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PREDICTION OF ANTHROPOMETRIC ACCOMMODATION IN AIRCRAFT COCKPITS

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The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Instruction 40-402.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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Designing aircraft cockpits to accommodate the wide range of body sizes existing in the US population has always been a difficult problem for Crewstation Engineers. The approach taken in the design of military aircraft has been to restrict the range of body sizes allowed into flight training, and then to develop standards and specifications to ensure that the majority of the pilots are accommodated. Accommodation in this instance is defined as the ability to 1) adequately see, reach, and actuate controls; 2) have external visual fields so the pilot can see to land, clear for other aircraft, and perform a wide range of missions (ground support/attack or air-to-air combat); and 3) if problems arise, be able to escape safely. Each of these areas is directly affected by the body size of the pilot. The USAF is considering relaxing body size entrance requirements so that smaller and larger people could become pilots. Existing accommodation problems will become much worse.

This dissertation describes a methodology for correcting this problem and demonstrates it by predicting pilot fit and performance in the USAF T-38A aircraft based on anthropometric data. The methods described can be applied to a variety of design applications where fitting the human operator into a system is a major concern. A systematic approach is described which includes: defining the user population, setting functional requirements that operators must be able to perform, testing the ability of the user population to perform the functional requirements, and developing predictive equations for selecting the future users of the system.

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PREFACE

This project was presented as a dissertation to Ohio State University. However, it was a group effort. A number of people helped in various stages of its' completion. Ken Kennedy, who has been my friend and mentor at AFRL, helped develop the aircraft measurement methods, and assisted me in gathering the T-38 data. Jeff Hudson also helped gather and organize data, and was one of the team that developed the Multivariate Models program discussed in Chapter 5. Richard Meindl also helped develop that technique. Joyce Robinson has helped me assemble databases for many years, and continued her kind and patient support on this project. Finally, Patrick Files did the initial editing of the manuscript and Tina Brill helped with formatting.

To each of these people I offer my thanks and a cold one the day this dissertation is accepted.

ABSTRACT

Designing aircraft cockpits to accommodate the wide range of body sizes existing in the U.S. population has always been a difficult problem for Crewstation Engineers. The approach taken in the design of military aircraft has been to restrict the range of body sizes allowed into flight training, and then to develop standards and specifications to ensure that the majority of the pilots are accommodated. Accommodation in this instance is defined as the ability to:

- Adequately see, reach, and actuate controls;
- Have external visual fields so that the pilot can see to land, clear for other aircraft, and perform a wide variety of missions (ground support/attack or air to air combat); and
- Finally, if problems arise, the pilot has to be able to escape safely.

Each of these areas is directly affected by the body size of the pilot. Unfortunately, accommodation problems persist and may get worse. Currently the USAF is considering relaxing body size entrance requirements so that smaller and larger people could become pilots. This will make existing accommodation problems much worse.

This dissertation describes a methodology for correcting this problem and demonstrates the method by predicting pilot fit and performance in the USAF T-38A aircraft based on anthropometric data. The methods described can be applied to a variety of design applications where fitting the human operator into a system is a major concern.

A systematic approach is described which includes: defining the user population, setting functional requirements that operators must be able to perform, testing the ability of the user population to perform the functional requirements, and developing predictive equations for selecting future users of the system.

Also described is a process for the development of new anthropometric design criteria and cockpit design methods that assure body size accommodation is improved in the future.

KEY WORDS: Anthropometry, Crewstation Design, Pilot Selection Criteria, Female Accommodation, Cockpit Ergonomics, Operational Requirements

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CHAPTER 1

INTRODUCTION

Two recent policy decisions by the U.S. Government have created an immediate need for anthropometric data and accommodation performance data for people of extreme body size in USAF cockpits. In addition, the ability to predict accommodation levels based on an individual's anthropometric data has become very important.

The first of these policy changes occurred when the Secretary of Defense (Aspin Memorandum, Apr 93) and Congress expressed the need for the services to expand opportunities for military women by opening career paths that had previously been restricted to males. This has resulted in a small number of women being trained in and assigned to Fighter Aircraft.

This policy change has created a problem. All existing USAF aircraft were designed to accommodate a male pilot population with a minimum Stature of 64 inches and a minimum Sitting Height of 34 inches. Traditional cockpit design practice was to perform anthropometric surveys on the existing pilot population and to use summary statistics from those surveys as design requirements for aircraft. On the small end of the design range, 5th percentile male pilot values for critical body dimensions were used as minimum design points. Those members of the population smaller than the minimum design values sometimes had to stretch in order to be accommodated. Unfortunately, of those females meeting the minimum entry requirements (~45% of military women) a very large percentage fall below 5th percentile male values. On the large end, 95th percentile male values were used as design limits. Larger pilots may have clearance and escape problems.

Previous experience has shown that assignment of individuals to aircraft in which: they are too small to adequately reach switches and controls, see over the nose to land, achieve full rudder throw with brakes, move the control stick to the full range of it's capability, or have escape clearance problems, are at increased risk for mishap.

The second policy change occurred when Congress and the Department of Defense directed the Joint Primary Air Training System (JPATS) to accommodate a much wider range of body sizes than are currently allowed to enter flight training. The JPATS aircraft will be the primary trainer for both the USAF and Navy for the next 30 or so years. This change in design philosophy was necessary because body size restrictions for becoming a pilot prevent the majority of women from entering flight training. While smaller males will also benefit from a change in design philosophy, the largest impact will be felt in the female military population. Unfortunately, this policy change has the potential to dramatically increase body size fit problems.

The JPATS aircraft was designed to accommodate 97% of the "general female military population." While this group must meet all of the other criteria for entry into flight training, it is not subjected to the 34 inch Sitting Height and 64 inch Stature limitation. It appears that individuals of 31 inches in Sitting Height and 58 inches in Stature will be able to fly the JPATS aircraft. For that reason, the US Air Force is now considering expansion of the body size entrance requirements (AFI 48-123) for Undergraduate Pilot Training (UPT). This change is intended to provide essentially equal opportunity for both genders for entry into flight training.

At the same time, larger pilots are also being allowed to enter flight training. The current maximum size for pilots is 40 inches in Sitting Height, and 77 inches in Stature. While the large body size restriction has been in place for several years, some individuals have had the size requirements waived, and been permitted to become USAF pilots.

While it will be possible for pilots of extreme body size to operate the JPATS aircraft when it is completed, these pilots must continue training in either the T-1 (Tanker/Transport trainer) or the T-38 (Fighter/Bomber trainer). After that training they will be assigned to one of the other 40 or so types of aircraft in the USAF fleet. Our previous experiences in evaluating accommodation in some of these aircraft indicated pilots smaller than the 5th percentile or larger than the 95th percentile design requirements could have difficulty operating them. Therefore, a much larger percentage of the population will be at even greater risk if entrance requirements are relaxed.

While currently only a few accident investigations have reported body size as a cause of the mishap, we appear to be very near the limits of current aircraft accommodation. A change to pilot entrance requirements could create a very dangerous situation.

This research project focuses on the T-38 aircraft. This aircraft was selected since it is the next step (after JPATS) in flight training for pilots headed to the Fighter/Bomber track of Specialized Undergraduate Pilot Training. Five questions related to accommodation are addressed in this research.

ANTHROPOMETRIC SAMPLES

1) What are the anthropometric profiles of the *current* male and female pilot populations, and, the *potential* pilot populations if size restrictions are removed?

Chapter 2 addresses sample construction. That is, the creation of several anthropometric datasets. These datasets must be representative of current male and female pilots as well as those individuals who could be pilots if anthropometric restrictions for entry into flight training were not in place. The USAF has not performed an anthropometric survey on female members since 1968 or male pilots since 1967. Because those surveys are now outdated, a sample representative of the current population is needed.

To create current datasets, the 1988 U.S. Army Anthropometric Survey (Gordon et al, 1989) "datapool" was used. In the Army survey, researchers used a stratified sampling strategy for age categories and over-represented specific ethnic/racial groups. This was done so that in the future if there are demographic shifts in the Army population, restructured subsets could be constructed which keep the "working database" current. The datapool includes over 200 measurements on more than 5,000 subjects. Using a similar philosophy, herein Army datapool is restructured to match USAF demographic profiles.

This was accomplished by selecting subjects from the Army datapool representative of the age, race, and height/weight profiles of the USAF population. In doing so, the significance of each of these parameters on anthropometric dimensions was studied. Age was examined since growth is not always complete in the military population, and because pilots must be college graduates. This cuts the lower end of the pilot age distribution off at 21 years. Younger subjects may need to be excluded from the dataset due to incomplete growth. Age categories of 5 years were compared to check for secular and growth differences within the datapool. Similar statistical approaches were then applied to examine ethnic differences in anthropometric distributions.

The results of these tests indicate that it may be improper to combine African-American and European-American samples in the same dataset in the proportions existing in the current USAF pilot population (~85% European-American) because significant differences in body type may be hidden in the summary statistics. It may be necessary to separate these groups for statistical analysis because the accommodation problems each group encounters may be quite different.

Next, since Height and Weight restrictions for the Air Force are different from those of the Army, comparisons of their effect on the resulting samples are necessary. Weight differences obviously effect many well correlated anthropometric dimensions (such as Waist Circumference or Hip Depth). A key examination was to assure that all of these restrictions have not resulted in a violation of the multivariate normality assumption used in other analyses. BiModal distributions may result from combining two very different samples.

OPERATIONAL REQUIREMENTS

2) What tasks must be performed in an aircraft to safely and effectively operate it?

Chapter 3 addresses the establishment of the "operational requirements" for the T-38. These requirements establish the pass/fail criteria which pilots must perform to safely operate that particular aircraft. While it is obvious that all controls must be reachable in an aircraft, which ones must be reached in an emergency condition? In an emergency, the inertial reel restraint system may lock, or, due to adverse G forces, the pilot may be pushed into a difficult position from which to reach a particular control. For these reasons, critical reaches as well as minimum visual fields (to see the landing zone, or other aircraft in a formation) were defined. This research was done at the Instructor Pilot Training School at Randolph Air Force Base, Texas. This school is a unique resource since it is where instructor pilots are trained. The entire syllabus of training maneuvers as well as student errors and emergency procedures for recovery from them are the focus of this training. A panel of Instructor Pilots and Safety Officers was assembled to discuss and define the operational requirements for the aircraft.

The areas defined are: minimum external visual field, the "critical controls list" (which controls need to be accessible during emergency situations where the pilot may have a locked inertial restraint system or be unable to reach a long distance), adequacy of rudder pedal and brake reach, the necessary range of stick/yoke mobility, and adequate clearance space for control operation and ejection.

COCKPIT MAPPING

3) By using "cockpit mapping" techniques, can the performance of an individual in a particular cockpit be accurately predicted from anthropometric measurements, and, can these data be used to predict accommodation percentages for the population?

Chapter 4 describes the anthropometric evaluation used to determine which body sizes are able to meet the minimum accommodation criteria once the operational requirements set has been defined. Cockpit Mapping is the technique used to make measurements on a sample of subjects performing the operational requirements in a crewstation. Regression equations based on sample data are then used to predict performance levels for the population. The methods which will be used in this research require at least 20 test subjects representing as well as possible the extremes of body size within the potential user population. Samples of roughly this size were decided upon based on previous experience with these types of data. Typically, some data editing is required. If fewer than 20 subjects are used it becomes difficult to determine which subject data should be considered outliers.

When combined with the critical tasks list discussed earlier, these data can be used to assess the impact of accommodation limits on the entire population in terms of the percentage which can or cannot operate a particular aircraft safely. By applying the results of the performance evaluation in the cockpit to the datasets constructed to represent the pilot population, the severity of the non-accommodation problem that exists for the current pilot population as well as the severity of the problem if anthropometric entrance requirements are changed can be determined.

FUTURE DESIGN CRITERIA

4) What anthropometric statistical methods should be used to design future cockpits so that accommodation levels can be increased?

Chapter 5 presents the creation of new statistical techniques for the design of future aircraft. The traditional method of design uses lists of 5th and 95th percentile values for a large number of dimensions. Primarily body segment lengths. Nearly all current USAF aircraft were design in this way. Unfortunately, this method leads to many errors and misconceptions since percentiles are not additive, and do not describe variability in body proportions. A multivariate technique for describing body size variability should be used to specify new aircraft design and existing aircraft modifications.

Using a Principal Components technique developed by Meindl, Hudson, and Zehner (1993), several small subsets of body types which exhibit the range of size and proportional variability existing in the larger population will be constructed. If the body size variability exhibited by these subsets is accommodated into a new aircraft design, then the target percentage of the total population will. This system is now in place for the design of new USAF aircraft.

CREWSTATION DESIGN METHODOLOGY

5) Using the data and information described above, what methodology should be used to incorporate anthropometric information into the design of an aircraft.

Chapter 6 describes a step-by-step methodology for using these data in the design of a cockpit. This methodology should be used in place of outdated Military Design Standards such as 1333 C (Aircrew Station Accommodation Criteria For Military Aircraft). This Standard uses the traditional "percentile man" philosophy as well as a number of seemingly arbitrary design rules in crewstation designs.

While this dissertation addresses a very specific design problem, the methodologies described can be applied to a variety of design applications where fitting the human operator into a system is a major concern. A systematic approach which includes: defining the user population, setting functional requirements that operators must be able to perform, testing the ability of the user population to perform the functional requirements, and where necessary, developing new design criteria and methods that assure accommodation, is the key to a successful human engineering design.

CHAPTER 2

ANTHROPOMETRIC SAMPLES

There is little recent large-scale anthropometric survey data available for the general military population, and essentially no data for female aviators. The USAF has not performed an anthropometric survey of it's female personnel since 1968 (Clauser, 1970), and that sample consisted primarily of medical workers. Male pilots have not been surveyed since 1967 (Kennedy, 1986). Therefore, an anthropometric dataset representing potential USAF pilots had to be created. These datasets will be used to calculate the effect of accommodation problems in terms of the percentage of the potential pilot population experiencing fit problems. The data sets will also be used to demonstrate new methods of deriving specifications so that accommodation problems will not recur in new aircraft designs.

Among military anthropometric surveys, only the 1988 U.S. Army Anthropometric Survey (Gordon, 1989) is large enough to create a sample representative of potential aviators for this analysis. In that survey, professional anthropometrists measured thousands of soldiers. The measurement team undertook extensive pre-survey training as well as reliability (repeatability) testing, and conducted continuous quality control testing while in the field. A stratified sampling strategy was used to over-represent specific racial/ethnic and age groups. The sampling strategy was designed so that the resulting data pool could be restructured to represent any proportional mix (percentages of these various groups) existing in the current or future Army population. This makes the Army survey an excellent resource for development of a potential aviator dataset.

DATASET CONSTRUCTION

Obviously, the Army sample was not intended to represent USAF aviators. USAF pilots must fall between 64 and 77 inches in Stature, and between 34 and 40 inches for Sitting Height. The Army survey consists of a wide range of military specialties, the vast majority of which are not subjected as pilots are to occupational body size selection criteria. However, by applying a number of constraints to the original survey data and selecting only individuals who meet specific requirements relevant to aviators, an acceptably representative sample of the potential USAF pilot population can be culled from the Army population. Rather than a sample of the existing pilot population, this study builds samples of individuals who could become pilots in the future. The constraints considered to make the sample representative of potential pilots are: age, race, and the USAF Height/Weight category restrictions. Each constraint is discussed below.

While over 200 measurements were taken in the Army survey, only a small subset of these measurements is needed for cockpit design. Typically, cockpit designers are most interested in two types of measurements: limb lengths, for laying out reaches to rudders, hand controls, and escape clearance envelopes; and torso heights, for setting seat location for maximum external vision and overhead clearances. Other dimensions are mainly used for protective equipment such as parachutes and restraint harnesses. For the comparisons given below, gross body size descriptors are used, which include traditional length, breadth, and circumferences measurements. A total of 23 anthropometric measurements from the Army survey (Table 2.1) were determined to be relevant for this study. Measurement descriptions are included as Appendix A. Not all of these dimensions will be used in subsequent chapters, they are included here for the initial investigations.

Three sets of data containing these measurements were constructed from the Army survey for subsequent analyses. The first will be used to examine age differences in anthropometric dimensions, the second will be used to look at the effect of race/ethnicity on body size and proportions, and the third to examine the effect of USAF Height and Weight restrictions.

Table 2.1. Cockpit Relevant Measurements.

Stature	Thigh Circumference (proximal)
Sitting Height	Knee Circumference
Eye Height Sitting	Chest Depth
Shoulder Height Sitting	Waist Depth
Functional Reach	Hip Breadth
Buttock-Knee Length	Thigh Clearance
Buttock-Popliteal Length	Biacromial Breadth
Knee Height Sitting	Shoulder-Elbow Length
Foot Length	Elbow-Wrist Length
Foot Breadth	Bideltoid Breadth
Span	Hand Length
	Hand Breadth

AGE STRUCTURE

USAF aviators must be college graduates (generally, age 21 or older), so it seems sensible to eliminate all individuals under age 21 from the sample. Subjects under 21 should be eliminated to limit the effects of incomplete growth; these could slightly increase mean values for some dimensions. The figures below (2.1 through 2.2 and table 2.2), however, show that eliminating subjects under 21 is unnecessary. Age intervals were established for a sample of 590 European-American female subjects drawn from the Army data pool. Race was used as a selection criteria to avoid any complicating factors due to ethnic anthropometric variability. The age groups for the sample are: 1=18-20 (N=97), 2=21-25 (N=139), 3=26-30 (N=147), 4=31-35 (N=142), 5=36-45 (N=65). Group 5 has a larger age range than the others due to the lack of data on individuals over age 36 in military data sets (high ranking members of the military are difficult to schedule for data gathering sessions). Group 1 consists of a three-year interval for age. Twenty-one is a natural cutoff for the age category since it is the approximate age of college graduates and complete growth (Krogman and Iscan, 1986).

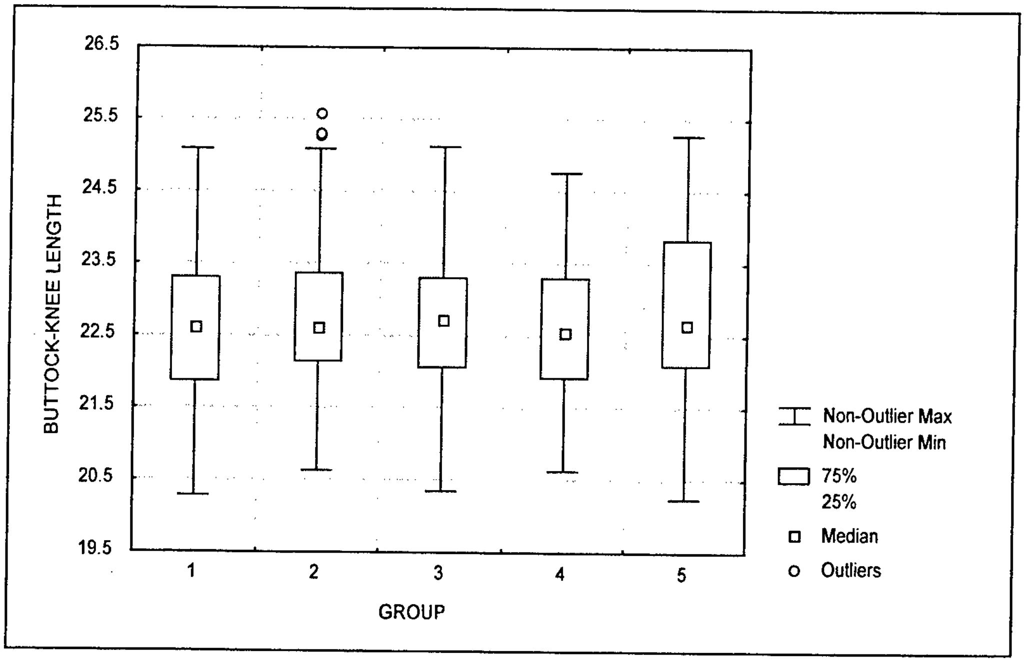

Figure 2.1. Buttock-Knee Length Comparison by Age.

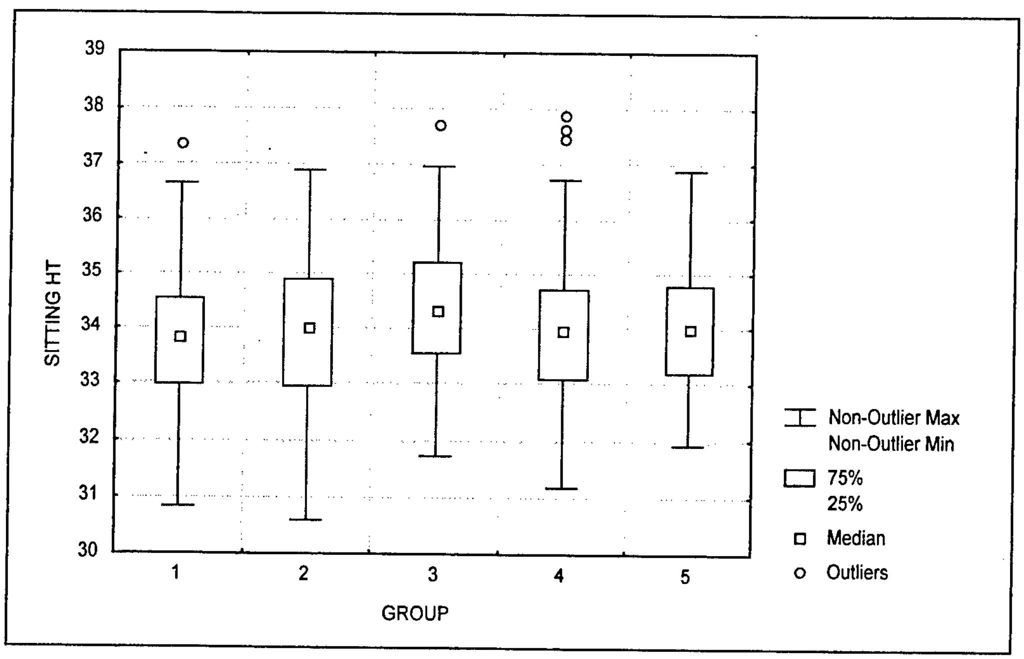

Figure 2.2. Sitting Height Comparison by Age.

ANOVA and MANOVA tests were used on Sitting Height, Stature, and Buttock-Knee Length to evaluate univariate and multivariate differences in the mean values for these groups. Measurement descriptions are listed in Appendix A. Results showed significant differences in the means of these groups (Wilks' lambda = .93, p=.000027). Group 3 is slightly different (larger in the torso) than the rest of the sample. Differences in the means for these groups are only a few tenths of an inch. However, the correlation/covariance structures of these groups are essentially the same. The Box M index (Box, 1949) is used to test the homogeneity of covariance matrices. The results here were: $\chi^2_{24} = 22.8$, p= .53, illustrating that the matrices are not significantly different. Therefore, the separate groups can be considered as coming from one population.

Table 2.2. Mean Comparisons by Age Group.

	BUTTKNEE	SITHT	STATURE	N
G_1:1	22.6	33.8	64.0	97
G_2: 2	22.7	33.9	64.2	139
G_3: 3	22.7	34.3	64.6	146
G_4:4	22.6	34.0	63.8	142
G_5: 5	22.8	34.1	64.2	65
All Groups	22.7	34.0	64.2	589

On a plot, the differences between mean values appear as follows:

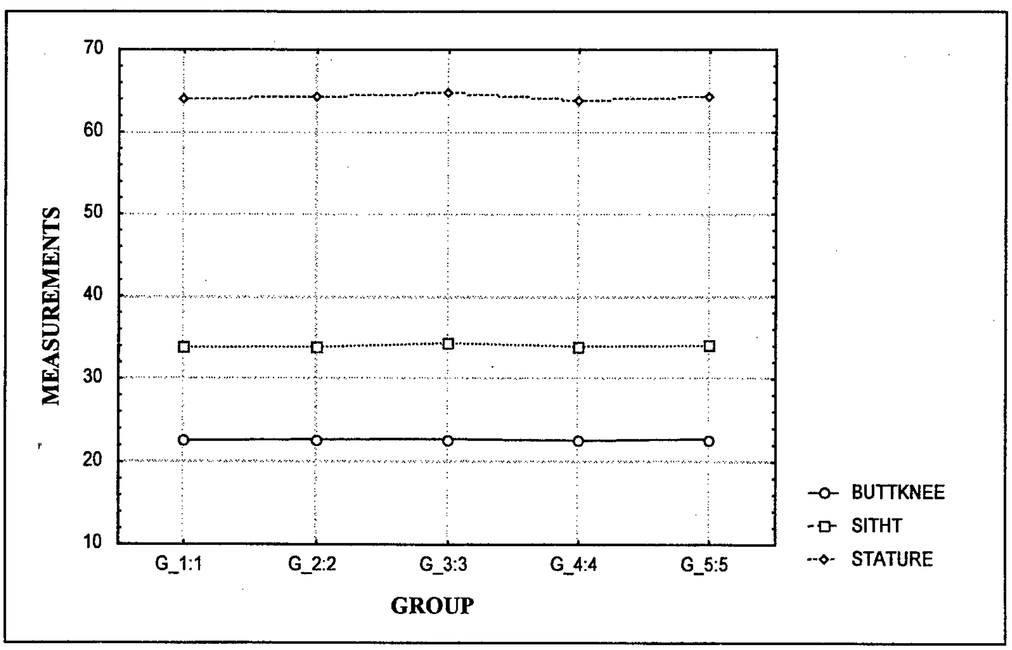

Figure 2.3. Plot of Mean Values for Measurements.

If growth or secular trends were involved, this plot would look quite different. Incomplete growth would appear as smaller values for group 1, and secular trends would not show a flat line as in figure 2.3. Therefore, the age structure of the sample is not considered to be an important variable where basic cockpit dimensions are concerned. For mass-related dimensions, however, such as breadths and circumference measurements, there appears to be a relationship between these measurements and age. The box plot below shows an example of this relationship for Waist Breadth. Following it is a plot of means showing several circumferences.

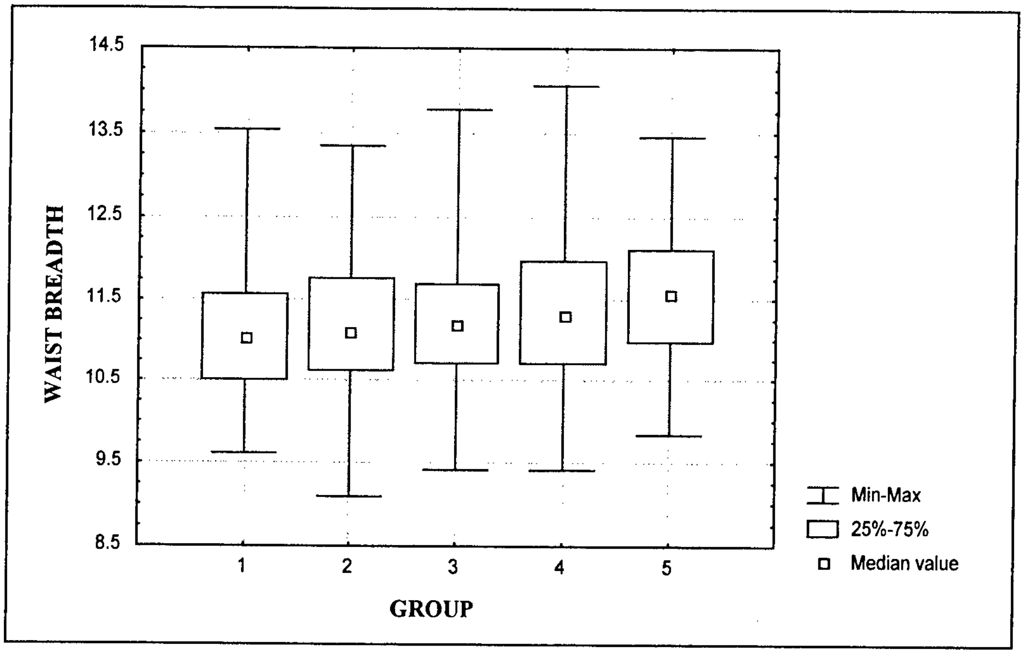

Figure 2.4. Comparison of Waist Breadth by Age.

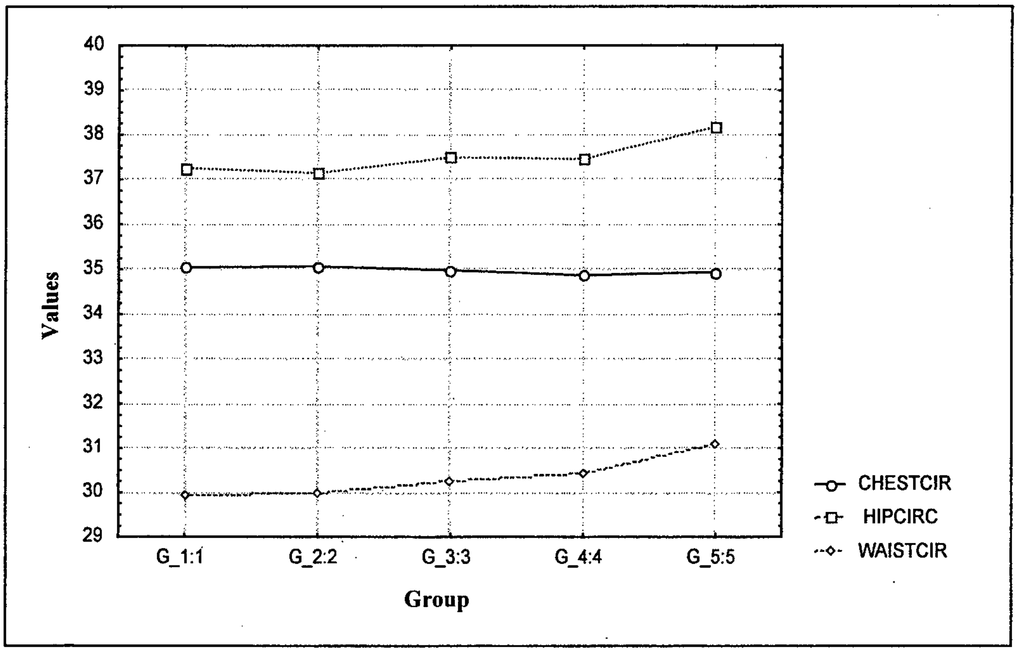

Figure 2.5. Plot of Circumference Means.

