STINFO COPY

AFRL-HE-WP-TR-2007-0016

A Methodology for Evaluating Advanced Operator Workstation Accommodation

Jeffrey A. Hudson

Advanced Information Systems
A General Dynamics Company
5200 Springfield Pike, Suite 200
Dayton OH 45431-1289

Gregory F. Zehner
Julia Parakkat

Air Force Research Laboratory
Human Effectiveness Directorate
Wright-Patterson AFB OH 45433

Hyeg Joo Choi

Oak Ridge Institute for Science and Education (ORISE)
P.O.Box 117
MS 36 Oak Ridge TN 37830

November 2006
Interim Report for October 2005 – October 2006

Approved for Public Release;
Distribution is Unlimited.

Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Interface Division
Collaborative Interfaces Branch
Wright-Patterson AFB OH 45433

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report was cleared for public release by the Air Force Research Laboratory [insert TD site] Public Affairs Office and is available to the general public, including foreign nationals. Copies may be obtained from the Defense Technical Information Center (DTIC) (http://www.dtic.mil).

TECHNICAL REVIEW AND APPROVAL

AFRL-HE-WP-TR-2007-0016

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

FOR THE DIRECTOR

//signed//
DANIEL G. GODDARD
Chief, Warfighter Interface Division
Air Force Research Laboratory

This report is published in the interest of scientific and technical information exchange, and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*
1 Nov 2006

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
October 2005 to October 2006

4. TITLE AND SUBTITLE
A Methodology for Evaluating Advanced Operator Workstation Accommodation

5a. CONTRACT NUMBER
In-House

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
63231F

6. AUTHOR(S)
Jeffrey A. Hudson *
Gregory F. Zehner **
Julia Parakkat **
Hyeg Joo Choi ***

5d. PROJECT NUMBER
2830

5e. TASK NUMBER
30

5f. WORK UNIT NUMBER
15

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Advanced Information Systems*
A General Dynamics Company
5200 Springfield Pike, Suite 200
Dayton OH 45431-1289

Oak Ridge Institute for Science and Education***
P.O. Box 117
MS 36 Oak Ridge TN 37830

Air Force Research Laboratory**
Human Effectiveness Directorate
Wright-Patterson AFB OH 45433

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Materiel Command
Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Interface Division
Collaborative Interfaces Branch
Wright Patterson AFB OH 45433-7901

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/HECP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-HE-WP-TR-2007-0016

12. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

AFRL/PA Cleared 2/27/07 AFRL/WS-07-0422.

14. ABSTRACT

While the Human Systems Engineering (HSE) process is wide and varied during system development, part of it must seek to maximize mission effectiveness through experimentation and analysis in two areas: 1) physical layout – to ensure the widest physical accommodation range of operator body size and proportion, 2) reduction of performance reducing fatigue. This white paper outlines a methodological approach that should be used to optimize and evaluate the physical and functional aspects of candidate designs for future Advanced Operator Workstations (AOWs).

15. SUBJECT TERMS
Anthropometry, Comfort, Fatigue, Multivariate Accommodation, Workstation Design, Operator Workstation

16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Scott M. Galster
U	U	U	SAR	36	19b. TELEPONE NUMBER (*Include area code*)

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI-Std Z39-18

THIS PAGE IS INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I. Introduction 1
II. Physical Layout of Operator Station – (Anthropometric Accommodation) 2
A. Sample Selection – Estimating the Operator Population 2
B. Multivariate Method – Generation of AOW Anthropometric Boundary Cases 3
C. Visualization and Anthropometric Analysis in CAD 6
D. Accommodation Analysis 8
III. Minimization of Performance-Reducing Fatigue 9
A. Operator Workstation Layout 9
Reach Zones 10
Handedness 10
Posture and Eye Postion 11
IV. Hardware Component Selection and Integration 12
A. Space Allowed 12
B. Displays 13
C. Seating 13
D. Measuring Comfort 13
V. Discussion 16
Appendix A. Multivariate Accommodation Method 17
Appendix B. Relevant Workstation Dimensions from available standards 25
References 27

List of Figures

Figure 1. Location of Anthropometric Variables..... 4
Figure 2. Comparison of Nearest Neighbor CAESAR Scans of the overall large male and the overall small female. 5
Figure 3. Contrast of Nearest Neighbor CAESAR Scans of a female with a short torso and long limbs (left) vs. a female with a tall torso with short limbs (right) 6
Figure 4. Female Safework model whose posture has been edited to match live subject data seated in an F-16 ejection seat. 7
Figure 5. Nearest Neighbor CAESAR Scan to Overall Small Female Anthropometric Case – segmented, and re-postured for import to CAD drawing. 8
Figure 6. Foot rests and table secured arm rests to aid operators in varying their posture..... 13
Figure A1. PCA bivariate and 99.5% boundary for the First and Second Principal Components for one gender of the JPATS population..... 18
Figure A2. 95% Accommodation Sphere……. ……..….21

List of Tables

Table 1. Relevant Variables to AOW Workstation 4
Table 2. Evaluation Measures..... 16
Table A1. Women's Principal Component Analysis..... 20
Table A2. Men's Principal Component Analysis 20
Table A3. Factor – Variable correlations (loadings) for both women and men PCAs..... 20
Table A4. Women: Model Point Variable Values..... 22
Table A5. Men: Model Point Variable Values 22
Table A6. BMC2 Boundary Anthropometric Cases..... 23
Table A7. Female Summary Statistics..... 23
Table A8. Male Summary Statistics 24
Table B1. Comparison of Standard Dimensions and PCA Cases..... 26

Acknowledgements

This research was funded by Dr. Scott Galster of AFRL/HECP. It was part of the Advanced Interfaces for Battle Management Command and Control (AIBMC2) program. It was also supported in part by an appointment to the Research Participation Program at the Air Force Research Laboratory, Human Effectiveness Directorate, Bioscience and Protection, Wright Patterson AFB administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and AFRL/HEP

THIS PAGE IS INTENTIONALLY LEFT BLANK

I. Introduction

The physical layout of the operator workstation is a design challenge characterized by continuous change. As human interface technology advances, traditional standardized workstation layouts may become a thing of the past. As part of the design process we are forced to imagine where technological advances may lead us - and how best to integrate components from possibly disparate applications into a complete system for our airborne and ground-based operators. We must also keep in mind that in some cases, operator missions are being increased to over 12 hours. Rather than try to anticipate future interface issues, this white paper outlines a methodological approach that should be used to optimize and evaluate the physical and functional aspects of candidate designs for future Advanced Operator Workstations (AOWs). While the Human Systems Engineering (HSE) process is wide and varied during system development, part of it must seek to maximize mission effectiveness through experimentation and analysis in two areas: 1) *physical layout* – to ensure the widest physical accommodation range of operator body size and proportion; 2) *reduction of performance-reducing fatigue* – not only through seat and component adjustability and layout, allowing multiple working postures for each potential operator, but also through "hot spot"-reducing seating technology.

These activities are all part of a multivariate anthropometric accommodation approach (currently used by the Air Force Research Lab (AFRL)) that includes:

1) Quantifying the important variation in size and shape of the projected operator population,
2) Generating subsequent representative boundary anthropometric cases for testing the design in CAD (computer-aided design) with digital human models, followed by (3)
3) Live subject testing in prototype workstations to quantify the actual percentage of the operator population that should be accommodated.

Accommodation requirements are stated in MIL-STD-1472F to be 95% or more for both genders. This military standard, and other specification guideline publications for human-machine-interface design, should be referred to when applicable to the AOW system (e.g., JSSG-2010-3, MIL-HDBK-759c, NASA-STD-3000, BSR/HFES 100 (2002)). Various operator body shapes and sizes will be considered accommodated if they can perform critical tasks given worst-case scenarios.

However, controlled experiments should be conducted for assessing mission effectiveness when causal factors, normally associated with fatigue, are varied (e.g., component placement and seated posture). If statistically significant improvements in mission effectiveness are demonstrated for any fatigue-minimizing feature (i.e., component placement or configuration, change in operator behavior or process), it must be considered an important design driver for accommodation considerations.

Any technological improvements or innovations made for displays, input devices, communications, or seating offer an opportunity for comparative experimentation to determine any potential improvement and benefit for inclusion in workstation design.

II. Physical Layout of Operator Station (Anthropometric Accommodation)

Currently available design standards such as MIL-STD-1472F, JSSG 2010-3, NASA-STD-3000, and BSR/HFES 100, etc. include lists of generalized anthropometric minimums and maximums to be used for workstation design. (Some of these are summarized in Appendix B.) While these standards (as well as many textbooks) typically do a good job of highlighting the anthropometric issues that need to be considered (e.g., factors related to workstation posture), the anthropometric measures they report are univariate percentile values generated from databases that do not necessarily represent the typical AOW population. And more importantly, these values are often presented in a way suggesting that combining a collection of extreme univariate values can be used to generate an anthropometric case of design interest. It was common practice in the past to combine a set of 5th percentile univariate values to build a "smallest" 5th percentile human model and 95th percentile values to generate a "largest" model, with the intent of accommodating 90% (5th through 95th) of the population that fall "between" these two percentiles. However, human models generated in this fashion do not represent anything close to real people. This univariate "tinker toy" assembly approach for constructing anthropometric cases does not reflect the body proportions that exist in real human populations, and the resulting design is sure to accommodate something other than the targeted 90%. Variation in human proportion is real, and for seated workstation design it is best described by the multivariate method employed by the US Air Force for cockpit accommodation (Zehner, Meindl, and Hudson 1993). Some of the standards do reflect this thinking, however. In JSSG-2010-3 (4.3.1) it clearly states that "A multivariate analysis shall be used to determine accommodation," while in MIL-STD-1472F (5.6.3) we are advised as follows:

> "New anthropometric technologies enabling measurements not previously possible are emerging. Designers should take advantage of these new capabilities to obtain new data to meet requirements in 5.6.2."

The statement above refers not only to applying a multivariate approach in the workstation layout methodology, but also to the use of the US Air Force's 3D anthropometric database known as CAESAR (Civilian American and European Surface Anthropometry Resource). Any future work should employ both the USAF multivariate method as well as the CAESAR 3D database to generate a statistical sample that represents the future population of operators for anthropometric considerations.

