ANTHROPOMETRIC ACCOMMODATION IN USAF COCKPITS

Gregory F. Zehner
Human Engineering Division
Armstrong Laboratory
Wright-Patterson AFB Oh.

N94-33630

ABSTRACT

Over the past three years a new set of methodologies has been developed to specify and evaluate anthropometric accommodation in USAF crewstation designs. These techniques are used to improve the ability of the pilot to reach controls, to safely escape the aircraft, to achieve adequate mobility and comfort, and to assure full access to the visual field both inside and outside the aircraft.

This paper summarizes commonly encountered aircraft accommodation problems, explains the failure of the traditional "percentile man" design concept to resolve these difficulties, and suggests an alternative approach for improving cockpit design to better accommodate today's more heterogeneous flying population.

INTRODUCTION

There is a considerable body of evidence detailing body size accommodation design problems encountered by USAF pilots in a variety of cockpits. Most commonly these difficulties are: the inability to reach both hand and foot operated controls; limitations on control authority due to stick interference with the legs; inadequate clearance for ejection; limitations on external visibility; difficulty seeing instruments or labels inside the cockpit; inadequate overhead clearance which prevents the pilot from sitting erect in the correct ejection posture; and finally a generalized lack of mobility due to overall cramped accommodation.

Specifications

The goal of the procurement process for USAF aircraft has been to write specifications which ensure that the body size of a very large portion of the USAF population will be accommodated in the design. Traditionally this has been attempted by using percentiles to specify how much of the USAF population is to be accommodated. Typical specifications have read: "The system shall be designed to allow safe operation by the fifth percentile pilot through the ninety-fifth percentile pilot". But how is a 5th or 95th percentile pilot defined? And once defined, how is the design evaluated to determine if the required level of accommodation has been achieved?

There are a number of errors inherent in the "percentile man" approach which have resulted in marked difficulties for a number of pilots operating or escaping from their aircraft. To correct these deficiencies a multivariate alternative to the percentile approach has been developed to more accurately describe body size variability of the USAF flying population. A number of body size categories called "representative cases" are calculated, which, when used in specification, design, and testing of new aircraft can greatly improve the desired level of accommodation. These "representative cases" not only describe the typical "small" and "large" pilot (as the percentile approach attempted to do), but, expand these categories to include individuals with variable body proportions such as people with short torsos and long limbs. Two technical reports are in preparation which describe this new approach in detail (Zehner 1992, Meindl 1993).

Evaluations

It is not enough to write specifications whose desired end is to accommodate a more variable population. An additional step in meeting this goal is a thorough evaluation of the cockpit design to verify if it will in fact accommodate ALL of the intended user population. While cursory evaluations of new designs have always been performed, these efforts have never been given the level of support they require. A third USAF technical report (Kennedy 1993) currently in preparation, describes evaluation techniques for ensuring optimum body size accommodation. The technique goes beyond merely verifying that the specifications have been met; it attempts to define the body size limits of persons who can safely operate a particular aircraft.

The Changing Pilot Population

This issue is critical in today's Air Force because the demographics of the pilot population are beginning to change. In the 1950s and 1960s (when most of our current aircraft were being designed), the USAF pilot population was almost exclusively a white male domain. Anthropometric databases reflected these demographics and, as a result, body size descriptions in aircraft specifications did too. The current mix of males and females of many races greatly changes the anthropometric profile of the population. The body size restrictions for entry into undergraduate flight training in AFR 160-43 have also changed. Larger pilots than ever before are being admitted, and discussions currently taking place may well result in lowering restrictions to allow smaller people into pilot training as well. Changes such as these should only be made after serious consideration of the effect and consequences of allowing individuals to fly aircraft which were not designed to accommodate their particular body size. Any rational consideration of changing body size criteria for aviators must include data that describes the limits the aircraft imposes on the pilot. If there is a high probability that the long legged pilot will strike the canopy bow during ejection, or that short legged pilot will not be able to get full rudder throw, then these individuals should not be allowed to fly that particular aircraft.

