DCIEM No. 88-TR-32

REPRESENTATION OF MAN USING CAD TECHNOLOGY: USER BEWARE

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INTRODUCTION

In workplace design, the ergonomist aims to optimize worker comfort, safety and performance. To do this, he must consider relationships between the operator and his work, the work environment, and the equipment used. Anthropometry, the scientific measurement of the human body, provides techniques which the ergonomist uses to estimate man's reach, vision, body clearance and body posture within the workplace. For example, two-dimensional drawing board manikins, composed of articulated scale representations of body segments, are used to describe man in side view; and stick-figure manikins are used to provide reference loci from which reach distances, visual angles and eye positions can be calculated. Partial and whole-body manikins are used to convey more realistic likenesses of man by representing anatomical landmarks, body contours and segment masses.

Each of these tools is appropriate for isolated applications but none is singularly satisfactory for general-purpose workplace design. The major reason is that they are limited in their abilities to represent the anthropometric variability between individuals. There are also problems associated with the availability of these tools, the cumbersome nature of their use, and the questionable validity of their results (Rothwell, 1985).

More and more, computer-aided design (CAD) is replacing traditional manual design functions (e.g., drafting, calculating, analyzing) with computer packages that utilize interactive computer graphics (Majchrzak et al., 1987). This has revolutionized the methods to model and simulate the physical environment. But relatively few CAD program developers have used this approach to represent the human component of the man-machine system (Bonney et al., 1979; Kingsley, Schofield and Case, 1981). A major factor influencing this deficit is the lack of mathematical models of the human body with respect to its shape, joint articulations and motions. Still, man-modelling CAD offers better ways to represent man in the man-machine system than do traditional anthropometry tools (Rothwell, 1985).

One major advantage of man-modelling CAD is the potential to model complex individual differences. The technology also offers the potential to model atypical body structures and functions (e.g., in designing for physically disabled persons). Another advantage is the ability to view the man-machine system in three-dimensions. This facilitates the consideration of issues such as cross-body reaches, asymmetrical postures and postural stability (Rothwell and Hickey, 1986). By encouraging iterative explorations of complex man-machine relationships, it can be argued that man-modelling CAD leads to more thorough workplace evaluations than do manual techniques.

The use of CAD to represent man's anthropometry also has disadvantages. Some problems stem from the limitations that anthropometric source data impose on how the man-models can be defined (e.g., using only external body measures). Other problems arise from our limited understanding of how man should be modelled (e.g., the underlying assumptions used to generate and manipulate man-models, population representation using percentile data). There are also problems that stem from the nature of CAD technology itself. For instance, demand for detailed input data and compelling graphic displays imply inherent model validity that may not be justified. These problems persist because few CAD systems are evaluated rigorously and little basic research is conducted to resolve outstanding modelling problems (e.g., how to derive internal link structures from external anthropometric data).

Man-modelling CAD is not the universal remedy to represent man's physical attributes in design. Part of the reason is that, at present, CAD systems do not provide expertise in anthropometry or workplace design. Instead, they offer the user the freedom to manipulate design elements in many different ways. It is implicit, then, that the user must understand a) how man-models can and should be used to represent man's physical characteristics, and b) how workplace elements should be manipulated to address design objectives. Furthermore, CAD man-models do not replace the use of human subjects in design fitting trials. Rather, they allow the designer to consider man-machine interactions in early design stages. Finally, as with any computing system, individual CAD packages are subject to programming errors, some of which are not immediately obvious. The user must beware of the potential for such errors, and make an effort to understand how the capabilities and limitations of a given system will affect design work.

The following sections of this paper illustrate that expertise in anthropometry and workplace design are required of those who elect to use man-modelling CAD. Some insights are provided into the availability and nature of the technology. Following this is a general discussion of man-modelling and workplace-modelling issues, and the factors that should be considered when performing an ergonomics assessment of the man-machine model. The message can be viewed as a warning insofar as the technology should not be used naively, and not all systems satisfy all workplace design objectives.

SYSTEM AVAILABILITY

A survey (Hickey, Pierrynowski and Rothwell, 1985) conducted to identify existing computer man-modelling programs found that some 33 programs employed man-models while approximately 40 more incorporated single or isolated measures of human characteristics (e.g., maximal reach, visual field angles, task time). Only a few of these programs attempted to represent the various body sizes, proportions and joint articulations of man. Also, little detailed information was available on these programs, making it difficult to classify the types of analyses they perform. Changes in the program names and gaps in reporting updates made it difficult to identify new or independent modelling efforts. The conclusion from the survey was that the written literature is currently a poor source of information regarding the characteristics and uses of man-modelling CAD systems.