A. Sample Selection – Estimating the Operator Population

The first step in any accommodation analysis is to define the user population and then to estimate it with a statistical sample. The US Air Force has not had an anthropometric survey since 1967. The USAF population must be estimated using other sources of anthropometric data such as CAESAR. The AOW operators will be active duty men and women with a demographic makeup similar to that found in the Joint Strike Fighter (JSF) CAESAR anthropometric database (Hudson et al., 2003). This sub-sampling of CAESAR resulted in

646 men and 695 women that, when plotted in multivariate space, fall within the max/min boundary shell defined by the original JSF anthropometric cases (99%+ male accommodation, ~98% female). This 3D sample is now considered representative of Joint Service members that could become pilot candidates. This sample of body sizes was specified for procurement of the JSF (as well as the T-6) and is characterized with a broad stature range of 4'10" to 6'5".

Key points regarding the JSF CAESAR database include:

- This 3D sample was constructed by sub-sampling from the North American CAESAR database. It was done to augment the JSF *cockpit accommodation* anthropometric cases with a modern 3D database to be used specifically for JSF Personal Protective Equipment (PPE) issues.
- The subjects took three different body postures (2 seated, 1 standing) in order to be 3D laser scanned. The scans were stored along with the summary statistics of 40 traditional 1D anthropometric variables and 59 additional 1D measurements extracted from their scans.
- Any anthropometric dimension found to be lacking in the database, but considered important to AOW operator fatigue minimization, or accommodation, can be extracted from the 3D scans and included in the multivariate analysis.

B. Multivariate Method – Generation of AOW Anthropometric Boundary Cases

The first step in the multivariate method is to select anthropometric variables, or body dimensions, that are considered relevant to workstation design. Earlier work at AFRL on workstation design resulted in the analysis described below. This will be used as an example in subsequent sections. The 14 anthropometric variables (below in Table 1 and Figure 1) represent not only heights and lengths of the limbs and trunk, critical in workstation accommodation (black font), but also some lengths, breadths and circumferences associated with the ability to move around in the seat (red font) – a key behavior that helps to reduce fatigue, called "dynamic sitting," which is considered important to achieve optimum seating for prolonged periods (Grieco et al., 2003).

Table 1. Relevant Variables to AOW Workstation

Table 1
Relevant Variables to AOW Workstation
1. Thigh Clearance
2. Popliteal Height
3. Abdomen Depth
4. Buttock-Popliteal Length
5. Acromial Height, Sitting
6. Arm Length (Shoulder to Elbow)
7. Buttock-Knee Length
8. Elbow Height, Sitting
9. Eye Height, Sitting
10. Hip Breadth, Sitting
11. Knee Height, Sitting
12. Shoulder Breadth
13. Thigh Circumference Max Sitting
14. Thumb Tip Reach

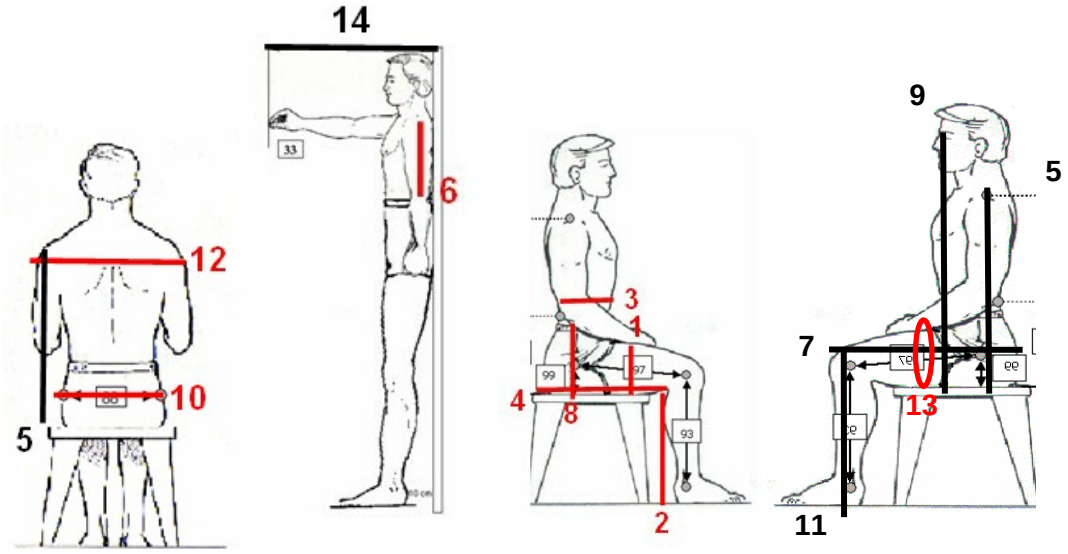

Figure 1. Location of Anthropometric Variables

A Principal Components Analysis (PCA) was run on the JSF CAESAR sample – men and women separately – to identify and quantify the important variation in the 14 variables above. In simple terms, the PCA is a multivariate analysis that finds and simplifies the simultaneous variation in a large set of variables by reducing them to a smaller set of new variables called "Principal Components." Details of this type of analysis are explained in depth in Appendix A. On the first component, or axis, all 14 variables increase or decrease together, hence we name this component "size." Thus, PC 1 or size, represents the greatest contributor to total variation in the sample and simply describes the presence of large and small people. In one direction of PC 2 the limb lengths increase while robustness of the subjects decreases. In the opposite direction on PC 2, the reverse is true - limb lengths

decrease as robustness increases. Thus, PC 2 describes the second most important contributor to variation – a contrast in limb lengths and robustness. PC 3 is also a contrast in body proportions – specifically, limb length and torso height.

Twenty-eight mathematical boundary cases representing a 95% accommodation for both men and women were derived from the output of the Principal Component Analysis. In the following analysis these cases were then reduced to 8 (4 men and 4 women) by removing overlapping extremes between the sexes: the smallest male, for example, was excluded because the smallest female would ensure his accommodation. Anthropometric values for these cases are listed in Appendix A. To visualize the anthropometric range in these cases, the JSF CAESAR scans for the "nearest neighbors" to the mathematical cases are contrasted in Figures 2 and 3 below. These are not photographs but rather color and texture maps on the raw range data of their body surfaces recorded during the whole-body laser scan.

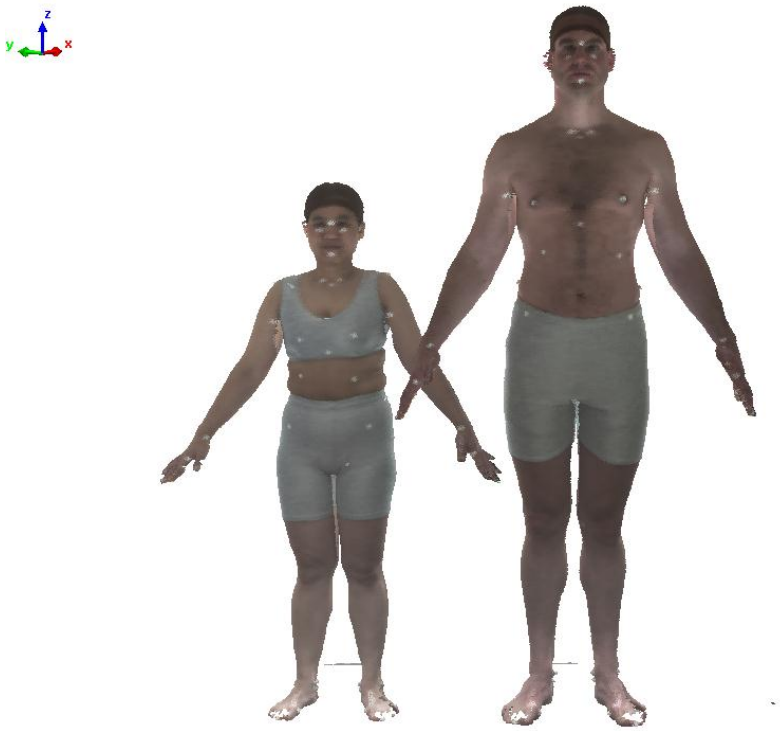

Figure 2. Comparison of Nearest Neighbor CAESAR Scans of the Overall Large Male and the Overall Small Female. These scans include color and texture mapping.

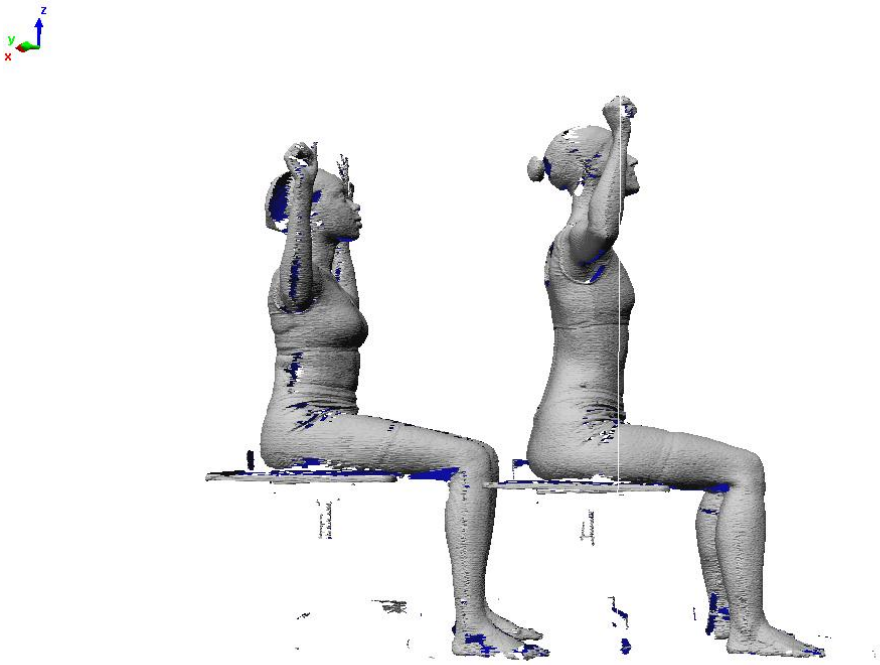

Figure 3. Contrast of Nearest Neighbor CAESAR Scans of a Female with a Short Torso and Long Limbs (left) vs. a Female with a Tall Torso with Short Limbs (right). These scans just show the polygonal model with no color mapping.

