DYNAMIC ANTHROPOMETRY

William E. Thornton

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center

Abstract

Interfacing human operators with increasingly complex machines and tasks is a continuing problem both in the space program and our world at large. The first major difficulty in improving man-machine design processes is scarcity, expense and limitations of human anthropometric/kinesimetric data. Our efforts to make such data more available and useful to design engineers and other professionals include collection, collation and publication of existing data, collection of data using improved techniques from our own population and the design of an automatic goniometer and an improved kinesimeter. The latter gives a more complete and automatic characterization of human motion and the data may be used with manual or computer methods to interact with engineering designs.

Quality of the man-machine interface frequently determines performance of the man-machine unit often overriding performance of the machine design or ability of the operator. This interface becomes increasingly important with machines of greater complexity and higher performance. It is especially important in the space program where machines and men are often operated beyond customary performance limits. This situation is further complicated by new environments such as 1/6 gravity and weightlessness. Results of operating in such unknown environments resulted in crewmen squeezing into form-fitted space suits after their torsos had "grown" 2 inches in weightlessness [1][2] or trying to work at one-g compatible stations with a natural posture that does not allow sitting or standing as we know it [1][3][4]. It was also found that human bodies change size and shape in weightlessness and these findings had major impact on biomedical investigations [1][5]. Thus, anthropometrics made a major intrusion into space operations. A second anthropometric demand was made when the Space Shuttle was required to accommodate a population from the 5 to 95 percentile, male and female in contrast to the previous relatively homogenous male population [6]. Also, the need for exact knowledge of the dynamic characteristics of man's motion is acute and increasing as men begin to truly work in space.

Although some of our problem areas are esoteric, the human body is universal hence our problems are also reflected in industry, medicine, human performance and research on earth. Problems of designing man into his machines did not begin with the space program - as anyone knows who has driven a variety of motor vehicles or used tools of different designs or operated high performance or complex equipment. Our machines on earth are becoming increasingly complex with higher performance and in turn demand more and more of the man. This is true, not only of aircraft and other elements of the transportation industry, but in all of our efforts as we attempt to maximize productivity, whether in a secretarial office or on a production line or a loading dock. Casual inspection will frequently show less than optimum man-machine interface. Safety could particularly benefit from improvements in this area. Virtually all of our living and working areas are designed around young healthy adult norms and we do not, for example, even know the physical limitations of advancing, to say nothing of old age. Yet there is no question that marked changes occur in size, shape and performance with increasing age [7][8]. In medicine, evaluation of physical function, its improvement or loss is usually at best an estimate. In short the use of quantitative anthropometric/kinesiologic data is not routinely a part of the analytical and design process of the majority of the machines and tasks in use today. Rather a few rules of thumb, some "norms" and more or less cut and try efforts with mockups and a tiny population sample are often resorted to.

After working this problem in one way or another over the years, it appears that the first difficulty in making anthropometry a part of the engineering process is lack of suitable data about the human body and the cost and difficulty of obtaining such data. It has been our experience that once the engineer is provided with the pertinent and necessary dimensions, ranges of motions and forces of the human operator, he can accommodate the machine design to them without undue difficulty. In any event machine designs can be changed while our body design is fixed.

Measurement of man is a major problem and not surprisingly, for the human body not only comes in an wide range of heights and weights but with an amazing range of "component" sizes and shapes. A 5th percentile or 50th or 95th body rarely has parts in proportionate size [9]. Further, the body tissues are elastic, non-linear, and often actively mobile while components are connected through joints which designers have yet to completely emulate or even exactly describe [10]. Further, the human is very sensitive to many positions and stimuli.

At the same time, measurements of the static dimensions of the body are made with modified scales, calipers, clinometers and goniometers that have been available for centuries [11]. The measurements are all manual,require considerable skill to make and demand a great deal of tedious handling. Measurements of the dynamic characteristics of the body are made only with difficulty and even then they are often static points on a continuous and varying curve such as isometric strength determinations or else use photographic or other methods requiring large amounts of expensive and tedious effort. Another difficulty is that classical anthropometric data is frequently not readily applicable to everyday use, e.g., active angles are often defined as the motion that a point on a given bone may make relative to another bony "landmark" but this is often quite different from the range of angular motion that say, the hand can produce on a handle. Further, existing data is frequently well hidden in obscure and scattered places.