PROBLEMS WITH PERCENTILES

A percentile is a very simple statistic. It shows the relative ranking of an individual point in a given distribution. For example, in the distribution for the body dimension, Stature (1967 USAF pilot sample), the fifth percentile value is 65.8". This means simply that five percent of a population is shorter than 65.8", and ninety-five percent of the same population is taller than 65.8". This example points up two problems with the percentile approach. First, percentiles are only relevant for one dimension at a time (univariate), and second, they are specific to the population they were calculated upon.

The Univariate Problem

Previously, USAF policy has been to ignore the smallest 5% of the pilot population in design specifications. The 5th percentile was the starting point. But, in attempting to describe or categorize an individual as a 5th percentile person, a single value (such as stature) tells us essentially nothing about the variability in remaining measurements on that individual's body. Consider Weight, for example. Individuals of 65.8" in stature in the 1967 anthropometric survey of pilots (Kennedy 1986) ranged from 125 lbs. (less than 1st percentile) to 186 lbs. (74th percentile). So, what weight should be assigned to the 5th percentile pilot? A logical conclusion is to consider the 5th percentile for BOTH measures. However, using 5th percentile in weight (140 lbs.) and 5th percentile stature (65.8") simultaneously to classify an individual as a 5th percentile pilot, presents a new problem. Only 1.3% of the 1967 survey were smaller on both measures, while 9% were smaller for one or the other of those criteria. This problem becomes much worse with each additional measurement that must be used in the design. It is not difficult to see that the use of percentiles to specify a complex design will lead to uncertainty as to exactly what body size values should be used and what percentage of the population will be accommodated (or excluded) after production.

The Exclusion Problem

A few body dimensions are critical to laying out the crewstation: Sitting Height (for clearance with the canopy), Eye height Sitting (for adequate vision), Buttock-Knee Length and Knee Height Sitting (for escape clearance with instrument panel and canopy bow), Shoulder Breadth (for side clearances), and Functional Reaches (to operate controls and rudders). Generally a group of measures such as this is listed in a specification or standard along with 5th and 95th percentile values for EACH. This gives the misleading impression that if these values are used as design criteria, 90% of the population will be accommodated. This is not the case as can be seen in Figure 1. Since an individual need only be disaccommodated for any one of these measures to invite potential problems in operating or escaping the aircraft, these measures must be looked at SIMULTANEOUSLY to determine the percentage of the population described by the measurements.

In figure 1, the pilot population is represented by the shaded bar. It is a simple matter to screen the population with 5th and

95th percentile values for Sitting Height and retain the desired 90% of the population. However, when those same individuals are also screened for 5th to 95th percentile values for Buttock-Knee Length, their numbers drop again. With the application of each additional cockpit relevant dimension, the group diminishes until, finally, only 67% of the original pilot population remains. In other words, as many as 33% of the pilot population could experience difficulty operating an aircraft that fully met specifications. Historically, such large numbers of USAF pilots have not in fact experienced body size related problems with their aircraft. But, this is due only to the design philosophy of USAF contractors, not the government specifications.

THE MULTIVARIATE ACCOMMODATION METHOD

What follows is a brief description of an alternative to the use of percentiles that corrects the deficiencies described above, while retaining the original intent of using percentiles in specification and design. That is, the recommended technique uses anthropometric data to develop and purchase equipment that accommodates a specific range of body sizes in the user population. Two examples of the approach are given below: a very simple two-measurement scenario, and a more complex cockpit layout which makes use of more measurements.