Waist Breadth, Waist Circumference, and Hip Circumference show increases with age while Chest Circumference does not. These differences are roughly an inch on the mean. These differences are very significant, with a Wilks Lambda of .934 and P=.000081. Again, the covariance structure for these groups are not different (Box M, χ^2_{24} 26.12, p = .35). Group 5 accounts for most of the differences in these dimensions, probably because group 5 has a larger range of ages (36 – 45) than the other groups. The USAF has strict Height/Weight standards that eliminate overweight people from the service. Were this not the case, differences between age groups might be more extreme.

Of the age related changes examined here, limb dimensions do not appear to be affected by age group. Torso and stature measurements begin to show the pattern expected where incomplete growth is involved. However, group 4, 5 and 6 show reduced values compared to group three. It is possible that secular growth trends were most evident in the era between groups 3 and 4, and that when growth is complete in groups 1 and 2, a different pattern will emerge. However, for purposes of sample construction, the mean values of group 1 are offset by the small values for groups 4 and 5. Therefore, for cockpit design applications the age of the sample is not of concern. It would be for clothing and protective equipment, where mass related measurements are important.

RACE/ETHNICITY

The effect of racial/ethnic background on anthropometric dimensions is well-documented (Krogman and Iscan, 1986; Trotter and Gleser, 1952; Giles and Elliot, 1962). Significant differences between racial/ethnic groups exist in many anthropometric dimensions as a result of climatic adaptations. The interest here is in how these differences affect the design of equipment that must closely fit the human body and the way an individual fits into a cockpit. Can these groups be combined in a design sample, or must they be analyzed separately? Samples of 100 females and 200 males from four ethnic categories were selected from the U.S. Army datapool for comparison. The racial/ethnic categories discussed here were established by interview during the 1988 Army survey. Four major groups are compared: European-American (1), African-American (2), Hispanic-American (3), and Asian-American (4). These categories were established by self-identification and interview during the 1988 US Army Anthropometric Survey. They are used for consistency and refer to American populations descended from specific geographic areas.

In Figures 2.6 and 2.7 Box and Whisker plots were used to demonstrate univariate differences between these groups. ANOVA and t-tests showed highly significant differences between these groups (except for Sitting Height where there is little difference between group 2 and group 3).

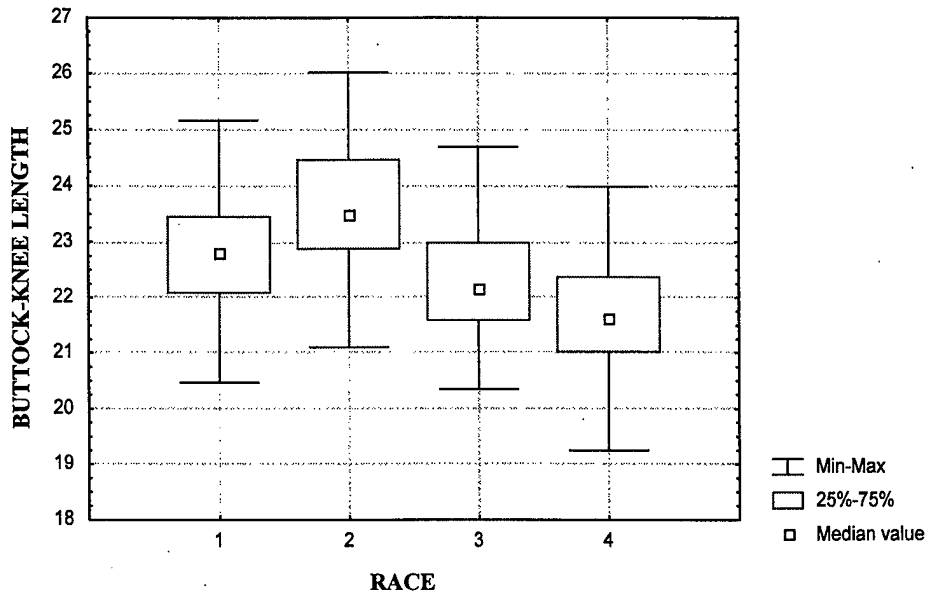

Figure 2.6. Plot of Buttock-Knee Length by Group.

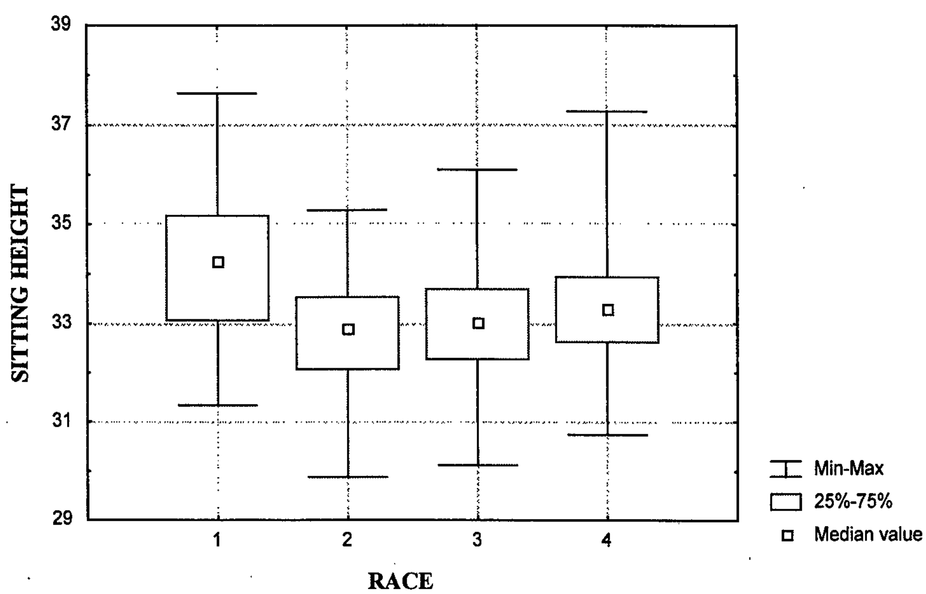

Figure 2.7. Plot of Sitting Height by Group.

Differences in the limb and torso lengths are immediately apparent. Simply expanding the analysis to two-dimensional space is enlightening (Figures 2.8-2.11 and Table 2.3). Allen's Rule (Roberts, 1978) describes changes in the torso/limb proportions of a population relative to their proximity to equatorial regions. Climatic adaptations such as large torso sizes with large amounts of subcutaneous fat improve tolerance to the cold. Also, the relative amount of exposed surface area is used as an explanation of differences in torso/limb proportions. These differences are also observed in the groups discussed here. The European-American (large Sitting Height, short Buttock-Knee length) and African-American (short Sitting Height, long Buttock-Knee length) samples show the predicted patterns of body proportions.

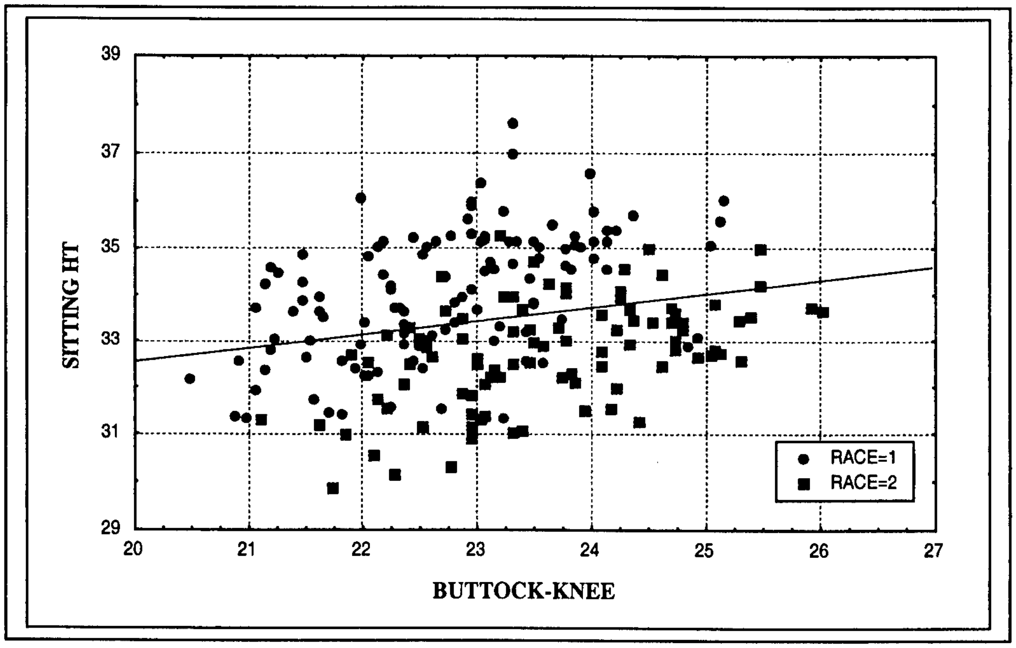

Figure 2.8. Euro-American (race 1) and African-American (race 2) Body Proportions.

Group 2 shows an interesting contrast in these two measurements. On the mean, African–Americans exhibit the largest Buttock-Knee lengths of the four groups and the smallest Sitting Heights. This pattern confirms Allen's rule when compared to Group 1 (European-Americans). Group 1 also appears to confirm Allen's rule (in reverse). The Hispanic-American and Asian-American classifications combine people from wide geographical areas (Asian includes the Pacific Islands to far northern populations), and recent emergence (Hispanics as a group have only been recognized a few hundred years). The results for these groups are inconclusive but illustrative. The plots on the following page compare the other groups to Group 2.

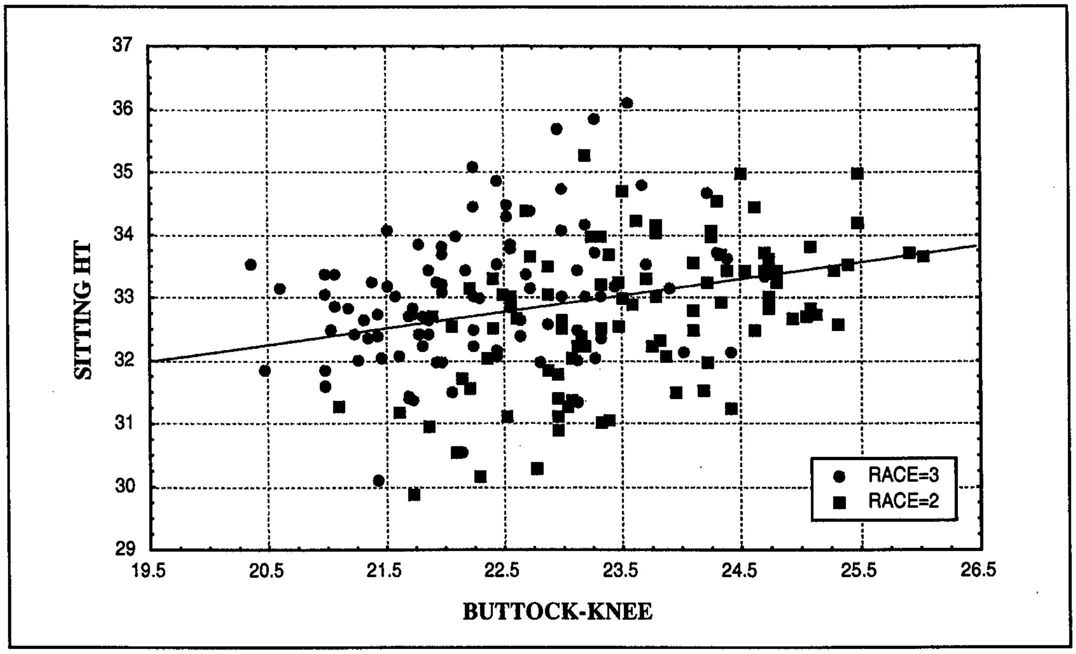

Figure 2.9. African-American (race2) and Hispanic-American (race 3) Body Proportions.

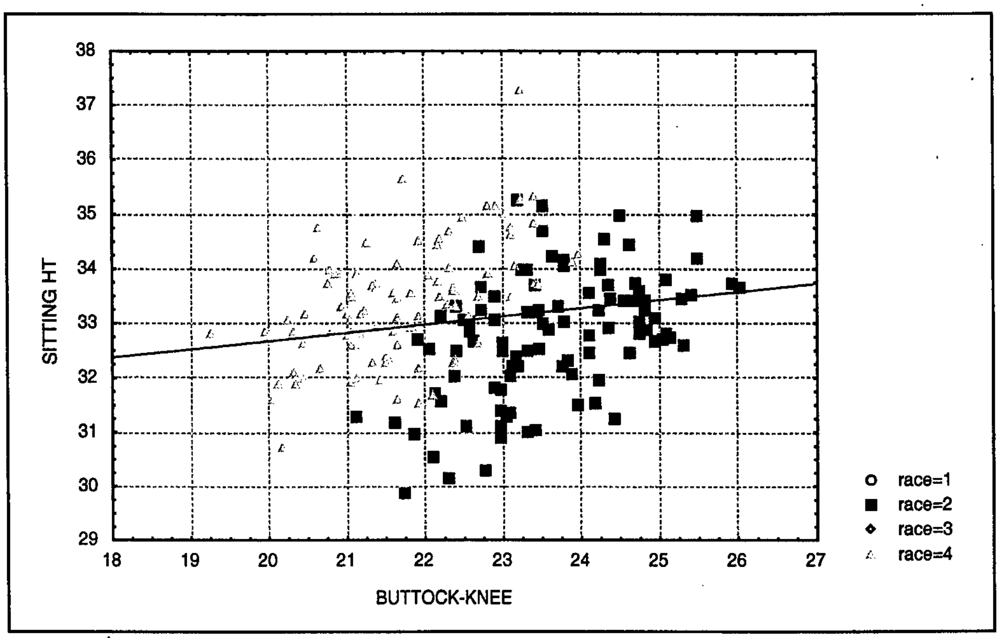

Figure 2.10. African-American (race 2) and Asian-American (race 4) Body Proportions.

The following bivariate plot compares Hispanic-Americans and Asian-Americans.

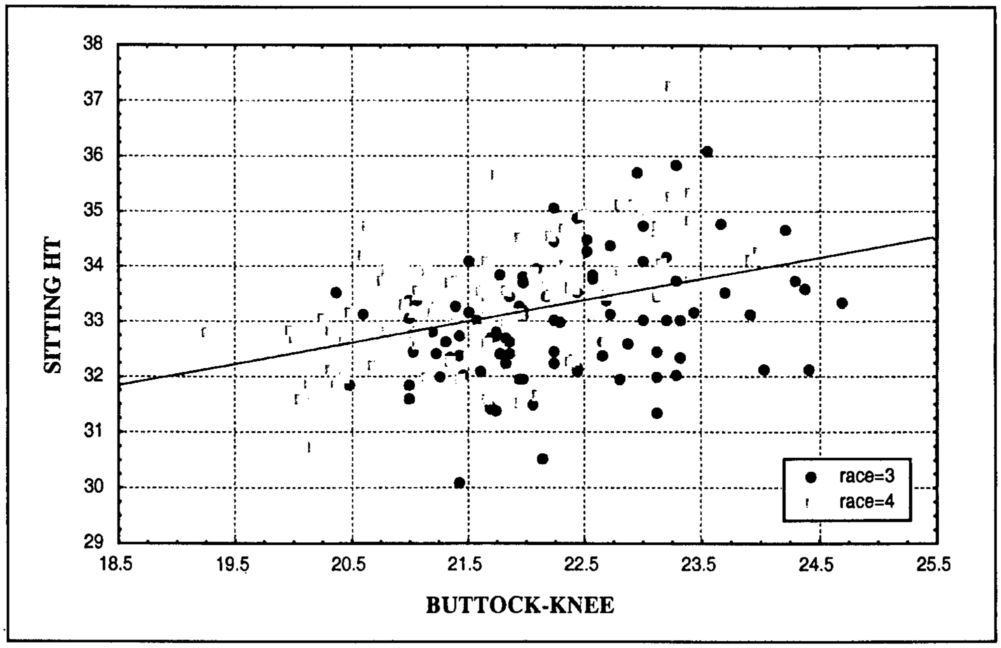

Figure 2.11. Asian-American (race 4) and Hispanic-American (race 3) Body Proportions.

The trend in torso height differences appear to exist in Hispanic-American and Asian-American groups to a lesser extent than the European-American and African-American samples. The limbs appear slightly different as well. The differences in these four groups are real, and significant (MANOVA p~0.00) and the end points of the ranges in the Box and Whiskers plots for the limbs show two-inch differences between these samples. These differences are important for setting rudder adjustment and ejection clearance parameters. The torso differences are important for setting eye position and overhead clearances.

COMBINED SAMPLES

Since there are obvious differences in these samples, it is important to understand how the statistical integrity of each group will be affected by mixing these groups into a combined sample. Since USAF pilots must be college graduates, the race/ethnic mixture of the potential pilot population should be similar to the Department of Education (DOE) data for college graduates. In 1992 the DOE reported that of American college graduates, approximately 85% were European-American, 5% African-American, 5% Hispanic-American, and 5% Americans of Asian/Pacific Island descent (David Rose, Naval Air Systems Command, personal communication, 1993). When these groups are added together to create a mixed population of those proportions, the resulting summary statistics are heavily influenced by the large percentage of European-Americans. This group will be called the DOE mix in subsequent analyses. Univariate statistics calculated on mixed groups, such as the mean and associated percentiles, are reasonably representative of the largest group, but may not describe variability existing in the smaller groups. This is a problem for designs that are based on univariate statistics calculated on populations with unequal racial/ethnic representation. The following tables compare statistics for each ethnic group with the DOE sample, and a sample mixed with equal representation of all four ethnic groups discussed above. All values are in inches.

Table 2.3. Comparison of Stature Summary Statistics.

Group	Mean	Standard Dev.	5th percentile	95th percentile
DOE mix	64.3	2.6	59.7	68.3
Equal ethnic mix	63.3	2.6	59.0	67.6
Euro-Am	64.4	2.7	59.8	68.3
Af-Am	64.2	2.5	59.6	68.1
As-Am	62.0	2.3	58.5	66.0
Hisp-Am	62.5	2.1	59.1	66.3

Table 2.4. Comparison of Sitting Height Summary Statistics.

Group	Mean	Standard Dev.	5th percentile	95th percentile
DOE mix	34.1	1.4	31.6	36.1
Equal mix	33.3	1.3	31.4	35.6
Euro-am	34.2	1.4	31.6	36.1
Af-am	32.8	1.1	31.0	34.6
As-am	33.4	1.1	31.7	35.2
Hisp-am	33.0	1.1	31.4	34.8

Table 2.5. Comparison of Buttock-Knee Length Summary Statistics.

Group	Mean	Standard Dev.	5^{th} percentile	95^{th} percentile
DOE mix	22.7	1.0	21.1	24.3
Equal mix	22.6	1.2	20.6	24.8
Euro-am	22.8	1.0	21.2	24.2
Af-am	23.6	1.1	21.9	25.4
As-am	21.7	1.0	20.2	23.3
Hisp-am	22.3	1.0	21.0	24.1

The problems with this technique have affected many USAF aircraft designs. Previous design practices for most USAF equipment relied on Government specifications for anthropometry that were lists of 5^{th} and 95^{th} percentile values for mixed populations (for example, Military Standard 1472). The authors of these standards assumed that by using 5^{th} and 95^{th} percentile values of a mixed population, 90% of the population would be covered in the design specification. This is incorrect (this point will be discussed at length in chapter 5): using these values, 10% of the mixed population is ignored for *each* dimension. While none of the groups in tables 2.3 – 2.5 have 90% accommodation rates, some of the separate ethnic groups have a much lower accommodation level. Using just three dimensions (Stature, Sitting Height, and Buttock-Knee Length) and removing any individual in the six samples outside the 5^{th} and 95^{th} percentile values for the DOE sample results in the following percentages for each group.

Table 2.6. Accommodation Percentages by Ethnic Category.

Sample	DOE	EQUAL ETHNIC MIX	EURO-AM	AF-AM	HISP-AM	AS-AM
PERCENT INCLUDED	80%	69%	84%	53%	77%	58%

In Tables 2.3 through 2.6, the DOE mix group is very similar to the European-American sample data. The DOE mix data does not represent the Asian-American, Hispanic-American, African-American, or equal mix group distributions. If univariate summary statistics are to be used (even though this is an improper specification method), each set of sample statistics must be calculated separately and the results compared.

Small design points must be determined from the smallest 5th percentile dimension and the large design points from the largest 95th percentile. However, univariate body size descriptors miss the variation in body proportions that are dramatically different in these groups. ANOVA, and MANOVA, tests show that all of these groups are significantly different at levels from around 0.05 down to ~0.00

These differences indicate that, for these particular anthropometric dimensions, it is inappropriate to combine these samples before computing summary statistics. Adding a number of additional measurement variables from Table 2.1 only made the comparisons worse. However, for cockpit related dimensions the Box M tests of the Covariance Matrices were non-significant. The data represent only one population when relationships among these variables are considered. Their correlation/covariance structures are similar, but their means are different. For this reason, separate and combined samples for each of these groups will be considered in future analyses. Without this type of analysis, the accommodation rates for a given group would be unclear. Therefore, subsequent sections of this report discuss the effects of accommodation problems for each of these groups separately.

Body Fat

Last, the USAF and Army have different entrance requirements concerning Height and Weight. These restrictions are applicable to all of the groups mentioned. The USAF has strict standards that are set in one-inch increments of Stature with a minimum and maximum weight associated with each. The Army "data pool" had to be screened to only accept individuals within these bounds. Tables 2.7 and 2.8 compare the DOE sample with the 1988 Army working database. To avoid complicating this analysis, only those subjects ages 25 to 35 and of European decent were compared.

Table 2.7. Comparison of Means: Army vs DOE Sample.

	ARMY MEAN	DOE MEAN
ACROMION HT	22.4	22.3
AGE	29.5	29.6
BUTTOCK KNEE	22.9	22.7
CHEST CIRC	35.8	35.0
EYE HT	29.7	29.7
HIP CIRC	38.3	37.5
KNEE HT	20.1	20.0
SITTING HT	34.2	34.2
SPAN	64.9	64.8
STATURE	64.4	64.4
THIGH CIRC	22.8	22.1
WAIST CIRC OMPHALION	31.5	30.4

Table 2.8. Comparison of Ranges and Standard Deviations: Army vs DOE Sample.

	ARMY MIN	DOE MIN	ARMY MAX	DOE MAX	ARMY SD	DOE SD
ACROMION HT	19.7	19.6	25.4	25.4	1.0	1.0
AGE	26.0	26.0	34.0	34.0	2.6	2.7
BUTTOCK KNEE	19.5	20.1	25.7	25.2	1.1	1.0
CHEST CIRC	29.3	29.3	42.4	40.5	2.5	1.9
EYE HT	25.4	25.4	34.0	34.0	1.2	1.2
HIP CIRC	31.3	31.3	45.3	42.2	2.3	1.9
KNEE HT	16.0	17.7	23.0	22.6	1.0	0.9
SITTING HT	29.7	29.7	37.9	37.9	1.2	1.2
SPAN	53.4	56.5	72.7	72.1	2.9	2.8
STATURE	56.2	58.4	71.5	71.5	2.5	2.4
THIGH CIRC	18.4	18.4	28.6	25.6	1.7	1.3
WAIST CIRC OMPHALION	25.0	25.2	43.6	39.7	3.3	2.4

Body length measurements in these tables are very similar. Only the circumference measurements differ significantly. This was expected. The large differences in maximum values for the army population when compared to the DOE sample reflect the more stringent USAF height/weight requirements.

Conclusions

These comparisons indicate that age is not an important factor (if over age 18) when comparing limb and torso length dimensions, but it is important for circumferences and other measurements that are correlated with mass. These measurements increase with age. The Height/Weight screening the Air Force uses makes a significant difference in sample composition. Samples for USAF application must be structured with this in mind. The largest contributing factor in sample construction is ethnic background. Large differences between racial groups and the resulting design values can introduce unexpected accommodation problems when samples are combined. Separate groups must be compared when creating anthropometric samples for aircraft and equipment design.

Subsequent chapters will use four separate groups, screened for USAF Height/Weight requirements, and the DOE mixed group for comparisons. The DOE sample evaluations are used because that group best represents the effect of accommodation problems on the overall USAF population. The equal mix group violates the multivariate normality assumption needed for many tests and has been dropped.

CHAPTER 3

OPERATIONAL REQUIREMENTS

The T-38A is a two-seat, twin engine, supersonic jet trainer. This aircraft is used to train future fighter/bomber pilots when they have finished primary training in the T-37.

The next step in this research is to determine what the minimum and maximum sized pilots must do to be considered accommodated in this particular aircraft. These tasks are called operational requirements. These requirements are a set of pass/fail criteria which pilots must perform to operate the aircraft safely.

There are two sources for precedents on setting operational requirements lists. First, for each USAF aircraft, there are a set of requirements documents which were developed during procurement of the aircraft. The documents list the vision, reach, and clearance requirements for that particular aircraft. Prior to purchasing the aircraft, USAF engineers tested the design to determine if the requirements had been met. The original documents for the T-38A are unavailable since the aircraft was purchased over 40 years ago. However, most of the requirements from that time period were based on Military Design Standards.

These Standards set strict guidelines for the design of military aircraft. For example, Military Standard 850 (Aircrew Station Vision Requirements for Military Aircraft) defined visual requirements for a cockpit. Eleven degrees over-the-nose vision (ONV) was required as a minimum for most cockpits. However, the Standard gives no justification for requiring -11 degrees. Would nine degrees ONV be enough to pilot the aircraft safely? How do we determine how much vision is enough?

For reach to controls, Military Standard 1333B (Aircrew Station Accommodation Criteria For Military Aircraft) lists critical controls for various restraint/emergency conditions, and determined the cockpit layout for many of the aircraft designed in the 1970's though 1980s. However, it was typically required that many controls be reachable with a locked shoulder harness inertial reel. Since USAF pilots do not fly with locked shoulder harnesses in normal circumstances, it seems strange that Standard 1333B requires pilots to reach non-emergency controls (i.e. the landing gear handle) in that restraint configuration.

Many of these controls are out of reach for average sized male pilots when the harness reels are locked.

Both of these Standards have been very useful, but in an attempt to anticipate pilot requirements prior to aircraft design, the standards had to be generalized across platforms and missions. They have fallen out of favor as being both too general and too restrictive.

Current design practice essentially ignores these standards. For recently designed aircraft, vision and critical control requirements are specifically tailored. This process is called establishing functional requirements. The minimum visual angle is determined by the aircraft mission. The downward vision requirement for a Ground Attack Aircraft may be quite different than the requirement for a Training Aircraft. Target acquisition may require much greater visual fields toward the ground to perform the mission effectively. For air-to-air combat missions, vision above and to the rear may be more important to the pilot than vision toward the ground. For these reasons, functional requirements for specific designs offer the opportunity to fine-tune a crewstation design to reflect best the mission of the aircraft, and avoid sacrificing improved capabilities in specific areas to follow the strict guidance of a generalized Military Standard.

The second source of information on pilot and mission performance requirements is the Technical Order the USAF publishes for each aircraft. This document is essentially an operating manual for the aircraft. All of the emergency procedures (focusing on which controls to activate during an emergency) which may be necessary during flight are described in this manual. However, Technical Orders do not describe visual or clearance requirements. The Air Force adds to Technical Orders over time as pilots gain experience in the aircraft. Unfortunately, many of the emergency procedures are developed as a result of an incident.

To arrive at realistic pass/fail performance requirements for an aircraft, we must bridge the gaps between generalized and functional design standards, and the experience-based Technical Order. The design documents are anticipatory, and the Technical Order is time dependent, it only changes AFTER a mishap. The proper method for setting minimum accommodation criteria must be based on a consensus of the experienced users of the system.

T-38 Operational Requirements

For this research, T-38 instructor pilots at Air Education and Training Command determined the operational requirements. Their experience allowed us to determine if the Military Standard minimum requirements were realistic, or if there were some other limiting factor for that aircraft that should define the minimum requirements. The resulting pass/fail requirements were established in a six-step process.

The first step was to establish a panel of eight Instructor Pilots. These pilots were interviewed to help us understand the operational characteristics and mission environment of the aircraft and to help define an initial set of "pass/fail criteria." As a group, we reviewed the appropriate Military Design Standards and the emergency procedures from the Technical Orders for the T-38A.

The next step was to observe pilot control inputs during emergency flight procedures. This was done in a high-fidelity flight simulator. We were able to watch pilots' actions during emergencies and determine the amount of stick and rudder input they used, as well as which controls and switches would be needed during an emergency where the pilot would be experiencing adverse G forces. Adverse G conditions arise when the aircraft changes direction at high speed. The most frequent occurrence of these forces is in tight turns. The pilot is forced into the seat pan and relative body weight increases up to seven-fold. The strength required to reach and operate controls in these conditions make this a very difficult scenerio.

Next, we assembled an initial draft set of reach requirements, a description of when and why those actions are necessary, and created a questionnaire that was circulated to 40 instructor pilots at the Instructor Pilot Training School at Randolph AFB, Texas. The questionnaire is shown below.