Most man-modelling CAD systems have been developed for governmental or university research purposes. Although several programs are used for general military applications (Richards and Companion, 1982), the majority focus on automotive or aerospace problems. Only a few man-modelling systems are available commercially, and the costs to make these systems functional can be prohibitive. Several systems can be obtained through cooperative agreements with their developers. However, the conditions for using them can be limiting (e.g., in exchange for consulting services or cooperative developmental support). In either case, few system developers provide the user with access to the source code, or freedom to modify the software.

SYSTEM USE

The reasons for wanting to use man-modelling CAD are diverse. One may seek to animate sequences of man-machine interaction, to augment analyses of operator reach, vision and body clearance, or to obtain an effective tool for communicating design ideas to managers or customers. Although such objectives are legitimate, it is possible that no system will suit all the needs of the user. Even when useful systems are found, associated costs may overshadow their advantages.

In deciding to employ man-modelling CAD, the user may believe that the expertise of anthropometry and workplace design specialists will be provided (e.g., that the system incorporates heuristics and algorithms necessary to interpret and evaluate model specifications, and to present optimal design solutions). In fact, most man-modelling systems do not provide this expertise and are best suited to users who are already knowledgeable about anthropometry and workplace design.

Essentially, man-modelling CAD allows the user to create and manipulate entities that represent the physical characteristics of man and the workplace; the extent to which the user *can* model and manipulate these characteristics varies widely among systems. The extent to which the user *should* model and manipulate these characteristics varies according to the application.

The user may desire numerous modelling capabilities, but trade-offs exist between the conveniences and costs of acquiring those capabilities (Lane, 1982). For instance, increased modelling capabilities often imply demands for detailed data. Sometimes, these data are laborious or time-consuming to obtain, if they can be obtained at all (e.g., enfleshment-modelling, calling for breadth and depth data for each major link segment). In turn, detailed input data may reflect model detail that demands increased computational loads. As a consequence to obtaining more modelling capabilities, then, the user may require more resources to address the application. Therefore, the user must determine modelling needs on the basis of the design objectives, and not succumb to the urge to model all attributes of the man-machine interface.

Other implications of using man-modelling CAD should not be underrated. Its use can have affects that range from the way design work is structured, to how results are interpreted and communicated to others. It can impose demands for physical, operational and maintenance support of computing hardware and software, and can have significant impact on the skills and design strategies required of the user. Therefore, the technical, management and human-computer aspects of using CAD must be considered. These issues are discussed more thoroughly by Majchrzak et al. (1987).

SELECTED MODELLING ISSUES

The Man-Model

It appears that many of today's anthropometric man-models have similar origins and are based on similar principles. Yet, they offer significantly different ways to define and manipulate their respective man-models. To follow are some of the factors that should be considered by the potential user.

Individual versus Population Representation. In workplace design, anthropometry data are usually used to represent populations or individuals that must be accommodated by the design. In some cases, the user may employ anthropometric dimensions that do not represent any particular population or individual in order to explore the boundaries of body combinations that fit the geometry of the design (e.g., for the purpose of operator selection). Each of these design/evaluation approaches has implications on the way that man should be modelled using computer.

To represent the physical characteristics of a population, anthropometric data are usually expressed as means and standard deviations from which percentiles are calculated. Commonly, a percentile is interpreted as the percentage of a population having *one* body dimension of a certain size, or smaller (Damon, Stoudt and McFarland, 1966). This use of anthropometric data to assess accommodation of a population has been criticized because it fails to consider the interactions of anthropometry variables (Bittner and Moroney, 1974).

Some CAD systems deviate from the conventional use of percentiles by generating man-models that have the same percentile on *all* body dimensions. This modelling technique is misleading in that it implies that the sums of individual dimensions (expressed as percentiles) can be equated with composite dimensions (also expressed as percentiles). For example, a man-model having 95th percentile stature is mis-represented as being equivalent in height to a man-model having 95th percentile measures for all body segments that contribute to stature. This technique also results in the generation of proportionate models. At the least, CAD systems must use percentile data appropriately. If the technology is to show superiority over traditional techniques, it must represent more than just percentiles and proportionate man-models. It must be able to represent the disproportionate body sizes that make up the population. Hence, man-modelling CAD programs should make use of sophisticated statistical methods to manipulate population data (e.g., Monte Carlo simulation, use of multi-variate statistics, etc.) and to represent individual extremes of a specific population.