A Bivariate Example

A bivariate frequency table (Fig. 2) is very similar to the univariate distribution for which percentiles are suitable. The difference is that two measurements are considered simultaneously. In this example, the distribution of Stature in the 1967 USAF flyers survey is plotted on the horizontal axis, while Weight is plotted on the vertical axis. Each individual pilot is plotted on the graph at the point where his (in 1967 the pilot population was all male) stature and weight intersect. Using the mean value for both stature and weight as a starting point, an ellipse can be statistically imposed on the graph which includes any desired percentage of the population inside of it. A 90% ellipse is shown in the figure. Also shown on this figure are the intersection points for the mean (point X), and points similar to the 5th and 95th percentile concept (points 1 and 2) in that they persons who are small or large on both measures.

The Two Point Assumption

Another erroneous assumption that has been made over the years is that if the 5th and 95th percentiles of a distribution are used as design points, all individuals between these two points will be accommodated in the design. However, selecting only those individuals who are small or large for both Stature and Weight does not describe all the variability in body size that must be considered in a design. That is because an individual located at point 3 (a short heavy person) is just as likely to occur in the population as any other individual along the perimeter of the ellipse. There are many short heavy people as well as tall thin ones (point 4). A multivariate approach would pick, at the very least, four points (subsequently called "representative cases") from along the perimeter of a circle and use them to describe size variability. In this case the representative cases would describe people who are: short and light (1), short and heavy (3), tall and light (4), and tall and heavy (2). The rationale for the multivariate approach is that several individuals spread along the edge of a circle better represent the extreme body types within the circle (not only in size - but in proportions), than does the use of two points in the distribution.

In designing a cockpit, of course, more than two variables are needed to ensure the proper fit of an individual and his or her equipment. Obviously, the bivariate approach will be inadequate as soon as a third body size variable such as leg length is considered. The two-dimensional problem now becomes a three dimensional one and the circle becomes a sphere. More than four representative cases would be necessary to describe the various combinations of these measures. It would now be necessary to describe tall heavy pilots with long legs, tall heavy pilots with relatively short legs, and so on. As each additional measurement is added to the design, an additional dimension or level of complexity is added to the analysis with the accompanying geometrical expansion of the number of representative cases which would have to be considered in the design. Clearly the problem becomes unworkable very quickly.

Principal Component Analysis

Principal Component analysis is a statistical approach which helps get around this problem. It is a data reduction procedure which reduces the number of measurements needed to describe body size variability by combining a large number of measurements into a small set of eigenvectors (a group or combination of related measures) based upon their correlation or co-variance. A set of these eigenvectors and a reduced set of representative cases can be used to describe (in multivariate terms) the body size variability in a population. Indeed, most cockpits and workstations can be accomplished with two or three eigenvectors. This means that a bivariate circle or tri-variate sphere can be used to define population limits. Representative cases are selected from the perimeter of the bivariate or surface of the sphere to encompass those individuals within. The results can be graphically demonstrated.

Another feature of the principal component technique is that each individual is ranked multivariately using standardized Z scores on each measurement of interest. This permits alteration of the size of the circle or sphere with scale adjustment only, making in possible to easily change or adjust the percentage of the population to be accommodated. Principle component analysis also can be used to eliminate redundant measurements, by determining the proportion of body size variability each eigenvector explains, so that only the most relevant representative cases are considered as design points. The current specification philosophy in the USAF is to use six cockpit related variables to define six to eight "representative test cases". Designing a cockpit on the basis of these cases should make it possible to consider a design that will accommodate as many as 99% of current pilots. Six USAF representative cases which have been used in several aircraft procurement programs are shown in Table 1. Traditionally used 5th and 95th percentile values from MIL. STD. 1472 are given in Table II for comparison purposes.

While there are many measurements that could be included to describe the representative cases, most are simple clearance dimensions such as Shoulder Breadth, which can be dealt with as minimum and maximum expected values. In most cases it does not matter if the widest shoulders are found on an individual with a tall sitting height or a short one. Both sets of shoulders must clear the sides of the cockpit. Based on that reasoning, a number of minimum and maximum expected values for other measurements are included in the specifications when they are not dependent on seat or rudder pedal position. These are shown at the end of Table I.