C. Visualization and Anthropometric Analysis in CAD

Throughout the design process for operator stations, Computer Automated Design (CAD) products such as CATIA, Pro/E, Unigraphics, etc. are typically used for a variety of reasons including creation, editing, and integration of the 3D geometry for the mechanical design drawings. For HSE accommodation work the inclusion of representative digital human models into the CAD geometry is essential for visualizing anthropometric problems and generating "first look" estimations of performance for the different anthropometric cases. However, Digital Human Models (DHM), like CATIA's V5 Human, lack realistic tissue and seat cushion deformation, as well as proper modeling of the effect of restraint systems, and are not considered replacements for live human subject testing in mock-ups. During a past study to standardize a validation method for DHMs, Oudenhuijzen, Zehner, and Hudson (2002) found great inaccuracies in the five major digital human modeling systems when they were compared directly to digital data taken from live subjects in a cockpit workstation. The greatest contributors to DHM error were identified as 1) initial positioning and posturing of the digital model in the seat, and 2) tissue and seat compression. Currently, AFRL is again collaborating with TNO (The Netherlands Organization) to create digital posture profiles (at rest and during reaches) that will serve as input files for the Safework model (now V5 Human as part of Delmia or CATIA). These posture profiles (specific to the operator seat) must be generated and used as input to the posture constraint editor. This method should result in a great increase in the fidelity of the V5 human models and improve any

anthropometric analyses conducted. Along with this information, the anthropometric dimensions offered by the AOW boundary cases (Appendix A), can be used as input to generate human models for preliminary accommodation analyses in the AOW operator station CAD model.

In addition, this line of study should be augmented with carefully chosen live subjects who are whole-body scanned while seated in the AOW seat. This should be done following the CAESAR protocol. Their anthropometry can then be used as input for generating V5 digital models. Anthropometric analyses with these models, enhanced with digitally recorded live subject performance data in the AOW seat, as well as with the seated scans, will greatly improve the accuracy of the results of any human model. Below in Figure 4, a female Safework model is illustrated that has been positioned with a digital posture profile; this is the actual position and posture for this subject while seated in an F-16 ejection seat.

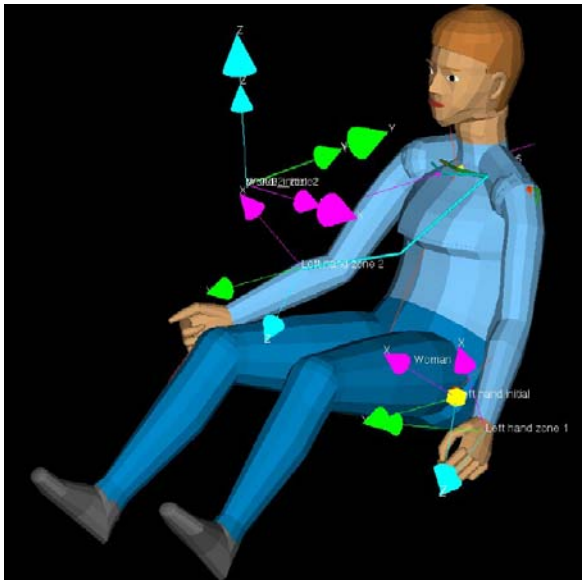

Figure 4. Female Safework Model Whose Posture Has Been Edited to Match Live Subject Data Seated in an F-16 Ejection Seat

In Figure 5, below, the CAESAR subject who is a “nearest neighbor” to the overall small female anthropometric case has been inserted into a CAD model of the AOW console. The CAESAR scan was segmented with cut-planes at the limb joints, pelvis, neck and trunk, and at the neck and head. A USAF program, INTEGRATE 2.8 (Burnsides 2004), was used to segment the scan, locate the joint centers, and then reposition the segments into an arbitrary seated work posture. The re-postured scan was then converted to a polygon mesh and imported to CAD as an IGES file. This was done simply for visualization of the small anthropometric case in the seat (particularly with respect to her 13.4” Popliteal Height), which was moved down and forward. The keyboard was rotated down and the monitor was moved toward the small female model and tilted up.

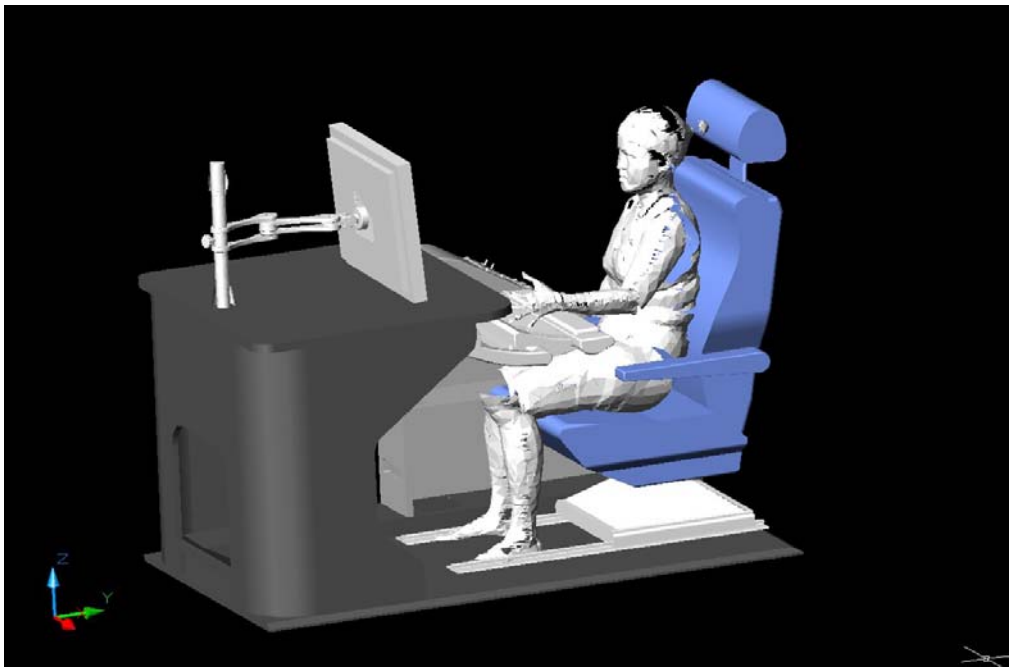

Figure 5. Nearest Neighbor CAESAR Scan to Overall Small Female Anthropometric Case – Segmented and Re-postured for Import to CAD Drawing

D. Accommodation Analysis

Calculation of the accommodation level for an AOW operator station is ultimately dependant on one question: *What do the operators need to do to complete the operator mission?* Or, more specifically, what are the physical requirements for viewing information on displays, for reaching equipment controls and input devices, and what actions and postures do they need perform? This inquiry also includes issues such as operational clearances between operator body parts and the console, as well as clearance during normal ingress/egress and emergency egress. To answer these questions a thorough AOW Operator Task Analysis is required. The list of these physical tasks and operational clearances makes up what are commonly known as the *functional requirements* to perform the mission in any given operator station. (For the USAF Cockpit Inventory Study the aircraft functional requirements were drafted by appointed groups of pilots, for each aircraft, and then signed off by their Command (Zehner and Hudson, 2002)).

The process of *fit mapping* the prototype operator workstation, which uses a sample of live subjects, will allow body size requirements (minimum and maximum values) to be assigned to the most critical of the functional requirements. This is done with a sample size large enough to allow statistical analysis. Variation between operators for initial position and posture in the seat, which is difficult to address, is included in the statistical distributions. The resulting set of critical anthropometric values from the analysis will define what is called the *accommodation envelope* for the prototype operator workstation. Using the parameters from the accommodation envelope and the JSF CAESAR database, it will be possible to estimate the accommodation

percentage for men and women and compare it to a specification (95% in MIL-STD-1472F 5.6.2.1). This fit mapping process verifies the accommodation level targeted, and assumed present, in the operator station based on design changes following digital human model analyses. Fit mapping is also an excellent method for identifying anthropometric problem areas in the operator station design.

III. Minimization of Performance-Reducing Fatigue

A. Operator Workstation Layout

Overall operator fatigue can be caused by many factors including sleep deprivation, perceived high or prolonged levels of emotional stress, and background cabin noise levels associated with flight, etc. With respect to the *layout* of the operator workstation, musculoskeletal fatigue generated by factors related to the posture and loading of the operator's body throughout time on station are of great concern. And more specifically, localized fatigue that causes a *reduction in mission effectiveness* should draw greatest focus and serve as design drivers.

Much of the past research in the Human Factors field has been focused on finding the ideal sitting posture for a seated workstation. However, sitting in any single posture, even a specified "optimum posture," for a long period of time will result in fatigue (Laville 1980). Grieco (2004:145 cit. Cantoni et al. 1984, Grieco 1986) states that no single posture should be maintained for a prolonged period and suggests that the optimum seating conditions are achieved through regular changes in posture. This is called "Dynamic Sitting" or "Posture Variation." This concept is most applicable to the AOW given the length of time on station for the operators. Hence, postural fixity is a real risk factor that needs to be addressed.

Controlled experimentation should allow quantification of the relationships between mission effectiveness and 1) a range of seated postures imposed by the workstation layout and its adjustability, and 2) duration in, and sequence of, these postures. At the conclusion of this extensive study it is anticipated that fatigue-minimizing "dynamic postural envelopes" would be defined for the set of AOW anthropometric cases (which estimate the range of body size and proportion in the operator population). To take advantage of these findings future operators could need training on the adjustment settings and timing sequence to achieve their specific postural envelopes. It is interesting to note that, during a workstation postural study, Henriques (1985) found that only 5% of computer workstation users had voluntarily adjusted their seat and other equipment. Grandjean (1987), as well, showed that computer operators moved only very occasionally and did not noticeably change posture. These studies suggest that fatigue flags are often ignored, or lost in the focus of work, until numbness and pain reach a noticeable level – but then it is often too late for prevention. It is possible that, for AOW development, timed posture changes that are driven automatically and obtained through integrated motors or pneumatic systems in the adjustable hardware could be developed (seat, keyboard tray, display, work surface, etc.).