To represent an individual, the CAD system must be able to accept a unique set of anthropometric data as input. These data must be interpreted in ways that convey the individual's specific physical dimensions that are important to his or her fit to the design. Therefore, the user must be satisfied that the system can generate valid man-models that are based on individual data.

Gender Representation. The standard practice in man-modelling is to generate a manikin that is derived from male data. In most cases, systems that claim to model females accept female data as input and then use data derived from studies on males to generate link lengths, represent joint mobilities, and so on. Since the skeletal and muscular features of males and females differ in numerous ways, it is not known how well the male-derived data can be generalized to females (Lane, 1982). Therefore, it is possible that no available system will satisfy the need to represent females in a design.

Body Segment Representation. Man-model link structures often dictate the number of body segments and joint articulations that are represented. Calvert, Chapman and Patla (1982) recommend that the human body can be represented using 23 links, if details of the hands and feet are ignored. Some man-modelling CAD developers count single point landmarks (e.g., an eye location reference point) as links, giving the impression that the model has a more detailed link structure than is the case. Similarly, some count different functional conditions of single links as separate, independent links (e.g., fingertip and palm reach references counted as two separate hand links). Therefore, the user must examine the link structures of candidate man-models to ensure that major body segments needed for the application are represented.

To define body segment geometries, some CAD systems require external body dimensions from which the man-model's link lengths are derived using *standard* formulae (e.g., those of Dempster (1955)). The user must be satisfied that such formulae appropriately model the individuals or populations to be represented. Other systems call for internal link length data. Because anthropometric data are not normally collected to satisfy this need, the user may have to transform external data to internal data when precise segment lengths must be modelled. In either case, the user may be faced with the task of transforming internal link lengths back to external body measures when reporting the anthropometry of the man-model.

Joint Representation. To model man's movement characteristics, most computer man-models allow rotation about body segments representing major joint centres. Usually, those rotations model movements in only one or two planes, treating all joints as either hinge or pin joints. Unless the user needs to model multi-axial joint rotations (e.g., to indicate realistic joint excursions at the spine, hip or shoulder), this level of joint modelling should be satisfactory. The onus is on the user to make this judgement.

The various movements that occur at the joints are commonly referred to as flexion, extension, abduction, adduction, medial rotation and lateral rotation. These movement notations refer to the relative change in position of body segments, with respect to their proximal joint centres. When using CAD, it is advantageous to be able to define the body segments' spatial orientations that result from these movements. Euler angle sets, consisting of three rotations about two axes (i.e., z,y,z rotations), provide one way of expressing these orientations. For example, in a movement sequence, a body segment may be rotated by 20 degrees flexion (x-axis), 5 degrees adduction (y-axis) and 5 degrees lateral rotation (z-axis). The same orientation can be achieved through one unique set of Euler rotations (e.g., in this case, by rotations of 76 degrees, 21 degrees and -82 degrees about the z, y and z axes, respectively). Flexion of an additional 10 degrees (x-axis) yields another unique Euler angle set (e.g., 79, 32, and -84 degrees about the z, y and z axes, respectively). The user may find that familiarity with this notation is necessary to interpret man-model manipulations.

To limit the freedom of a man-model's joint movements, various CAD systems impose constraints on link articulations. In man, functional joint constraints are influenced by muscle flexibilities, body enfleshment and mechanical structures at each joint. For example, most people can flex more at the hip with flexed knees than with fully extended knees. These relational constraints are hard to quantify, making them difficult to model. Perhaps for this reason, CAD man-models usually have constraints that are expressed for each joint, in isolation, without regard to body posture. Therefore, the user must incorporate an understanding of man's physical movement capabilities when manipulating the man-model about its joints.

Enfleshment Representation.

Link segment enfleshment is another modelling option that requires the user's consideration. A principle decision is whether or not enfleshment modelling is necessary to satisfy the design objectives. For example, body surfaces may not be crucial for distance-based evaluations of reach and visual interference (Lane, 1982). However, they are necessary for evaluations of body clearance and operator *fit*.