The six so-called cockpit measurements however MUST be considered as COMBINATIONS because it is very important to consider problems of an individual who has, for example, a very short sitting height and long legs. This pilot would adjust the ejection seat all the way up to attain proper over-the-nose vision, and adjust the rudder carriage full forward to accommodate the long legs. In this seat position the knee/shin may be much closer to the bottom edge of the instrument panel where it represents an ejection injury potential. In the case of non-ejection seat aircraft with a yoke or wheel, the vertical distance between the seat and the bottom edge of the wheel becomes reduced causing the possibility of interference problems with the leg (particularly during cross-control maneuvers). Similarly, the position of the shoulder during reach to controls is a matter of some important. Imagine two individuals with short arms reaching down to a control on a side panel. If the shoulders of one are several inches higher than the shoulders of the other, their ability to reach that control will differ considerably. Now imagine the same two individuals reaching to an overhead control. These examples are but a few of many which suggest why, for some measurements, COMBINATIONS of body proportions are more useful than minimum and maximum values or percentile lists.

When all of the representative cases in a given distribution can function safely, efficiently, and comfortably in a cockpit, individuals in between these extremes should be similarly well accommodated.

EVALUATION METHODS

Currently, all aircraft designed for the USAF are evaluated during the proposal stage (on paper, CAD, or mock-up) and revisited several times during development to ensure that anthropometric requirements are being met. Using accommodation of the representative cases described above as a contract requirement, test subjects representing those sizes are selected and fit tested in the crewstation. Small test subjects are used to determine if pilots of similar size will have: adequate internal and external vision; the ability to reach all controls; the ability to reach all CRITICAL controls with locked inertial reels; have full control authority with the seat full up; and the ability to achieve full rudder throw and brake. Large test are used to determine: overhead clearance; operational clearances; ejection clearance with cockpit structures such as the canopy bow, glareshield, instrument panel, and canopy sill; and full control authority with the seat in various adjustment positions. It is usually necessary to test at least a dozen subjects in order to account for variations in body posture and shape. Subjects of exactly the same size as the representative cases are nearly impossible to find. Therefore, miss distances (or excess) are added to subjects' anthropometric dimensions where necessary to arrive at appropriate values, or, several subjects each having a few of the required characteristics, are used to simulate each of the "representative cases".

CONCLUSION

Multivariate accommodation techniques for describing body size variability in the user population will remove the ambiguity currently associated with government anthropometric requirements. Once proper specifications for cockpits or other workstations have been documented, thorough evaluations must take place to ensure the design meets those specifications. This approach has been used by the USAF in a number of recent aircraft procurements and has significantly enhanced the resulting product. Approximately 30 aircraft competing for various contracts have been evaluated to date. Problems for large pilots problems such as potential canopy bow strikes, limited control authority, inadvertent control activation, and inadequate clearance overhead have been revealed during these hands-on evaluations. For small pilots problems involving inadequate external vision, problems reaching critical controls, difficulties in turning the aircraft because of inadequate space between the seat and bottom of the yoke, and inability to reach the rudders have all been found. A major benefit of this technique is that it is used throughout the procurement and design cycle. In this way accommodation problems can be discovered and corrected early in the design phase, or the aircraft can be prevented from entering the inventory until such defects are taken care of.