REACH REQUIREMENTS QUESTIONNAIRE

Name/Rank_______________

Phone # (DSN)_____________

T-38 Operational Requirements
Pilot Reach Survey

AETC Studies and Analysis Squadron and Armstrong Laboratory (AFMC) are conducting a study to determine the body size limits for the T-38. The USAF has lost several aircraft because pilots were unable to reach controls during an emergency situation. In emergency circumstances when an aircraft may be subjected to adverse G, a pilot must reach certain controls to recover. Since we cannot take data during such an event, we simulate adverse G conditions by locking the inertia reels and measuring pilot's ability to reach various controls. By defining the critical controls, which must be reached, the USAF could determine if it is safe to expand the physical size standards for UPT, and future crewstation designs could be improved.

In this survey, we ask you to review the controls listed below so that we may determine appropriate pass/fail criteria to safely operate the T-38.

Your experience makes you the Air Force's best source of information on T-38 operating requirements.

***Please place a check mark by controls you feel would have to be reached in an adverse G emergency**: Feel free to add any controls you feel we have overlooked. We welcome any comments you would like to add as well.*

Table 3.1. Reach Requirements Questionnaire.

REF #	CONTROL	REQUIRED?
1	EJECTION HANDLES	
2	INERTIA REEL LOCKING LEVER	
3	THROTTLE-IDLE	
4	THROTTLE-MAX	
5	SPEED BRAKES	
	CONTROL STICK:	
6	-NEUTRAL	
7	-FULL FWD, NEUTRAL ROLL	
8	-FULL FWD, LEFT	
9	-FULL FWD, RIGHT	
10	-FULL AFT, NEUTRAL ROLL	
11	-FULL LEFT/RIGHT	
12	NOSE WHEEL STEERING BUTTON	
13	FLAP LEVER	
14	AUXILIARY FLAP SWITCH	
15	ENGINE START BUTTON	
16	ENGINE START CIRCUIT BREAKER	
17	IGNITION CIRCUIT BREAKER	
18	BATTERY SWITCH	
19	GENERATOR SWITCH	
20	FUEL BOOST PUMP SWITCHES	
21	FUEL SHUTOFF SWITCH	
22	CROSSFEED SWITCH	
23	CANOPY JETTISON	
24	EXTERNAL STORES JETTISON	
25	CABIN PRESSURE SWITCH	
26	LANDING GEAR LEVER	
27	OXYGEN DILUTION LEVER	
28	OXYGEN EMERGENCY LEVER	
29	OXYGEN SUPPLY LEVER	
30	STABILITY AUGMENTER CB's	

REF #	CONTROL	REQUIRED?
31	YAW DAMPER SWITCH	
32	FULL RUDDER	
33	FULL RUDDER WITH TOE BRAKES	

The results of this questionnaire were used to validate the results of the pilot panel discussion. The ability to reach the following controls is considered essential during a reels-locked or High-G emergency and will become reach pass/fail criteria.

Ejection Handles
Inertial Reel Locking Lever
Throttles – idle and max
Full Rudder (in flight)
Full Rudder and Toe Brake (on the ground)

The rest of the controls could be accessed by either unloading the G forces on the aircraft (by slowing down or straightening the turn) or unlocking the inertial reel. Pilots felt these controls were not immediately essential during a limited mobility situation. The control stick seems to be a surprising omission from this list. However, only the full-forward and full-forward-left positions are difficult to reach. By pushing the stick forward, the G-forces on the aircraft are reduced. When the G-forces are reduced, the pilot can lean forward and easily reach the forward stick positions.

External Vision Requirements

The third step in establishing pass/fail criteria was to conduct study flights to determine minimum visual requirements. These flights were needed to determine the minimum over-the-nose visual angle required for landing as well as a variety of formation flights and rejoins. During actual flights, instructor pilots assessed the minimum ONV needed to see the end of the runway during no-flaps approach and landing. During formation flights, they determined the lowest eye positions from which to obtain adequate aft vision for flying lead, and the required lateral visibility for wing formation, rejoining formations, and for tactical formation flight from the wing position. Pilots established the lowest acceptable eye position by flying the entire test protocol from their normal seat position, and then lowering the seat in one-inch intervals each time they repeated the protocol. By measuring the pilot's Sitting Eye Height and locating the lowest seat position they determined to be safe, we calculated the shortest Sitting Eye Height which would be able to achieve the pass/fail eye position with the seat adjusted full-up.

The results indicate that the flight situations in which it is most difficult to maintain adequate ONV are during a no-flap approach and a formation re-join. A no-flap approach requires a high angle of attack (the aircraft's nose is pitched up) for the aircraft to compensate for the loss of lift. During this approach, the nose of the aircraft may block the pilot's view of the ground. While experienced pilots can land the aircraft using peripheral cues, the instructor pilots were adamant that student pilots should not be trained from that visual perspective.

Also, a great deal of the training in the T-38 involves formation flying. When a pilot's eye position is too low in the cockpit, it is difficult or impossible for him or her to see a wingman during rejoin of the formation. In this stage of flight, one aircraft approaches a formation from the side to join it. To slow the lateral closure rate, the pilot rolls the aircraft away from the formation. This raises the wing on the formation side and can obscure the formation from view. If the formation is hidden from view, the pilot is not able to judge distance to the other aircraft.

This portion of the study required four test flights, for a total of eight pilot data points. Pilots gathered data during the phases of flight listed in table 3.2. This table lists for each phase of flight, the mean value for minimum Sitting Eye Height with the seat adjusted full-up.

Table 3.2. Minimum Eye Heights for Various Phases of Flight (values in inches).

Phase Of Flight	MINIMUM EYE HT
No-Flap Landing	29.3
Rejoin Lead	28.6
Rejoin Wing	29.5
Fingertip Lead	28.0
Fingertip Wing	27.8
Route Lead	28.2
Route Wing	27.8
Fighting Wing	29.0

During formation flights pilots must visually keep track of the other aircraft. These test flight results indicated wing rejoins and no-flap landings require the most external vision. To maintain adequate visibility during the phases of flight tested, pilots need a minimum Sitting Eye Height of 29.5 inches.

Finally, the T-38 is currently undergoing an avionics upgrade (designated T-38C) which will add a Head-Up Display (HUD). The HUD displays vital aircraft information to the pilot and sits on top of the main instrument panel glareshield. The design of the HUD optics requires that the pilot stay within a small range of eye positions to see all HUD symbology. Pilots must be able to see all information on the HUD.

In the T-38C, the lowest eye position for adequate HUD visibility will correspond to the original design eye location for the aircraft: -11 degrees vision over the nose. Not surprisingly, this is the value that Mil Std 850 imposed on the T-38 design in the 1950s.

With the addition of the HUD, we have two pass/fail criteria for external vision in the T-38: 29.5 inches for formation rejoin and no-flaps landing, and –11 degrees over the nose for attaining full HUD field of view. The final step in the process was to submit the final list of operational requirements for the T-38 to AETC headquarters for review and approval. Personnel at all levels of AETC agreed the requirements were correct. Final approval was given by General Lloyd Newton (AETC/CC).

For large pilots, clearance space for operation and escape are the main accommodation problems. Pilots should not fly if they could be injured by aircraft structures during turbulence or ejection. This includes: No overhead contact with the canopy when the pilot's head is placed in the seat headbox prior to ejection, no contact between the pilot's shins and the main instrument panel, and no contact between the pilots knees and the glareshield, or canopy bow during ejection. With the operational requirements officially complete, we were then able to begin the anthropometric portion of the research.

CHAPTER 4

COCKPIT MAPPING

The approach in the anthropometric portion of this research relies on numerous test subjects representing as well as possible the extremes of body sizes within the potential user population. In a very real sense, we use the subjects as human "tools" to establish limits of body size accommodation. Each subject is measured both statically in the laboratory, and as they perform the list of operational requirements in the cockpit. Excess and miss distances are measured so that minimum ability levels can be calculated.

Each area of accommodation discussed below may involve different numbers of subjects, depending on the amount of variability we expect. For example, overhead clearance is a straightforward measure in which clearance above the head is added to the subject's Sitting Height. When the seat is positioned full down, the subject's Sitting Height plus the clearance space sum to the largest Sitting Height that could be seated with no head clearance. Because there is little variability in results, just four large subjects are averaged to arrive at the final value. For reach to controls however, subject results vary a great deal because of harness fit, strength, motivation, and a number of anthropometric variables. We use a larger number of subjects and perform multiple regression analysis to produce the final results for this area of accommodation. Model I regression is used in this research. Appendix C discusses in depth the differences between Model I and three types of Model II regression. The difference in these methods is - when there is "error" in both the independent (anthropometric dimensions) measurement and the dependent measure (ONV, reach to controls, etc.). Model I may not be appropriate. However, according to Sokal and Rohlf (1995), Model I regression can still be used when any one of three conditions exist. First, when the errors in measurements are controlled by the investigator (such as assignment to a class). Second, when the magnitude of the errors in the anthropometric variate and the error in the application measurement are not correlated. In this application they should be random. Third, Sokal and Rohlf also conclude that when the intentions of the investigator are prediction, Model I regression should still be used. That is certainly the case in this research. Even though two of these arguments can be made in this research, Model II regression techniques were still applied to the data. Appendix C shows that there is very little difference between Model I regression and in the predicted values of ONV for a given Eye Height when using Major Axis Regression or Bartletts Three Group method (both are within 0.2 degrees). However, Reduced Major Axis regression differs by 1.75 degrees. For these reasons, it appears that Model I regression is appropriate in this work.

For the T-38, we examined seven aspects of anthropometric accommodation:

1. Overhead clearance.
2. Rudder pedal operation.
3. Internal and external visual field.
4. Static ejection clearances of the knee, leg, and torso with cockpit structures (i.e. canopy bow)
5. Operational leg clearances with the main instrument panel.
6. Operational leg clearance with the control stick motion envelope and pilot's ability to attain the full range of stick travel.
7. Hand reach to controls.

In some aspects of accommodation (overhead clearance and vision, for example), anthropometric relationships are obvious and fairly simple. Overhead clearances are directly related to Sitting Height. Vision out of the aircraft, primarily ONV, is directly related to Sitting Eye Height. For these measures, multiple anthropometric dimensions are unnecessary to explain accommodation levels.

Other measures of accommodation are more complex. For example, operational clearance of the body with the control stick motion envelope can be restricted as the stick is pulled aft. There often is not room between the thighs to roll the aircraft left and right. This results in limited aileron movement, reduced roll rate, and could change aircraft flight characteristics at the wrong time. Limitation of stick motion is influenced by Sitting Eye Height, Thigh Circumference, and Buttock-Knee Length. The relationship between the upper seat positions (used by pilots with small Sitting Eye Height) and Thigh size seems to be the most critical. In Figure 4.1, stick clearance problems can be visualized by imagining that the motion of the upper end of the control grip is similar to the base of an inverted pyramid.

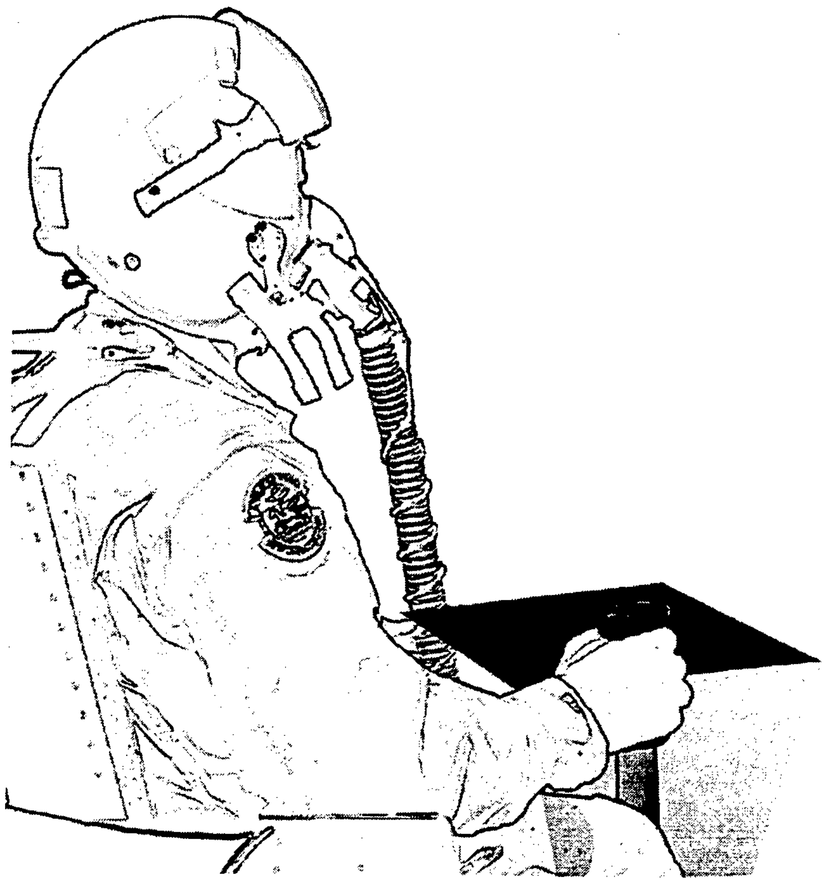

Figure 4.1. Control Stick Range of Motion.

As the seat is raised to improve external vision, the range of stick travel side-to-side increases relative to the pilot's legs. Extremely large pilots will typically use the full-down seat position, and the control stick is usually so far above the thighs that interference does not occur. However, small pilots are typically adjusted as high in the seat as possible to gain adequate over-the-nose vision. In this seat position, the stick often contacts their thighs. Also, pilots with long legs are typically able to spread their knees apart, making a greater space available between the thighs for control stick movement. Small pilots may not be able to spread their legs while keeping their feet on the rudder pedals.

For these reasons, subjects of various sizes are tested with the seat adjusted to numerous positions in the cockpit. This allows examination of the subject in progress, and it also allows us to extrapolate measurements to subjects of neighboring sizes and varying proportions. Measurements are taken which allow prediction of an individual's ability to be accommodated. For example, if a subject with the seat adjusted to the full-up position, misses reaching to the landing gear handle by 1.5 inches, that subject's anthropometric dimensions will be regressed against the 1.5 inch miss distance for that seat position. Many subjects must be run in a variety of seat positions to calculate all the different combinations of size and seat positions possible for reaching controls. We use a similar approach for many of the other aspects of accommodation listed above. Regression provides a best-fit estimate for the sample measured. The estimate is similar to the "average" answer for a group of people of the same size. These data should therefore be considered accurate estimates, not exact data points.

Test Sample

The T-38 study of small pilot accommodation included 22 small test subjects, each equipped in the full complement of flight gear used by Air Education and Training Command. Prior to measurement of their capabilities in the cockpit, each subject was measured on 18 traditional anthropometric dimensions (descriptions of these measurements are included as Appendix A). The female sample was not selected to be representative of the overall body size distribution of the pilot population. Instead, subjects were selected to represent the small size extremes of the population while retaining a reasonably normal distribution for each measure. Figure 4.2 compares this sample (T-38) to the USAF baseline population (DOE sample) selected from the 1988 US Army Anthropometric survey (see Gordon, 1989, and Zehner, 1996).

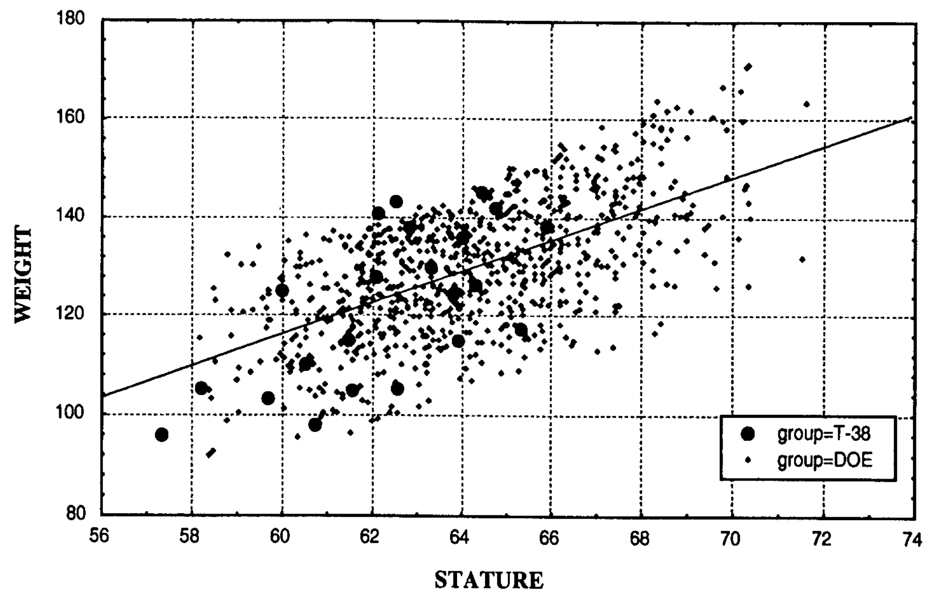

Figure 4.2. Comparison of Test Sample Small Subjects with Base Population.

Each of the following sections are based on slightly different measurement methods and each has unique assumptions associated with it. Therefore, the format for the sections will be as follows:

1. A description of the accommodation problem being examined.
2. A statement of the operational requirement established by AETC that each pilot must be able to perform.
3. An explanation of the measurement methodology and assumptions made for that area of accommodation.
4. A description of the anthropometric measurements related to that area of accommodation.
5. The results of the analyses.
5. A discussion of the magnitude of the accommodation problems on the populations described in Chapter 2.

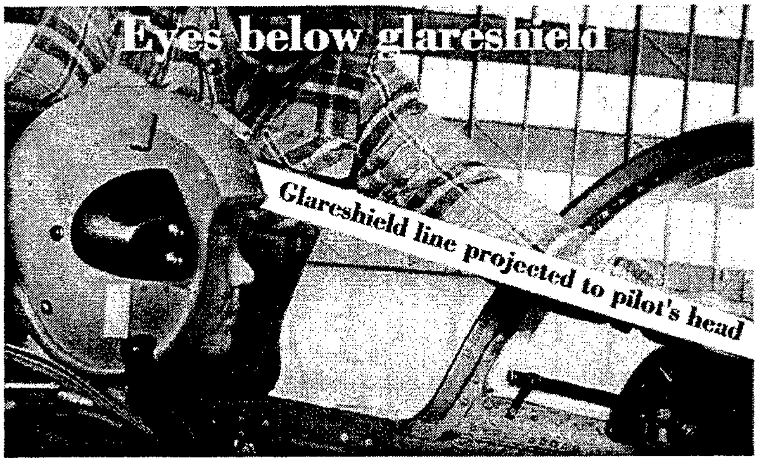

Figure 4.3. Small Subject in the Forward Cockpit of the T-38.

Problem

For small pilots, external visual field can be so restricted that they cannot see the runway during a landing (especially during a no-flap approach), or they may have difficulty seeing their wingman during a formation rejoin. Small subject eye position may be below the aft edge of the glareshield. Also, with the addition of a HUD as part of the avionics upgrade for the T-38, small pilots may not be able to see all of the symbology on the display.

Operational Requirements

The lowest point from which a pilot can see all HUD symbology is along a line -11 degrees (down vision) relative to the aircraft water line. This level is tangent to the glareshield (see the glareshield line in Figure 4.3). When the pilot is at this level, he or she can see the base of the pitot tube where it attaches to the nose of the aircraft. AETC instructor pilots direct student pilots to adjust their seat high enough to see that structure. This allows the instructor to describe a standard sight picture that the student should see during various maneuvers. From this position, the student pilot will be able to see the runway during a no-flap landing, and will be able to see his or her wingman during a formation rejoin.

Methods and Assumptions

Vision in the T-38 was measured in two body postures in the front cockpit and one in the rear. In the front crewstation, ONV was measured with subjects looking straight ahead over the nose of the aircraft. Subjects were instructed to keep their heads level (i.e. in the Frankfurt Plane). An Abney Level (Figure 4.4) was used to measure the depressed elevation angle to the ground over the nose of the aircraft.

Figure 4.4. Over-the-Nose Vision Measurement.

After the first measure was completed, subjects were allowed to stretch their head and neck up and aft to obtain a better view of the ground, and we repeated the measurement.

Measurements were taken in the full-up seat position and the part of the aircraft that blocked the subject's view of the ground was recorded. The structure that blocks the subject's vision toward the ground is important during data analysis. The nose of the aircraft is roughly 20 feet forward of the pilot. If the pilot's view of the ground is broken by the nose of the aircraft, a one-inch change in seat position will have little effect on the pilot's vision angle. However, if the test subject is so short that his or her eye is below the glareshield (see Figure 4.3) and the nose of the aircraft is obscured, the limit of the forward field of view is about two feet in front of their nose. A one-inch change in seat position in that geometric relationship has a much larger effect on forward visual capability. During data analysis, these subjects must be kept separate so that the linear relationships between eye height and vision over the nose can be preserved.

In the rear cockpit of the T-38, forward vision over the nose is not possible because of the aircraft design. For vision measurements in the rear cockpit, subjects were instructed to lean to the left and sight down the side of the forward crewstation ejection seat headbox.

Anthropometric Variables

The anthropometric dimension most related to vision ONV is Sitting Eye Height. This is the measurement from the seated surface (under the buttocks) to the pupil when the head is in the Frankfurt Plane (horizontal line of sight) and while the subject sits erect. Pearson's r is a measure of how weakly or strongly variables are related. For Sitting Eye Height and ONV, Pearson's r is .85 with a standard error of 0.6. The USAF baseline population (DOE sample) ranges from 26.1 inches through 35.6 inches for Sitting Eye Height. Current USAF pilots (those in the DOE sample meeting flight training body size limits) range from 28.9 inches to 35.6 inches.

Results

Figure 4.5 shows the ONV regression for the full-up seat position. It shows the degrees of over-the-nose vision flyers of a given Sitting Eye Height will be afforded with the seat adjusted full-up. The graph shows that people of very small Sitting Eye Height may only be able to see a few degrees over the nose when the aircraft is level. Depending upon the aircraft angle of attack during landing, these individuals may not be able to see the runway over the nose of the aircraft. The eye position necessary to see all HUD symbology is equivalent to an ONV angle of -11 degrees. This equates to a Sitting Eye Height of 29.75 inches when the seat is adjusted full-up. From this position, ONV for landing and formation rejoin are both within acceptable visual fields. Notice that in the graph, the data points do not fall on a single line. There is a great deal of variation in posture and eye position among subjects of similar eye heights. Keep in mind that regression predictions are essentially average visual angles for a group of individuals with the same Sitting Eye Height. Therefore, we would expect half of that group (with Eye Heights of 29.75 inches) to see -11 degrees or more and the other half to see -11 degrees or less. Fit checks (that is, putting a potential pilot in the cockpit and checking that he or she can reach controls, etc.) for people near that size may be in order. However, 29% of the USAF female baseline population would fall between 29.25 and 30.25 inches in Sitting Eye Height. These limits are at the edges of the intersection of the 95% confidence band and the –11 degree reference line in Figure 4.5. This could make fit checks a very frequent occurrence. Figure 4.5 includes large subjects for illustrative purposes. The visual obstruction faced by large and small test subjects was different.

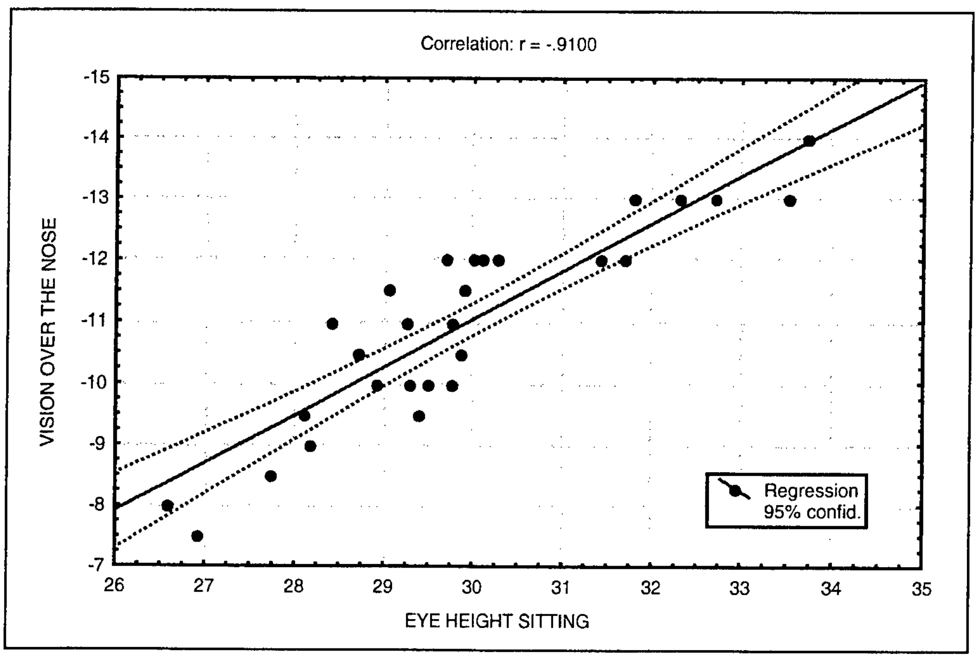

Figure 4.5. Prediction of Over-the-Nose Vision- 95% Confidence (seat full-up).

Percentages Affected

In the front cockpit, a 29.75-inch Sitting Eye Height is necessary to consistently see -11 degrees over the nose. Table 4.1 lists the percentages of the ethnic groups discussed in Chapter 2 able to see at least this much. The two columns labeled Female and Male Pilots are the same samples but they have been truncated to match USAF body size restrictions for Flight training. These are: Stature between 64 and 77 inches, and Sitting Height between 34 and 40 inches. The DOE mix is an estimate of the accommodation for the entire USAF population.

Table 4.1. Percentages of Various Ethnic Groups Accommodated for Vision in the T-38A.

RACE/ETHNIC GROUP	FEMALES	FEMALE PILOTS	MALES	MALE PILOTS
EURO-AM	52	96	90	94
AF-AM	10	62	68	84
HISP-AM	14	82	74	83
AS-AM	16	76	73	87
DOE MIX	42	86	87	94

The radical differences in accommodation rates is not unexpected given the differences in body size and proportion among these groups. Among male and female European-American pilots, however, accommodation rates are worse for males than females. This is surprising. Given that each pilot must have a Sitting Height of at least 34 inches, and that there are many more females near the 34-inch lower limit, this might indicate a taller forehead in males than females. The mean difference and range of differences calculated by subtracting Sitting Eye Height from Sitting Height are 4.5 (range=3.8 - 5.5) inches for females, and 4.8 (range=3.9 - 5.8) inches for males. This is not a large difference. The different percentages may also be a random effect of sampling.

For current USAF pilots (DOE mix), 14% of females and 6% of males will see less than -11 degrees ONV. The Sitting Eye Height measurement for the DOE mix (representing current pilots) is within 1 inch (.9 degrees) of that level. This value reflects the amount of change in the visual angle per inch of Sitting Eye Height. This ratio becomes important in subsequent sections. These figures are based on measurements taken with the subject's head held level (in the Frankfurt Plane). On the average, if the pilot tips his or her head back and stretches upward, an additional 1.3 degrees of vision is possible. Instructor pilots insisted that this small amount be reserved as a safety factor, since requiring a pilot to stretch to see the HUD symbology is not a good Human Factors design. Current pilots who are small in Sitting Eye Height may have difficulty seeing all HUD symbology without stretching. When the T-38C upgrade HUD is completed, we will determine the severity of this problem.

REACH TO RUDDERS

Figure 4.6. Small Subject Reaching for Rudders Forward Cockpit - T-38.

Problem

Like ONV, the ability to reach and actuate rudder pedals and brakes is affected by seat position. A pilot with very short legs may lower the seat to reach the rudder pedals. However, minimum vision levels (and, therefore, seat position) must be maintained throughout a mission. Under normal circumstances pilots should not be allowed to excessively sacrifice external vision. The pilot who is small in Sitting Eye Height will have to adjust the seat to achieve adequate vision. This moves the pilot farther away from the rudder pedals. If the seat can be lowered and acceptable vision out of the aircraft maintained (-11 degrees), the pilot can improve access to the rudder pedals.

Operational Requirements

The T-38 requires very little rudder input when in the air except during slow-flight "gun jinks". These radical maneuvers are used when trying to avoid enemy fire. The pilot slams full rudder and quickly pushes the stick in various directions causing extreme movements of the aircraft. In addition to jinks, maneuvering on the ground and maintaining control in case of a blown tire on landing or takeoff require the ability to apply full rudder and brake simultaneously. Measurements were made in a number of seat positions so that the effect of seat movement could be calculated.

Methods and Assumptions

In this analysis subjects placed their feet on the rudders with their toes on the brakes. Full rudder throw was defined as full rudder input, and full brake, with the knee fully extended. The subject was tightly restrained and not allowed to slide forward in the seat. This method of positioning the foot is an intentionally conservative estimate; under certain flight conditions, a great deal of strength is required to hold the pedal in.

Measurement was made to the rudder adjust position where the subject could just actuate the rudder and brake. A regression equation was developed using rudder position and leg length, and the leg length equating to a full aft rudder adjustment was calculated.

Anthropometric Variables

The measurement which best identifies the minimum leg length required to reach full rudder throw is a combined leg length. Buttock-Knee Length and Knee Height Sitting are summed to arrive at a new measure called Comboleg. For example, if a 42-inch combined leg length is required to obtain full rudder throw, it does not matter if an individual has a 23-inch Buttock-Knee Length and 19-inch Knee Height Sitting or a 22-

inch Buttock-Knee Length and 20-inch Knee Height Sitting. Their reach to rudders in the T-38 will be the same. The correlation between Comboleg and rudder adjust position is .96. Other measurements of leg length did not correlate as highly with rudder reach ability. This combined measurement could be misleading in aircraft where it is not possible to obtain full knee extension, however. If the knee remained flexed, the relative contribution of thigh and calf could be significant. Multiple regression would be appropriate in such a case.

The current USAF population (DOE mix) ranges for Comboleg are 37.8 inches to 52.4 inches. For those meeting current pilot size restrictions, the range is 40.7 inches to 52.4 inches.

Results

The graph below shows miss distance (negative numbers) to full rudder and brake for a variety of leg lengths. With the seat in the full-up position, a combination leg length of 43 inches is required to attain full rudder and full brake simultaneously. This requirement applies to both the front and back cockpits in the T-38.

