height, arm length, etc.) or a mass (such as total body mass or some segment mass) and can be defined either as an actual measure or a percentile value. For example, suppose the operator elects to define an individual with a sitting eye height of 34.5 inches. The program displays the range of body masses appropriate for a person having a sitting eye height of 34.5 inches and the user selects a mass value within this range. Based on these two values the program constructs a realistically proportioned man-model from regression equations. Of all the methods for dimensioning a man-model for workplace evaluation, this one is the most useful. It is both fast and accurate. It allows the user to call up a wide range of man-models with critical dimensions determined by the nature of the task. For example, when evaluating capability for reaching manual controls, the user may select "arm length" as the critical dimension. When evaluating foot pedals, "leg length" would be selected as the critical dimension. This technique allows the operator to concentrate on the evaluation without being distracted by complex manipulations of anthropometric data.

Manipulating the Model

The man-model can be positioned and moved about by commands from the lightpen or keyboard in on-line operation. The man-model can also be controlled by a complex task sequence generated by another program.

When evaluating a workplace with a variable geometry man-model, an important consideration is the ability to reach certain hand and foot operated controls. The hand of COMBIMAN, designed to perform the three primary reach functions, is made up of three links originating from the wrist.

1. Grip center (whole-hand grip)

2. Functional reach (finger grip, i.e., knobs)

3. Finger tip reach (push button)

These three links (shown in Figures 1 and 3) were designed specifically to evaluate the types of reach to and manipulation of controls found in the workplace, and to establish reach envelopes for various body sizes and configurations, as well as for individuals restricted by various items of clothing or protective equipment.

To use the reach routine, which can be applied to arms, legs or even the head, the operator uses the lightpen or a keyboard command to enter the point to be reached and a limb to perform the reach. He can limit an arm reach to arm movement only, arm-shoulder movement only, or arm-shoulder-trunk movement. These options are useful in evaluating the restraints of personal protective equipment, such as a shoulder harness. The results of a typical reach routine are shown in Figure 4. In this figure, two man-models are reaching for a control panel using an arm movement only. Both models have the same scale and both panels are the same distance from the seat reference point. In Figure 4A, the man-model has a 95th percentile sitting height based on the Air Force 1967 survey data. This man-model is able to reach the panel with a finger tip reach. In Figure 4B, the man-model, based on a 5th percentile sitting height, cannot reach the panel. The smaller man-model would have to extend the shoulder and lean the trunk toward the panel to reach the selected point.

Figure 4A also illustrates an off-axis view of the man-model. Also note that the model's left arm is extended 45° to the left of forward. In other words, the arm is parallel to the viewing plane and the panel is perpendicular to the viewing plane. This demonstrates some of the options available for manipulating and displaying the man-model and the workplace.

Of great importance in the design or evaluation of a workplace is a permanent record of the relevant configurations created during the on-line operation for future detailed examination. At any stage of design or evaluation, the operator may generate a printout and plot of the workplace. The printout provides detailed body dimensions of the man-model plus the coordinates of the workplace features. The plot of the workplace may be of any desired scale.

Visibility Plots

There are many techniques currently available for mapping the visual field of a workplace. These vary from special cameras to computer generated plots but they all share one disadvantage which seriously compromises their utility. This weakness is the definition of a fixed reference eye position. In aircraft design this arbitrary reference point, called the "Design Eye Position," is a measured distance from the neutral-seat-reference-point. Cockpit designers have long recognized the inaccuracy of the arbitrary "design eye position." Neither the pilot, nor any other worker normally sit erect and keep their heads in a fixed position as they perform their tasks; they turn their heads in the general direction of interest. In a narrow cockpit, a lateral eye displacement of six inches toward the

canopy frame would not be unusual, yet this displacement would drastically increase the pilot's look-down angle through the side canopy. No visibility plot with a fixed reference can begin to define the dynamic situation which actually exists.

COMBIMAN can define a complex range of head and eye positions with great accuracy. Because of this capability, the incorporation of visibility plots into the COMBIMAN programs was a logical development. In addition, because of the ease and accuracy with which the program handles three-dimensional geometry, the COMBIMAN visibility plots contain additional information which increases the utility of the output, specifically, the three-dimensional coordinates of the workplace with respect to the viewing angle. Using the cockpit once again as an example, the visibility plot program scans the frame of the canopy and plots the vertical viewing angle for each integer degree within the horizontal field-of-view. The printout shows the three-dimensional coordinates of the canopy frame at each five-degree increment of the horizontal angle. These coordinates are given in the aircraft coordinate system, so that any point in question may be precisely located on the cockpit drawing. Such a correlation between look-angle and workplace coordinates makes this type of visibility plot extremely useful to the design engineer since it provides accurate feedback of the effect of hardware modifications on the external visibility of the pilot. When evaluating the external visibility characteristics of a certain cockpit, the designer can easily vary any of the following:

A. Size of the operator (such as sitting eye height based on relevant anthropometric surveys).

B. Seat adjustment (vertically, horizontally, or both).

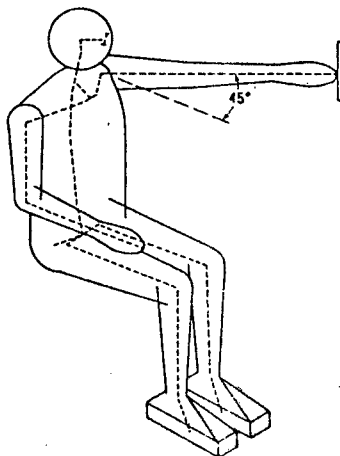C. Head position (which may be a complex function of upper body position).

D. Visual restrictions (helmet, helmet-mounted displays, etc.).

The limits of visual fixation and the limits of peripheral vision are superimposed over the plot of visual angles. These limits have meaning in the COMBIMAN plots which reflect realistic head mobility. With the conventional fixed eye reference visibility plots, the visual angles normally range ±180° in the horizontal plane, which is not realistic.

Future Development

In the near future, several features will be added to the COMBIMAN program which will further enhance its utility for workplace design and evaluation. Texas Tech University has just completed an analysis of paths of arm and hand motion while reaching to controls. The present reach routine consists of a single final position representing the completed reach (see also Dillhoff, et al., 1974). When the new data are integrated into the program, the reach will be completed in stages, similar to stop-action photography.

Human strength data are presently being gathered and will be incorporated into the model. These strength simulations will depend upon the direction of force application and the configuration of the man-model while applying these forces. COMBIMAN is well suited for this task because of the design and functioning of the link system. Since the amount of torque that can be generated at each joint is a function of the joint angle, the link system should not have to be modified to incorporate these data.

In addition to link system and enfleshed volume of the man-model, there are provisions for assigning a mass and moments of inertia to each of the body segments. The data for these variables are presently under analysis. When the segment mass and moments are incorporated into the model, it will be useful in evaluating the effects
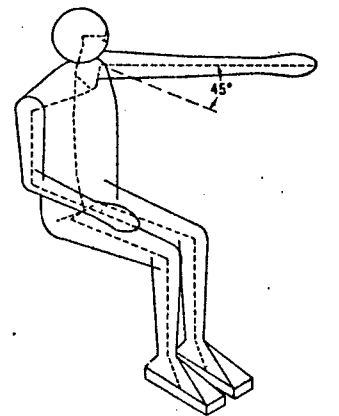

Figure 4a. COMBIMAN with 95th percentile sitting height reaching to control panel.

Figure 4b. COMBIMAN with 5th percentile sitting height is unable to reach the same panel.

of acceleration on the man-model.

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