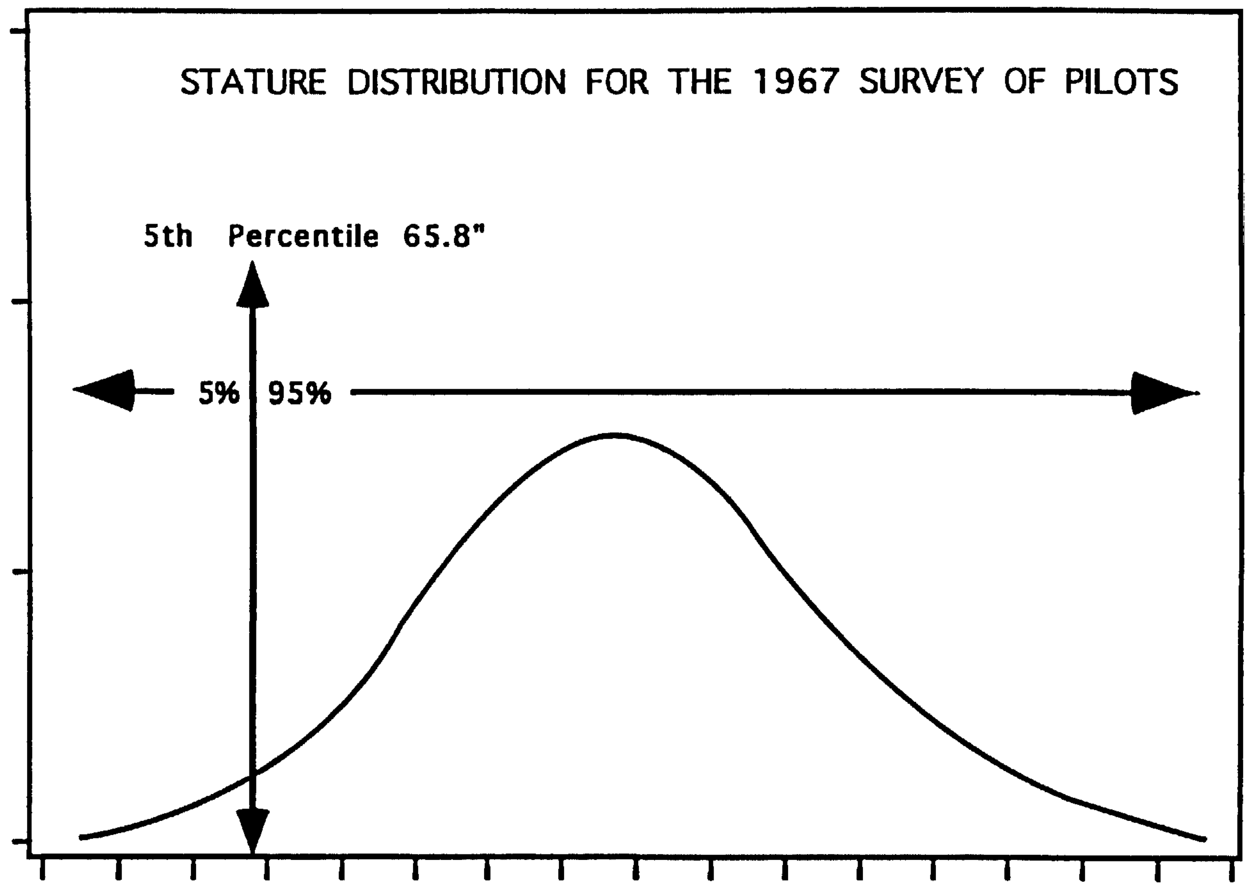

FIGURE 1

Normal Distribution For Stature: 1967 USAF Survey

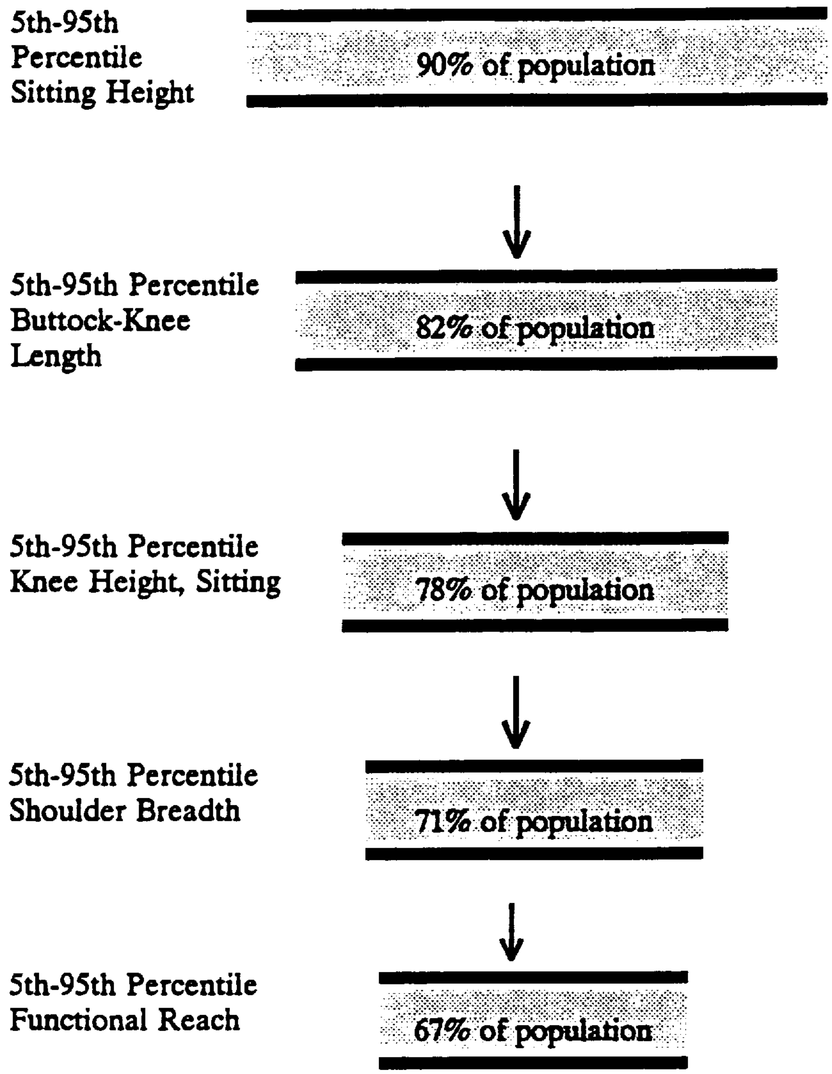

FIGURE 2

Diminution of Population Coverage with Successive Screening for 5th-95th Percentile Values of Selected Dimensions: 1967 USAF Survey Data

SMALL PILOTS

Case 1 Generalized Small Pilot

Thumb-Tip Reach	28.3
Buttock-Knee Length	22.1
Knee-Ht. Sitting	19.5
Sitting Ht.	34.0
Eye Ht. Sitting	28.9
Shoulder Ht. Sitting	21.3

Case 2 Shorter reach with higher shoulders

Thumb-Tip Reach	27.6
Buttock-Knee Length	21.3
Knee-Ht. Sitting	19.1
Sitting Ht.	35.5
Eye Ht. Sitting	30.7
Shoulder Ht. Sitting	22.7

Case 3 Shortest Torso

Thumb-Tip Reach	30.4
Buttock-Knee Length	23.9
Knee-Ht. Sitting	20.8
Sitting Ht.	32.4
Eye Ht. Sitting	27.9
Shoulder Ht. Sitting	20.5

PILOTS WITH CONTRASTING PROPORTIONS

Case 4 Short Sitting Ht. with very long limbs

Thumb-Tip Reach	33.9
Buttock-Knee Length	26.5
Knee-Ht. Sitting	23.3
Sitting Ht.	34.9
Eye Ht. Sitting	30.2
Shoulder Ht. Sitting	22.6

Case 5 Short Limbs with very large Sitting Ht.