Reach Zones

From a performance-based approach, a change of posture while conducting a repetitive task is considered not just evidence of discomfort, but also as a transition point from one type of movement to another - demarcating reach envelopes. When observing how people perform a simple reaching task, a person needs to introduce more parts of the body in order to reach the object as the distance of an object increases. At close distances the object can be reached simply by straightening an arm, an *arm-only reach*. As the reach distance increases, people will extend their shoulders forward and eventually have to lean forward, an *arm-and-torso reach*. At still farther distances a seated reach will no longer suffice and people will have to stand, a *standing reach*. Mark (1995) pointed out that there are two different types of maximum distance for each reach mode. One is the absolute maximum distance that a person could reach. This reach is as far as physically possible while conducting one type of reach (i.e., arm-only). This delineates the absolute critical boundary. The other type is the preferred maximum distance that a person would reach voluntarily with the same type of reach. This demarcates *preferred critical boundary*. Mark argued that people introduce other parts of their body at shorter distances than their absolute critical boundary for an arm-only reach, which indicates that the transition from arm-only reach mode to another mode would occur at their preferred critical boundary for their arm-only reach. This is because people rarely seem to commit to an extreme posture such as extending their arms or leaning forward as far as possible. Rather, people prefer to rotate their shoulder or lean their torso instead of extending their arm. Also, they would rather stand up to avoid an extreme forward lean. This result was repeated in follow-up studies (Mark et al., 1997; Gardner, Mark, Ward and Edkins, 2001) and showed that people tend to change their posture in order to avoid such extreme movements that would place them at increased risk for injury. These preferred postures during reach should be taken into account when defining the AOW workstation layout.

Choi et al. (2003) repeated similar experiments and observed how people actually reach on various azimuth lines, including the right shoulder plane, 30 and 60 degrees right of the right shoulder plane, and 15 and 30 degrees left of the right shoulder plane. It was observed that, on average, people introduced other parts of their body at 85% of their maximum arm-only reach distance and demonstrated a preference to stand up to complete a task when they reached 93% of their maximum seated reach capability. Hence, the final area actually reached by the same type of movement is smaller than its absolute maximum area of that movement and is considered the "comfort zone" for that reach. They argued that the reason for this trend may be due to the subject's attempt to minimize discomfort and fatigue. In other words, the selected posture is relatively the least uncomfortable (or the most comfortable) out of all the possible alternatives that could be used to complete the task. Therefore, the AOW layout should not only be based on minimum anthropometric dimensions to reach controls, but also include consideration for the relationship between maximum reach area and comfort zone, particularly for the smallest subjects.

Handedness

This preference-driven postural selection is also true for limb selection. Given that almost all people have a dominant hand, it was observed that the actual area of right and left hands used in uni-manual tasks was not symmetrical around the body median (Gabbard and Rabb, 2000; Stins,

Kadar and Costall, 2001). In general, people used their dominant hand voluntarily more often when they were allowed to use their preferred hand (Bryden, M.P., Singh, M., Steenhuis, R.E., and Clarkson, K.L., 1994). This trend is more distinctive when the required skill level of the task is increased. People tend to use their dominant hand more often when the task requires fine motor skills (moving a cup fully filled with water) than when the task is simple (picking up a small object). Also, it was reported that when people were instructed to perform the same task with their non-dominant hand in their dominant area (i.e., using the left hand in the right area for a strongly right-handed individual), the accuracy and speed were both impaired (Stins et al. 2001). Choi et al. (2006) varied object locations and observed subject hand selection during a simple reaching task. They pointed out that the boundary delineating right and left side for workstation layout was not observed at the body midline. Rather, the dominant hand was used throughout a larger region. They concluded that strongly right-handed people used their right hand up to their left shoulder plane for simple reaching tasks.

There have been a few other experiments to explain why people use their dominant (preferred) hand more often than their non-dominant hand. Recently, Farina et al. (2003) argued that muscles in the non-dominant side are more easily fatigued than those in the dominant side. They argued that this could be due to "long preferential use of the specific side." People use their dominant hand for longer periods of time, which causes gradual changes in the muscle fiber membranes of that side. This will eventually cause different performance levels between sides. Thus, when designing the workstation layout, handedness of the target population should be considered such that tasks with heavy loads or requiring fine motor skill could be easily accessed by the operators' dominant hand side without causing awkward postures.

Posture and Eye Position

Seated body posture is defined by the relative position of the body segments (head, neck, trunk, pelvis, and limbs) as the operator is supported by both the seat and the console. Past research on workstation posture offers specific optimal ranges for relative segment position to minimize fatigue. Most of these are documented in the design standards listed above (e.g., MIL-STD-1472F, etc.). As an example, the following discussion is a summary regarding the issues of display placement as it relates to eye position.

To minimize visual fatigue or eye strain in the ocular muscles, the display should be positioned for a downward gaze (below a horizontal from the eye) for all operators to view the entire screen (Jaschinski et al., 1998). Individual preferences for viewing distance seem to fall between 50 and 100 cm, while vertical down-look angles fall between horizontal and 15 degrees downward. In support of this, Psihogios et al. (1998) found that the preferred gaze down to the screen, for general computer users, ranged from horizontal to 17.5 degrees down. However, touch typists were found to prefer a gaze of 6 degrees below horizontal to their displays (Grandjean et al. 1983 and 1984). An interesting relationship between typing speed and posture has also been observed. For data input requiring high keystroke speeds, a forward lean of the trunk with the back supported by a back rest was preferred, while low keystroke speed is associated with leaning back into the seat at a greater angle (Berndsen & Delleman 1993).

In addition, De Wall et al. (1992) tested an optimal biomechanical posture in which the head's center of gravity would naturally fall above the axis of rotation, which would suggest that an up-look of just above horizontal would be best. However, with a large sample of CAD operators (who spent 90% of their time looking at the screen) it was found that their gaze angle ranged from 0 to 25 degrees downward, with 15 degrees down or lower being preferred. Apparently, other physiological factors influence the preferred downward gaze. Lower screen heights will also: 1) reduce the amount of exposed surface area on the eyeball, and hence reduce the drying out of eyes (Abe et al, 1995); as well as 2) avoid the muscle fatigue in the neck and upper back common with gaze angles above horizontal (Delleman 2004).

In another recent study, Allie, Purvis and Kokot (2005) recommended the optimum location of the display screen based on physical comfort as well as user preferences. They consider their conclusions to be a "middle ground approach," and suggest that the top of the display screen should be positioned no higher than 5 degrees below the horizontal line of sight (HLS) and the center of the display be no lower than at or 25 degrees below the HLS.

Results of most of these studies, on various body segments, found "preferred" posture as defined by their observations of subjects at their workstations. The implicit assumption is that the body will strike poses or postures that minimize discomfort and are therefore "optimal." For AOW workstation designs, controlled experiments should allow these "optimal" ranges to be determined and their real impact to mission effectiveness for representative AOW mission profiles quantified.

IV. Hardware Component Selection and Integration

A. Space Allowed

It is generally understood that the task of designing an AOW within environmental space limitations places physical design constraints on the console: footprint, height, weight, inter-console spacing, electrical/life support supply, and console features related to the reconfigurable mission suite layouts, etc. As described in sections above, operator-station-specific HSE work should focus on ensuring the desired physical accommodation level (95%+ for both men and women). This is characterized by research in the computer realm (i.e., refinement of anthropometric case definitions and their DHM generation for CAD analyses) as well as research in the laboratory (live subject studies to verify accommodation levels and to determine case-specific postural variation envelopes for maximizing mission effectiveness).

Any technological improvements or innovations made for displays, input devices, communications, or seating offer an opportunity for comparative experimentation in the lab to determine any potential benefit to upgrading the components of an AOW.

B. Displays

Flat-panel Liquid Crystal Displays (LCD) currently available are enormous space savers compared to the old clunky CRT boxes; they are also very adjustable, which is good for eye distance and downward gaze issues. A vibration laboratory (such as that in the Air Force Research Laboratory's Biomechanics Branch (AFRL/HEPA)) could be used to test their durability using aircraft-specific vibration profiles.

C. Seating

Designing to the concept of "Dynamic Sitting" or "Posture Variation" requires not just that operators of extreme size and proportion (defined by the AOW anthropometric cases) be accommodated in a particular console configuration afforded by hardware adjustments, but that they are also accommodated throughout a range of postures. This range of postures will be made possible not only by the obvious placement of hardware, but possibly by acquisition of new aircrew seats such as the Fixed Aircrew Seat Standardization System (FASS II), or a seat yet to be designed, or modifications to an existing seat as well as augmentation with foot rests and other support devices (Figure 6).

Figure 6. Foot Rests and Table-secured Arm Rests to Aid Operators in Varying Their Posture

Improved cushion technology (shape and materials) that allows better blood circulation and ventilation to the compressed thighs and buttocks will reduce "hot spot" areas characterized by localized pain, numbness, and sweat. It might also be feasible to explore seat modifications that include massaging devices as well as timed and automated movement of the seat, thereby moving the individual operator through their accommodated range of postural variation, which would be pre-defined based on their size and body proportion.

D. Measuring Comfort

The concept of comfort and discomfort must be defined prior to developing objective measurement methods. This definition will then inherently determine whether comfort and discomfort are measurable quantitatively. Because this concept - especially the "comfort" component - is a subjective feeling, how to define it is still not clear. Are they as closely related as two opposite ends on the same continuum? Or, are they two different structures affected by different sets of factors (Helander and Zhang, 1997; DeLooze, Kuijt-Evers and Van Dieën, 2003)? If they are dependent to one another, measuring either one would be enough to make

conclusions on both, because “no discomfort” would simply be interpreted as a state of comfort and vice versa. However, the state of “no discomfort” does not always mean comfort. It indicates that there is no noticeable physical pain. If a research purpose is to identify the causal factors of fatigue or pain symptoms and to ultimately reduce them, measurements should specifically focus on detecting those factors. Hence, depending on the focus of the research, the operational definition of comfort or discomfort should be operationally declared and the method used to quantify them must be determined accordingly.

There are two main methods for evaluating comfort or discomfort, i.e., subjective and objective measures (see Table 2). Subjective measures are questionnaires that include a list of questions regarding emotional feelings about either a specific body part or about the body as a whole, and having the subjects rank them on a point scale. Using the rank values, one could directly measure the level of comfort or discomfort of the subject. However, this questionnaire method is hard to quantify because the rating is based on personal preference or expression with no control for the bias. The scores cannot be compared between subjects without standardization. On the other hand, objective measures such as electromyography (EMG), pressure distribution or oxygen uptake are quantifiable, but they are indirect measurements; that is, they do not indicate comfort or discomfort directly. Only when there is a significant connection (high correlation) between the objective measurements with the subjective state of comfort or discomfort can the output be interpreted in terms of comfort or discomfort (DeLooze et al., 2003).