As in the Vision section above, it is possible to misclassify individuals who fall within the confidence band of the regression-predicted values. Individuals between 42.5 inches and 43.5 inches in Comboleg could be fit-checked to determine if they can reach full rudder and brake.

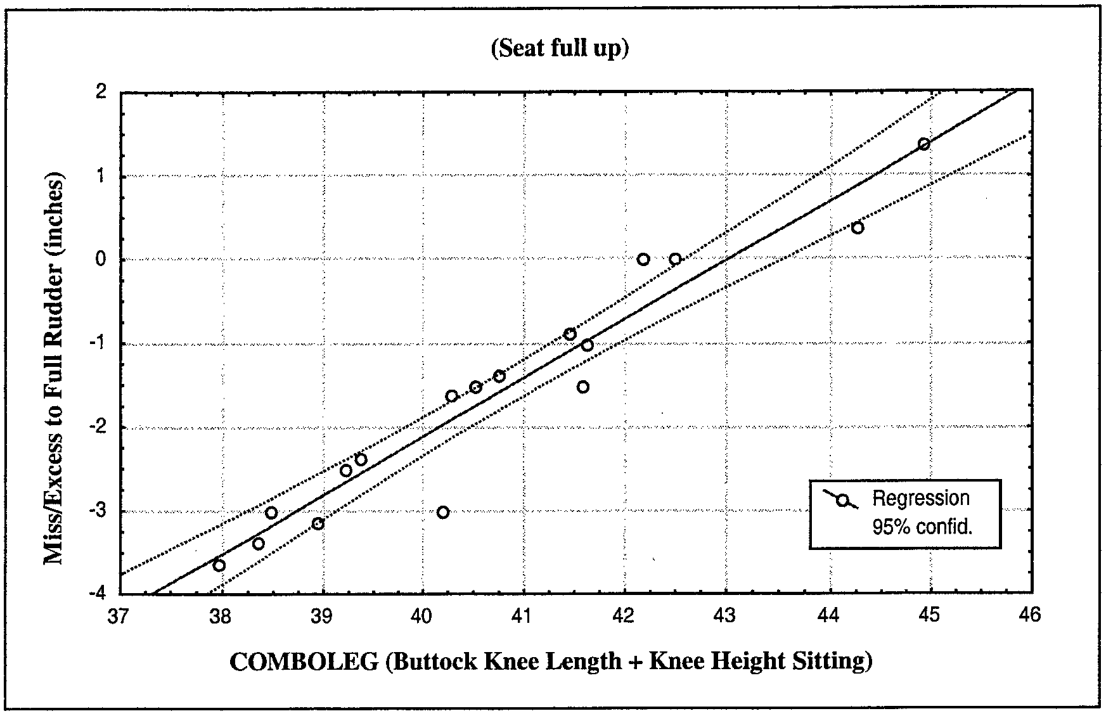

Figure 4.7. Prediction of Reach to Rudders and Brake – 95% Confidence.

Percentages Affected

Two steps are necessary to determine the percentage of the various populations accommodated on rudder pedals. Two steps are required because, if a pilot's legs are too short to reach the rudders, it may be possible to lower the seat to get closer. A lower seat position is acceptable if the subject still has adequate (-11 degrees) ONV in the lower seat position. In other words, if the pilot has a Sitting Eye Height of over 29.75 inches, the seat can be lowered by the excess amount, moving the pilot closer to the rudder pedals. Given the location of the rudders relative to the seat, for every inch the seat is lowered, the pilot moves ½ inch closer to the Rudders. To determine the percentage of the population accommodated thus far, we mathematically simulate adjusting the seat so that each person in the following calculations sees exactly -11 degrees over the nose. For example, if a pilot has a Sitting Eye Height of 30.75 inches, we subtract 29.75 and multiply that amount by 0.5. The resulting value is subtracted from the pilot's leg length. This equation tells us that, with the seat adjusted one inch down, a 42.5-inch combination leg length would be required to operate the rudders. From that seat position, we determine if the subject can reach full rudder input and full brake. This process continues for each subject in the database.

Table 4.2 lists accommodation percentages for vision and reach to rudders for the ethnic groups discussed in Chapter 2. The DOE mix is an estimate of the accommodation for the entire USAF population.

Table 4.2. Percentage of Various Ethnic Groups Accommodated for Vision and Rudders in the T-38A.

RACE/ETHNIC GROUP	FEMALES	FEMALE PILOTS	MALES	MALE PILOTS
Euro-Am	42	86	83	83
African-Am	10	62	68	68
Hispanic-Am	9	69	69	69
Asian-Am	8	57	55	55
DOE-mix	29	71	87	82

Several numbers in this figure deserve explanation. First, the African –American percentages, after screening out those who cannot reach rudders, are the same as the percentages that remained after screening out those who could not see over the nose. All African–American in the database with a Sitting Eye Height over 29.75 inches also have a combined leg length over 43 inches. Another odd result is that the percentages for males and male pilots in Table 4.2 are the same. This is because there are only a small number of males under 34 inches in Sitting Height and 64 inches in Stature. Screening for vision over the nose removed all males who could not also reach rudders.

The distance the rudders would need to be moved aft to accommodate a larger percentage of these populations is unclear, however. A person 58 inches tall, with a Sitting Eye Height of 26.8 inches, and a combination leg length of 38.9 inches would miss full rudder by 4.1 inches with the seat full-up. This is a misleading figure, however, because this person would need to raise the seat an additional 3 inches to see the minimum -11 degrees visual angle over the nose of the aircraft. If it were possible to modify the seat that much, miss distance to the rudders would be increased to 5.6 inches. The interplay between these two measurements must be kept in mind before modifying the aircraft.

For current USAF pilots, 29% of females and 18% of males will not be able to apply full rudder and brake and still be able to see –11 degrees over the nose. While essentially all current pilots are within one inch of reaching full rudder and brake and one inch of seeing –11 degrees over the nose, they are now stretching in two directions to attempt to pilot their aircraft.

ARM REACH TO CONTROLS

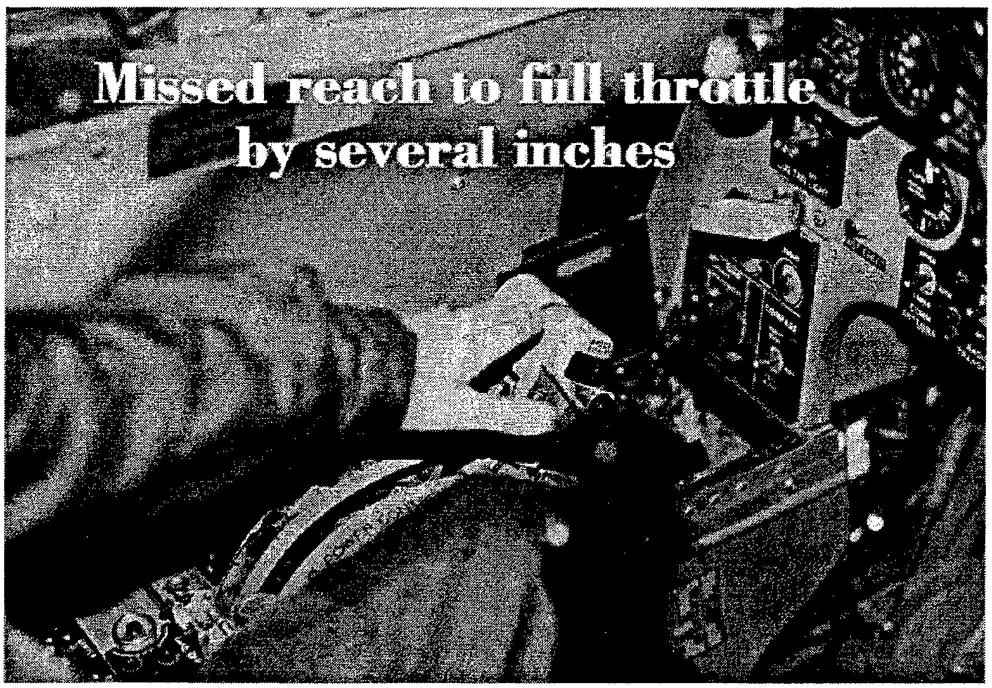

Figure 4.8. Small Subject Reaching Toward the Throttles Forward Cockpit T-38.

Problem

Pilots must be able to reach and operate hand controls to safely fly an aircraft. In normal flight conditions, with the inertial reels unlocked, this is not a difficult task. Under adverse-G conditions, however, or when there is an inadvertent reel lockup, small pilots will have difficulty reaching many controls. Inadvertent reel locks happen in aircraft much as they do for some automobile seat belts. Turbulence (bumps) or rapid movements cause the mechanism to lock up. But unlike an automobile, the aircraft pilot must flip a switch on the front edge of the seat to release the mechanism. Until that is done, the pilot's movements are very restricted.

Operational Requirements

AETC determined that pilots must be able to operate the inertial reel lock, grasp the ejection handles, retard the throttles, and operate the speed brake with a locked inertial reel. The throttles are the most difficult of this group to reach, so they are the only control discussed here. Surprisingly, the ability to reach to the outer edges of the control stick range is not a requirement with a locked inertial reel. Given the geometry of the T-38, a pilot who is just able to reach and retract full-forward throttles would miss full forward stick by 1.25 inches. AETC feels that even under high-G conditions, a pilot would be able to stretch 1.25 inches in the unlikely event that full-forward stick was necessary. Pushing the stick forward should unload +Z G-forces (downward along the spine), allowing the pilot to separate his or her shoulder from the seat back and lean forward to reach. Reach ability was measured to a great many other controls as well, in case these operational requirements change in the future. The additional controls are listed in order of reach difficulty in Appendix B.

Methods and Assumptions

Several factors other than body size affect reach capability in an aircraft cockpit. The design, fit, and adjustment of harnesses, personal protective equipment, survival gear, body strength, and motivation, all influence the act of reaching. Due to these factors, reach is the most difficult area of accommodation to accurately quantify. For that reason, we liberally edited outlier subjects. Subjects more than 2 standard errors away from the predicted values for a given reach (residual analysis) were examined for possible deletion.

Reach to controls was based upon two harness configurations (Figures 4.9 and 4.10): first, with the reels locked and shoulders against the seat back. This is referred to as a Zone one restraint condition (MIL.STD 1333C). Next, we evaluated reach in Zone two, where the reels are locked but shoulders are allowed to reach out toward the control with a maximum stretch.

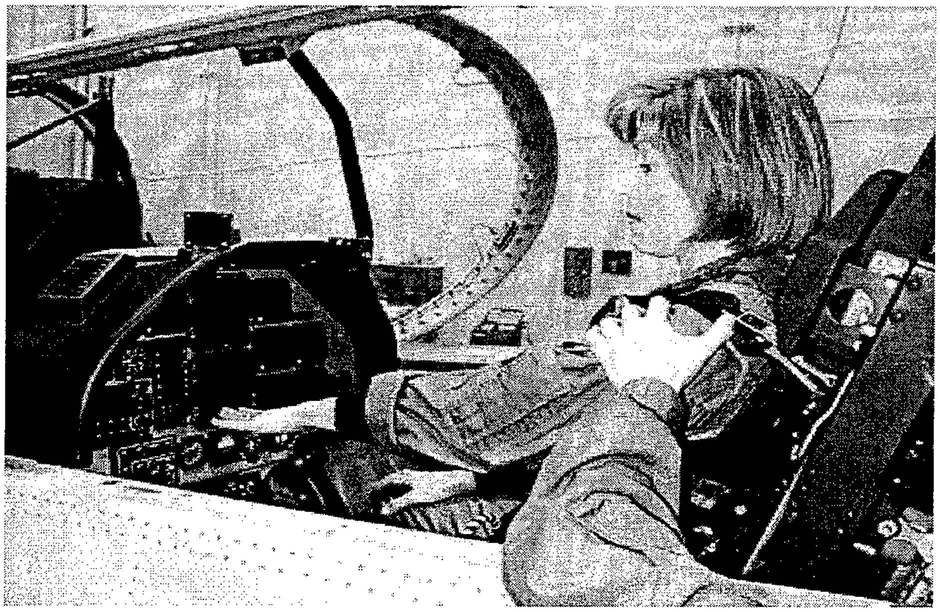

Figure 4.9. Zone 1 Reach Position.

Figure 4.10. Zone 2 Reach Position.

We realize that inertial reels are not locked under normal flight conditions, but safety concerns dictate looking at "worst case" scenarios. In Zone 3 (Figure 4.11) the harness is not locked and the subject is allowed to lean forward to gain access to controls. All subjects were able to reach all controls of interest in a Zone 3 harness configuration.

Figure 4.11. Zone 3 Reach Position.

Reach was initially measured in the full-up seat position, and then repeated in a lower seat position to determine the change in reach ability for an increment of seat adjustment. Measurements were taken from the interface point on the body to its respective contact point on the control. For retracting the throttle, we measured from the crease between the middle and distal phalange on digit 3 to the forward side of the throttle in the full afterburner position (the most forward position of the throttle). Miss or excess distances were measured and regressed against body dimensions to determine the body sizes and proportions just able to retract the full-forward throttle.

Anthropometric Variables

Reach to a particular control is a function of arm length (Span) and torso height. Torso height plays a large role in seat adjustment, since the pilot must seek at least minimally adequate vision. Moving the seat up, however, moves the pilot further from some controls.

Arm reach may also be affected by the width of the shoulders, primarily because of the restraint system. Subjects with narrow shoulders may find the torso harness in a position relative to the humeral head that restrains forward movement of the shoulder. Wide-shouldered subjects are relatively free to move around the shoulder straps while stretching. A large number of anthropometric dimensions were tested to determine the best model for the prediction of reach capability. The added accuracy of many variables was marginal. For example, Pearson's r for the multiple regression between Shoulder Height, Span, and miss distance to the throttle is .85 with a standard error of 0.7. Dropping Shoulder Height Sitting made no difference in the results. The lack of difference is surprising since changes in Shoulder Height Sitting should have the same effect on reach to controls as changes in seat position. Our explanation for this anomaly is that reach data are sometimes not very repeatable, and that small differences in Shoulder Height Sitting are cancelled out by variations in posture.

Seat position effects were calculated by averaging differences in reaches for each subject between the full-up seat position and the down-one-inch seat position. The results indicate that for each inch the subject lowers the seat, miss distance to the throttle is reduced by 0.9 inches (range = .25 to 1.75 inches). A 2.5-inch smaller Span measurement would reduce miss distance by 0.9 inches. This relationship is important since pilots with tall Sitting Eye Heights can lower the seat to get closer to the controls. Again, in the analysis, subjects were mathematically positioned so that they would see at least the minimum -11 degree visual angle. The USAF sample ranges for Span are 55 inches to 82 inches. For current pilots, the range is 62.8 inches to 80 inches.

Results

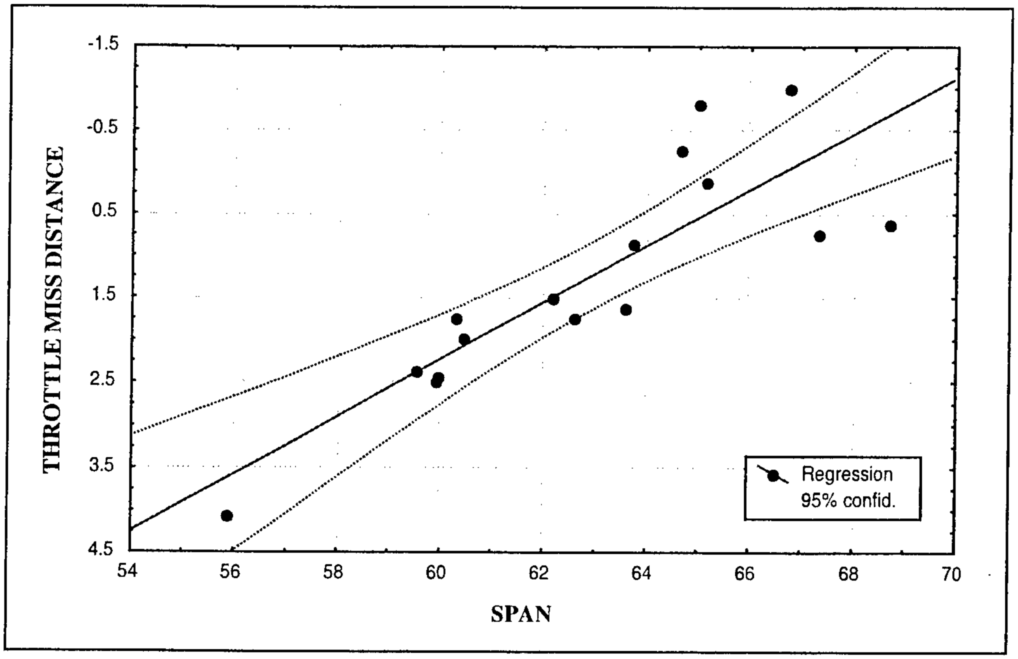

Figure 4.12. Prediction of Reach to Throttle – 95% Confidence.

The r value of .851 indicates a reasonable prediction for reach to controls based on only one anthropometric variable. Using one anthropometric variable greatly simplifies determining whether a pilot can be assigned to the aircraft. A minimum measurement of 66.5 inches for Span will be required to reach full throttles with the seat full-up.

Percentages Affected

As with rudders, two steps were necessary to determine the percentage of the various populations accommodated on reach to throttles. Two steps were required because, if a pilot's arms are too short to reach the controls, he or she may be able to lower the seat to get closer to the controls. Lowering the seat is acceptable if the subject still has adequate (-11 degrees) ONV in the lowered seat position. During data analysis, therefore, we mathematically adjust the seat so that each person in the following calculations sees -11 degrees over the nose. From that seat position, we determined if the subject could reach the throttles well enough to retard them when they are full forward.

If an individual has a Sitting Eye Height one inch greater than 29.75 inches, he/she could lower the seat one inch and therefore reduce the reach to throttles by 2.5 inches in Span (keep in mind that arm span measurement includes both arms and shoulder width). Table 4.3 lists accommodation percentages on both Vision and Reach to Throttles for the ethnic groups discussed in Chapter 1. The DOE mix is an estimate of the accommodation for the entire USAF population. These individuals may not be able to reach rudders (that will be discussed below).

Table 4.3. Percentage of Various Ethnic Groups Accommodated for Vision and Reach to Throttle.

RACE/ETHNIC GROUP	FEMALES	FEMALE PILOTS	MALES	MALE PILOTS
Euro-Am	39	78	88	93
African-Am	10	62	68	84
Hispanic-Am	9	69	71	81
Asian-Am	11	72	68	85
DOE-mix	30	81	88	94

Among current USAF pilots, 81% of females and 94% of males will be able to easily see –11 degrees over the nose and retract the throttle. Essentially, all current pilots that are not accommodated are within one inch of seeing –11 degrees over the nose and/or another inch from reaching and retracting full throttle. They have to stretch in two directions to pilot their aircraft.

Our example person (58 inches tall with a Sitting Eye Height of 26.8 inches, and an arm span of 59.2 inches) would miss retracting the throttle by 2.5 inches with the seat full-up. This is once again a misleading figure, because this person would need to raise the seat an additional 3 inches to see the minimum -11 degree visual angle over the nose of the aircraft. If it were possible to raise the seat that much, miss distance to the throttle would increase to 5.2 inches. Again, the interplay between two measurements must be considered before modifying the aircraft.

TOTAL ACCOMMODATION RATES FOR SMALL PILOTS

The accommodation areas of reaching to rudders and the throttle were considered separately from other areas of accommodation so that the effects of each could be examined independently. Vision was included in both analyses, however, since seat position has such a major impact on reaches. But, in order to be assigned to this aircraft, a pilot should be fully accommodated in all three areas discussed so far: vision, reach to rudders, and reach to controls. The following Figure shows the percentages of the study populations accommodated in all three areas simultaneously.

Table 4.4. Percentage of Various Ethnic Groups Accommodated for Vision, Rudders, and Reach to Throttle in the T-38A.

RACE/ETHNIC GROUP	FEMALES	FEMALE PILOTS	MALES	MALE PILOTS
Euro-Am	36	73	82	86
African-Am	10	61	68	84
Hispanic-Am	7	54	68	78
Asian-Am	7	50	54	70
DOE-mix	27	63	86	91

For each of the female samples, these percentages are only estimates. The sample sizes started at 100 for each ethnic group and shrank rapidly. For example, the Asian-American female group started with 100 individuals. After screening for pilot size criteria only 14 were left. Next, those 14 were screened for vision, rudders, and reach. Eleven, eight, and seven, respectively, were left after each screening. Therefore, these percentages are very gross estimates. The very restrictive trend caused by successive screening is more important than the exact number in the sample.

Among current USAF pilots (the DOE mix), only 63% of females and 91% of males can perform all of the operational requirements established for this aircraft. Even worse, as many as 50% of the pilot candidates in specific ethnic groups – people now eligible to enter flight training - will not be able to meet the operational requirements. The initial goal of the investigation of T-38 body size accommodation was to determine if body size selection criteria could be relaxed to allow smaller pilots into flight training.

The answer is obviously no! No subjects with Sitting Height (34 inches) and Stature (64 inches) measurements lower than the flight training body size entrance requirements (AFI 48-123) met the operational requirements.

At the present time, Training Command should consider selecting small pilots based upon Sitting Eye Height, Arm Span, and Combination Leg length. As accommodation data becomes available for all USAF aircraft (Zehner, 1998), decisions on the overall cutoff for flight training, as well as restrictions for specific aircraft, can become USAF policy. In the case of the T-38, assignment to this aircraft should be more restrictive, not less.

LARGE PILOT ACCOMMODATION

OVERHEAD CLEARANCE

Figure 4.13. Large Subject in AFT Cockpit T-38.

Problem

Inadequate overhead clearance in an aircraft (Figure 4.13) can interfere with pilot performance and can be an ejection hazard. If the pilot is unable to sit erect with his head firmly in contact with the seat headbox, poor spinal positioning could result in an injury during ejection. Also, pilot mobility and his or her ability to check the sky for other aircraft directly behind (the "six o'clock" position) is reduced. Both of these problems are exaggerated when the aircraft is under negative G-forces or is inverted. The pilot's head is then forced into the canopy.

Methods and Assumptions

During these measurements, the pilot sat erect with the head held in the Frankfurt Plane (horizontal line of sight). The space between the top of the head and the underside of the canopy was measured. In addition, clearance space had to be verified in a manner to ensure that the pilot could place his head fully into the head box before ejection and have sufficient side space for checking the sky for other aircraft directly behind him (the "six" position). The seat provided a five-inch measuring device for us. Since the seat adjusts upward and aft, the angle that the head moves during seat adjustment is the same as if a larger pilot were positioned in the seat in the full-down position. The critical space for head clearance is not the space directly above the head, but the distance along a line set at 15 degrees aft from vertical (the angle of the seat back and ejection rail). We began with the subject in the full down seat position and adjusted the seat upwards until the head contacted the canopy. His or her mobility to turn and "check six" were then tested, and the seat was adjusted down until head mobility was acceptable. Seat position was recorded, and the distance from the seat full-down position was added to the subject's Sitting Height. If there was still clearance space when the seat was positioned full-up, that space was measured along the 15-degree seat rail line.

Since helmet designs in the military are subject to change, these measurements were taken two ways: bareheaded for overall clearance, and with the HGU-55/P (the current flight helmet) to test mobility. When a new helmet comes into the inventory, the HGU-55/P data may become obsolete and will need to be replaced. The bareheaded data must then be used in conjunction with new measurements that describe the change in the position of the top of the pilot's head and mobility changes with respect to the canopy caused by the new helmet. This dimension must be measured and subtracted from the bareheaded clearance values listed here. Fifteen subjects were measured with and without the current USAF flight helmet (HGU-55/P) and the mean difference in these measurements was 1.5 inches.

Operational Requirements

Since these measurements are taken to contact with the canopy, an additional value should be determined for the minimum space acceptable between the canopy and helmet. Pilot mobility is greatly diminished when the head is in contact with the canopy. Typically, pilots place a closed fist on top of their helmets and adjust the seat until their hand touches the canopy. This equates to roughly 3.5 inches of clearance space. A final clearance value for this aircraft has not been determined at Training Command. For this analysis we used one inch as the absolute minimum clearance space between the helmet and canopy.

Anthropometric Variables

Sitting Height is the only anthropometric variable of interest for overhead clearance. The correlation between Sitting Height and Overhead Clearance is -.92. The range of Sitting Heights in the general military population is 29 inches through 42 inches. A.F. Instruction 48-123 only permits pilot's 34 inches through 40 inches in Sitting Height to enter UPT.

Results

For the T-38 (front cockpit), the largest Sitting Height that can fit under the canopy with no helmet and with the seat full-down is 48.5 inches. With the HGU-55/P on the pilot's head, the value is reduced 1.5 inches, to 47 inches. These are extremely large values. No one will have overhead clearance problems in the front cockpit of the T-38.

The rear cockpit maximum values with the seat full down are 41.5 inches (bareheaded) and 40.0 inches (with HGU-55/P helmet). Some pilots will experience head contact in the rear cockpit, particularly during inverted or negative-G flight. Since clearance in the aft cockpit primarily affects instructor pilots, AETC may need to consider a Sitting Height restriction of somewhat less than 40 inches for instructor pilots. We are suggesting 39 inches. With the seat full-up, a pilot with a 35 inch Sitting Height would be in contact with the aft cockpit canopy while wearing the HGU-55/P. If additional clearance space is desired between the pilot's head and the canopy, that amount should be subtracted from the maximum value.

Percentages Affected

In the front cockpit, no pilot will have overhead clearance problems. In the aft cockpit, the tallest current pilots (40-inch Sitting Height) will contact the canopy with their helmet. Less than 1% of the pilot population will be in contact with the canopy. However, during inverted flight, it may be difficult for pilots somewhat shorter to function. If the fist-on-the-helmet approach is used as a minimum clearance requirement in the aft cockpit of the T-38, 3.5 inches must be subtracted from the 40–inch maximum Sitting Height value. That calculation results in a maximum Sitting Height of 36.5 inches. Forty-five percent of the DOE mix male pilot population are over that value. This is clearly an extremely limiting requirement. Therefore, the affected percentages in Table 4.5 below are listed in increments of one-inch clearance space.

Table 4.5. Percentage of Pilots Having Less Than Adequate Clearance Space.

ETHNIC GROUP	ZERO CLEARANCE	ONE INCH CLEARANCE	FIST (3.5") CLEARANCE
EUROPEAN-AM	0	1	45
AFRICAN-AM	0	1	15
HISPANIC-AM	.5	1	13
ASIAN-AM	0	.5	16
DOE MIX	.5	3	46

LEG CLEARANCE

Two measurements of accommodation were made concerning leg length accommodation in the aircraft: ejection clearance with the knee and operational shin clearance with the main instrument panel.

LEG CLEARANCE TO THE CANOPY BOW

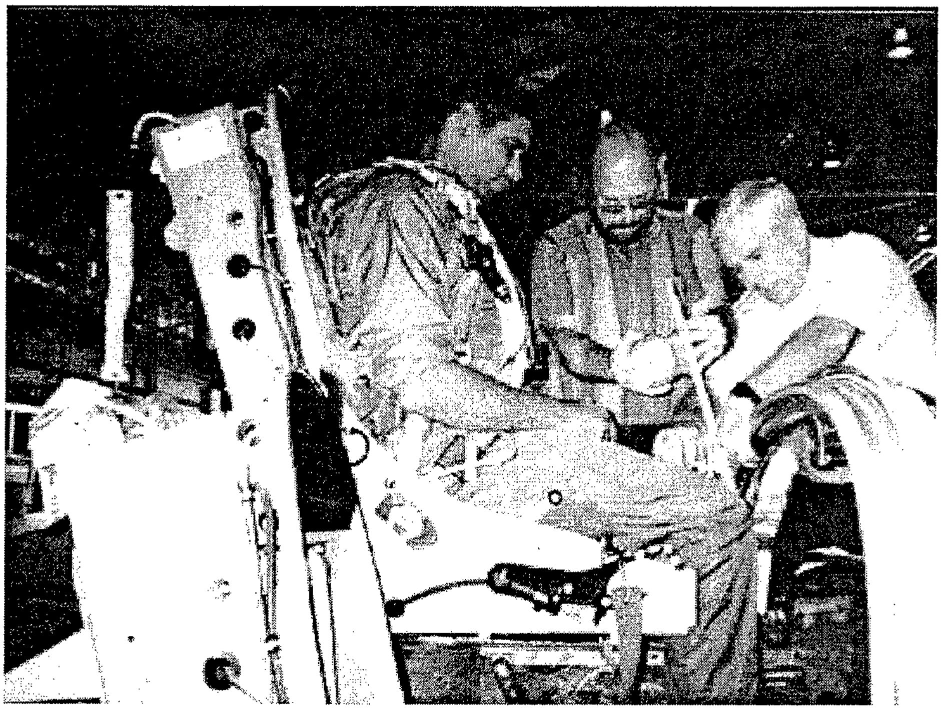

Figure 4.14. Leg Clearance to the Canopy Bow.

Problem

Clearances for escape were measured to the Canopy Bow (Figure 4.14) to ensure the pilot would not strike this structure during ejection. Ejection clearance in this case is unaffected by seat position.

Operational Requirement

No contact with cockpit structures during ejection is acceptable.

Methods and Assumptions

The subject's thigh was held perpendicular to the ejection rail angle. The subjects' feet and buttocks were pulled aft into the seat and the subject was firmly restrained. A steel rod was then placed on the anterior surface of the knee and projected upwards at the same angle as the ejection seat path. This allowed us to see the track the knee would take during an ejection. The space between the steel rod and any cockpit structure in reasonable proximity to the path of the knee was measured.