Our conclusion was that the best stimuli to improve man-machine interfaces would be provision of pertinent data to the design engineer in a readily available format and at an affordable cost. Some of the areas which we are seeking to improve include:

- o Collection of existing data in a readily usable form and making it generally available.
- o Bridging the gap between anthropometric data and engineering requirements by explaining, converting or modelling the data into engineering formats.
- o Collecting data in formats useful to as many professions as possible.
- o Standardizing methodology and terminology where possible.
- o Improving the efficiency of anthropometric measurement techniques by modification or design of automated procedures where necessary and possible.
- o Improving data collection, storage and analysis with emphasis on automated procedures (this is inseparable from improved mensuration devices and techniques).
- o Broadening the scope of traditional kinesologic measurements to make it practical to measure the major motions of which man is capable in terms of position, velocity, acceleration and forces and to do this in a fashion that provides easily usable data. Such procedures must be practical in terms of time, expense and investment.
- o To develop computer and other techniques which allow interaction of the design of the machine with the anthropometric-kinesiologic data gathered.

These efforts continue at NASA JSC and some of our attempts to date will be described in accompanying papers by James L. Lewis and John T. Jackson which describe the computer interfacing of man-machine designs [12] and data collection and presentation [13].

Collection, Collation and Publication of Existing Data

A three volume Anthropometric Source Book; Vol. I Anthropometry for Designers, Vol. II Handbook of Anthropometric Data and Vol. III Annotated Bibliography of Anthropometry, was published last year and it is planned to periodically update this with additional volumes as required [13]. This series attempted to collect or reference all available anthropometric data from around the world, including U. S. and U. S. S. R. data from space, put it in usable formats and explain the applications and use of it including engineering design aids such as mannikin designs.

A second in-house effort is collection of data from astronauts and a representative population of potential space travelers, storage of the data in a usable computer file and extraction of the most significant statistical parameters. This data includes major linear dimensions, girths, angles, isokinetic strengths, estimated percent body fat, etc., of 200+ final applicants for the astronaut candidate selection. Emphasis was placed on data most likely to be useful to the designer.

Improved Measurement Techniques

A major effort was made toward increasing efficiency and accuracy during data collection. Calibrated inexpensive wooden jigs which allowed multiple measurements in a single position were used wherever possible rather than separate measurements with an anthropometer. Functional jigs which simulated actual working conditions rather than anatomically referenced angles were used where dictated. Isokinetic strength measurements were made of the major body segments, arms, trunk and legs, both ex- and eccentric, over their full range of motions. Calibrated multiple view reference photographs were taken and I might add have been most valuable data.

Measurement of active body angles is the most time-consuming and error prone of the usual anthropometric procedures and a new device was developed which greatly increased efficiency and accuracy. See Figure 1. This Automatic Video Goniometer (AVG) consists of a small TV camera, a master control with a microprocessor and a standard typewriter/terminal. A series of jigs containing coded point sources of illumination may be quickly attached to any movable body segment. The segment is placed at one extreme of motion and its axis angle is measured either with respect to local vertical or to a second reference axis. Measurement of the reference points on the video raster is done automatically and in seconds. Measurement of the segment axis angle at its other extreme is made and the microprocessor calculates, displays and on command prints the angular value in an annotated format printed from its ROM. Data may also be sent directly to a separate computer for processing or digital storage. Accuracy is $\pm 1^{o}$ and a complete survey of the body's major angles may be made in a fraction of the time taken by manual goniometric techniques. Cost of the machine may be quickly recovered from personnel time savings alone and both measurement and logging errors are virtually eliminated.

Fig. 1. Photograph of the Automatic Video Goniometer in use. The subject is holding a bar with reference lamps which are being scanned by the TV camera and displayed on the monitor with the angle of the lights being measured and printed by the microprocessor control and terminal shown.

Improved Measurement of Human Motion (An improved Kinesimeter)

To charactize motion of human body segments in physical terms requires the essentially continuous measurement, without mechanical interference, of location in three dimensions, velocity, acceleration and force of a selected point(s) on the reference.

A number of systems have been devised to measure the various aspects of continuous motion of the body including strength [14][15][16][17], but none have combined the above and motion is limited to single planes in most systems. AMRL's COMBIMAN [18] is probably the most comprehensive system to date. It is a computer program which generates from mathematical models the motions predicted for an individual, after his static anthropometric characteristics have been inserted in the model. It models but does not measure motions.

Over the past 4 years the concept and hardware for more comprehensive kinesiologic measurements has been developed by the author. The first stages of the system are in initial use for Shuttle suit testing at this time. See Figure 2.