The accommodation laboratory at Wright-Patterson Air Force Base (WPAFB) has conducted several experiments in an effort to understand comfort-related effects on performance in various operator environments. According to previous research on seat comfort/fatigue, physical pain and strain were highly related to discomfort, while comfort was assessed by feelings of well-being and relaxation (Helander & Zhang, 1997; Helander, 2003). Most of the time, experiments on flight seats have examined fatigue, safety, and health, and their effects on performance. A series of tests have been conducted to develop quantitative methods for determining seat cushion comfort during long-term sitting in confined cockpits. The eventual goal of these tests is to maximize comfort and performance by defining seat and seat cushion parameters (Parakkat, Pellettiere, Reynolds, Sasidharan & El-Zoghbi, 2006). The rationale behind these experiments is that if the relationship among discomfort, performance and the cushion parameters (i.e., size, material, dynamic characteristics) could be explained quantitatively, then the effects that cause fatigue or symptoms such as blood pooling or numbness due to long-duration mission could be mitigated. Additionally, the performance profile over time of target populations may be predicted based on discovered facts (i.e. cushion characteristics). This series of tests included over 200 eight-hour continuous seated test sessions on operational and prototype ejection seat cushions, including static and dynamic configurations. Peak pressure, muscular fatigue, lower extremity oxygen saturation, performance scores, and subjective discomfort data were collected over the course of the 8 hours. Research findings indicate that pressure distribution characteristics, including magnitude of pressure and contact areas, are highly correlated with comfort. Additionally, cushions may be ranked according to ability to mitigate muscular fatigue, prevent lower extremity blood pooling, and maintain task performance over time. By continuing this research effort, predictive models of seated comfort may be developed. These models are necessary to understand the level at which comfort affects performance in cognitively demanding situations and may be used in varied operator environments.

Interestingly, similar biomechanical and physiological problems facing aircrew also affect ground control station operators, and thus findings targeted toward the pilot population can readily transcend into applications for control station operators. The accommodation laboratory has investigated effects of workstation adjustability and fit to the operator in order to identify appropriate performance measures that must be employed to delineate between optimum and sub-optimum workstation configurations. The results indicated that workstation configuration affects postural adaptation and muscular fatigue, subjective levels of discomfort, task performance and cerebral oxygenation. Even the short tasking time of 80 minutes affected posture adaptation, muscular fatigue and discomfort. Operation time increases subjective levels of discomfort at a faster rate for the poorly accommodated workstation. During missions exceeding several hours in length, the physical effect of the control station could be further exacerbated and could lead to effects on the operator's cognitive performance. The results also indicated that regional cerebral oxygenation monitoring may be used as a potential predictor of performance degradation.

For workstation designs, it is important to consider all sizes of potential users when designing for comfort. In addition, designs must take into consideration the effect of synergistic positioning of all components of the workstation on all of the operator's body components. As demonstrated in the above investigational efforts, the cognitive implications of the mission will go hand-in-hand with the physical ergonomics, perhaps more noticeably for longer missions. Simply put, that which needs constant attention must be easy to monitor and controls that are used most often must be easy to reach and manipulate in order to maximize the operator's physical ability to perform the tasks and to sustain optimal mission performance.

Table 2. Evaluation Measures

Measurement		Outcome	Detecting
Subjective	LPD (Local Postural Discomfort)	12-point scale, 0-no discomfort, 11-maximum discomfort	Discomfort
	Overall physical condition	10-point scale, 1-bad, 4-not well, 7-OK, 10-great	Comfort/Discomfort
Objective	Pressure	Pressure distribution in different color coding within contact area	Potential discomfort factor (hot spot)
	EMG (Electromyography)	Median frequency of target muscle activity	Muscular fatigue
	Oximeter (Oxygen saturation)	Oxygen saturation of the tissues on the target area (below the buttocks region for seat comfort)	Localized oxygenation level (comfort and tolerance relationship)
	*Working posture Liao and Drury (2000)	Frequencies of postural shift or changes in joint angles	Noticed discomfort
	*Stadiometer Van Dieën et al(2001)	Stature loss/gain	Potential load on spinal column

*Object methods found from literature search, but not used in the experimentations done in Accommodation Laboratory at WPAFB

V. Discussion

Each of the areas discussed above (physical accommodation, comfort/fatigue quantification and operator-preferred reach postures) must be considered in the context of mission performance. If an operator physically does not fit into a work area (too small to reach controls or too large to fit between a fixed seat and the operator work surface), performance will obviously be degraded. If there is discomfort from the head up-look angle or hot spots from the seat are intense, performance will again suffer. These examples are of extreme situations. Our current challenge is attempting to quantify these areas of accommodation and comfort/fatigue so that comparisons between prototype workstations can be made. Eventually, we should be able to identify slight effects and improvements in performance. If successful, these methods could and should be used to improve design philosophy and techniques for Advanced Operator Workstations.

Appendix A. Multivariate Accommodation Method

Principal Components Analysis

Principal Components Analysis (PCA) can be helpful in both understanding the relationship between relevant measurements and in reducing the set of dimensions to a small manageable number. This technique, which was pioneered by Bittner et al. (1986 & 1987) has been effectively applied to aircraft cockpit crew station design (Zehner, Meindl, & Hudson 1993; Zehner, 1996) and will prove just as useful for AOW.

Generally, for any design problem the important human dimensions have some relationship with each other. For example, Sitting Height and Sitting Eye Height are highly correlated. The paired relationships between a set of dimensions can be expressed as either a correlation or a covariance matrix. PCA uses a correlation or covariance matrix and creates a new set of variables called "principal components," which can be envisioned as a rotated coordinate axis system lying in the multivariate distribution; its origin is the center of the multivariate distribution. The total number of principal components is equal to the number of original variables, and the first principal component will always represent the greatest amount of variation in the multivariate distribution. The second principal component describes the second greatest, and so on. An examination of the relative contributions, or correlations, of each original dimension and a particular principal component can be used to interpret and "name" the component. For example, the first principal component usually describes overall body size, and is defined by observing a general increase in the values for the original anthropometric dimensions as the value, or score, as the first principal component increases.

The premise in using PCA for accommodation case selection is that if most of the total variability in the distribution can be represented in the first two or three components, then the PCA approach can be used to select the cases to achieve a designated level of accommodation. For example, to write the anthropometric specifications for cockpit design in the JPATS (Joint Primary Air Training System) aircraft, Zehner et al. (1996) used the first and second principal components from a PCA on six cockpit-relevant anthropometric dimensions. The first two components explained 90% of the total variability for all six combined measurements. This was approximately the same for each gender (conducted in separate analyses). They then used a 99.5% probability ellipse on the first two principal components to select the initial boundary cases. One of the genders is shown below in Figure A1. Combination of the initial set of cases from both genders (with some modification) resulted in a final set of JPATS cases that offered a final accommodation of 95% for the women and 99.9% for the men. The first principal component was defined as size, while the second was a contrast between limb length and torso height (short limbs/tall torso vs. long limbs/short torso).

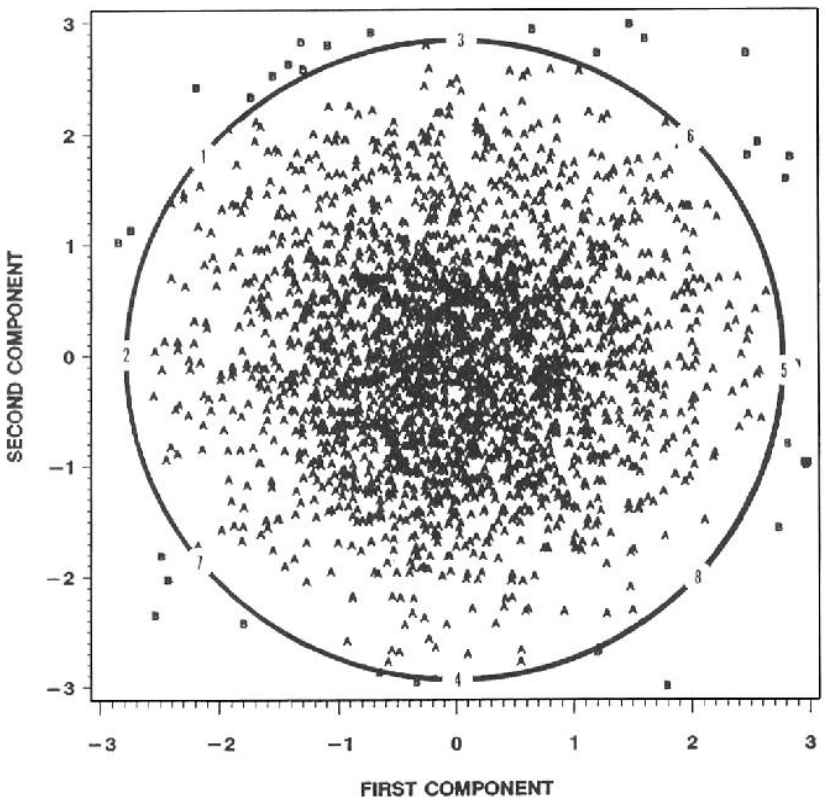

Figure A1. PCA Bivariate and 99.5% Boundary for the First and Second Principal Components for One Gender of the JPATS Population. Initial cases 1-8 for this gender are regularly distributed around the boundary shape.

Unlike compiled percentile methods (or compiled bivariate approaches when there are more than two variables), the multivariate principal component analysis takes into account the simultaneous relationship of three or more variables. However, since all of the dimensions put into the analysis are given equal weight, accommodation based on the components will include some of the variability of the possibly less important dimensions at the expense of the more important ones. Hence, the principal component method for finding representative cases is ideally applied when the relative proportions of all the variables *at once* are *equally* important to the solution.

Careful selection of variables for the principal component analysis is the key to its success. The variables must characterize the application environment as well as offer relevant combinations of anthropometric measures. It is not advisable to include sets of dimensions that are highly correlated and redundant in the design approach. Instead, pick a key dimension that represents them all. For example, Stature will be highly correlated with both Buttock-Knee Length and Torso Height. If it is not truly required as part of the design it should not be included in the PCA. Large numbers of highly correlated (and redundant) variables could influence the alignment of the principal component axis system and erroneously define the principal components – and possibly submerge the variable relationships that need highlighting for an efficient anthropometric design.