Among CAD systems that model body surfaces, some do not offer the user freedom to change the enfleshment envelope of the man-model. Systems that do allow enfleshment alterations do so in different ways, and to different degrees. Some require segment breadth and depth data, or circumferences, while others require mass, volume or somatotype characteristics. In any case, the user must determine the extent to which enfleshment modelling is needed and the data that can be provided, given available data sources.

Consideration must also include how CAD systems interpret enfleshment input data. For example, if breadth and depth values are required to describe enfleshment about a link segment, where along the long axis of that link are those enfleshment values ascribed? Unfortunately, such information is usually difficult to obtain. At the least, system developers should provide the user with the source(s) of research used to make enfleshment-modelling decisions. In any case, the user must choose to rely on the validity of the man-model, or conduct an independent evaluation of its representation of human body shape.

Other Considerations. Other attributes of the man-model influence the way it can or should be used. Some systems employ reference loci to represent functional landmarks on the man-model. For example, binocular and/or monocular eye reference points are often located relative to the head link of the man-model. In this case, head link length influences assessments of what the man-model can *see*. Similarly, seated height sometimes determines the location of the man-model's shoulder joint in which case it also influences assessments of reach. The user must assess the functional implications of these model-attributes and how accurately they must represent man.

Computer-generated manikins can represent the effects of personal equipment and clothing only to a limited extent. However, if the user has access to appropriate functional anthropometry data, influences due to clothing or equipment may be considered by manipulating the man-model's characteristics. For example, movement restrictions imposed by heavy clothing may be modelled by manipulating joint constraints, or the bulk of heavy clothing may be modelled by manipulating the man-model's enfleshment envelope. Similar approaches are possible for modelling physical disabilities, and in general suggest how man-modelling CAD can facilitate non-traditional manipulations of anthropometric data.

The Workplace Model

In workplace design, there is little value in providing sophisticated models of man if there is no way of relating them to design structures. Therefore, the user who creates appropriate man-models may also be expected to create (or at least manipulate) models of workplace components.

The available CAD systems offer varying facilities to create workplace models that have different levels of complexity. The suitability of their respective modelling approaches depends largely upon three things: the requirements of the application, the availability of appropriate input data, and the user's preferred modelling strategy. Each of these issues must be considered before using CAD to model the workplace.

The great advantage of CAD is that the workplace can be described in three dimensions. The model can take several forms. At the simplest level it is defined as a series of x,y,z space coordinates. More commonly, simple primitives (e.g., boxes, cylinders spheres and cones) are used to construct desired shapes. In more sophisticated CAD programs, smooth curves that closely resemble the true shapes of the objects are modelled. Still more sophisticated systems represent the rigid or deformable characteristics of workplace items when subjected to an external force. Most commonly, edges and vertices (called wireframe models) are used to define the boundaries of the items (Majchrzak et al., 1987).

Workplace items are best modelled with respect to their relative spatial and logical (hierarchical) relationships. These relationships help to establish functions of different objects. For example, if a book lies on a desk, the hierarchy can be defined such that the book *belongs* to the desk and so moves when the desk is moved. But in order to take advantage of these relationships, the modeller must a priori specify the spatial and hierarchical structures of workplace components. Then, model data must be formatted to convey these relationships and the limits of their manipulations. These data are sometimes communicated to the system through the use of Euler operatives (as described earlier).

In representing the workplace, the onus is on the user to keep sight of the purpose of modelling, and to work only to the level of accuracy and realism that the application demands. For example, a CAD system may boast accuracy in the order of millimetres, but it may be unnecessary to define workplace models to that level of accuracy. Furthermore, the accuracy of available input data may impose limits on the accuracy that can be demanded of the models. Over-designing must also be guarded against. Complexity can cause unwanted distraction, or even counter the design objectives by encouraging modelling to inappropriate levels of detail. For example, it may be necessary only to model workplace surfaces that face the operator or influence reach, vision and body clearance. Or, items such as reach and vision targets may be best represented as reference loci rather than replicas of real objects. In all probability, schematic models of design items will suffice, minimizing other potential computer-modelling problems (e.g., storage of irrelevant data, time to update the graphics image, data error-checking, etc.). Modelling decisions such as these usually must be made by the user.