Primary use of this kinesimetric system is the more or less complete measurement of the reach or range of motion envelopes of any anatomical segment of the human body. Simultaneous force measurements along a series of axes will define forces available in the reach envelope. With this data in stored form (tape, disc, etc.) we now have a characterization or abstraction of the mechanical properties of a given, individual body which will allow reproduction of any portion of the movement/force envelopes for study by graphic or numerical processes. Of equal importance, the data may be interfaced by suitable software programs with any desired design for analysis and interactive design studies as well as quantitative analysis of design interfaces with sample populations. Essential to this concept is a data collection system simple and inexpensive enough to collect samples on a large population.

By using orthogonal TV cameras with point source (light) detection and a computer, the paths of several points in space are simultaneously tracked and locations stored. A cable arrangement connected to an isokinetic ergometer [19] simultaneously and continuously measures forces along a given axis. Such a system using three ordinary TV cameras, a CYBEX ergometer and a Data General Eclipse® computer with XY plotter has been in use for several months and is slated for continued improvement. This present system samples two light sources every 50 ms plus maintaining a reference sample position. (Plans are to increase the number of points to 15 with sample rates of 100/sec).

An initial application has been in reach studies/force studies especially as regards space suits. In this case a source is placed on the thumb tip and reach envelopes are swept out by repetitive maximum reach vertical swings over the entire range of motion of the arm. See Figure 3. Approximately 1000 points/min may be collected with the present system.

Fig. 2. Photograph of Kinesimeter cameras and ergometer with a subject in a seated position. Light sources tracked by the cameras are on the R arm.

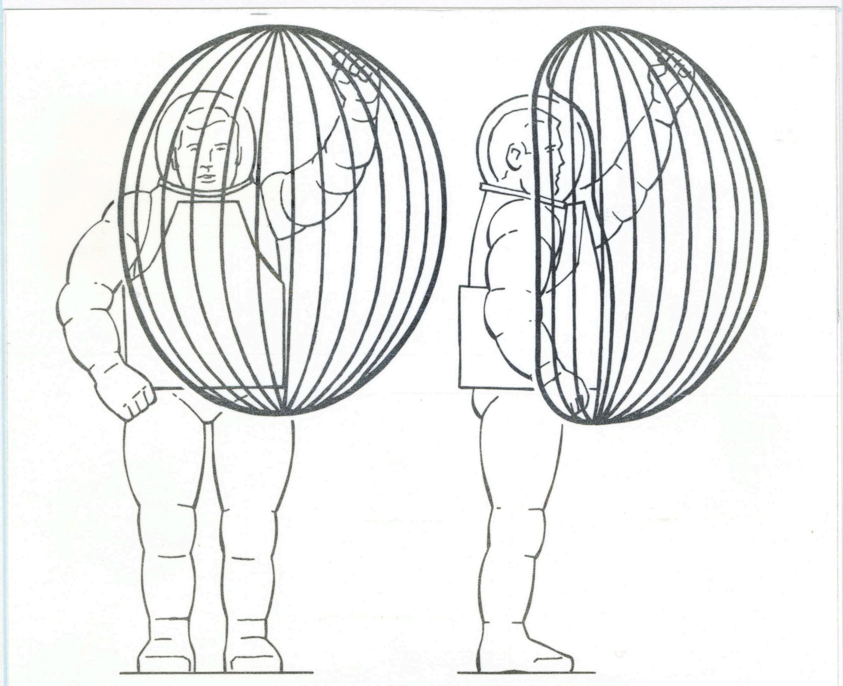

Fig. 3. Sketch of subject making vertical arm sweep to define maximum reach envelope. He will also trace out the reach envelope along his suit, helmet, etc.; i.e., a complete closed envelope will result.

These points are stored in three dimensions (rectangular coordinates) on disc. A computer algorithm plots each crossing of a selected horizontal plane on a calibrated sheet. Peripheral points are connected such that the maximum reach for any or all horizontal planes may be quantitatively plotted. See Figure 4.