This posture is the best possible ejection position. While our examination of other areas of accommodation may have been conservative attempts to account for the worst possible situation, our examination of ejection clearances is not. The pilot may be in any position prior to ejection depending upon what the aircraft is doing. However, to achieve repeatable results, this was considered the best method to use. Dynamic parameters, such as sliding forward beneath the restraints and thigh compression into the seat cushion during ejection, have not been quantified. If these parameters are defined at a later date and it is determined that (for example) one inch of static clearance prior to ejection is necessary to avoid leg injury during ejection, that value can be subtracted from the static maximum leg length given here to arrive at a "safe" maximum leg length.

Anthropometric Variables

The anthropometric measurements of interest for ejection clearances are: Buttock-Knee length and Knee Height Sitting. A reasonable expected range of values for the general military population for Buttock-Knee length is 19 to 28.5 inches. For Knee Height Sitting, the general military population range is 15.5 through 26.5 inches. For the current USAF flying population, these ranges are 20 through 28 inches for Buttock-Knee length, and 18.5 through 25.5 inches for Knee Height Sitting. Since only a small number of subjects were used for this analysis, no correlations were run.

Results

The maximum static Buttock-Knee length that clears the canopy bow in the front cockpit of the T-38 is 30.8 inches. For the rear cockpit, it is 32.8 inches. No current pilot will strike these structures if reasonably positioned in the seat. All pilots should have at least three inches of leg clearance during ejection. If the canopy does not jettison prior to ejection, this value is reduced to 29.5 inches in the front cockpit, and 31.5 inches in the rear cockpit. While these values are still outside the ranges of Buttock-Knee lengths in the population, they assume near perfect body position prior to ejection.

OPERATIONAL SHIN CLEARANCE

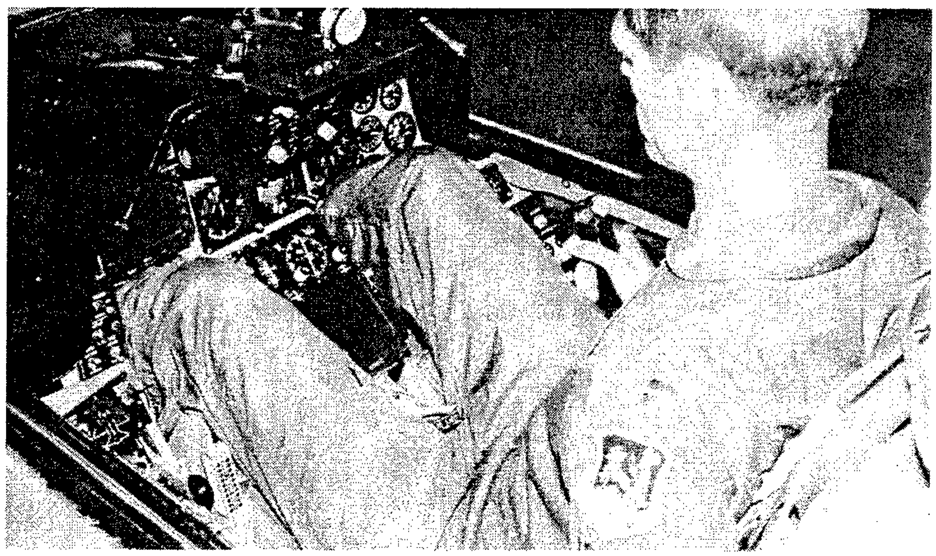

Figure 4.15. Shin Clearance with the Instrument Panel (example is from the F-16).

4.9.1 Problem

A number of aircraft provide inadequate shin clearance with the main instrument panel (Figure 4.15). The F-16 and TA-4 are two examples. A number of ejection injuries can be related to this lack of clearance. In this study, operational clearance was measured forward from the shin to the bottom edge of the main instrument panel to ensure ejection clearance with the main instrument panel and to ensure the pilot has space to operate the rudders. When a pilot's shins are in hard contact with the instrument panel, it is not possible to shift lower body position during a long flight. This becomes very uncomfortable and fatiguing. Also, during ejection the shins are dragged across the lower edge of the instrument panel. While these injuries are not severe, they are unnecessary.

Operational Requirements

The pilot must be able to operate the rudder pedals and must not be injured during ejection.

Methods and Assumptions

The subject was positioned and restrained firmly in the seat. Shin clearance was measured from the front side of the calf perpendicular to the bottom edge of the instrument panel. Measurements were taken with the feet on neutral rudders, and with full rudder input (to both the active and passive leg). The rudder carriage was adjusted to the farthest forward position in which the subject could attain full rudder throw.

Results

In the T-38, neutral rudder position is the worst case for clearance. Surprisingly, knee height had very little effect on shin clearance, while increases in Buttock-Knee Length reduced the amount of clearance at the shin significantly. We were also surprised that seat position did not affect clearance. For the T-38, static shin contact with the instrument panel would not occur until Buttock-Knee length exceeded 30.75 inches.

No current pilot will experience shin contact in this aircraft when reasonably positioned in the seat. All current pilots should have at least three inches of shin clearance.

LARGE PILOT FINAL ACCOMMODATION PERCENTAGES

For large pilots, the T-38 is a very accommodating aircraft. Only a small percentage of pilots will contact the canopy in the rear cockpit. A minimum overhead clearance value should be established; our recommendation is one inch. This would prevent 2% to 3% of the male population from becoming instructor pilots (students fly in the front cockpit, instructors in the rear).

DISCUSSION

It is not surprising that there are relatively large percentages of current pilots who are not accommodated in this aircraft. The T-38 was designed to 5th and 95th percentile male pilot data from the 1950 USAF anthropometric survey. That design philosophy accepted the premise that 10% of the pilot population could have accommodation problems. That only 12% of current large and small male pilots (DOE mix) are beyond these bounds is surprising given the non-additive nature of percentiles (Zehner, 1992).

The high percentage of female pilots (37% to 50%) not accommodated in the T-38 is also not surprising. Earlier analyses have confirmed that a high percentage of female pilot's fall below the 5th percentile male pilot values. These pilots have learned to compensate for their body size by stretching, flying with a loose harness, or have not been in an emergency situation where immediate access to full rudder or throttle was required to survive.

Lowering body size requirements for the T-38A is not possible in its current configuration. Current pilot body sizes are already straining the accommodation limits of the aircraft. Allowing even smaller pilots to fly the aircraft in its current configuration would not be safe.

STICK INTERFERENCE WITH THE THIGH

One final anthropometric accommodation problem exists that we are unable to quantify. When the seat is full-up, there is very little space between the thighs for stick roll authority (pulling the stick full aft and moving it left and right all the way to its limits). This problem is made worse if the pilot has short legs. For small subjects, reach to rudders is so difficult that the knee is fully extended and the pilot is unable to spread the thighs apart to make room for the stick. However, the relationship between body size measures and stick/thigh interference was unclear. The correlation between anthropometric measures and stick interference problems was near zero. However, 13 of 19 subjects tested with the seat full-up had stick movement restricted by one to two inches. While this problem cannot be predicted for certain body types at this point, this discussion is included because the problem may get worse if the aircraft is modified. If pilots are moved further up the seat rails to improve vision, or further forward in the seat to improve reach capability, their relationship with the control stick changes. Therefore, any change to the seat in the T-38A must be followed by careful examination of stick interference problems that may be created.

For pilots with very large legs (Figure 4.16), these problems will also occur, particularly for pilots who also have a short Sitting Height.

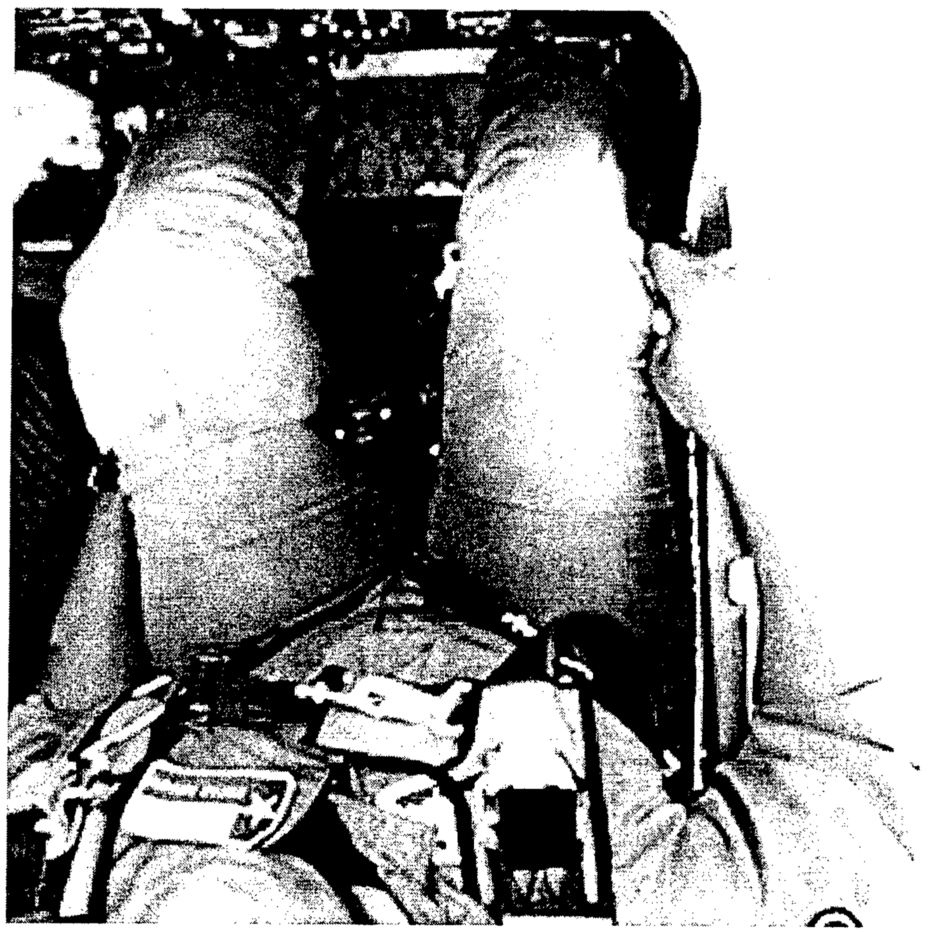

Figure 4.16. Limited Range of Stick Roll Due to Thigh Contact (T-3 example).

CHAPTER 5

FUTURE DESIGN CRITERIA

Chapter 4 clearly demonstrates that the percentile method of specifying body sizes and the resulting aircraft designs resulted in a great many actual pilots outside the accommodation range. Military personnel of every size and shape must be able to operate complex equipment safely, effectively, and comfortably, and personnel responsible for writing specifications for and procuring complex workstations and personal protective equipment are continually challenged to accommodate and fit an increasingly diverse population. In writing specifications, the goal is to ensure that the body size and proportions of the population will be accommodated in each item or system to be procured. In the past, procurement officers have used percentiles to specify the portion of the population that must be accommodated. Typically, specifications read: "The system shall be designed to allow safe operation by the fifth percentile female pilot through the ninety-fifth percentile male pilot." Lists of fifth and ninety-fifth percentile body measurement values were then attached as an appendix.

This chapter points out the statistical drawbacks inherent in the percentile approach, and presents a more suitable multivariate method for describing variability in body size. The effect of using this method on accommodation levels of the various ethnic groups previously described will also be investigated. The proposed method is based on the pioneering work of Bittner et al. (1986). For a detailed statistical description of the USAF technique, see Meindl et al. (1993).

PERCENTILE LIMITATIONS

A percentile is a very simple statistic. It shows the relative ranking of a given individual for a single measurement and is expressed in terms of the percentage of people who are smaller than that individual for that measure. For example, if the fifth percentile value for Stature is 65.8 inches, this simply means that five percent of the measured sample is less than or equal to 65.8 inches, and ninety-five percent of the same sample is taller. Two limitations of the percentile approach are immediately apparent. First, percentiles are only relevant for one dimension at a time (univariate), and second, they are specific to the sample from which they are calculated.

While a fifth percentile Stature value can be accurately located, for design purposes that value tells us little or nothing about the variability of other body dimensions of individuals with fifth percentile Stature. Many people mistakenly assume that the fifth percentile for both Stature and Weight represents a "fifth percentile" person. In fact, only 1.3 percent of subjects in the 1967 survey of USAF personnel (Kennedy, 1986) were smaller than the fifth percentile for both measures, while 9% were smaller for one or the other. This problem is compounded with each additional measurement used to specify a person's size. Thus, at worst, use of percentiles can mean that workspaces or equipment are not suitable for anyone. For example, a piece of protective clothing designed to fit all fifth percentile measurements probably will not fit anyone. At best, the use of percentiles means that the percentage of a given population that can be accommodated is unknown.

The use of a single percentile level to represent multiple body measurements presents still another problem: the values are not additive. Robinette and McConville (1981) found that fifth percentile values for individual measurements could not be added together to equal fifth percentile Stature. Seven body linkage measures that can be summed to equal an individual's stature were rank ordered for a population. Next, the fifth and ninety-fifth percentile values for those measurements were calculated. When the percentile values were summed, the results for the small measures were several inches less than the fifth percentile Stature and for the large values, several inches greater than the ninety-fifth percentile value for Stature.

Using data of this type could result in a design which is much smaller (or larger) than necessary to accommodate the desired percentage of the population. This problem is particularly apparent when percentiles are used with anthropometric data to develop human body models for computer programs or crash test dummies.

REGRESSION MODELING

Regression analysis is one method that has been used to approximate a percentile person while avoiding some of the pitfalls of percentiles. This approach has been particularly useful in constructing crash test dummies. It begins with one or two "key dimensions," such as Stature and Weight, and predicts values for a number of other measurements statistically. In practice, this approach provides the "average" value for the additional measurements for a group of individuals of the entered Stature and Weight (independent variables). The chief advantage of the regression approach is that the predicted numbers are additive. That is, if one were to use a particular or specific value for Stature in a regression equation to predict the previously discussed seven body linkage measurements, the resulting predicted values would add up to exactly the value of Stature that was input into the equation.

The drawback to the regression approach is that it provides "average" values for the predicted measurements. In any population there are people who are much larger or smaller than the predicted body size for each measurement other than Stature and Weight. For example, when ninety-fifth percentile Stature (74.3 inches) and Weight (215.9 lbs) from the 1967 USAF survey are used to predict Sitting Height and Head Length, the regression method resulted in a predicted Sitting Height (38.6 inches) at the ninety-third percentile for that population -- fairly close to the desired ninety-fifth percentile. However, the predicted value for Head Length of a person of this Stature and Weight ranks at the sixty-sixth percentile. Since Stature and Weight have little correlation with the length of the head, the resulting prediction for that measurement ranks closer to the "average" for the entire population. Obviously, if extreme head dimensions are required, regression based on Stature and Weight will not suffice.

Thus, although the use of regression predictions provides additive values that can be assembled, the results may not be as uniformly extreme as are usually desired when the intention is to look at the ends of the body size distribution. Furthermore, in practical application, neither the percentile method nor the regression approach takes into account the fact that humans manifest considerable variation in their *combinations* of dimensions; that is, there are numbers of individuals who combine short torsos with long limbs, or tall, heavy bodies with small heads. For designing three-dimensional crash dummies, the regression method of arriving at appropriate body segment sizes may be the only feasible approach, due to the cost of producing many sizes of dummies. Its limitations are apparent, however.

The USAF Multivariate Accommodation Method

The USAF Multivariate Accommodation Method (Meindl, Zehner, and Hudson, 1993) is an alternative to the percentile and regression methods described above. It corrects the deficiencies of both while retaining the concept of accommodating a specific percentage of the population in the design. Briefly, the Multivariate Accommodation Method is based on Principal Component Analysis. This technique allows reduction of a long list of measurements to a smaller, more manageable number, and then enables designers to select the desired percentage level of a population to be accommodated. This desired percentage of the population is represented by a small set of selected boundary conditions which take into account not only size variance but proportional variability as well. These boundary conditions represent individuals who are uniformly large or small, as well as those whose measurements combine, for example, small torsos with long limbs, and vice versa. Two examples of the approach are given below: a simple two-measurement example, and a basic cockpit layout example.

Bivariate Distribution for Accommodation

A bivariate distribution (Figure 5.1) is analogous to a univariate distribution curve, except that, in a bivariate distribution, two measurements are plotted simultaneously. In this example, the distribution of Stature in the 1967 USAF Male Pilot survey is plotted on the vertical axis, and Weight is plotted on the horizontal axis. Each individual pilot is plotted at the point where his Stature and Weight intersect.

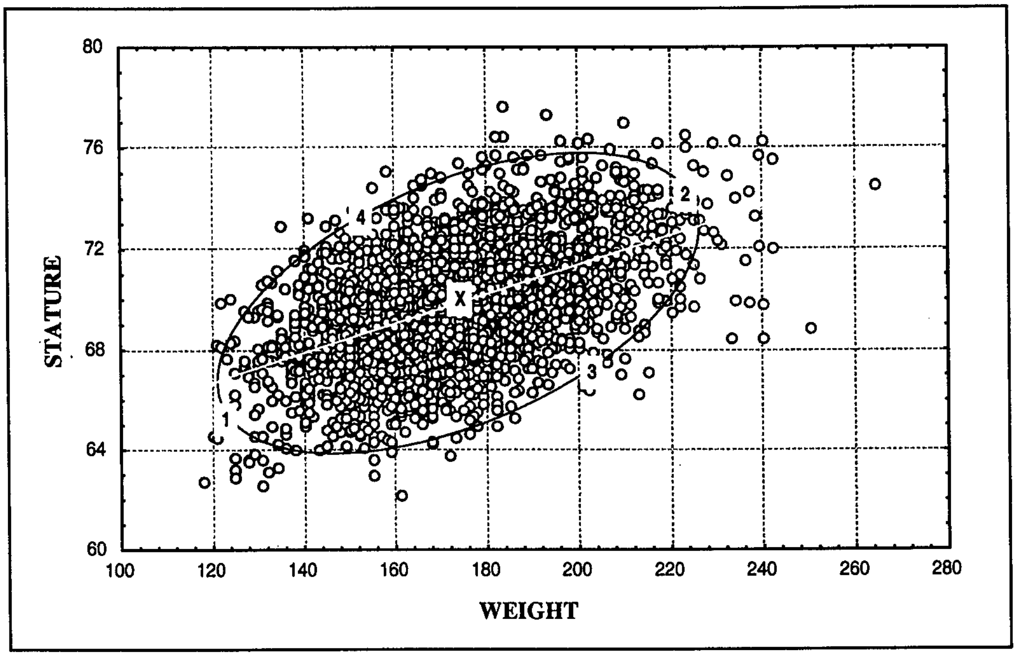

Figure 5.1. 95% Ellipse on Stature and Weight Bivariate (for 1967 USAF survey).

Using the mean value for both Stature and Weight as a starting point (X), an ellipse can be imposed on the plot that includes any desired percentage of the population. The 95% ellipse in Figure 5.1 passes near points (1 and 2) that are similar to the fifth and ninety-fifth percentile pilot concept. That is, they represent pilots who are small or large for both values. However, since selecting only the individuals who are small or large for both Stature and Weight does not describe all the variability in these measures that should be considered in a design, the ellipse also intersects those points representing a short, heavy person (3), and a tall, thin person (4), that are just as likely to occur in the population as any other individual along the perimeter of the ellipse. The correct bivariate accommodation approach would select a number of points, subsequently called boundary conditions or model points, along the perimeter of the ellipse and use them to describe extreme size and proportional variability. The rationale is that several individuals spread along the edge of an ellipse better represent the variety of extreme body types that must be accommodated than does the use of only two points in the distribution.

In the design of a workstation, of course, more than two variables are needed to ensure the proper accommodation 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 head volume is considered. The two-dimensional problem shown above now becomes a three-dimensional one, the ellipse becomes an ellipsoid, and more than four boundary conditions (points on the surface of the ellipsoid) are necessary to describe the various combinations of these measures. That is, it now becomes necessary to describe tall, heavy pilots with large heads, and, tall, heavy pilots with small heads, etc. 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 boundary conditions that must be considered in the design. Clearly, the problem becomes difficult to interpret very quickly.

Principal Component Analysis

Principal Component Analysis (PCA) is a statistical approach that avoids the complexity of sequential bivariates for many measures. PCA is a data reduction procedure which reduces the number of measurements needed to describe body size variability by combining a number of related measurements into a smaller set of factors or components based on their correlation or co-variance.

In constructing an accommodation ellipse (like the bivariate plot shown in Figure 5.1), each factor can be considered as one "measurement." Each subject in the database can be ranked according to these new variables (components). For simplicity, standardized scores (Z scores are mean=0, SD=1) for each individual in the sample are calculated for each factor. If two principal axes are plotted, this standardizing procedure turns the ellipses into circles. If three axes were selected, the ellipsoid would appear as a sphere.

The "average" individuals in a multivariate distribution occupy their own unique positions in multi-dimensional space (based on their physical measurements). In bivariate space, these individuals are located at or near the mean for both dimensions (X in Figure 5.1). In three-dimensional (or multi-dimensional) space, “average” individuals can be thought of as closely surrounding the multivariate mean position in all directions. A good way to visualize this is to imagine small hyper-ellipsoids within the distribution space, centered at the multivariate mean. Typically sized and proportioned individuals are distanced from the mean position, and are contained only within much larger hyper-ellipsoids. Selection of the "volume" of these concentric ellipsoid shells controls the percentage of the population that is included within the ellipsoid shell, and conversely, the proportion excluded (outside the ellipsoid shell).

The Principal Components Analysis (PCA) solution provides four advantages:

1. New linear combinations of the original anthropometric measurement variables provide the same number of orthogonal (mutually independent) principal components. Each of these components explains different amounts of the original morphometric variation contained in the measurement space (Dillon and Goldstein, 1984). It is important to emphasize that this measurement space is constructed of axes which exhibit no multi-collinearity (i.e., these new axes show no correlation within the population).

Some of the new principal components represent major axes of variation, while some are much less important. Those principal components, which account for minimal variation, can be discarded. This reduces the number of variables that must be considered, and is one of the main advantages of a PCA analysis.

2. PCA may also reveal that some of the original anthropometric measurements are needless redundancies. The subsequent elimination of a variable can only be justified after its careful consideration in a truly multivariate context -- that is,

after understanding its simultaneous relationships with all other variables. The PCA can then be re-run after these measurements are dropped. In a cockpit design, the variables needed are usually known at the beginning of the project, and a value is needed for each. While Sitting Height and Acromion Height Sitting may be redundant in a PCA, one is needed for establishing overhead clearance, while the other is needed for placement of the restraint system attachment points. Eliminating variables must be approached very carefully.

3. The original measures should cluster into related morphometric classes along the major axes. In other words, certain "families" of variables will tend to load more heavily on various components. These loadings are instructive. They indicate the relationships between measures that represent the real dimensions of human metric variability, and those that will be relevant in the cockpit design.

4. When standardized, the principal components solution represents a new distribution that lends itself well to the determination of the volume and surface of the ellipsoidal shells that, with scale adjustment only, will encompass any given percentage of the population efficiently.

Turning the standardized PCA-based distribution into boundary conditions, that is, representative of extreme body types, requires the following steps:

1. Determining the appropriate ellipsoidal accommodation shell (i.e., exact ninety-five percent or ninety-eig

ht percent of the population to be accommodated). This accommodation shell can best be determined by iteration centered on the multidimensional mean. Since anthropometric sample data are not exactly multivariate normal, simple symmetric adjustment of the sizes of the major axes by trial and error is most efficient.

2. Solving for the standardized component scores that yield the appropriate shell surface locations. This is done geometrically, at the ends of each major axis, and at the midpoints of each quadrant between the major axes (in bivariate space).

3. Determining the actual metric values for each of the initial body measurements that were selected from the PCA analysis, at the selected surface locations (boundary conditions).

The resulting points on the surface of the concentric ellipsoid shells represent extreme individuals that are situated symmetrically from the median operator (i.e., that "average" individual who may be best characterized as the arithmetic mean of all the variables). For instance, in a three-component example, the extreme individuals are positioned exactly at the mid-surfaces of each of the eight octants of each accommodation ellipsoid. Therefore, the design of any workstation which is compatible with these extreme individuals should also accommodate all of the individuals who are closer to the multivariate mean.

For most cockpit and workstation designs, the total number of relevant measures can be reduced to two or three factors or axes. This axis system allows a designer to use a bivariate circle or tri-variate sphere as the shell defining population boundary conditions. The results can be graphically demonstrated. The following example uses six cockpit-related variables to demonstrate the approach. A 99.5 percent accommodation shell is described for the Air Force flying population based on the DOE mix anthropometric data, and for each of the ethnic groups discussed in previous chapters.

Cockpit Accommodation Example

This analysis uses the six cockpit dimensions considered critical in Chapter 2. These are: Sitting Height, Eye Height Sitting, Acromion (Shoulder) Height Sitting, Arm Span, Buttock-Knee Length, and Knee Height Sitting. Although many other measurements could arguably be included, most are simple clearance dimensions that can be dealt with in terms of minimum and maximum values.

The six measurements listed above, however, must be considered in varying combinations. It is important, for example, to consider the accommodation problems of an individual with a very short Sitting Height who also has very long legs. This individual would adjust the ejection seat to maximum height to attain proper over-the-nose vision, but would also adjust the rudder carriage full forward to accommodate the long legs. This configuration could bring the knee or shin close enough to the bottom edge of the instrument panel to create the potential for an ejection injury. In aircraft with a yoke (steering wheel), this configuration reduces the vertical distance between the seat and the bottom edge of the wheel, thus increasing the likelihood of interference problems, particularly during cross-control maneuvers (full left rudder while turning the yoke to the right).

The Multivariate Accommodation Models program developed at the Air Force Research Laboratory (Robinson, 1992), allows users to select data relevant to their design problems from military anthropometric surveys and measurements, and to choose a population accommodation percentage for determining the design limits.

Listed below is the output from an analysis using the six measurements cited above and the DOE mix anthropometric data (the effect of this method on ethnic groups will be discussed later). The first portion of the printout (Table 5.1) describes simple summary statistics for those measurements in that sample. Table 5.2 is the correlation matrix for these variables.

Table 5.1. DOE Sample Summary Statistics.

VARIABLE	MEAN	STD DEV
Sitting Ht	34.0	1.3
Eye Ht Sitting	29.5	1.3
Acromion Ht Sitting	22.2	1.0
Buttock-Knee Lth	22.7	1.0
Knee Ht Sitting	20.0	1.0
Span	64.9	2.9

Table 5.2. Correlation Matrix for DOE Mix Sample.

	Acromion Ht Sitting	Buttock-Knee Lth	Eye Ht Sitting	Knee Ht Sitting	Sitting Ht	Span
Acromion Ht Sitting	1.00	0.45	0.86	0.51	0.87	0.50
Buttock-Knee Lth	0.45	1.00	0.50	0.84	0.51	0.77
Eye Ht Sitting	0.86	0.50	1.00	0.56	0.98	0.58
Knee Ht	0.51	0.84	0.56	1.00	0.57	0.87
Sitting Ht	0.87	0.51	0.98	0.57	1.00	0.58
Span	0.50	0.77	0.58	0.87	0.58	1.00

Table 5.3 displays the factor correlation matrix for the two components which, analysis shows, account for most of the variation among these variables. This matrix is calculated by matrix multiplication of the analysis eigenvectors (not shown) by the square root of the eigenvalues (table 5.4). There are two uses for this matrix. First, the factor correlation matrix is used to interpret the components the same way the eigenvectors are, however in this case the data are given in terms of correlation coefficients (a value of 1.0 indicates a perfect correlation) between a component score and the original measurement. Notice that in this figure all the values of Factor I are relatively high positive values of about the same magnitude. Thus, Factor I, as is often the case, is a good predictor of general overall body size.

Table 5.3. DOE Sample Factor Correlation Matrix.

VARIABLE	FACTOR I	FACTOR II
Sitting Ht	0.89015	-0.41204
Eye Ht Sitting	0.88539	-0.41744
Acromion Ht Sitting	0.82854	-0.44847
Buttock-Knee Lth	0.79083	0.48521
Knee Ht Sitting	0.85013	0.44664
Span	0.84150	0.40941

Factor II, on the other hand, shows a marked contrast between the first three measures and the second three. The values are positive for the three limb dimensions and negative for the three torso dimensions. This contrast allows individuals to be ranked or classified based upon the relative sizes of these two body components and is the basis for discriminating between individuals with varying body proportions.

The Eigenvalues listed below describe the amount of variability in these dimensions accounted for by each of the combined factors.

Table 5.4. Eigenvalues for DOE Sample.

Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
4.23498	1.15710	0.27486	0.16948	0.13974	0.02386
70.582%	19.28493%	4.58096%	2.82462%	2.32895%	0.39760%

The first two Principal Components accounted for 90% of the anthropometric variability in this sample. The third component described the variability and contrast between upper and lower limb dimensions. Some individuals display relatively short arms for their leg length, while others have short legs compared to their arms. The metric difference between these conditions was small, and this component only explained an additional 4% of the total variance in the group. The added complexity of additional design model points is not warranted for a 4% gain. For that reason, the analysis was cut off at two components.

Next the program establishes eight representative model points (boundary conditions) when two factors are selected. Figure 5.2 is an example of a bivariate distribution showing individuals in the DOE mix sample distributed (via Z scores) with regard to the two factors. The superimposed ellipse represents a 99.5% accommodation model. That is, 99.5% of the subjects in this sample appear within the boundary that is defined by the eight model points. We use 99.5% ellipses for cockpit accommodation, to assure near total accommodation.

The vertical scale on Figure 5.2 displays overall body size of each subject (Factor I) ranked as Z scores. Point Y is the smallest overall and Point W is the largest. These two points are at zero on the horizontal scale. This axis represents the contrast factor (Factor II) between limb and torso dimensions. Point Y represents individuals whose limbs and torsos are both small, and Point W represents those large in both limb and torso dimensions. This contrast is similar to the fifth and ninety-fifth percentile concept.