Integration of the Man- and Workplace Models

Once the representations of man and the workplace have been defined, they must be integrated into a working model that will support the analyses to be performed. Generally, this requires that the user manipulate and interpret their relative orientations. To do this, the user often relies on graphics images prepared by the CAD system. Therefore, the system should offer the flexibility to alter those images (e.g., change the perspective and orientation of the displayed model). As basic manipulation techniques, it is desirable that the system's capabilities include shift, rotate and scale functions. Facilities to store and restore working views of the model also should be accessible.

Some CAD systems check all model manipulations to assure that pre-defined modelling constraints are not violated (e.g., functional movement restrictions on workplace items). The user must define each of these constraints. If error-checking mechanisms are not provided, the user must define the constraints, plus be prepared to inspect the model visually (and perhaps quantitatively) whenever it is manipulated.

Depending on the format and purpose of the input data, the use of colour in the graphic display can contribute significantly to the interpretation of the model. For example, colour can be used to differentiate workplace components according to criteria that are relevant to the analyses (e.g., functional groupings of displays, controls, structural panels; reach targets; vision targets; etc.). If colour is employed, the user must be prepared to establish and assign the coding-conventions.

Some modelling features have associated functional costs. For example, an Aitoff projection (which gives a 360 degree flat representation of a view, superimposed on a reference grid) can present what an operator *sees* (theoretically), in a way that is fairly easy to interpret. But this is at the expense of considerable computation time. As another example, wireframe modelling is sometimes augmented by a facility that projects a display of the model with all hidden lines removed. A clear image of the model is produced, but again with a high associated computation time. Although the user may choose to use such features infrequently, they can provide effective means to communicate design solutions.

Evaluation of the Man-Machine Model

In some ways, CAD forces the user to take a standardized approach to a task that was previously more of an art-form. Where *common sense* and *good judgement* in evaluating a design were once prominent, explicit criteria must be defined to determine success or failure of design objectives. These criteria must account for the degrees of accuracy in the man and workplace models (e.g., if items in the workplace are modelled to 1 cm accuracy, assessments of reach may require an allowable *miss* distance of 1 cm). The effort required to determine these evaluation criteria must not be underestimated. Their impact on results of the man-machine system evaluation must be understood.

One example is the the placement of the computer man-model in the workplace model. Many computer systems do not account for governing variables such as gravitational forces, postural changes or tissue compression when positioning a man-model in a workplace model. Usually these are left to the discretion of the user. Hence, the user must ensure that the man-model is positioned in a stable, natural posture, and that its relative location with respect to the workplace (e.g., the relationship of bony landmarks to known reference points on a seat surface) is realistic.

Man-modelling systems currently do not produce goal-oriented reach sequences. Instead, the manikins' links are moved in the direction of a defined reach target without regard to a *comfortable* or *probable* terminal posture. This is usually done by extending connecting links in the direction of the target until it is reached or passed. Frequently, these reaches are initiated from the shoulder joint (for arm reaches) or the hip joint (for leg reaches) with no regard for movement of the links of the torso. In addition, the influences of simultaneous reaches (e.g., on posture, joint constraints, reach obstructions) usually are not considered. It must be appreciated that two reaches made at the same time are treated as single, independent reaches. For these reasons, the user's expertise is needed to interpret reaches performed by the man-model.

Some systems provide no means, other than visual inspection, to assess the physical interference of workplace components with the man-model. Systems that do evaluate body clearance generally do so by determining instances of overlap between the models of man and the workplace. They do not normally identify obstructions imposed on the man-model by the man-model (e.g., reaches made through the body). In any case, derivation of a man-model's enfleshment (e.g., surfaces, edges, or free form curves) is important for evaluations of body clearances. If enfleshment is not derived from appropriate data, or not representative of population characteristics, then body clearance assessments must be rated accordingly. Even if the enfleshment envelope correctly represents the human form, the user must consider the influence of tissue compression on the assessment.

In light of the limitations of man-modelling CAD systems to provide expertise, the user must temper evaluations of man-workplace models with knowledge of man's physical characteristics and their implications on workplace design. The user must also take into account the assumptions that were used throughout the modelling stages, and that contributed to the system evaluation criteria. These tasks are often more difficult than originally expected.

Usually the user must acquire new skills and adopt new personal strategies to interpret CAD solutions. For example, three-dimensional computer displays can pose perceptual problems. The graphic images are free-floating and ignore the influences of gravity, motion, lighting, etc., and usually provide no visual frames of reference to indicate an item's relative size, orientation or relationship to other objects. The requirement to manipulate design specifications in three-dimensions, and unfamiliar terminology add to the task's difficulty. When the results obtained contradict the user's judgement, interpretations of design solutions can be particularly challenging. This is because the computer-generated results can seem so objective and the graphics images can seem so precise. Indeed the precision and analytical capabilities perceived by the novice CAD user often exceed the system's true capabilities.