It is equally important to set an acceptable level for explained variance in the model (ex. 90% variance explained by Principal Components 1 and 2 in the above cockpit example). This threshold, set by the researcher, determines the number of principal components required, which in turn affects the number of cases necessary to represent the boundary shell. If it takes five components to explain 90% of the variability in the distribution, the number of cases, regularly distributed on the 5-D boundary shell, can become staggering.

In addition, after cases are selected based on the PCA method, it is advisable to compare the sample anthropometry, subject by subject, against the minimum and maximum anthropometric values offered by the PCA cases. The resulting percentage of those accommodated, from this "Yes/No" check, should be compared to the original desired level of accommodation.

PCA can also be used to calculate simply the strength of correlation between dimensions. This can help identify the variable to select as the most important single dimension to represent a set of related dimensions, thus offering a mathematical approach for picking a "key dimension" for use in the design.

Finally, the multivariate principal component solution to accommodation assumes that proportions between all variables are relevant to the application. This will not always be the case, however. It is possible that, for an aspect of a given application, a range or threshold for an anthropometric dimension becomes critical, while at the same time other dimensional values have no bearing. To use the cockpit application as an example, knee clearance with the canopy bow during an ejection involves only one critical body dimension. To avoid collision, the Buttock-Knee Length of the pilot must be short enough to ensure clearance. During an ejection, the relationship of Buttock-Knee Length to the pilot's other dimensions is of no concern, but during normal flight its proportion to other dimensions is relevant. Because ejection survival is a no-compromise issue, an adjustment to, or the inclusion of, a representative case reflecting this Buttock-Knee Length maximum, plus a safety factor, is appropriate in the accommodation model. Because real-world applications are not always ideal, modification of the representative cases generated from a principal component solution might be needed to construct a more useful and practical model for accommodation.

JSF CAESAR PCA for AOW 14 Variables.

Tables A1 and A2, below, report the result from the Principal Component Analysis (PCA) for JSF CAESAR women and men, respectively. Any eigen value over 1.0 indicates a meaningful principal component and is retained. The remainder of the 14 principal components is removed (PC4 – PC14). For both analyses, you can see that Principal Component 1, *overall size*, is the dominant contributor to variation in the distribution, while the *robustness/limb length contrast* (PC2) and *limb/torso height contrast* (PC3) contribute almost equally to the total variance. The 3 PC solution explains over 77% for women and over 79% for men for the total variation in their respective distributions.

Table A1. Women's Principal Component Analysis

PC #	Eigenvalue	% Variance Explained	Cumulative
1	6.20	44.3	44.3
2	2.50	17.9	62.2
3	2.09	15.0	77.1

Table A2. Men's Principal Component Analysis

PC #	Eigenvalue	% Variance Explained	Cumulative
1	7.01	50.1	50.1
2	2.19	15.7	65.8
3	1.90	13.6	79.3

Table A3. Factor – Variable Correlations (Loadings) for Both Women and Men PCAs

	Women			**Men**		
	Factor 1	**Factor 2**	**Factor 3**	**Factor 1**	**Factor 2**	**Factor 3**
1. Thigh Clearance	-0.551092	-0.484645	-0.056432	-0.493558	-0.432388	-0.247598
2. Popliteal Height	-0.752046	0.519554	0.201751	-0.814950	0.467303	-0.020562
3. Abdomen Depth	-0.314196	-0.703031	0.036867	-0.419506	-0.601129	-0.221455
4. Buttock-Popliteal Length	-0.819186	0.021620	0.292095	-0.816794	0.272541	-0.243041
5. Acromial Height, Sitting	-0.613873	0.290628	-0.701286	-0.700907	-0.007223	0.676206
6. Arm Length (Shoulder to Elbow)	-0.752388	0.325678	0.204864	-0.764091	0.364609	-0.107583
7. Buttock-Knee Length	-0.881925	-0.043095	0.288341	-0.897732	0.172792	-0.220361
8. Elbow Height, Sitting	-0.100173	0.054879	-0.957412	-0.216263	-0.309465	0.891659
9. Eye Height, Sitting	-0.638950	0.355708	-0.570611	-0.713193	0.089877	0.588966
10. Hip Breadth, Sitting	-0.600572	-0.625508	-0.106737	-0.725234	-0.504808	-0.028539
11. Knee Height, Sitting	-0.867147	0.308525	0.178637	-0.901475	0.320812	-0.067911
12. Shoulder Breadth	-0.567430	-0.359922	-0.096361	-0.608193	-0.496285	-0.110391
13. Thigh Circumference Max Sitting	-0.593675	-0.711073	-0.126263	-0.634645	-0.642315	-0.195654
14. Thumb Tip Reach	-0.797802	0.245453	0.187907	-0.844574	0.263684	-0.122197

In Table A3, above, the principal component (factor), correlations with the anthropometric variables are listed for both men and women. This is used to determine the groups of variables that get large or small together, or contrast (go up while the other goes down) as you move through the distributions. The principal components are interpreted (named) as follows: PC 1 – Overall Size, PC 2 – Contrast of Robustness/Limb Length, PC 3 – Contrast of Torso Height/Limb Length. The variables in black font represent those traditional for physical accommodation in aircraft cockpits (i.e. clearance, reach, etc.), while those in red font are variables selected because of their relationship to fatigue reduction and mission performance.

AOW Anthropometric Case Generation

Representative cases from the distribution are selected based on the accommodation level desired in the workstation. For AOW, we would like greater than 95% accommodation. Since our multivariate analysis resulted in three PCs, or dimensions, 95% of the JSF CAESAR distribution, in principal component space, can be contained by a sphere. Below, in Figure A2, this is shown around the women's distribution – 95% are included in the sphere of accommodation. We operate under the assumption that if the workstation accommodates the extreme sizes and proportions represented by anthropometric cases on the surface of the sphere, then all inside are accommodated. Fourteen mathematical boundary cases from the surface of the shell are selected geometrically from the intersections of the Principal Component Axes and the sphere (Model Points 1 through 6) and at the center of each octant (Model Points 7 through 14). This is done for both the men and women, resulting in 28 boundary cases (below in Tables A4 and A5) for each sex.