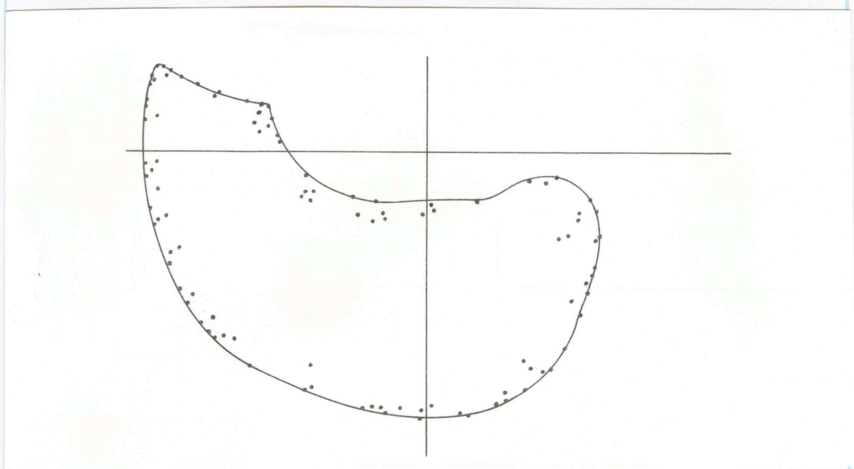

Fig. 4. Reach envelopes in the horizontal planes are developed by precisely plotting on calibrated paper, each crossing of the plane as determined by a computer algorithm. The peripheral or maximum reach points are then connected. Software is in work to allow the computer to extract a continuous envelope from which such intersecting curves will be directly plotted.

From these plots, models, drawings or dimensions of the envelope in other planes may be made. See Figure 5.

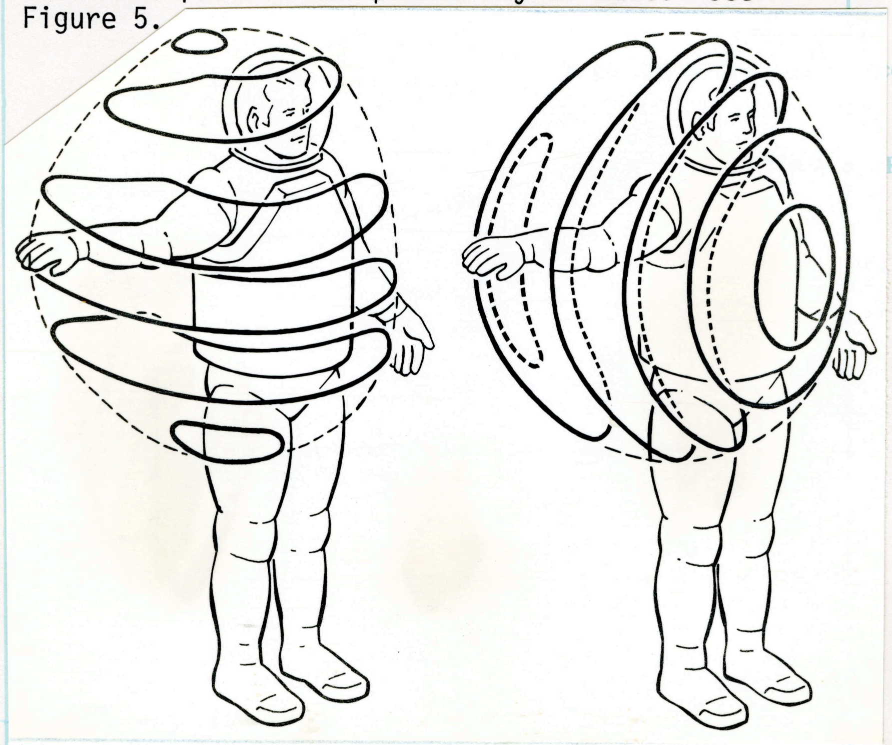

Fig. 5. Intersection of the measured reach envelopes with planes, or any other surface, may be calculated and displayed. Horizontal and vertical transverse "cuts" through the envelope are shown in this sketch.

Figures 6 and 7 show reach in the horizontal plane at shoulder level for subjects in shirt sleeves, the Apollo suit and Shuttle prototype suit. Force measurements have been made but lack of funds has prevented development of analysis software and manual plotting is proceeding slowly.