SUMMARY

Successful workplace design and evaluation call for the representation of man's physical characteristics as they relate to his environment. Man-modelling CAD is one method of obtaining this representation. The distinctions of this technology from manual anthropometric techniques are appreciable. It offers the potential to model such characteristics as disproportionate body parts, body enfleshment, joint constraints and vision parameters in ways that far exceed the capabilities of manual techniques. Furthermore, its flexibility offers great potential to explore different designs and to arrive at solutions that are derived from iterative work.

In spite of its advantages, the decision to use this technology must be weighed carefully. The objectives of the application, and the needs of the technology and the user must be considered. The capabilities and limitations of the system's software must be understood, as far as possible. This can be facilitated by asking the system developer to provide results of validation studies, data sources, precise input data requirements, examples of other system applications, demonstrations, training requirements, associated maintenance costs, and plans for future system developments.

The user of man-modelling CAD must possess expertise in anthropometry and workplace design. This is evident from the issues that must be addressed when modelling man and the workplace. First, the user must understand man's physical characteristics and how they can be represented using CAD. Second, he or she must understand the influences of system capabilities and deficiencies on design work. Finally, the results obtained must be kept in perspective; computer models are only as good as the input data and modelling assumptions used for their creation and manipulation. The design process does not end here; man-modelling CAD does not replace the use of human subjects in the design/evaluation loop.

REFERENCES

Badler, N. I., 1982, Human body models and animation, IEEE Computer Graphics and Applications, 2:6-7.

Bittner, A. C., and Moroney, W. F., 1974, The accommodated proportion of a potential user population: compilation and comparisons of methods for estimation, in: "Proceedings of the Human Factors Society 18th Annual Meeting," Santa Monica, California, 376-381.

Bonney, M. C., Blunsdon, C. A., Case, K., and Porter, J. M., 1979, Man-machine interaction in work systems, International Journal of Production Research, 17:619-629.

Calvert, T. W., Chapman, J., and Patla, A., 1982, Aspects of kinematic simulation of human movement, IEEE Computer Graphics and Applications, 2:41-50.

Damon, A., Stoudt, H. W., and McFarland, R. A., 1966, "The Human Body in Equipment Design," Harvard University Press, Cambridge.

Dempster, W. T., 1955, Space requirements of the seated operator: geometrical, kinematic and mechanical aspects of the body with special reference to the limbs, WADC TR-55-159, Wright Air Development Center, Wright Patterson AFB, Ohio.

Hickey, D. T., Pierrynowski, M. R., and Rothwell, P. L., 1985, Man-modelling CAD programs for workspace evaluations, DCIEM Contract Report, Defence and Civil Institute of Environmental Medicine, Downsview, Ontario.

Kingsley, E. C., Schofield, N. A., and Case, K., 1981, SAMMIE: a computer aid for man machine modeling, Computer Graphics, 15:163-169.

Kingsley, E. C., 1982, CAD and the human operator, unpublished document, Compeda Ltd, Stevenage, U.K.

Lane, N. E., 1982, Issues in the statistical modeling of anthropoemtric data for workplace design, in: "Anthropometry and Biomechanics: Theory and Application," R. Easterby, K. H. E. Kroemer and D. B. Chaffin, eds., Plenum Press, New York.

Majchrzak, A., Chang, T., Barfield, W., Eberts, R., and Salvendy, G., 1987, "Human Aspects of Computer-Aided Design," Taylor and Francis, London.

Richards, J. M., and Companion, M. A., 1982, Computer-aided design and evaluation techniques (CADET), AFWAL-TR-82-3096, U.S. Air Force Wright Aeronautical Laboratory, Wright Patterson AFB, Ohio.

Rothwell, P. L., 1985, Use of man-modelling CAD systems by the ergonomist, in: "People and Computers: Designing the Interface," P. Johnson and S. Cook, eds., Cambridge University Press, New York.

Rothwell, P. L., and Hickey, D. T., 1986, Three-dimensional computer models of man, in: "Proceedings of Human Factors Society 30th Annual Meeting," Santa Monica, California, 216-220.