Thumb-Tip Reach	29.7
Buttock-Knee Length	22.7
Knee-Ht. Sitting	20.6
Sitting Ht.	38.5
Eye Ht. Sitting	33.4
Shoulder Ht. Sitting	25.2

Table I. Multivariate "Representative Cases" (values in inches)

LARGE PILOTS

Case 6 Generalized Large Pilot

Thumb-Tip Reach	35.6
Buttock-Knee Length	27.4
Knee-Ht. Sitting	24.7
Sitting Ht.	40.0
Eye Ht. Sitting	35.0
Shoulder Ht. Sitting	26.9

Case 7 Longest Limbs

Thumb-Tip Reach	36.0
Buttock-Knee Length	27.9
Knee-Ht. Sitting	24.8
Sitting Ht.	38.0
Eye Ht. Sitting	32.9
Shoulder Ht. Sitting	25.0

Case 8 Largest Torso

Thumb-Tip Reach	33.3
Buttock-Knee Length	25.4
Knee-Ht. Sitting	23.2
Sitting Ht.	41.4
Eye Ht. Sitting	35.9
Shoulder Ht. Sitting	27.6

For additional measures of importance, the simple clearance values listed below represent the largest and smallest values for any one dimension that can be expected for pilots. The small values do not necessarily accompany the small flyers listed above, nor do the large. These values could occur at any seat position and should be considered in that light.

Shoulder Breadth	14.1 - 21.6
Forearm to Forearm Breadth (seated)	14.5 - 25.5
Hip Breadth (seated)	11.7 - 18.1
Shoulder to Elbow Length (arm flexed)	12.5 - 16.6
Elbow to Fingertip Length (arm flexed)	16.2 - 23.2
Buttock to Popliteal Fossa Length (leg flexed)	16.5 - 23.2
Popliteal Height Sitting	15.0 - 21.2
Boot Size	6 - 13
Thigh Clearance (sitting thickness)	3.8 - 8.0
Chest Depth	6.6 - 12.2
Chest Circ.	30.0 - 48.0
Waist Circ.	26.0 - 44.0
Thigh Circ.	18.0 - 30.0
Weight	103.0 - 245.0
Interpupillary Distance	2.0 - 3.0

Table I. Continued (values in inches)

Sitting Height	34.7"	38.8"
Eye Height Sitting	30.0"	33.9"
Shoulder Height	22.2"	25.9"
Buttock-Knee Length	22.1"	25.6"
Knee Height Sitting	20.4"	23.6"
Thumb Tip Reach	29.1"	34.3"

Table II. 5th and 95th Percentile Values (from MIL-STD 1472)

Bittner, A.C., R.J.Wherry, F.A. Glenn, CADRE: A Family of Manikins for Workstation Design. Technical Report 2100.07B. Man-Machine Integration Center, Naval Air Development Center, Warminster, PA. 1986

Kennedy, K.W., A Collation of United States Air Force Anthropometry. Technical Report AAMRL-TR-85-062. Harry G. Armstrong Aerospace Medical Research Laboratory, Wright-Patterson AFB. OH. 1986

Kennedy, K.W., G.F. Zehner, Anthropometric Accommodation in Aircraft Cockpits: A Methodology for Examination. Technical Report (in prep), Crew Station Directorate, Human Engineering Division, Armstrong Laboratory, Wright-Patterson AFB. OH. 1993

Meindl, R.S., A Multivariate Anthropometric Method for Crew Station Design. Technical Report AL/CF-TR-1993-0054, Crew Systems Directorate, Human Engineering Division, Armstrong Laboratory, Wright-Patterson AFB OH. 1993

Zehner, G.F., R.S. Meindl, J.A. Hudson, A Multivariate Anthropometric Method for Crew Station Design: Abridged. Technical Report AL-TR-0164, Crew systems Directorate, Human Engineering Division, Armstrong Laboratory, Wright-Patterson AFB. OH. 1992

Session H5: BEING THERE: PROTOTYPE AND SIMULATION FOR DESIGN

Session Chair: Dr. Jane Malin