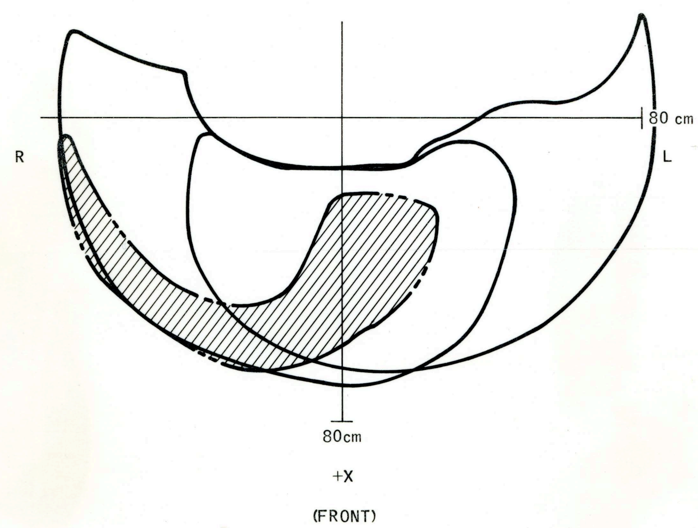

Fig. 6. Comparison of shirt sleeved maximum reach just below shoulder level with R arm reach (shaded) of another slightly larger subject in an Apollo "space suit" at 3.8 psi. Unsuited subject had a slight asymmetry producing somewhat more than usual variation in right and left reach patterns.

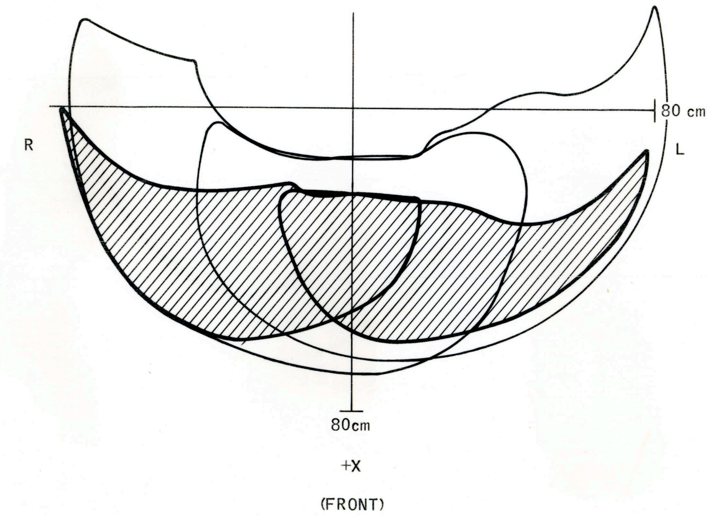

Fig. 7. Same subject showing shirt sleeve reach and reach in a prototype suit (shaded area) at 4.0 psi just below shoulder level. Plots were inadvertently misaligned during reproduction. Working error limits are ±1 cm with this system.

Figure 8 shows a planned format for the force displays.

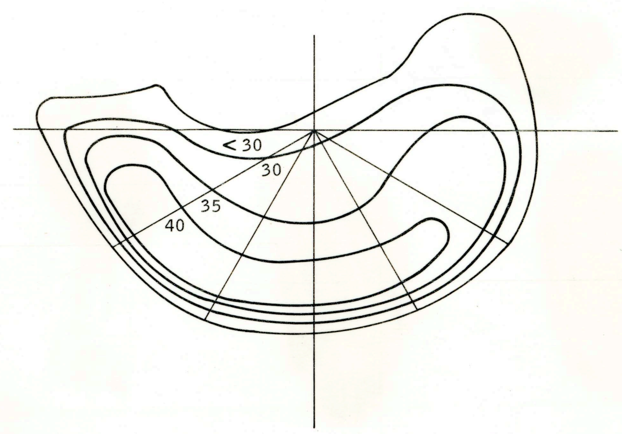

Fig. 8. Sketch of force plot presentation of unsuited right arm. A series of iso-force envelopes will be generated from repeated force/position measurements in several axes. These may then be treated like the reach envelopes.

Range of motion is just one class of measurements which may be made with this system. Complex motions involving several points with their individual instantaneous positions, velocities and accelerations in three dimension may be routinely studied, both in health and disease. Maximum performance studies such as throwing or running may be made in the same way.

The system is simple enough to be used in a variety of situations and we expect to use it in water immersion (simulated weightlessness) and weightless studies. At the present reduced illumination, not darkness, is required. When we go to a high speed solid state IR system, we will be able to operate at high light levels. It now requires only 3-4 minutes time to make a full range of motion study of a limb segment with correspondingly short preparation time. The equipment is operable by one person. With refinement a desk top microcomputer system complete with graphics is practical. Hopefully, this will become a system affordable by any group which requires collection of kinesimetric data from a sizable population, either in the field or lab.