Points C and B also represent small individuals, but display marked contrast between limb and torso dimensions (Factor II), as is apparent in table 5.5 through 5.7. Point C has similar leg size to Point Y, but has a two-inch larger Sitting Height. Point B has two-inch longer legs than Point Y, but similar torso dimensions. Together, these three points (Y, C, and B) better represent variability in small people than does a single point that is small on all dimensions (Y).

Similarly, on the large end of the body size scale, Points D and A are nearly as large as Point W, but also show contrasting torso and limb dimensions. Point D exhibits two-inch shorter limb measures, but a similar torso to Point W, while Point A has the two-inch smaller torso, but similar limbs. Finally, Points Z and X are fairly average on overall body size but show the most extreme contrast in limb and torso dimensions.

The third part of the program output lists standardized Z scores for each of these representative points (for each of the six original measurements). Z scores are calculated in terms of standard deviations from the mean. The Z scores are used to locate the position of each Model Point on the surface of the ellipsoid. The Z scores are converted to percentile values in the fourth part of the output for easier interpretation of the body types. This further delineates the differences between the representative points.

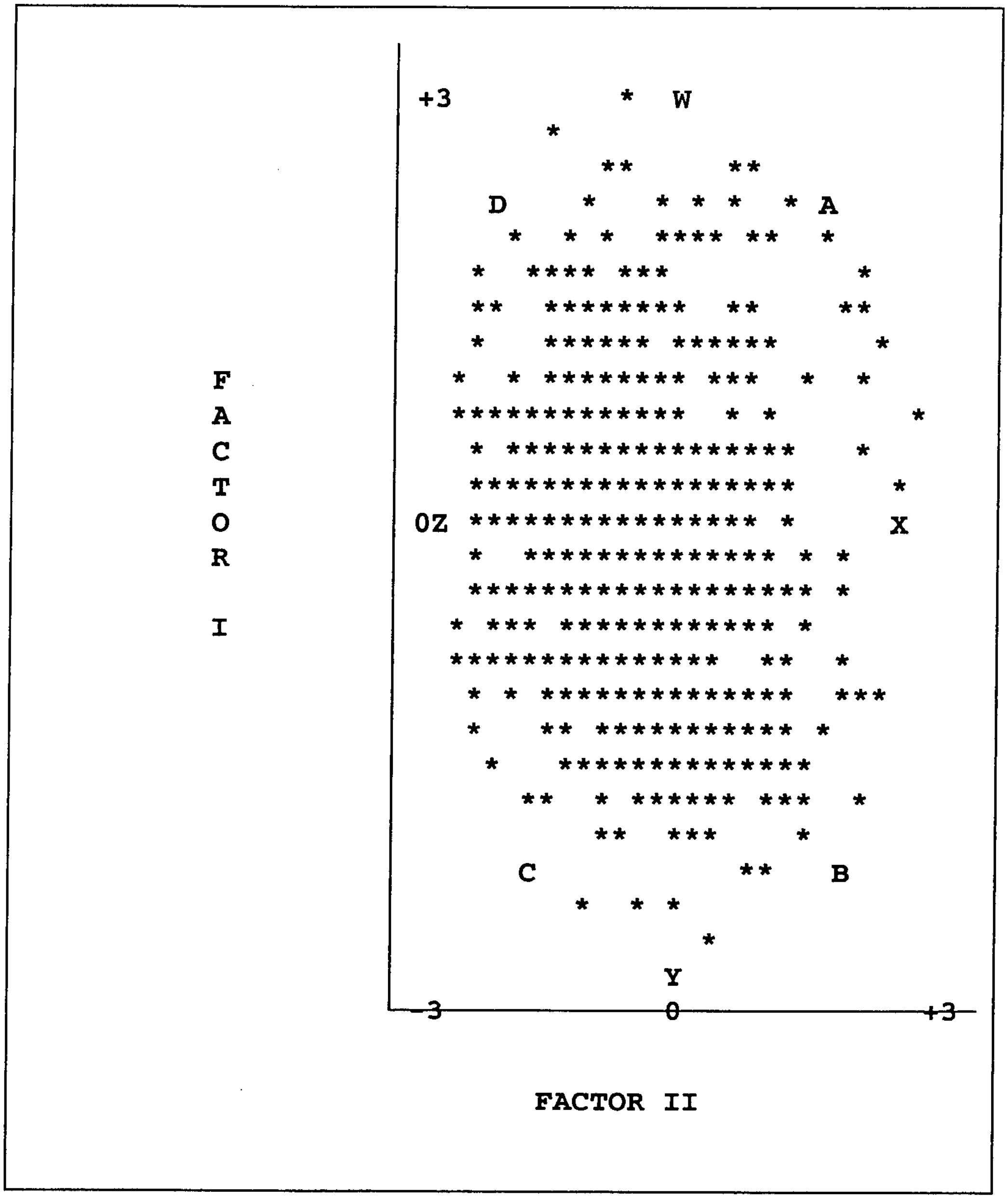

Figure 5.2. Boundary Conditions - 99.5% Ellipse.

Table 5.5. Variable Z-Scores for '2-D MAN' Model Points.

	A	B	C	D
Sitting Ht	1.149	-3.131	-1.149	3.131
Eye Ht Sitting	1.125	-3.132	-1.125	3.132
Acromion Ht Sitting	0.914	-3.07	-0.914	3.07
Buttock-Knee Lth	3.068	-0.735	-3.068	0.735
Knee Ht Sitting	3.118	-0.97	-3.118	0.97
Span	3.007	-1.039	-3.007	1.039
	W	X	Y	Z
Sitting Ht	3.027	-1.401	-3.027	1.401
Eye Ht Sitting	3.01	-1.419	-3.01	1.419
Acromion Ht Sitting	2.817	-1.525	-2.817	1.525
Buttock-Knee Lth	2.689	1.65	-2.689	-1.65
Knee Ht Sitting	2.89	1.519	-2.89	-1.519
Span	2.861	1.392	-2.861	-1.392

Table 5.6. Percentile Values for '2-D MAN' Model Points.

	A	B	C	D
Sitting Ht	87	0	12	99
Eye Ht Sitting	86	0	13	99
Acromion Ht Sitting	81	0	18	99
Buttock-Knee Lth	99	23	0	76
Knee Ht Sitting	99	16	0	83
Span	99	14	0	85
	W	X	Y	Z
Sitting Ht	99	8	0	91
Eye Ht Sitting	99	7	0	92
Acromion Ht Sitting	99	6	0	93
Buttock-Knee Lth	99	95	0	4
Knee Ht Sitting	99	93	0	6
Span	99	91	0	8

Points W and Y appear to have uniform percentile values for all dimensions, but this is due to rounding.

The final step in this analysis (table 5.7) is to convert the Z-score positions back into anthropometric measurement values for the standard scores for each of the eight point positions. This is accomplished by matrix multiplication of each point back through the factor correlation matrix and is the second use for this matrix.

Table 5.7. Variable Values for '2-D MAN' Model Points.

	A	B	C	D
Sitting Ht	35.49	29.93	32.5	38.06
Eye Ht Sitting	30.92	25.54	28.08	33.46
Acromion Ht Sitting	23.12	18.98	21.22	25.36
Buttock-Knee Lth	25.86	21.97	19.58	23.47
Knee Ht Sitting	23.04	19.07	16.99	20.95
Span	73.55	61.85	56.15	67.85
	W	X	Y	Z
Sitting Ht	37.92	32.17	30.06	35.81
Eye Ht Sitting	33.3	27.71	25.7	31.29
Acromion Ht Sitting	25.1	20.59	19.24	23.76
Buttock-Knee Lth	25.47	24.41	19.97	21.03
Knee Ht Sitting	22.82	21.49	17.21	18.54
Span	73.12	68.88	56.58	60.82

The traditional approach of using "percentile people" in cockpit layouts for aircraft with ejection seats has led to the assumption that small flyers position the seat full up and the rudder carriage full aft. Large flyers adjust for the opposite configuration. In aircraft that do not have ejection capability, the seats adjust fore and aft as well as up and down. The fifth and ninety-fifth percentile pilot designation leads to the assumption that small pilots fly full up and full forward while large pilots fly full aft and full down. Point W (generalized large) and Point Y (generalized small) do just that. However, Points A (similar limbs but smaller torso) and D (similar limbs but longer torso than W) may be slightly more difficult than W to fit into a cockpit designed on this basis. These points are similar to W in overall size (Stature) but would have their seats adjusted differently. In aircraft equipped with an ejection seat, Point A should have the seat 2.3 inches higher than Point W to achieve comparable ONV. In this position, leg clearance with the instrument panel may be reduced. Point D would adjust the seat to the same height, but has two to three-inch shorter limbs to reach the rudder pedals. The same argument holds for the small points. The varying proportions cause the seat to be positioned in different places to achieve similar ONV angles. The effect of these seat position changes is to move the point of origin for any reach to controls or clearance measurements to different points in the cockpit.

Additional consideration must be given to the "combination" Point X (shortest torso, longest limb) and Point Z (longest torso, shortest limb). Point X has limbs one to two inches shorter than Point W (the generalized large), but would adjust the seat 5.6 inches higher. The knee or shin could be much closer to the instrument panel, and stick/yoke clearance could be greatly reduced in this configuration. Similarly, Point Z has limbs one to two inches longer than Point Y (generalized small), but should adjust the seat about 5.7 inches lower. Reach to controls for these two points will again be quite different.

Each of these representative points should be considered in a cockpit design because each will fly with the seat and rudder carriage adjusted to different points and will be in a different position relative to controls and cockpit structure. If a workspace is designed to enable all these model points to operate efficiently, then all other less extreme body types and sizes in the target population (within the circle or ellipse) should also be accommodated.

RACIAL/ETHNIC VARIABILITY

As discussed in Chapter Two, in analyses of mixed samples, some statistical summarization techniques cause the unique body size variability of various groups to disappear when one group greatly outnumbers the others. Although each of the groups discussed in Chapter Two are present in the USAF flying population (represented by the DOE mix), 85% of that group is European-American. How well do the results of this new technique represent each of the groups it comprises?

In this section each group was analyzed separately and the results compared. Only the anthropometric variable values from Figure 5.7 were compared for this analysis.

The interpretation of each of the points remains the same, that is, Point A remains the boundary condition representing the longest legs of the group, and so on. The following tables (5.8 through 5.15) arrange the Point conditions for each group and the DOE sample together for ease of comparison. The most extreme condition for each point is highlighted.

Table 5.8. Model A Comparison: Longest Limbs.

POINT A	EURO	AF	ASIAN	HISP	DOE
Sitting Ht	35.6	33.9	34.5	33.9	35.5
Eye Ht Sitting	31.0	29.4	29.8	29.5	30.9
Acromion Ht Sitting	23.3	22.1	22.1	22.0	23.1
Buttock-Knee Lth	25.4	26.2	24.2	24.8	25.9
Knee Ht Sitting	22.7	23.2	21.7	21.8	23.0
Span	72.4	74.7	70.2	70.3	73.6

Model Point A establishes the longest limbs of the eight points. The Torso dimensions are large, but not the largest of the group. The DOE mix falls short of the African-American limb length (the difference in Span is over an inch), but exceeds the other three groups.

Table 5.9. Model B Comparisons: Shortest Torso.

POINT B	EURO	AF	ASIAN	HISP	DOE
Sitting Ht	30.5	30.0	30.5	30.2	29.9
Eye Ht Sitting	26.1	25.7	25.9	25.7	25.5
Acromion Ht Sitting	19.4	19.0	19.1	19.2	19.0
Buttock-Knee Lth	22.2	23.1	20.9	22.0	22.0
Knee Ht Sitting	19.2	19.8	18.3	19.0	19.1
Span	61.5	64.7	60.6	62.0	61.9

Model B has the shortest torso of the eight Points. For this model point, the DOE mix actually goes beyond the range of the other samples by a tenth of an inch. While the limbs are not as small as the Asian point, this model is primarily used to establish the smallest torso.

Table 5.10. Model C Comparison: Smallest Limbs.

POINT C	EURO	AF	ASIAN	HISP	DOE
Sitting Ht	32.7	31.8	32.3	32.2	32.5
Eye Ht Sitting	28.3	27.5	27.7	27.7	28.1
Acromion Ht Sitting	21.3	20.5	21.1	21.1	21.2
Buttock-Knee Lth	20.2	21.1	19.1	19.8	19.6
Knee Ht Sitting	17.5	18.2	16.5	17.4	17.0
Span	57.4	60.1	55.5	57.3	56.2

Model C represents the smallest limbs of the points. While the torso is small, it is not as small as point B. The DOE sample point is roughly ½ inch larger than the Asian-American point B limbs.

Table 5.11. Model D Comparison: Largest Torso.

POINT D	EURO	AF	ASIAN	HISP	DOE
Sitting Ht	37.8	35.6	36.2	35.9	38.1
Eye Ht Sitting	33.2	31.1	31.6	31.5	33.5
Acromion Ht Sitting	25.1	23.5	24	23.8	25.4
Buttock-Knee Lth	23.4	24.1	22.4	22.6	23.5
Knee Ht Sitting	21	21.6	19.9	20.2	21
Span	68.3	70.1	65.1	65.6	67.9

Model D represents the largest Torso dimensions of the points. The limbs are within one standard deviation of the mean, so their length is not critical. Again, the DOE sample exhibits the largest torso of the samples.

Table 5.12. Model W Comparison: Largest Overall Size.

POINT W	EURO	AF	ASIAN	HISP	DOE
Sitting Ht	37.7	35.5	36.1	35.7	37.9
Eye Ht Sitting	33.1	31	31.5	31.3	33.3
Acromion Ht Sitting	25	23.4	23.7	23.5	25.1
Buttock-Knee Lth	25	25.8	24	24.2	25.5
Knee Ht Sitting	22.6	23.1	21.5	21.6	22.8
Span	72.6	74.5	69.6	69.6	73.1

Model W is the largest overall body size point. All measures must be examined simultaneously. The DOE model has the largest torso, and limbs longer than any sample except the African-Americans. The lower limbs are close (.6" less combined), and the arm span differs by more than one inch. However, the 2.4-inch difference in Sitting Height would make the DOE sample point W the overall largest individual.

Table 5.13. Model X Comparison: Extreme Contrast - Short Torso/Long Limbs.

POINT X	EURO	AF	ASIAN	HISP	DOE
Sitting Ht	32.6	31.6	32.1	31.6	32.2
Eye Ht Sitting	28.1	27.2	27.5	27.2	27.7
Acromion Ht Sitting	21	20.2	20.2	20.2	20.6
Buttock-Knee Lth	24.2	25.1	23	23.9	24.4
Knee Ht Sitting	21.3	21.8	20.4	20.8	21.5
Span	67.8	70.6	66.5	67.1	68.9

Model X has the most extreme contrast of long limbs and a short torso (point Z will have the opposite proportions). These points are near average on the overall size component, but is at the ends of the PCA axis for contrasting proportions. The African-American point X shows the smallest torso and longest limbs. The difference between the African-American Sitting Height and Buttock-Knee length is 6.5 inches. The DOE sample difference is 7.8 inches. Clearly, the DOE sample is not the most extreme here.

Table 5.14. Model Y Comparison: Smallest Overall Size.

POINT Y	EURO	AF	ASIAN	HISP	DOE
Sitting Ht	30.6	30.1	30.6	30.4	30.1
Eye Ht Sitting	26.2	25.8	26	25.9	25.7
Acromion Ht Sitting	19.6	19.1	19.5	19.6	19.2
Buttock-Knee Lth	20.5	21.5	19.3	20.3	20
Knee Ht Sitting	17.6	18.3	16.7	17.6	17.2
Span	57.2	60.3	56.1	57.9	56.6

Model Y has the smallest overall size of all the points. It is located at the extreme (small) end of the PCA size axis and near the mean on the proportion axis. Again, all measures must be examined simultaneously. While the torsos of the DOE and African-

American samples are the smallest, their limbs are not as small as the limbs of the Asian-American sample. The small difference in Sitting Height (0.5 inches) is exceeded by the limb difference (1.2 inches combined). The DOE and Asian samples are close enough to be interchanged.

Table 5.15. Model Z Comparison Most Extreme Contrast Large Torso/Small Limbs.

POINT Z	EURO	AF	ASIAN	HISP	DOE
Sitting Ht	35.7	34.1	34.6	34.5	35.8
Eye Ht Sitting	31.2	29.7	30	30	31.3
Acromion Ht Sitting	23.6	22.3	23	22.8	23.8
Buttock-Knee Lth	21.4	22.2	20.3	20.7	21
Knee Ht Sitting	18.9	19.6	17.8	18.5	18.5
Span	62	64.1	59.2	60.5	60.8

Like model X, model Z is located near the mean on the size axis, but model Z is at the opposite end of the proportion contrast axis. Point Z has a large torso, but short limbs. As in Point Y, the DOE sample exceeds all other samples on torso size, but is not as extreme as the small limbs from the Asian-American sample. Again, these two samples could be interchanged.

The DOE sample is the most extreme of these boundary conditions for three of the eight, and interchangeable for two more of the eight points. Only the longest limbs (African-American), shortest limbs (Asian-American), and most extreme contrast of long limbs and short torso (African-American) points are not encompassed by the DOE sample. These are the critical design points. In general, the DOE sample is still very close to the extremes of the separate populations. The roughly one-inch shorter limbs of the Asian-American sample would make reach to rudders more difficult, and the leg clearance problems for the African-American sample would be slightly worse. The following table combines each of the most extreme models from the previous analyses so that direct comparison can be made to the DOE sample.

Table 5.16. Most Extreme Models from Individual Female Groups.

MOST EXTREME FEMALE MODELS	AF A	DOE B	ASIAN C	DOE D	DOE W	AF X	ASIAN Y	DOE Z
Sitting Ht	33.9	29.9	32.3	38.1	37.9	31.6	30.6	35.8
Eye Ht Sitting	29.4	25.5	27.7	33.5	33.3	27.2	26	31.3
Acromion Ht Sitting	22.1	19.0	21.1	25.4	25.1	20.2	19.5	23.8
Buttock-Knee Lth	26.2	22.0	19.1	23.5	25.5	25.1	19.3	21
Knee Ht Sitting	23.2	19.1	16.5	21	22.8	21.8	16.7	18.5
Span	74.7	61.9	55.5	67.9	73.1	70.6	56.1	60.8

Table 5.17. DOE Female Sample Results.

DOE MIX FEMALE	A	B	C	D	W	X	Y	Z
Sitting Ht	35.5	29.9	32.5	38.0	37.9	32.2	30.1	35.8
Eye Ht Sitting	30.9	25.5	28.1	33.5	33.3	27.7	25.7	31.3
Acromion Ht Sitting	23.1	19.0	21.2	25.4	25.1	20.6	19.2	23.8
Buttock-Knee Lth	25.9	22.0	19.6	23.5	25.5	24.4	20.0	21.0
Knee Ht Sitting	23.0	19.0	17.0	21.0	22.8	21.5	17.2	18.5
Span	73.6	61.9	56.2	67.9	73.1	68.9	56.6	60.8

In a cockpit design, the ranges of smallest to largest values are useful for establishing parameters such as the seat adjustment range, or location of restraint system attachment. These ranges are also instructive for comparing the differences in Tables 5.16 and 5.17.

Table 5.18. Comparison of Female Measurement Ranges.

Measurement	DOE sample range	Most extreme models range
Sitting Ht	29.9 – 38.1 range = 8.2	29.9 – 38.1 range = 8.2
Eye Ht Sitting	25.5 – 33.5 range = 8.0	25.5 – 33.5 range = 8.0
Acromion Ht Sitting	19.0 – 25.4 range = 6.4	19.0 – 25.4 range = 6.4
Buttock-Knee Lth	19.6 – 25.9 range = 6.3	19.1 – 26.2 range = 7.1
Knee Ht Sitting	17.0 – 23.0 range = 6.0	16.5 – 23.2 range = 6.7
Span	56.2 – 73.6 range = 17.4	55.5 – 74.7 range = 19.2

Notice that the DOE sample represents the torso sizes of all groups, but its limb length ranges are smaller.

MALE COMPARISONS

In an aircraft design, the large values for all measurements will usually be set by the male sample anthropometry. Therefore, the same analysis was run on the male sample to see if the same patterns resulted, and to set the large measurement values by comparing them with the female values. Here only the most extreme model points are presented in Table 5.19 (similar to table 5.16), followed by Table 5.20 listing the DOE mix sample results (similar to table 5.17), and finally a comparison of ranges in Table 5.21 (similar to Table 5.18).

Table 5.19. Most Extreme Models from Individual Male Groups.

MOST EXTREME MALE MODELS	AF A	AF B	ASIAN C	DOE D	DOE W	AF X	ASIAN Y	DOE Z
Sitting Ht	36.5	31.5	34.1	40.3	40.1	33.5	32.04	38.18
Eye Ht Sitting	31.7	26.9	29.3	35.4	35.2	28.8	27.21	33.43
Acromion Ht Sitting	23.7	19.8	22.4	27.0	26.7	21.4	20.56	25.4
Buttock-Knee Lth	27.8	24.0	19.7	24.7	26.8	26.4	19.96	22.34
Knee Ht Sitting	25.4	21.5	17.9	22.8	24.7	23.9	18.05	20.33
Span	82.0	70.1	60.4	74.0	79.3	77.1	60.88	67.26

Table 5.20. DOE Sample Results All Male Models.

MALE DOE MIX	A	B	C	D	W	X	Y	Z
Sitting Ht	37.6	32.3	35.0	40.3	40.1	34.4	32.54	38.18
Eye Ht Sitting	32.7	27.6	30.3	35.4	35.2	29.6	27.87	33.43
Acromion Ht Sitting	24.7	20.6	22.9	27.0	26.7	22.1	20.86	25.4
Buttock-Knee Lth	27.2	23.4	21.0	24.7	26.8	25.8	21.41	22.34
Knee Ht Sitting	25.0	21.0	18.8	22.8	24.7	23.5	19.12	20.33
Span	80.0	69.1	63.0	74.0	79.3	75.8	63.78	67.26

Table 5.21. Comparison of Male Measurement Ranges.

Measurement	DOE sample range	Most extreme models range
Sitting Ht	32.3 – 40.3 range = 8.0	31.5 – 40.3 range = 8.8
Eye Ht Sitting	27.6 – 35.4 range = 7.8	26.9 – 35.4 range = 8.5
Acromion Ht Sitting	20.5 – 27.0 range = 6.5	19.8 – 27.0 range = 7.2
Buttock-Knee Lth	21.0 – 27.2 range = 6.2	19.7 – 27.8 range = 8.1
Knee Ht Sitting	18.8 – 25.0 range = 6.2	17.9 – 25.4 range = 7.5
Span	63.0 – 80.0 range = 17.0	60.4 – 82.0 range = 21.6

The only difference in the selection of the most extreme boundary conditions for male vs. female samples is for Model point B (shortest torso). For females, the DOE sample was selected at Model point B because it is one-tenth of an inch smaller for Sitting Height than the African-American model. For males, the African-American sample is eight-tenths of an inch smaller than the DOE sample. This makes a difference in the ranges between male and female groups for the torso measures.

While the DOE sample is close to representing all of the combined groups, the differences between these groups would be better preserved by using the most extreme model method. This means that several analyses will be necessary to adequately represent the variability for these groups, the results compared, and the most extreme model points selected. Creation of another sample with equal representation of each ethnic group violates the multivariate normality assumption required for PCA.

Finally, is it necessary to use all eight male points and all eight female points to define a cockpit design population? Since the smallest female model (Y) is much smaller than the smallest male model (Y), why repeat the design process for both points? Tables 5.22 and 5.23 align each model point for males with the corresponding female point. Again, the most extreme model point is highlighted.

Table 5.22. Most Extreme Models A-D, Male/Female Comparison.

MOST EXTREME MODELS	AF MALE A	AF FEM A	AF MALE B	DOE FEM B	ASIAN MALE C	ASIAN FEM C	DOE MALE D	DOE FEM D
Sitting Ht	36.4	33.9	31.5	29.9	34.09	32.3	40.28	38.1
Eye Ht Sitting	31.7	29.4	26.85	25.5	29.27	27.7	35.44	33.5
Acromion Ht Sitting	23.7	22.1	19.84	19.0	22.4	21.1	26.98	25.4
Buttock-Knee Lth	27.7	26.2	23.97	22.0	19.74	19.1	24.74	23.5
Knee Ht Sitting	25.4	23.2	21.48	19.1	17.85	16.5	22.75	21
Span	81.9	74.7	70.11	61.9	60.39	55.5	73.98	67.9

Table 5.23. Most Extreme Models W-Z, Male/Female Comparison.

MOST EXTREME MODELS	AF MALE W	AF FEM W	AF MALE X	DOE FEM X	ASIAN MALE Y	ASIAN FEM Y	DOE MALE Z	DOE FEM Z
Sitting Ht	40.05	37.9	33.51	31.6	32.04	30.6	38.18	35.8
Eye Ht Sitting	35.15	33.3	28.81	27.2	27.21	26	33.43	31.3
Acromion Ht Sitting	26.67	25.1	21.38	20.2	20.56	19.5	25.4	23.8
Buttock-Knee Lth	26.76	25.5	26.35	25.1	19.96	19.3	22.34	21
Knee Ht Sitting	24.67	22.8	23.85	21.8	18.05	16.7	20.33	18.5
Span	79.25	73.1	77.09	70.6	60.88	56.1	67.26	60.8

Notice that for model points X and Z, both male and female models are highlighted. It is difficult to pick which is more extreme for application to a cockpit design. Both are extreme contrasts between limb and torso lengths. Inclusion of both will cause an additional pair of design points, bringing the total to 10. This will result in assurance of better overall accommodation. Figure 5.3 shows a bivariate plot of the Sitting Heights and Buttock-Knee length measures for the ten individual models selected above. The distribution appears to be very regular. The next two figures (Figures 5.4

and 5.5) show these points superimposed over the combined male and female DOE samples, and finally, the extreme model points are superimposed on all of the ethnic groups, male and female, combined. The model points appear to fit the sample distributions well except for the lower left corner of the bivariates. The sample data set may not be perfectly normal.

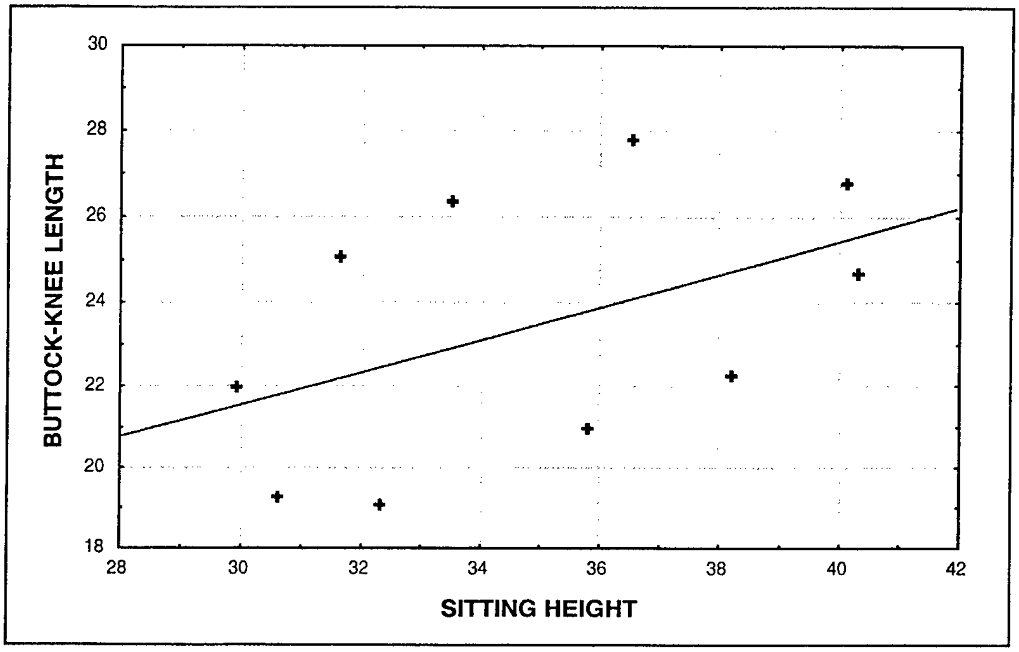

Figure 5.3. Sitting Heights and Buttock-Knee Length for 10 Extreme Model Points.

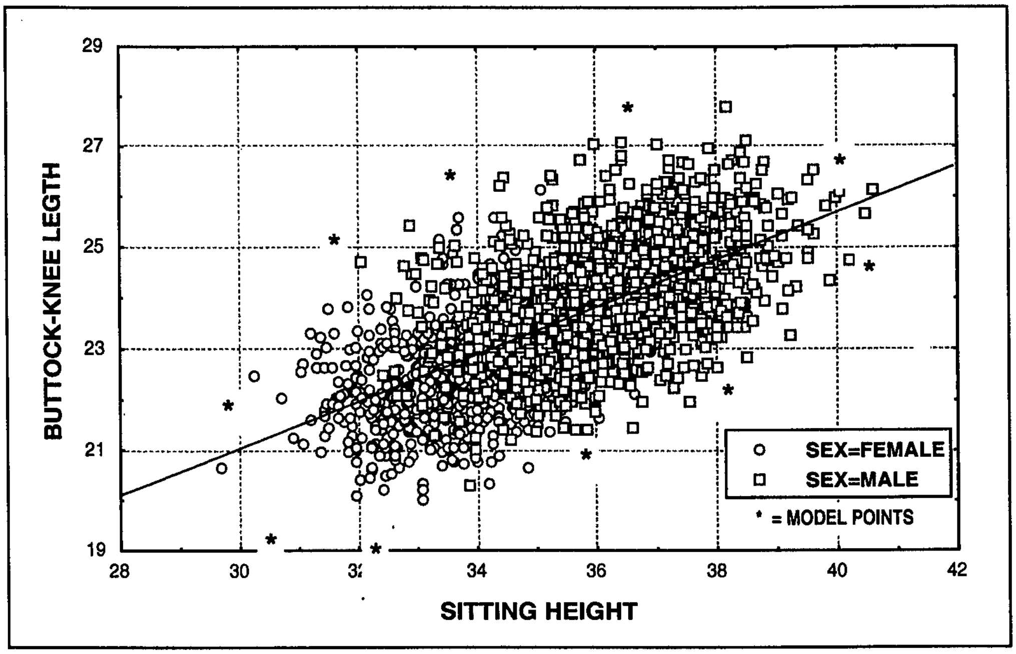

Figure 5.4. Extreme Model Points Superimposed on the DOE Males and Females.