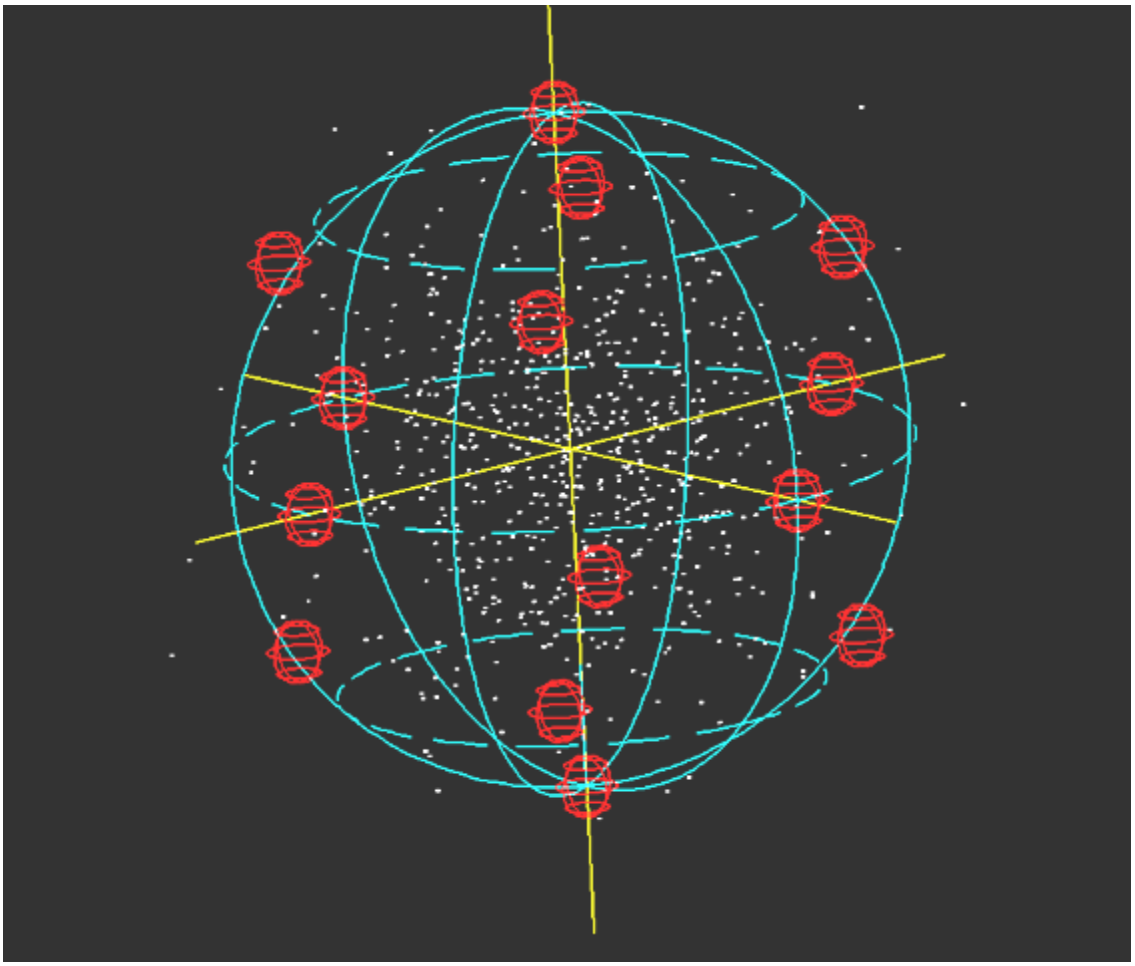

Figure A2. 95% Accommodation Sphere

Table A4. Women: Model Point Variable Values

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Thigh Clearance	4.8	4.9	5.6	6.4	6.4	5.7	4.7	5.7	5.5	4.8	6.6	5.6	5.7	6.5
2. Popliteal Height	13.4	17.1	16.2	17.8	14.1	15.0	15.5	18.1	13.8	14.9	15.6	13.1	17.4	16.3
3. Abdomen Depth	8.6	7.2	9.8	10.8	12.2	9.6	7.7	9.0	10.6	7.5	11.7	10.4	8.8	11.9
4. Buttock-Popliteal Length	15.8	18.6	19.5	21.3	18.5	17.6	17.6	20.7	17.5	16.5	19.5	16.4	19.6	20.6
5. Acromial Height, Sitting	20.3	23.3	20.0	24.4	21.4	24.7	20.4	22.8	19.3	23.1	24.3	22.0	25.5	21.6
6. Arm Length (Shoulder to El	10.6	13.1	12.8	14.0	11.6	11.9	12.0	14.0	11.2	11.5	12.6	10.6	13.5	13.2
7. Buttock-Knee Length	19.7	22.7	23.9	26.0	23.0	21.8	21.6	25.1	21.7	20.4	24.1	20.6	24.0	25.3
8. Elbow Height, Sitting	9.0	9.4	6.4	9.6	9.1	12.1	7.6	7.9	7.4	10.8	11.0	10.6	11.2	7.7
9. Eye Height, Sitting	27.3	31.3	27.6	32.4	28.5	32.1	27.9	30.8	26.3	30.5	31.8	28.9	33.4	29.2
10. Hip Breadth, Sitting	13.4	13.3	15.1	17.6	17.7	15.9	12.8	15.2	15.3	13.2	18.2	15.8	15.7	17.7
11. Knee Height, Sitting	17.3	21.1	20.6	22.9	19.1	19.5	19.4	22.6	18.2	18.7	20.8	17.5	21.9	21.4
12. Shoulder Breadth	15.0	15.6	16.3	18.0	17.5	16.8	15.0	16.7	16.1	15.3	18.1	16.4	17.0	17.8
13. Thigh Circumference Max	19.8	19.2	22.2	26.0	26.6	23.5	18.5	22.1	22.9	19.3	27.2	23.6	22.9	26.4
14. Thumb Tip Reach	25.5	30.0	29.8	32.4	27.9	28.2	28.1	32.1	26.8	27.1	29.9	25.9	31.1	30.8

Table A5. Men: Model Point Variable Values

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Thigh Clearance	5.5	5.6	6.0	7.4	7.3	6.9	5.2	6.3	6.1	5.7	7.7	6.7	6.8	7.2
2. Popliteal Height	14.8	19.0	17.4	20.1	15.9	17.5	16.8	19.8	15.0	16.8	18.1	15.1	19.9	18.1
3. Abdomen Depth	9.0	8.4	9.7	11.8	12.4	11.2	8.1	9.7	10.4	8.9	12.8	11.2	10.5	12.0
4. Buttock-Popliteal Length	16.1	20.0	18.2	22.0	18.1	19.9	17.4	20.8	16.3	18.4	20.7	17.3	21.8	19.7
5. Acromial Height, Sitting	21.1	23.7	26.4	26.5	23.8	21.2	23.7	26.8	23.7	20.7	23.8	20.7	23.8	26.8
6. Arm Length (Shoulder to El	11.4	14.2	13.0	15.2	12.4	13.6	12.6	14.8	11.5	12.9	14.0	11.8	15.1	13.7
7. Buttock-Knee Length	20.7	24.8	23.3	27.5	23.4	24.9	22.0	26.0	21.2	23.0	26.2	22.2	26.9	25.2
8. Elbow Height, Sitting	8.7	8.4	12.2	10.1	10.4	6.6	10.1	10.9	11.2	6.8	8.8	8.0	7.6	12.0
9. Eye Height, Sitting	28.6	32.3	34.6	35.2	31.5	29.2	31.8	35.6	31.3	28.7	32.0	28.2	32.5	35.1
10. Hip Breadth, Sitting	12.4	13.0	14.4	16.7	16.0	14.6	12.4	14.9	14.1	12.5	16.7	14.2	15.0	16.6
11. Knee Height, Sitting	18.7	23.2	21.8	25.3	20.8	22.3	20.6	24.5	19.3	20.9	23.4	19.6	24.8	23.1
12. Shoulder Breadth	17.1	17.5	18.8	21.2	20.8	19.5	16.8	19.1	18.7	17.2	21.5	19.1	19.6	21.1
13. Thigh Circumference Max	19.9	19.9	22.2	26.6	26.6	24.3	18.8	22.6	22.7	20.0	27.7	23.8	23.8	26.5
14. Thumb Tip Reach	27.6	33.1	31.2	36.1	30.5	32.4	29.8	34.7	28.3	30.5	33.9	29.0	35.4	33.1

However, 28 anthropometric boundary cases are not necessary to ensure the 95% accommodation for men and women. Instead, for this preliminary work we will assume that the boundary cases located at the axis intercepts will suffice. This trims us down to a more manageable 12 cases; however, some of these are redundant. For example, the largest overall female is eclipsed by the overall large male (PC 1 cases). Hence, she is not needed to represent an extreme large size and is omitted. This is done again for the Robustness/Limb Length Contrast on PC 2, and here the male is omitted because the short-limbed, robust female is more extreme in contrast. In addition, the slight male with long limbs is retained while the female is removed. And finally, the smallest male is removed, who is certainly covered if we accommodate the overall smallest-sized female. That leaves 8 mathematical anthropometric boundary cases, 4 men (M) and 4 women (W), that are listed below in Table A6. For PC 3, Torso Height/Limb Length contrast, both extremes for both sexes are kept at this time. If any are

found to be redundant, they can be omitted later. Summary statistics for the 14 variables are reported in Table 7 (women) and Table 8 (men).

Table A6. Boundary Anthropometric Cases

	Females (inches)				Males (inches)			
Case Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Matematical Model Point:	W1	W3	W6	W5	M6	M2	M4	M3
Thigh Clearance	4.8	5.6	5.7	6.4	6.9	5.6	7.4	6.0
Popliteal Height	13.4	16.2	15.0	14.1	17.5	19.0	20.1	17.4
Abdomen Depth	8.6	9.8	9.6	12.2	11.2	8.4	11.8	9.7
Buttock-Popliteal Length	15.8	19.5	17.6	18.5	19.9	20.0	22.0	18.2
Acromial Height, Sitting	20.3	20.0	24.7	21.4	21.2	23.7	26.5	26.4
Arm Length (Shoulder to Elbow)	10.6	12.8	11.9	11.6	13.6	14.2	15.2	13.0
Buttock-Knee Length	19.7	23.9	21.8	23.0	24.9	24.8	27.5	23.3
Elbow Height, Sitting	9.0	6.4	12.1	9.1	6.6	8.4	10.1	12.2
Eye Height, Sitting	27.3	27.6	32.1	28.5	29.2	32.3	35.2	34.6
Hip Breadth, Sitting	13.4	15.1	15.9	17.7	14.6	13.0	16.7	14.4
Knee Height, Sitting	17.3	20.6	19.5	19.1	22.3	23.2	25.3	21.8
Shoulder Breadth	15.0	16.3	16.8	17.5	19.5	17.5	21.2	18.8
Thigh Circumference Max Sitting	19.8	22.2	23.5	26.6	24.3	19.9	26.6	22.2
Thumb Tip Reach	25.5	29.8	28.2	27.9	32.4	33.1	36.1	31.2

Table A7. Female Summary Statistics

	Valid N	Mean	Minimum	Maximum	Std.Dev.
Thigh Clearance	685	5.6	4.3	7.1	0.47
Popliteal Height	692	15.6	12.8	19.2	0.94
Abdomen Depth	690	9.7	7.1	13.1	1.14
Buttock-Popliteal Length	693	18.6	15.5	21.8	1.07
Acromial Height, Sitting	693	22.4	19.3	26.5	1.08
Arm Length (Shoulder to Elbow)	694	12.3	10.1	15.5	0.74
Buttock-Knee Length	695	22.9	20.0	26.5	1.15
Elbow Height, Sitting	694	9.3	5.7	12.0	0.97
Eye Height, Sitting	692	29.9	26.1	34.3	1.28
Hip Breadth, Sitting	695	15.5	12.8	19.4	1.12
Knee Height, Sitting	695	20.1	17.5	24.0	1.04
Shoulder Breadth	695	16.6	14.2	19.3	0.85
Thigh Circumference Max Sitting	695	22.9	18.5	28.8	1.70
Thumb Tip Reach	695	29.0	25.2	33.8	1.40

Table A8. Male Summary Statistics

	Valid N	Mean	Minimum	Maximum	Std.Dev.
Thigh Clearance	626	6.5	4.8	8.3	0.61
Popliteal Height	644	17.5	14.6	21.3	1.04
Abdomen Depth	637	10.5	8.0	13.7	1.06
Buttock-Popliteal Length	643	19.1	15.8	23.2	1.15
Acromial Height, Sitting	646	23.8	20.2	27.6	1.23
Arm Length (Shoulder to Elbow)	646	13.3	10.2	16.0	0.81
Buttock-Knee Length	646	24.1	20.6	27.9	1.23
Elbow Height, Sitting	646	9.4	5.7	12.2	1.01
Eye Height, Sitting	646	31.9	28.0	35.9	1.48
Hip Breadth, Sitting	646	14.5	12.0	17.9	0.95
Knee Height, Sitting	646	22.0	18.7	25.9	1.18
Shoulder Breadth	646	19.2	16.0	22.1	1.06
Thigh Circumference Max Sitting	646	23.3	18.2	27.8	1.67
Thumb Tip Reach	646	31.8	27.5	36.3	1.60

Appendix B. Relevant Workstation Dimensions from Available Standards

Currently available design standards such as MIL-STD-1472F, JSSG 2010-3, NASA-STD-3000, and BSR/HFES 100 were reviewed to be compared with the recommendations from PCA. Out of those four design standards, MIL-STD-1472F was qualified for the comparison. JSSG 2010-3 and NASA-STD-3000 have no specific dimensional recommendation on the workstation layout and BSR/HFES 100 is a draft standard being updated, so the recommended dimensions from it might soon be out-dated.

Seated workstation dimensions from MIL-STD-1472F were first summarized as follows.

Work Surface: Lateral work space not less than 30 inches wide and 16 inches deep is desired, with a writing surface 24 inches wide and 16 inches deep. The work surface should be between 29 and 31 inches above the floor. Knee and foot room not less than 25 inches high and 20 inches wide and 18 inches deep should be provided beneath the work surface.

Seating: The seating shall provide an adequate support framework for the user population to perform mission functions without degradation of their alertness, cognition, strength or dexterity and without significant or lasting pain or injury.