It has not been possible to cover all the anthropometric efforts at JSC or elsewhere in NASA in this paper. Many additional and detailed measurements by conventional means are made by Crew Systems Division and their contractors in suit development. Extensive mockup work is done in a variety of areas by JSC and contractors. Dr. Herron's [20] stereophotogrammetric techniques have been used in pre- and postflight biomedical studies [21].

Other NASA centers are heavily involved also. Our efforts are miniscule when compared to work in government, industry and universities to improve collection and application of human data for design and research. One of the most promising of these is a planned major effort by NBS to establish an anthropometric data file at the national level.

Future

A major effort will continue at JSC to develop programs and display techniques which will allow computer interfacing of the data collected with new designs such as work stations and space operations. Hopefully, suit designers will use it extensively. It should be of major value in cockpit and similar layout and design. We hope to obtain space and resources for a lab which will have conventional anthropometric/kinesimetric facilities as well as the video goniometer and improved kinesimeter. The latter items would be interfaced directly with the computing facility for on-line analysis. A comprehensive computer data file should be a major asset of such a facility.

The next major step is interfacing of such data and facilities with the engineering profession. We certainly have cooperation thus far. One crucial point must never be forgotten - Anthropometric data and computer aided design such as being advocated here is not the final design process. Each design must finally be extensively tested by mockups and operational experience, with the total human body and being. We have abstracted information from a very complex organism and in the final analysis it is the man and whole machine that must function together; i.e., what we propose is an improvement in one part of the total design process. Once the design has reached the mockup testing phase, some of the techniques described should still be of use. For example, we hope to follow an iterative process in designs with the kinesimeter/computer, first to obtain as much information as possible in one-g prior to design, testing of the design in simulated weightlessness (water tank or aircraft parabolas) with the kinesimeter recording human interaction with the design and finally in true weightlessness where the kinesimeter data will greatly aid in confirmation of the design or the need for modification. The same process should also be applicable to one-g designs.

I also plan to explore the medical applications of the goniometer and kinesimeter with my colleagues. There are many areas of industrial and occupational medicine which have potential applications.

Finally, the improvements we have described are a limited effort. There are many areas of measurement of the body and its motions in which improvements are needed and within the state-of-the-art. For example, it is practical to make all of the static anthropometric measurements from one or two stereo views except for the cost of manual data reduction. Such stereo photographs have the added advantage of providing shapes and volumes and could be a more or less complete repository of all static body dimensions of a subject. This repository could be analyzed as needed. Computer handling of stereo photography is now being done commercially (Solid Photography R). An even greater efficiency could be realized with video techniques which would allow the whole process to be automatically done and eliminate the major cost of stereophotogrammetry.

A much modest advance would be automatic reading and recording of linear and girth measurements where conventional anthropometric measurements are made.

Conclusion

It is our obvious hope that present and planned efforts described here will provide the design engineer and other professionals with improved quantitative data needed to better understand human form and motion. If successful, the mechanical gap between man and his mechanisms may be narrowed a bit. This in turn should not only improve performance of the man-machine unit but also allow man better control of his devices. Possibly such improvements in these interfaces and control may even make man in general more comfortable with his machines.

The obverse of this is that when the rigors of measurement required for engineering are applied to the human body, the life scientists and medical profession will benefit in several ways, i.e., professionals of both sides of the human-machine interface gap will benefit.

It is recognized that the techniques and the machines described are incomplete and still require the test of time, however, if they do nothing more than interest or provide a point of departure for others concerned with this problem it will have been worth the effort.

Acknowledgements

Only a few of the contributors can be listed but John Jackson has been a most constant ally, aid and participant in all the efforts described. Bob Bond and Jim Lewis gave essential support to completion of the Goniometer and Kinesimeter which was solely supported by the Crew Station Design Section. Jim Lewis has also become a colleague in the development and use of improved instrumentation and procedures. My role in the Anthropometric Source Book was minor for it was conceived and executed by Spacecraft Design Division. Southwest Research Institute did the detailed design and fabrication of the Gonio-

meter and Kinesimeter both of which use an original video-detection tracking system by Mr. John Cater, project engineer.

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Biography

William E. Thornton, M.D., is a Scientist Astronaut at NASA JSC, Houston, Texas, and is also affiliated with the University of Texas Medical Branch. He is a jet pilot. His background includes physics, instrumentation (more than 15 issued patents), clinical medicine and biomedical research.