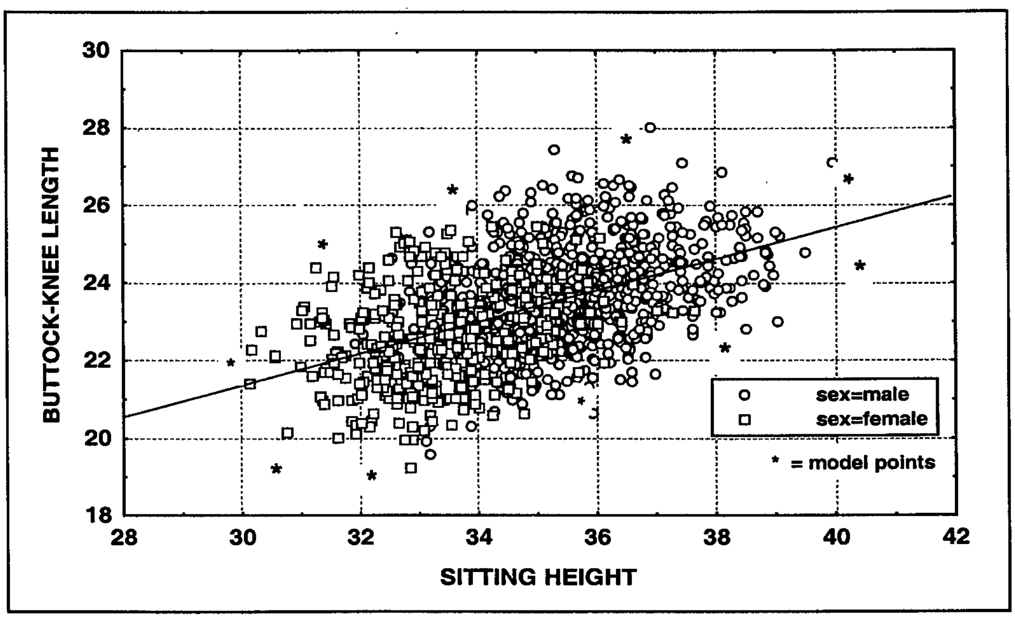

Figure 5.5. Extreme Model Points Superimposed on All Groups Overlay.

The mixed group distribution fits the extreme model point better than the DOE sample. That is to be expected. A 99.5% accommodation level exaggerates the effect of slight deviations from a perfectly normal distribution. Were a ninety-eight percent ellipse used, the fit would appear better at the small end of the distribution, but would fall farther inside the distribution at the large end of the scale. That would defeat the purpose of total accommodation. If we wish to accommodate all pilots that may be assigned to an aircraft, the boundary conditions must fall slightly outside the sample distribution.

The data sets described above represent essentially all individuals in the current U.S. Air Force population. This is a very wide range of variation. Current pilot entrance requirements limit body sizes to those falling between 34 and 40 inches in Sitting Height, and 64 to 77 inches in Stature. To develop a set of multivariate boundary conditions for a trucated population, the assumption of multivariate normality must be carefully guarded. Eliminating those subjects in the sample falling outside entrance requirements, results in more than half of the female sample being eliminated. The sample is very skewed when this is done. A separate program has been written within the Multivariate Models Program to "slide" boundary conditions toward the mean when values fall outside those desired. These models retain the original body segment proportions and interpretation of the model points, but can be size limited on any of the original measurements.

SUMMARY

Principal component analysis cannot describe all the variability in body size which must often be taken into account for a particular design. Some variability in the measurements is lost when a reduced number of components are used. Also, it can be a needlessly complex technique for calculating some dimensions. This occurs when only minimum or maximum values need to be known. In the case of Shoulder Breadth, for example, it does not matter if the widest or most narrow shoulders are found on an individual with a given Sitting Height. Shoulder Breadth is used to assure that wide shoulders clear the sides of the cockpit during ejection, and that narrow shoulders fit the restraint system properly. While measurements such as Shoulder Breadth must be considered in a cockpit design, the largest and smallest expected values for the measurement can be considered separately from the combinations of torso and limb size discussed above. Simple listing of the extreme values for measurements that are not related to seat position will suffice. However, this does not mean that a return to percentiles for these measurements is warranted. Dropping a significant percentage of a population for each measurement is a serious error. The values used should be at or very near the population minimum and maximum values for a given measurement. It must be re-emphasized that selection of the measurements deemed important in a design application may be the most important step in the entire process.

The cockpit accommodation example described above is relatively simple since only a small list of measurements and a restricted set of factors were selected. Computer programs such as COMBIMAN (Krauskopf, et al., 1989) or the Articulated Total Body (ATB) model (Fleck and Butler, 1975) require larger lists of measurements to define the body size of the individual models. COMBIMAN, for example, uses a list of 11 anthropometric measurements to establish modeling parameters. The Multivariate Accommodation Models program discussed here was run on the measurements CombiMan required to size the human model, and as expected, three factors were required to fully describe body size for this application. Not only were torso and limb lengths required, but body mass measurements (widths and depths) made a third factor necessary. The result of this third factor on the models was that the representative points encompassed many more combinations of body proportions (14) including, for example, a long limb, long torso, large widths/depths point as well as a long limb, long torso, small widths/depths point.

There are a number of multivariate statistical techniques that can be used to determine similar combinations of body size test points. The technique described here, however, when combined with lists of minimum and maximum values, gives accurate description of the body size and proportional variability existing in the population and, if used in designing workspaces, will greatly reduce the accommodation problems experienced by users. This assumes, of course, that the seat, rudder, and other moveable components can be adjusted in sufficiently small increments. Without such adjustability, it may be necessary, as Hendy (1990) suggests, to pick many more representative points than were used in this example to ensure the desired level of accommodation. However, for the purposes of writing anthropometric specifications, large numbers of representative points may overwhelm the designer, and thus be counterproductive.

CHAPTER 6

FUTURE DESIGN METHODS

We have now gone through development of anthropometric samples, established a method for determining operational requirements, developed a technique for measuring pilot fit in the cockpit, and proposed a new method for describing body size variability for the user population. This last chapter discusses how these methods should be combined to produce a new, more accommodating cockpit.

Designing aircraft cockpits to accommodate the wide range of body sizes in the U.S. population has always been a difficult problem for crewstation engineers. The approach taken in the design of military aircraft has been to restrict the range of body sizes allowed into flight training, and then to develop standards and specifications to ensure that the majority of the pilots are accommodated. Once again, accommodation in this application is defined as the ability to:

- adequately see, reach, and actuate controls;
- have external visual fields so that the pilot can see to land, clear for other aircraft, and perform a wide variety of missions (ground support/attack or air-to-air combat); and
- and finally, if problems arise, safely escape.

Each of these accommodation areas is directly affected by the body size of the pilot. The height of the pilot's eye in the cockpit determines the amount of available vision, arm length and shoulder height affect ability to reach and actuate controls, leg length affects reach to rudders and ejection clearances, Sitting Height determines overhead clearance, and shoulder width relates to lateral clearances.

Seat position obviously affects everything. By moving the seat up, the pilot may see the ground better, but is now further away from the rudders and controls, and may be too close to the canopy or overhead. Moving the seat forward may improve reach to the main instrument panel, but may put the pilot too close to the control stick to pull it to the full aft position, or the pilot's shins may strike the instrument panel during ejection. Accommodation is a multivariable problem. That is, variability or change in one dimension affects others as well. The goal is to find a position in the aircraft for each pilot where he or she is accommodated in all these areas so that safe and efficient operation is possible. Since accommodation problems are most severe in the Fighter/Attack aircraft and their associated Trainers (and to a lesser extent, all aircraft equipped with ejection seats), this chapter focuses on those aircraft. However, many of the same problems arise in all types of aircraft; therefore, some of the issues raised should be relevant to any crewstation designer.

BACKGROUND

Historically, crewstation design has been guided by documents such as Military Standard 1333. This document addressed accommodation by listing methods of design as a set of rules, much like the rules used to make clothing patterns. "Design Eye Point" was the starting point for a cockpit layout. From that point on the new drawing, the seat adjustment range was established so pilots in the range of eye heights associated with the user population (usually listed in Military Standard 1472) could all adjust their seat to reach that eye position. Next, from the design eye position, a 13-inch radius was drawn to represent space for the top of the pilot's head and to establish the canopy line. It is unclear why 13 inches was selected as the space radius; foreheads are not that large, even with helmets on! Similarly, a seemingly arbitrary value of 30 inches was selected for ejection clearance from the "seat back reference line" (a tangent to the compressed seat back cushion) to the main instrument panel or canopy bow. Though these values seem arbitrary, this approach usually worked rather well. The majority of accommodation problems have occurred when these standard practices were not followed (for example, the lack of shin clearance in the F-16 and T-4, or inadequate overhead clearance in the C-21 and in the aft seat of the T-38).

Two government philosophies are changing the way cockpits will be designed for future aircraft. First, the USAF is considering relaxing the body size entrance requirements for entry into Undergraduate Pilot Training (UPT) to increase recruitment of female pilots. This will cause existing pilot databases to become irrelevant. Second, Military Standards are being ignored to allow aircraft manufacturers more freedom to explore unique design solutions. These two developments will change the way pilot accommodation is approached, and fixed standards such as Military Standard 1333 will be rendered obsolete.

As previously discussed, nearly all current USAF aircraft were designed to accommodate a pilot population with a Sitting Height range of 34 to 39 inches. The old approach to specifications usually required accommodating a range of fifth to ninety-fifth percentile of the existing PILOT population. This equates to 34.9 inches to 38.8 inches (Zehner, et al., 1992). If the data in Chapter 5 were used, cockpit designers would be trying to design to a Sitting Height range of 29.9 to 40.3 inches. Similarly, much larger ranges of leg lengths, arm lengths, body mass, etc. will be specified as requirements for future aircraft designed for the military. This potentially new pilot population pushes the design envelope to new extremes and will require close examination of accommodation to determine if pilots with the desired range of body sizes can safely operate the aircraft. For example, an arm length of 26.1 inches for the shortest pilot was specified in a recent contract, while the longest thigh length was 27.9 inches. How can an aircraft be designed so that the short pilot is able to reach a control on the main instrument panel while still maintaining enough space for the large pilot to clear it with his legs during ejection? This chapter will discuss some of the accommodation "lessons learned" and suggest techniques for designing to accommodate extreme body sizes.

External Vision

External Vision is typically thought of as "Over-the-Nose Vision." Figure 6.1 illustrates the direction of measurement of a subject's over-the-nose vision.

Figure 6.1. Over-the-Nose Vision Measurement.

As Military Standard 1333 indicates, a good starting point for a crewstation design is the location of the pilot's eye. While the old assumption of a "design eye point" is flawed, it is conceptually relevant. Pilots do not, and, in most designs, cannot all fly from the same eye position in the cockpit. However, as a starting point to begin to locate the pilot in the design and to determine the seat adjustment range, it is still a useful concept. The range of possible pilot eye positions can be applied to the starting point. As discussed in Chapter 3, the requirement for visual field should be set by the user (or customer) before beginning the design. It should be either a hard requirement (for example, –18 degrees over the nose), or a functional requirement, such as "the pilot must be able to see the touch-down point during a no-flap approach." To quantify a functional requirement such as this, designers determine the over-the-nose vision angle requirement by examining aircraft pitch angle during approach and landing. They begin by assuming that the waterline of the aircraft is level when in level flight. The pilot is seated so low in the cockpit that the pilot's line of sight is just over the edge of the glareshield. Only the horizon is visible. This is a zero-degree ONV angle. If the glide slope of the aircraft in approach is three degrees down, the pilot would have to pitch the nose down three degrees to see the touchdown point, or, if trimmed level, the pilot would have to be raised to a three-degree over-the-nose visual angle to see the touchdown point. However, the worst-case approach is a no-flap landing. In a no-flap landing, the nose of the aircraft is pitched up to increase lift (typically three to six degrees; for this example we will use five degrees). While the pilot's visual angle has remained the same relative to the aircraft waterline, the visual angle relative to the ground (and runway) has decreased five degrees. Therefore, the minimum ONV angle can be calculated as the angle of the glide slope plus the pitch-up angle during a no-flap landing. In this example, the minimum ONV angle would be eight degrees downward vision relative to the aircraft waterline. This method of determining minimum visual angle was verified during flight tests of training aircraft to be the minimum acceptable (lowest) position to which the pilot could adjust the seat and still be able to see the touchdown point. In a good design, some additional visual angle should be included to compensate for turbulence during landing.

Another consideration related to eye position is the use of a head-up display (HUD). This device projects flight information on a transparent screen directly in front of the pilot's eyes. This allows the pilot to better operate the aircraft by keeping the outside world in view. A HUD may place additional requirements on the locus of possible pilot eye positions, because if the pilot's eye is not properly aligned with the display, the symbology of the HUD may not be completely visible. The specification for the HUD should show the fore/aft and up/down tolerance range for eye position.

Given this information and the range of Seated Eye Heights for the user population (defined by multivariate boundary points B and D), the crewstation engineer should be able to determine the amount of adjustability in the seat that will be required to place all pilots within the HUD eye box (that is, in a position at which all the HUD symbology is visible), and to assure the specified Over-the-Nose Vision.

The next step in the design process is to match the Seated Eye Height of the pilot to this minimum visual angle. Anthropometric measurements are taken in very strict, standardized postures which do not reflect the way a pilot sits in an aircraft. During the Eye Height measurement, the subject is forced to sit very erect when measured. When relaxed, however, people slump slightly while seated. Therefore, if a body size specification lists the smallest Eye Height Sitting as 27 inches, designers might assume that the Seat Reference Point (located at the intersection of two lines connecting the compressed seat back and seat cushions in the center of the seat; see Figure 6.1) is 27 inches below the Design Eye Point when the seat is adjusted full-up. This assumption would require the pilot with a 27-inch Seated Eye Height to sit very erect during landings. Little if any data exists on relaxed seated heights. While data allowing slumped postures are not very repeatable, they may give the best indication of the tolerance that may be required for this dimension. Without data, an estimate of one inch of slump should be sufficient. Once the seat location and eye position for the smallest pilot has been determined, the forward fuselage reference lines can be established so that the minimum downward visual angle can be achieved.

If a HUD is used in the aircraft, the eye location is important for tall pilots as well. The seat adjustment range must allow pilots to see the full range of HUD symbology. If no HUD is used, the main concerns with locating tall pilots in the cockpit are ensuring adequate overhead clearance and vision to internal displays and controls. Each of these will be discussed below.

Finally, the horizontal vision line must be established for all eye positions (particularly for the largest pilots) to ensure uninterrupted forward vision. In many aircraft, the canopy bow is directly in front of tall pilots' eyes, obstructing their view of the horizon. Military Standards such as 850 have placed restrictions on this annoying situation, but it still happens. The largest pilots should still have the canopy bow well out of the way of their horizontal vision line.

INTERNAL VISION

The replacement of needle-and-ball gauges with computerized displays has essentially eliminated parallax as a problem in vision to the instruments. With the old style instruments, pilot eye position could make a major difference in the values read from a gauge. The flat glass panels used today are not subject to parallax errors.

Presently, the major problems with internal vision are blockage of the field of view by body parts such as the knees, or the pilot sitting so high in the cockpit that the glareshield obscures the top portion of the instrument panel (Figure 6.2).

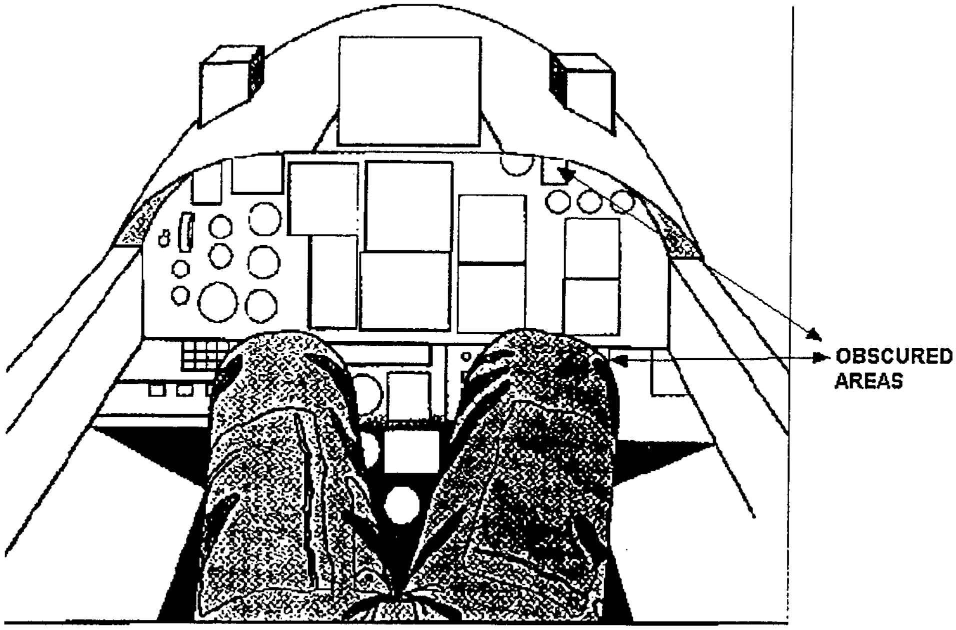

Figure 6.2. Internal Visual Obstructions.

The yoke control column in yoke-driven aircraft sometimes blocks the field of view directly forward of it. In one case, the majority of the Horizontal Situation Indicator (HSI) was obscured if the pilot's eye was low in the cockpit. Designers must be careful when locating displays near the top or bottom of the forward instrument panel.

Once the pilot's eye locations are determined in the crewstation, computer man models and drawing board mannequins can be useful tools for establishing visual angles to the glareshield and over obstacles such as the knees or the control column. However, mock-up trials are still the most reliable method of ensuring accommodation.

Overhead Clearance

Problems with head clearance are still seen in many aircraft in the USAF inventory. Pilots with Sitting Heights approaching 40 inches have difficulty sitting up straight and assuming the correct ejection posture. Pilots should be able to sit with an erect spine and with the head pushed back into the headrest. Figure 6.3 demonstrates a situation where this is not possible. This individual is at risk for neck injury.

Figure 6.3. Lack of Overhead Clearance.

With the seat in the full-down position, there should be overhead space for the largest Sitting Height (40 inches in the USAF, 41 inches in the Navy, model D of the multivariate models), the pilot's helmet (typically 1.5 inches is used to estimate the thickness of the HGU-55/P, but helmets with night vision capability or helmet-mounted displays may be much larger), and some clearance space overhead to allow for negative G forces, inverted flight, or turbulence. If the aircraft is to have through-the-canopy ejection capabilities, the pilot must be positioned below the canopy breakers. Notice the breakers on the top of the seat in Figure 6.3. This pilot would push through the canopy with his head!

Also, recent testing has shown that the shock wave caused by a high-speed bird strike can cause a deformation trough several inches deep in the canopy. This trough should not be allowed to strike the pilot's head.

If the pilot has adequate head clearance and visual capability, the canopy line can be established. Designers should still consider pilot mobility, however. New "low observable" aircraft designs (for example, the F-117) have used very angular canopy shapes. This shape could limit the pilot's ability to move his/her head to clear the sky or to check directly behind the aircraft. More clearance space may be necessary to provide the pilot adequate mobility. The amount of space at the sides of the pilot's head may also need to be considered.

Traditionally, fighter pilots place their fist between the top of their helmets and the canopy to position their seat. This is roughly a three-and-one-half inch clearance space. That ritual should be kept in mind. Three inches is enough to avoid the shock trough of a bird strike, and if the restraint system is effective, it should be enough to limit contact with the canopy during negative G flight. The canopy breakers should be placed above that position to assure they contact the canopy before the pilot.

REACH TO RUDDERS

Once the range of vertical seat adjustment has been set by the vision and overhead clearance requirements, a logical next step is determining the amount of adjustability in the rudder carriage necessary to accommodate the range of leg lengths in the user population.

One of the most limiting factors in accommodating smaller pilots in existing aircraft is reach to the rudder pedals. Since many pilots with short legs also have short Eye Height Sitting dimensions (R=~.5), they typically fly with the seat adjusted near full-up, and therefore farther away from the rudder pedals than a pilot with a large torso. A first design step would be to ensure that the shortest-torso pilot (model point B) can reach full rudder and full brake from the full-up seat position. Next, given the multivariate nature of body dimensions, the model points Y and C must be checked. Each point is evaluated by lowering the seat by the amount of the difference between their Sitting Eye Heights and Point B. Models Y and C have much shorter legs than point B. Point Y appears to have the body size most difficult to accommodate for rudders.

Large pilots with long legs usually adjust the seat full down (closer to the rudder pedals), and therefore set the forward carriage adjust point. This seat/pedal configuration also may bring the shins very close to the forward instrument panel. Male points A and W must be checked to set the forward carriage adjust position.

Several factors affect rudder layout in the crewstation. The relative heights of the heel rest line and seat pan throughout the seat adjustment range, and the relative angles of the seat pan and heel rest line, will determine the amount and range of flexion of the knee that pilots will exhibit. This angle can prevent direct scaling from the seat reference point forward to the rudder carriage location. Again, computer man models or drawing board mannequins can assist in this stage of the layout.

USAF evaluations of accommodation in aircraft use full rudder input *and* full brake input to determine if a pilot is able to adequately operate the rudders (Kennedy, 1995). Full rudder and brake input could be considered a functional requirement or a definition of accommodation in this area. The heel catch of the boot should remain in contact with the fully depressed rudder while the brake is fully applied. While this is an unusual maneuver for a pilot to perform, it is a conservative and repeatable method of determining a limit for acceptable accommodation. Questions concerning the amount of strength available for actuating the rudders or brakes when the pilot has to reach them with the tip of his or her toes are relevant and recurring. This technique should ensure full leg strength would be available if necessary. Finally, the distance between the rudder pedal and the heel rest position on the deck must be large enough to allow pilots with large feet to move the rudder without inadvertently applying the brakes. This can cause mishaps on the ground when using rudder-controlled nose wheel steering.

Shin Clearance

Lack of clearance between the pilot's shins and the main instrument panel (MIP) has been a problem in many military aircraft.

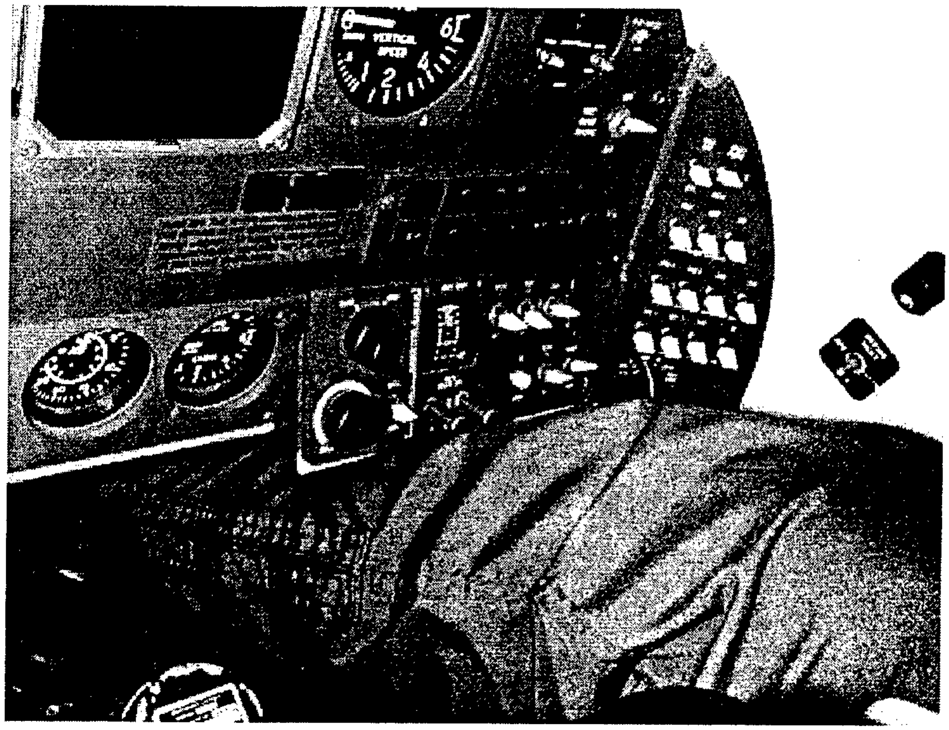

Figure 6.4. Lack of Shin Clearance.

Several instances of minor leg injuries to pilots during ejection have been reported. Mockups of recently proposed crewstations exhibited a dangerous lack of legroom. In one case, large pilots could not even place their feet on the rudder pedals due to blockage by the MIP. While ejection injury is the main concern, a lack of clearance space also forces large pilots to sit in one position during long flights and does not allow for shifting body posture to relieve discomfort.

Typically, the pilot's feet are underneath the MIP when operating the rudders, which places the feet outside the 30-inch ejection envelope called for in Military Standards. Designers commonly assume that, as ejection is initiated and the pilot is pulled up and aft along the seat rails, the feet and shins should swing aft as they depart the rudder pedals. However, computer simulations of ejection sequences with large pilots and the reported ejection-related leg injuries do not completely support this assumption. A good crewstation design should ensure that all pilots have adequate shin clearance.

Once the forward adjustment point for the rudder carriage is established, the male and female model points should then be tested for shin clearance. Using the same seat adjustment method as used for the rudder reach checks, the male points A, W, and X, and the female point X must be evaluated. This process forces the designer to examine variability in clearance throughout the range of seat adjustment positions. A trace of leg positions must be drawn to show where the pilot's legs and shins are located and how they move as the rudders are actuated. Accurate traces are needed for each of these body size test cases in the seat position appropriate to maintain adequate over-the-nose vision and overhead clearance.

After the range of necessary seat positions has been evaluated, the lower edge of the main instrument panel can be established. Several inches of clearance should be provided to ensure pilot mobility and safe escape. As knobs and switches are added to the main instrument panel, clearance may be altered.

ESCAPE CLEARANCES

If the pilot strikes a cockpit structure during ejection, devastating injuries can result. Canopy bows and the sills along the sides of the lower edge of the canopy are occasionally struck by the pilot during ejection. The 30-inch Military Standard distance is supposed to provide a margin of safety for these areas, but designers do not always adhere to the Military Standard. The analysis in Chapter 4 lists a maximum expected Buttock-Knee length in the USAF population of 27.7 inches (Point A). Years ago, when the standards were written and ejection tests were performed, the specifications listed a maximum Buttock-Knee length of 25.5 inches (ninety-fifth percentile). Test trials of subjects with Buttock-Knee lengths of 27.9 inches in crewstations that followed the 30-inch standard have shown that clearances to the canopy bow are less than one inch! The 30-inch clearance line is set from the "seat reference point" (located at the intersection of the compressed seat pan and the seat back cushions). Pilots' buttocks do not always fit all the way back into the seat at that point, and some space may be left void in that area. The pilot's knees then protrude further forward in the crewstation than expected. Complicating this problem are the dynamics of ejection. Little is known about shifting of body positions (submarining) during the initial phases of the ejection sequence. Some researchers have stated that there can be several inches of forward displacement of the knees during ejection. However, no reliable data exists to substantiate these opinions.

Obviously, if the pilot is experiencing high G forces (forcing the pilot down into the seat or forward), some slipping under the lap restraint could be expected. If the catapulting ejection seat also forces the pilot's knees forward, very large pilots would be even more at risk for significant injury. Clearly, the 30-inch envelope (forward) may not be sufficient. Several inches of clearance space between the pilot's knees and the forward canopy bows should be added to the design. Testing will begin soon on two separate aircraft using dummies with 27.9-inch Buttock-Knee lengths. These tests should provide more information on this issue.

Designers may also be required to follow the 30-inch standard for cockpit width, but historically, cockpit width has been allowed to vary. Crewstation widths of less than 24 inches have been produced. Current USAF specifications list 22.6 inches as the largest expected shoulder width (Bideltoid). This is a nude dimension. With pilots wearing survival vests and other personal protective equipment, the elbows can be considerably wider than the shoulders. Add to this width the action of raising the hands when pulling the ejection handle up, and the largest pilots will certainly be wider than 22.6 inches at the elbows. Recent evaluations fitting very wide pilots into narrow crewstations have verified this problem (Figure 6.5). Crewstations with widths less than 26 inches appear to be placing pilots at risk of contact injuries.

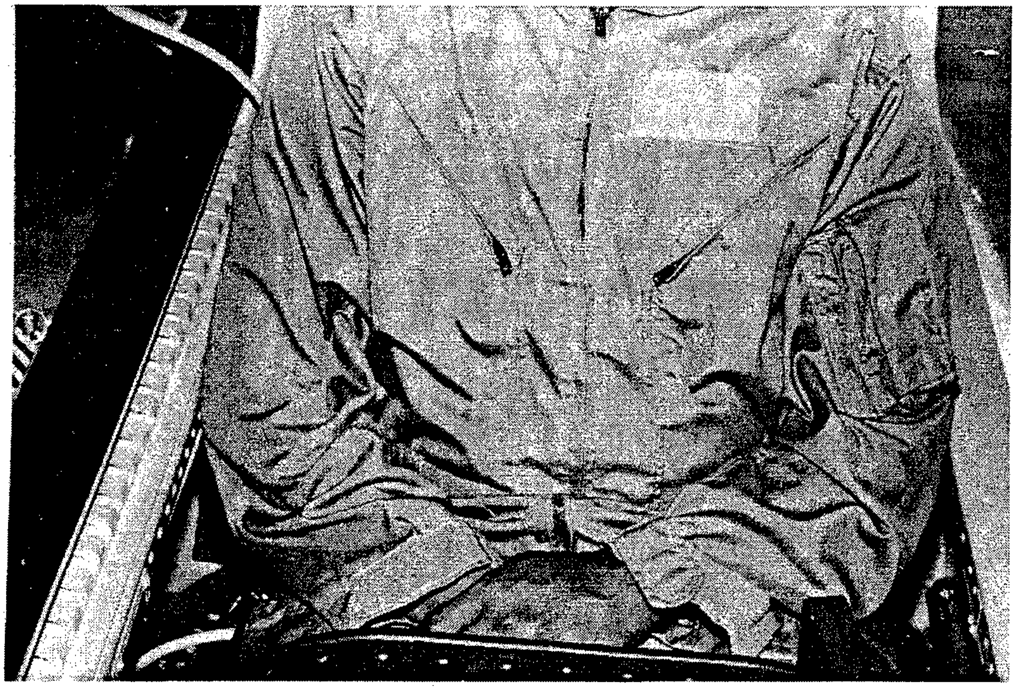

Figure 6.5. Lack of Elbow Clearance.

The 30-inch standard appears to be a reliable yardstick for the design of this area of the crewstation. Two points must be made here concerning cockpit width. First, it is not clear how serious the injuries to the pilot might be if the pilot contacts the sides of the crewstation on ejection. Testing with large dummies should indicate the potential for injuries. Second, if performance requirements call for smaller crewstations, the services could consider not assigning large pilots to aircraft with small crewstations.

ARM REACH TO CONTROLS

The ability of the pilot to reach the controls depends, again, on the type of aircraft and its mission requirements. Not only are the functional requirements for control layout mission-dependent, but the type and amount of Personal Protective Equipment that the pilot wears is generally mission-dependent, also. This equipment can make several inches of difference in a pilot's ability to move and reach controls. Before beginning cockpit layout, designers need to determine the encumbering effects of the protective ensemble.

Traditionally, reach capability and requirements have been broken into three reach zones based essentially on restraint conditions. Zone 1 represents high-G situations and guides designers to place primary and emergency controls in a position close to the pilot. When under High-G loading, it may be impossible for the pilot to stretch the arm and shoulder a long distance and accurately actuate a particular control. Not only does high-G loading make reaching difficult, it also makes it easy to bump or actuate the wrong switch. Very few controls are used when a pilot is in a tight-turn, high-G maneuver. The control stick, throttle, and ejection system controls are obvious inclusions in Zone 1, and possibly weapon systems for an air-to-air combat mission. The Zone 1 reach envelope represents the pilot's reach area with locked inertial reels and the pilot's shoulders firmly in contact with the seat back. Stretching the shoulder forward from the seat back is not permitted when evaluating ability to reach controls in this restraint configuration. While the pilot can move during high-G maneuvers, movement becomes very difficult. This rather conservative evaluative technique places critical controls in very close proximity for both typical flight situations and out-of-control emergency situations.

A couple of exceptions to the high-G criteria for Zone 1 controls serve notice as to the importance of proximity of certain controls. The close placement of the manual pitch override switch is an example of this. When an aircraft is pitching wildly out of control, the pilot may have difficulty reaching and actuating this switch, even though the G loading is not nearly as high as when in a tight turn. Another example of a Zone 1 control could be formation lights. While these controls are not actuated during a high-G maneuver, they are used during night formation flying, a time when looking down into the cockpit or stretching and moving to reach a control could lead to pilot disorientation.

Finally, for comfort of flight, the neutral stick and throttle positions have recently been included in Zone 1 lists. The pilot should not have to stretch to reach these positions. Each aircraft type may have different controls that should be included in the Zone 1 list. Zone 1 controls should be defined by the user pilot community and the aircraft designers.

Zone 2 refers to the area the pilot can reach with locked inertial reels, but the pilot can stretch forward as far as the restraint system will allow in order to access controls. This situation might occur when a crash or potentially dangerous situation (like approaching the target in air-to-ground missions) is imminent, and the pilot locks the inertial reel as a precaution. From this restraint condition, all emergency controls, primary flight controls, weapons systems, etc. should be accessible. The list of Zone 2 controls can be exhaustive and should be created with caution. The amount of time required to release the inertial reel lock, lean forward, and actuate a control is small. Placing a large number of controls in Zones 1 and 2 usually forces their location on side console instrument panels, and may interfere with human factors concerns, such as grouping controls based on function.

Finally, Zone 3 refers to the area the pilot can reach with unlocked inertial reels, with the pilot able to move as far as the unlocked restraint will play out. No controls should be located outside this condition or the pilot will not be able to reach them. For most "heavy" aircraft, the majority of controls are placed in this zone. In fact, in many aircraft, manual inertial reel locks are non-existent. This does not mean that control proximity is not important in aircraft without manual inertial reel locks. It means that the functional requirements will be different, and the definitions for Zones 1, 2 and 3 may not be adequate for this application. Certainly the throttles and control stick or yoke must be easily accessible, as well as any emergency controls which would be needed if the aircraft went out of control.

Evaluation of reach ability should include the small models B, Y, and C, in the appropriate seat positions. In addition, the male and female model Z should be checked. These models have relatively long torsos and short limbs. Reach to overhead controls may be difficult for them.

CONTROL STICK RANGE OF MOTION

Recent attempts to place small pilots into crewstations, which were not designed to accommodate them, have shown that one of the most difficult problems to solve is reach to the control stick. The most obvious problem is reaching to the full forward limits of stick throw, particularly the forward left corner (Figure 6.6).

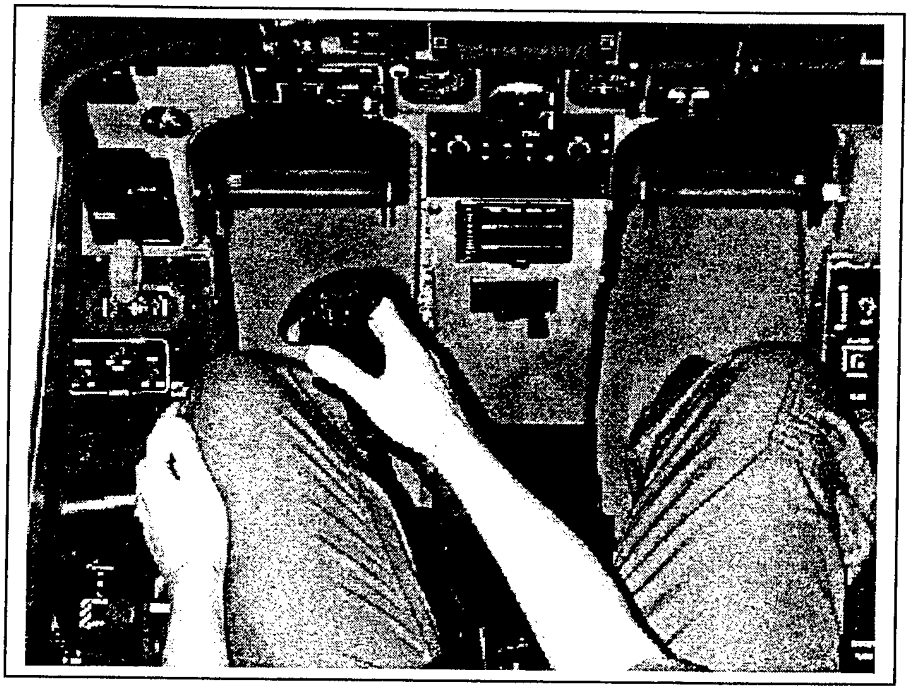

Figure 6.6. Reach to Full Forward-Left Stick.

Moving the stick side-to-side to the limits is also difficult, and is made more complicated by two different, but related, problems. First, a pilot with a short Eye Height Sitting will adjust the seat to the full-up position. This raises the position of the thighs to a higher position relative to the control stick. If stick motion is thought of as an inverted pyramid attached at its apex to the floor of the aircraft, it is easy to imagine that as the pilot adjusts the seat upward, the sides of the cone reach farther outboard and into the space which could be occupied by the thigh. As the pilot attempts to move the stick to the outboard limits (roll), full range movement can be limited by contact with the thighs (Figure 6.7).

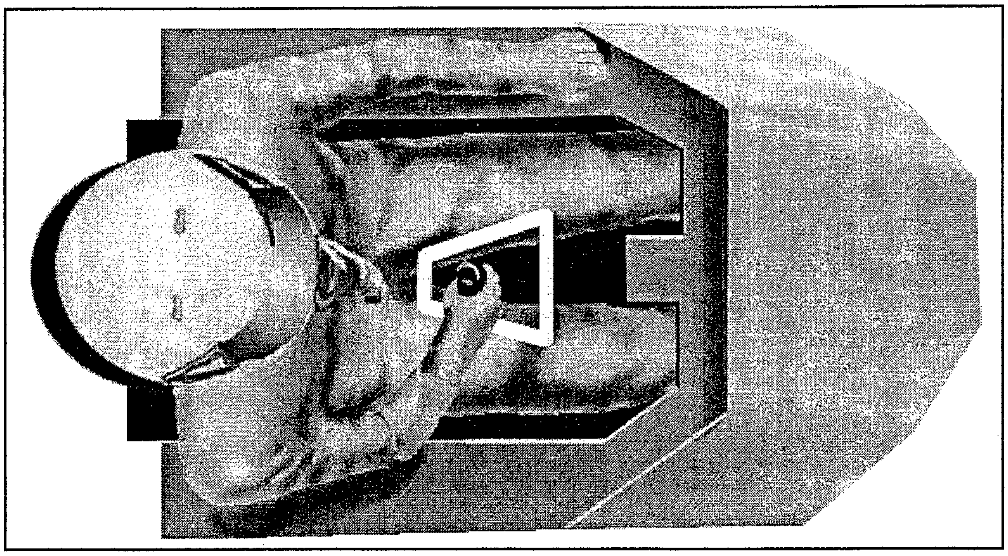

Figure 6.7. Stick Interference with the Thigh.

One often-discussed method of increasing an aircraft's accommodation of small pilots is to allow them to sit on cushions for increased over-the-nose vision. Stick interference that might result from raising the pilot's thighs must be carefully evaluated before attempting such a solution.

The second complicating factor in stick outboard range of movement is the length of the legs. Pilots with very long legs occasionally experience problems with stick interference (figure 6.8). This pilot has his leg pinned between the left side throttle and stick, limiting roll capability.

Figure 6.8. Knee Trapped Between the Stick and Throttle.

However, long-legged pilots usually have little difficulty spreading their knees apart or shifting in the seat to move the stick to its outboard limit. This can usually be accomplished while keeping the feet on (and in control of) the rudder pedals. Small pilots may not be able to do this. Our evaluations of existing aircraft have revealed that small pilots stretch their legs so far forward to engage the rudders that they cannot spread their knees apart. Also, as the pilot is moved forward in the cockpit (with back cushions or an adjustable seat) in order to better reach rudders or hand controls, the amount of space between the thighs decreases (imagine a V shape, with the point originating at the crotch and opening toward the knees). Again, quick fixes to accommodation problems may lead to other problems.

One way to approach these stick range of motion problems is to define a functional requirement, in this case an "operational range" of stick motion. Does the pilot ever have to pull the control stick full aft and all the way to the left or right limit? A number of aircraft manufacturers were recently asked this question. Their answers indicate that different aircraft appear to have quite different "operational ranges." Some aircraft are reported to require very little aft/left and aft/right stick movement, while others use the full range aft but very little forward/ left and forward/right stick movement. Opinions among pilots on the acceptability of using "operational range" as criteria for determining whether an aircraft accommodates a small pilot vary a great deal. Some pilots agree with the premise, but others insist that "if the stick will go there, the pilot should be able to put it there." In yoke-driven aircraft, a problem arises when small pilots adjust the seat high in the cockpit to increase over-the-nose vision. With the pilot elevated in the seat, the wheel strikes the upper part of the thigh when it is rotated (rolled) far to the right or left (Figure 6.9).

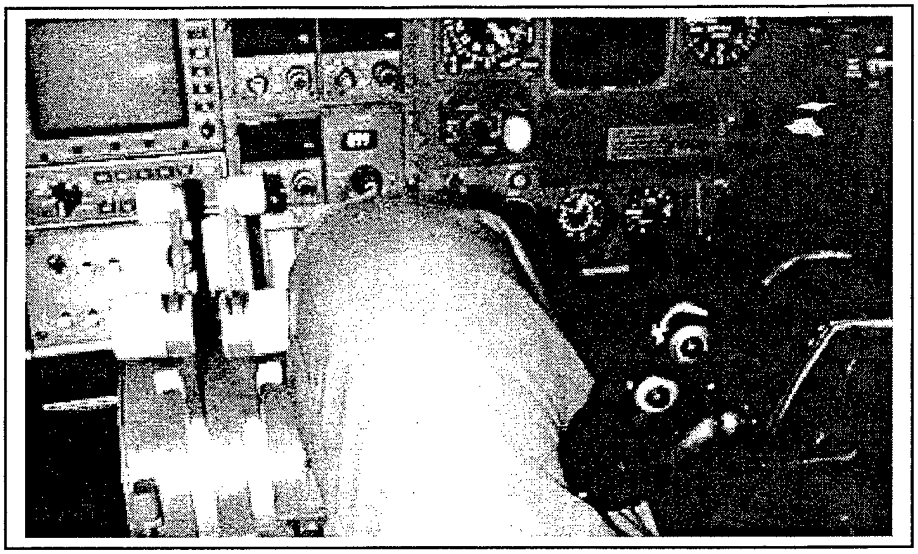

Figure 6.9. Yoke Interference with the Thigh.

Again, long-legged pilots are usually able to spread their knees far enough apart to allow the wheel to pass (while still keeping control of the rudders), but small pilots may not be able to do this. This problem was discovered for a contending aircraft during USAF procurement evaluations. More than half of available aileron movement was lost due to the wheel striking the thighs. Rudder control is a key indicator in evaluating successful accommodation because rudder input is usually required while using the ailerons, and the pilot may be attempting to cross control the aircraft. Cross-Controlling is when the Yoke is pulled aft and turned right, but left rudder is put in. This raises the right knee – which is the direction the Yoke is being turned. This can increase the potential for interference. Knee position may be quite variable depending upon what the pilot is trying to accomplish. Another point which should be kept in mind when dealing with yoke and stick interference problems is that even if a pilot is able to shift positions or spread the knees apart to avoid obstructing the stick, problems may still occur. The co-pilot may make a sudden control input that is prevented by contact with the pilot's legs. This interference could be disastrous in an emergency situation.

DISCUSSION

Crewstation designers typically learn to deal with anthropometric problems on the job. Outside of general coverage in Human Factors courses, little information exists on how to design to accommodate pilot body size variability. In recent years, Military Standard 1333 and 850 have fallen into disfavor for military procurements because of their strict rules, which may prevent unique designs from being attempted. Military Standard 1472 only deals with crewstation design in a very general manner and the anthropometric section of that standard can be misleading due to the continued use of percentiles to describe body size variability. Military Standard 1776 is the most recent attempt to guide crewstation designers while still allowing freedom to pursue new ideas. This document allows the aircraft specifications to be "tailored." That implies that the manufacturer and the government procurement agency should sit down and discuss the dimensional and accommodation requirements for the aircraft and "fill in the blanks" in the specification. However, the Guidance and Lessons Learned sections in this standard still reflect percentile-man thinking (that is, people are large or small and can be classified as a "ninety-fifth or fifth percentile man"), and the experiences are based on the past pilot population, not the expanded body size range that designers will have to accommodate in the future. These criticisms are not intended to discredit these standards. Each of these documents is a valuable resource for cockpit designers. However, as crewstations are designed to accommodate a larger range of body sizes, crewstation designers' difficulties will continue to increase, and some of the challenges may be problems never encountered before. Existing and past approaches will offer a great deal of good information, but will not reflect the problems associated with designing for a body size range extending from less than five feet in stature to nearly six and a half feet (Figure 6.10).

Figure 6.10. Body Size Range.

Similarly, the cockpit design issues discussed in this paper are based on current traditional cockpit designs. Future aircraft will undoubtedly present unique and unexpected problems that will have to be assessed very carefully to avoid compromising body size accommodation. For example, experiments were conducted years ago which considered supine pilot positions as a method of reducing the cross sectional size of the aircraft and as a potential solution to the effects of a high G-environment. While this pilot position would allow "thinner" designs and help to relieve the circulatory stresses the pilot faces under high-G forces, mock-up evaluations revealed problems in the pilot's ability to move and see overhead, and aft visual fields. This approach was dropped. However, pilot position has been considered a number of times since as a possible solution to a number of design problems and it will probably be considered again. This means that the crewstation designer will be faced with unique design environments in which anthropometric accommodation may be completely different than the "lessons learned" presented here and in the Military Standards.

Vigilance, careful attention to the mission requirements of the aircraft, and repeated fit testing with a range of body sizes equipped in the full flight ensemble of protective equipment remain the best approaches to ensuring body size accommodation.

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APPENDICES

APPENDIX A: ANTHROPOMETRIC MEASUREMENT DESCRIPTIONS

Measurement	Description
Abdominal Depth	The horizontal distance between the point of maximum protrusion on the abdomen and the same level on the back. The subject stands erect with the arms hanging relaxed at the sides.
Arm Length	The vertical distance between the subject's right acromion and the tip of the middle (or longest) finger on the right hand. The subject stands erect, looking straight ahead, with the arms hanging straight at the sides.
Buttock-Heel Length	The distance between the top of the subject's right buttock and the bottom of the right heel. The subject sits on the edge of a flat surface with the right leg fully extended and bent 45 degrees at the hip.
Buttock-Knee Length	The horizontal distance between the most protrusive point of the right buttock and the most forward point of the right knee. The subject sits on a flat surface, looking straight ahead. The thighs are parallel and the feet are in line with the thighs on a surface adjusted so the knees are bent 90 degrees.
Chest Depth	The horizontal distance between the chest and the back at the level of the right bustpoint on women or the right nipple on men. The subject stands erect, looking straight ahead, with shoulders and upper extremities relaxed. The technician takes the measurement at the maximum point of quiet respiration.
Frankfort-Plane	A standard plane of orientation of the head, realized when the lowest point in the margin of the left eye socket (orbit) and the left tragion (superior margin of the external auditory meatus) are in a common horizontal plane.
Shoulder Breadth (Bideltoid)	The horizontal distance across the maximum lateral protrusions of the right and left deltoid muscles.
Sitting Height	The vertical distance between the sitting surface and the top of the head. The subject sits erect on a flat surface with the head in the Frankfurt plane.
Sitting Knee Height	The vertical distance between the foot rest and the top of the right patella. The subject sits erect on a flat surface. The thighs are parallel and the feet are in line with the thighs on a surface adjusted so the knees are bent 90 degrees.
Sitting Shoulder (Acromial) Height	The vertical distance between the sitting surface and the tip of the right shoulder. The subject sits erect on a flat surface looking straight ahead. The upper arms are relaxed at the sides with the forearms and hands extended horizontally with the palms facing each other.

Span	The distance between the tips of the middle fingers of the horizontally outstretched arms. The subject stands erect with the heels together. Both arms and hands are stretched horizontally with the tip of the middle finger of one hand just touching a side wall. The technician measures from the wall to the tip of the opposite finger.
Stature	The vertical distance between the standing surface and the top of the head. The subject stands erect with the heels 10 cm apart and the head in the Frankfurt plane. The arms are relaxed at the sides and the weight is distributed equally on both feet.
Thigh Circumference	The maximum circumference of the upper thigh.
Thumbtip Reach	Measured horizontally from the vertical seat back or wall to the middle of the pad of the thumb, with the thumb and index finger together. The arm and hand are stretched horizontally in front of the body.
Weight	The weight of the subject as the subject stands on the scale, clad in lightweight garments with the weight distributed equally on both feet.

APPENDIX B: REACH MEASUREMENTS MADE IN THE T-38A

In compiling the following list, we consulted the T-38 T.O.-1 and considered all the controls associated with emergency procedures. Each subjects reach capability to these controls was measured.

Forward Cockpit:
Ignition inverter circuit breaker
Auxiliary flap switch
Yaw damper switch
Wing flap lever
Inertia reel lock lever
Throttle (max)
Fuel shut-off switch
Engine start button
Emergency landing gear handle
Radio transfer switch
UHF Center knob #5
Nav. volume knob
Landing gear lever
Downlock override button
AOA Index dimmer
Navigation mode switch
HSI Course set button
ADI Pitch trim knob
Master caution
Pitot heat switch
Boost pump switch
Canopy jettison handle
Generator switch
Oxygen supply switch
AIMS Control master switch
Lighting panel
Ejection handgrip
Control stick full-forward
Control stick left
Control stick full-forward and left

Aft Cockpit:
Stabilizer augment circuit breaker
Auxiliary flap switch
Wing flap lever
Inertia reel lock lever
Throttle (max)
Engine start (left)
Comm.-Nav. override switch
UHF #9
Nav. volume switch
Landing gear lever
Downlock override switch
AOA index dimmer
Navigation mode switch
HSI Course set
ADI Pitch trim knob
Master caution
Canopy jettison handle
Oxygen supply switch
Lighting panel (floods)
Ejection handgrip
Control stick full-forward
Control stick left
Control stick full-forward and left

APPENDIX C: MODEL I AND MODEL II REGRESSION ANALYSIS

This appendix discusses the differences between Model I and three types of Model II regression. When there is "error" in both the independent (anthropometric dimensions) measurement and the dependent measure (ONV, reach to controls etc.), Model I regression may not be appropriate. This is the case in this dissertation.

Three types of Model II regression were examined: 1) Bartlett's Three Group Method, 2) Reduced Major Axis, and 3) Major Axis Regression. For comparison, we re-analyzed the Over-the-Nose (ONV) vision data from Chapter 4. Figure C1 shows the data.

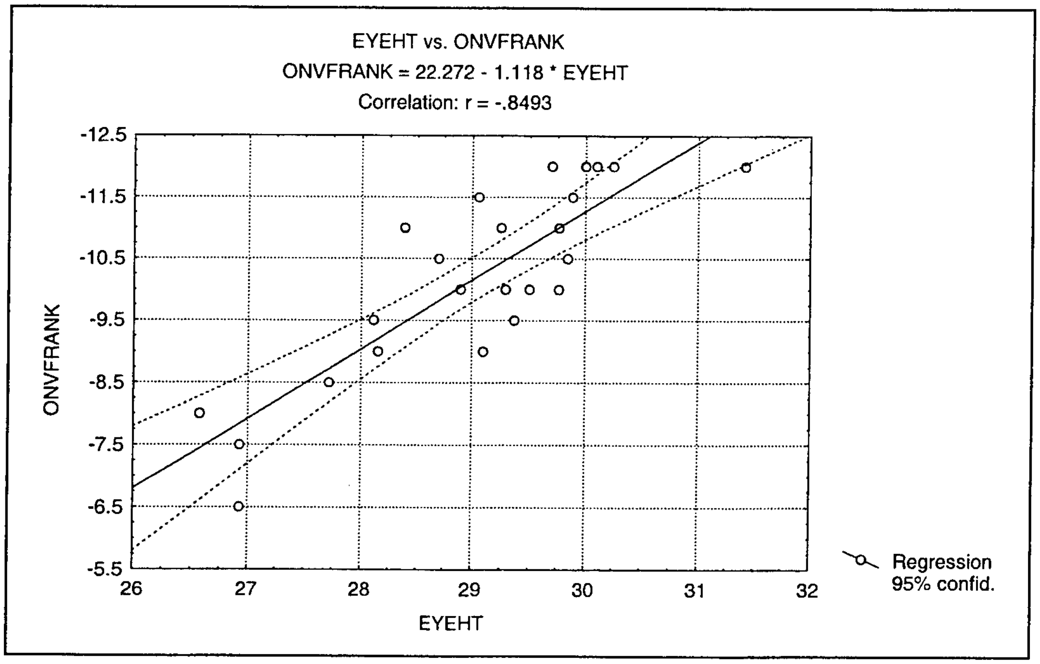

Figure C.1. Plot of Sitting Eye Height and ONV.

Pearsons' r is .85 with a Standard Error of 0.8. When the anthropometric measurement is considered to be an independent measure (as is always the case in this research), the Sitting Eye Height corresponding to –11 degrees ONV is 29.75 inches. However, if ONV were used as the independent measure instead, and Sitting Eye Height is predicted, the Sitting Eye Height corresponding to –11 degrees is 29.63 inches; a difference of 0.12 inches. Looked at another way, when ONV is the independent measure, the ONV associated with a 29.75 inch Sitting Eye Height is -11.3 degrees. These data will be compared to the Model II techniques discussed below.

Bartlett's Three Group method only uses 2/3 of the data gathered. All data points are rank ordered and placed into one of three equal sized groups based on the magnitude of the X variate (Group 1 is the smallest and group 3 is the largest). It is solved by: (Group 3 mean minus group 1 mean for the Y variable), divided by (Group 3 mean minus group 1 mean for the X variable). This provides the slope. The intercept is: the mean of the Y variable divided by (the slope times the mean of the X variable). The predicted value of ONV for 29.75 inches of Sitting Eye Height is 10.93 degrees; 0.07 degrees smaller than the prediction from Model I regression.

The second technique attempted was Major Axis Regression. Major Axis Regression assumes that the error is equal for both variates. This is not usually the case with accommodation data. Anthropometric data and performance data have quite different variances. In our data the ONV variance is 2.4 and for Eye Height it is 1.4. The Major Axis slope is calculated as: (the variance in Y minus the variance in X) plus - the square root of (the variance in Y minus the variance in x) squared, plus - four times (the covariance of XY) squared. The solution of that is divided by: two times the covariance of X and Y.

The formula for the intercept is the same as Bartlett's.

The ONV associated with 29.75 inches of Sitting Eye Height is –11.18 degrees; 0.18 degrees larger than Model I.

Finally, Reduced Major Axis was used. This technique calculates the slope based on the ratio between the Standard Deviations of the variables. Harvey and Pagel (1991) state "Reduced Major Axis produces that line which minimizes the sum of the products of vertical multiplied by horizontal deviations of points from a line. However, it does not make use of any information about the covariance between X and Y in calculating the slope. Thus, it can yield nonsensical results, such as a slope between two variates that are uncorrelated, and for this reason we do not recommend its use."

The slope is calculated as: the Standard Deviation of Y divided by the Standard Deviation of X.

Again, the intercept is calculated the same as Bartlett's.

The resulting ONV for a Sitting Eye Height of 29.75 inches is -9.2 degrees. This is different by 1.8 degrees from Model I.

When plotted, this value falls far below the regression line and any of the data measured. It is located at the intersection of the lines on Figure C2

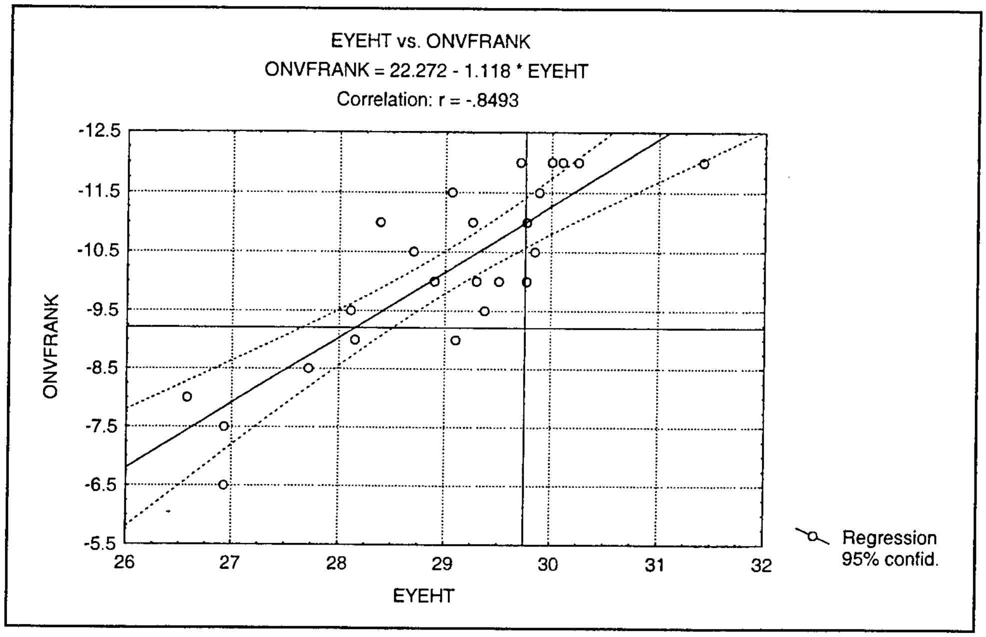

Figure C.2. Plot of Sitting Eye Height and ONV with Reduced Major Axes Prediction.

According to Sokal and Rohlf "research on and controversy over Model II regression continues, and definitive recommendations are difficult to make. Much depends on the intentions of the investigator. If the regression line is being fit for purposes of prediction, then simple linear regression techniques are generally applied."

They also state: Model I regression can still be used when any one of three conditions exist. First, when the errors in measurements are controlled by the investigator. This is the case in the current research. All anthropometric measures were carefully taken by one individual. They are assumed to be accurate.

Second, there is also no reason to assume that the magnitude of the errors in the independent variate and the error in the application measurement are correlated. They should be random. This is also the case with our research. The measurements made in the aircraft are so different from anthropometric measurements that there should be no relationship between measurement error of the two.

Third, these measurements are in different units and their variances are very different. This violates the assumptions of the Major Axis method.

Practically, there is very little difference between Model I regression and in the predicted values of ONV for a given Eye Height when using Major Axis Regression or Bartlett's Three Group method (both are within 0.2 degrees). However, Reduced Major Axis regression differs by 1.8 degrees, and its results make little sense.

A major difference between these techniques is that selection of independent and dependent variables is irrelevant in Model II. You get the same answer either way. For Model I, we always assume that the anthropometric measurement is independent of error and is used to predict thew dependent performance variable.

For those reasons it appears that Model I regression is appropriate in this work.