Seat pan and vertical adjustment: Seat pan should have a height from the floor adjustable from 15 to 21 inches in increments of no more than one (1) inch each. If the seat height exceeds 21 inches or cannot be lowered to 15 inches, a foot rest should be provided. The seat pan should have from 0 to 7 degrees rearward tilt, be between 15-18 inches wide and not more than 16 inches deep.

Footrest: If provided, footrests should contain at least 12 inch deep by 12-16 inch wide non-skid surfaces, and should be adjustable in both height and inclination.

Backrest: A supporting backrest should be capable of reclining at least between 100-115 degrees. The width should be at least 12-14 inches and shall engage the lumbar and thoracic regions of the back, and support the torso such that the operator's eyes can be brought to the "Eye Line" with no more than 3 inches of forward body movement.

Armrests: Modified or retractable armrest to maintain compatibility with associated work surface and ingress/egress shall be provided. Armrests integral to the chair and at least 2 inches wide and 8 inches long shall be provided. The armrest should be adjustable from 7.5 to 11 inches above the compressed sitting surface. The distance between armrests should be not less than 18 inches.

Control Placement: Typical controls mounted on a vertical surface should be located 8-34 inches above the sitting surface. Controls requiring precise or frequent operation should be 8-29 inches above the sitting surface.

Display Placement: Normal displays mounted on vertical panels should be located 6-46 inches above the sitting surface. Displays requiring precise and frequent reading should be located in an area 14-35 inches above the sitting surface and no further than 21 inches laterally from center line. The viewing distance from the eye reference point should be between 25-30 inches, governed by legibility of the smallest display detail. At greatest viewing distance the visual angle subtended by height of black and white characters should be not less than 4.6 mrad (16 min of arc) with 6.1 mrad (21 min) for colored characters.

To compare the recommended values for seated operations in MIL-STD-1472F with values from PCA boundary cases, each dimension was investigated to see whether the comparison is available and necessary. Out of all recommended workstation dimensions, a subset of those was selected. For example, workstation top surface width is not selected for the comparison because the rationale for finding its corresponding body dimension is insufficient and the recommended value for workstation top surface width is dependent upon the tasks. However, the bottom of workstation surface width is compared with the maximum hip breadth value from PCA to make sure there is no clearance issue. The following dimensions listed in Table B1 were selected.

Table B1. Comparison of Standard Measurements and PCA Cases

Workstation	(Corresponding relevant) Body dimension	MIL-STD-1472F		PCA Boundary cases	
		Min	Max	Min	Max
Work surface (bottom) for Knee room					
Height	Popliteal height + Thigh clearance	Not less than 25		18.3	27.5
Width	Seat pan width (+armrest width 2 in each)	Not less than 20		13.0 (17)	17.7 (21.7)
Depth	(buttocks-knee length) - (abdomen depth)	Not less than 18		7.5	19.1
Seating (Seat pan and Armrest)					
Seat pan height	Popliteal height	15	21	13.4	20.1
Seat pan width	(At least) Hip breadth	15	18	13.0	17.7
Seat pan depth	Buttock-popliteal length	Not more than 16		15.8	22.0
Armrest height	Elbow height (sitting)	7.5	11	6.4	12.2

Based on the comparison between MIL-STD-1472F and PCA boundary cases, workstation dimensions for the knee room and armrest height are recommended to be reconsidered. Knee room not less than 28 inches high and 20 inches deep should be provided beneath work surfaces. If the chair with armrests is used, knee room should be not less than 22 inches wide (18 inches for seat pan clearance with 2 inch armrests on both sides). The minimum value recommended for armrest height in the current standard is about one inch greater than that from PCA boundary cases, and the maximum value is one inch smaller - which provided 2 inches less adjustment range than the PCA boundary cases. Hence, to accommodate up to 95% of AOW cases, the current dimensions recommended in MIL-STD-1472F standard should be updated based on the most recent anthropometric database.

References

Abe, S., Sotoyama, M., Taptagaporn, S., Saito, S., Villanueva, M.B.G., and Saito, S. (1995). Relationship between vertical gaze direction and tear volume. In Grieco, A., Molteni, G., Piccoli, B., and Occipinti, E. (eds.) *Work with Display Units 94*. Amsterdam, Elsevier Science, pp. 95-99.

Allie, P., Purvis, C. and Kokot, D. (2005). Computer display viewing angles: Is it time to shed a few degrees? Proceedings of Human Factors and Ergonomics Society 49th Annual Meeting.

Berndsen, M.B., and Delleman, N.J. (1993). Guideline on the viewing angle for touchtyping VDU workers. In Luczak, H. Cakir, A., and Cakir G. (eds.) *Work with Display Units 92*. Amsterdam: North Holland/Elsevier Science, pp. 476-480.

Bittner, A.C., Glenn, F.A., Harris, R.M., Iavecchia, H.P., & Wherry, R.J. (1987). CADRE: A family of mannikins for workstation design. In Asfour, S.S. (ed.) *Trends in Ergonomics/Human Factors IV*. North Holland: Elsevier, pp. 733-740.

Bittner, A.C., Wherry, R.J., Glenn F.A. (1986). CADRE: A Family of Manikins for Workstation Design. (Report No.: 2100.07B) Man-Machine Integration Center, Naval Air Development Center, Warminster, Pennsylvania.

Bryden, M.P., Singh, M., Steenhuis, R.E., and Clarkson, K.L., (1994). A behavioral measure of hand preference as opposed to hand skill, Neuropsychologia, 32, 991-999.

Burnsides, D.R. (2004). INEGRATE 2.8: A New Generation Three Dimensional Visualization, Analysis, and Manipulation Utility. (Publication No.: AFRL-HE-WP-TR-2004-0169). AFRL/HECP, Wright-Patterson AFB, OH.

Cantoni, S., Colombini, D., Occhipinti, E., Grieco, A., Frigo, C., and Pedotti, A. (1984). Posture analysis and evaluation at the old and new work place of the telephone company. In Grandjean, E. (ed.) *Ergonomics and Health in Modern Offices*. London, Taylor & Francis, pp. 455-464.

Choi, H. J., Mark, L. S., Dainoff, M. J. and Harvey, T. M. (August, 2003). A performance based model of normal working area. *15th Triannual Meeting of the International Ergonomics Association*, Seoul, Korea.

Choi, H-J, Ye, L., White, W, Bowling, J., Mark, L.S., and Dainoff, M. J. (July, 2006) Location of the hand use transition in a performance-based work area, *International Ergonomics Association 16th Triennial meeting*, Maastricht, Netherlands.

De Looze, M.P., Kuijt-Evers, L. F., and Van Dieën, J. H. (2003). Sitting comfort and discomfort and the relationship with objective measures, *Ergonomics*, 46, 985-997.

De Wall, M., Van Riel, M.P.J.M., Aghina, J.C.F.M., Burdorf, A., and Snijders, C.J. (1992). Improving the sitting posture of CAD/CAM workers by increasing VDU monitor working height. *Ergonomics*, 35, 427-436.

Delleman, N.J. (1999). *Working Postures – Prediction and Evaluation*. Soesterberg, the Netherlands: TNO Human Factors.

Delleman, N.J. (2004). Head and Neck. In Delleman, N.J., Haslegrave, C.M., Chaffin, D.B. (eds.) *Working Postures and Movements: Tools for Evaluation and Engineering*. New York, CRC Press, pp. 87-107.

Eddy, D.R. and Hursh, S.R. (2001). Fatigue Avoidance Scheduling Tool (FAST). AFRL-HE-BR-TR-2001-0140, SBIR Phase I Final Report, Human Effectiveness Directorate Biodynamics and Protection Division, Flight Motion Effects Branch, Brooks AFB, TX.

Elliott, L. R., Dalrymple, M., Schiflett, S., Miller, J.C. (2004) Scaling Scenarios: Development and Application to C4ISR Sustained Operations Research. In Schiflett, S., Elliott, L., Salas, E., and Coovert, M. (Eds). Scaled Worlds: Development, Validation and Applications. Burlington, VT: Ashgate Publishing Company.

Farina, D. Kallenberg, L.A.C., Merletti, R. and Hermens, H.J.(2003). Effect of side dominance on myoelectric manifestations of muscle fatigue in the human upper trapezius muscle. *European Journal of Applied Physiology*, 90, 480-488.

Gabbard, C. & Rabb, C. (2000). What determines choice of limb for unimanual reaching movements? *The journal of General Psychology*, 127, 178-184.

Gardner, D. Mark, L., Ward, J., and Edkins, H. (2001). How Do Task Characteristics Affect the Transitions Between Seated and Standing Reaches? *Ecological Psychology*, 13, 245-274.

Grandjean, E. (1982) Fitting the task to the Man. Taylor & Francis Ltd. New York, NY. Pp. 317-325.

Grandjean, E. (1987) Postural problems in office machine work stations (introductory paper). In Grandjean, E. (ed.) *Ergonomics in Computerized Offices*. London: Taylor & Francis, 445-455.

Grandjean, E., Hunting, W., and Pidermann, M. (1983). VDT workstation design: preferred settings and their effects. *Human Factors*, 25, 161-175.

Greandjean, E., Hunting, W., and Nishiyama, K. (1984). Preferred VDT workstation settings, body posture and physical impairments. *Applied Ergonomics*, 15, 99-104.

Greico, A. (1986). Sitting posture: an old problem and a new one. Ergonomics, 29, pp. 345-362.

Grieco, A., Moltenni, G., De Devito, G. (2004). Pelvis. In Delleman, N.J., Haslegrave, C.M., Chaffin, D.B. (eds.) *Working Postures and Movements: Tools for Evaluation and Engineering*. New York, CRC Press, pp.143-184.

Helander, M.G. (2003). Forget about ergonomics in chair design? Focus on aesthetics and comfort!, *Ergonomics*, 46, 1306-1319.

Helander, M.G. and Zhang, L. (1997). Field studies of comfort and discomfort in sitting. *Ergonomics*, 40, 895-915.

Henriques, V.E. (1985). Ergonomics is good for what you need. *The Office*, pp 62-64.

Hudson, J.A., Zehner, G.F, Robinette, K.M. (2003). JSF CAESAR: Construction of a 3-D Anthropometric Sample for Design and Sizing of Joint Strike Fighter Pilot Clothing and Protective Equipment. (Publication No.: AFRL-HE-WP-TR-2003-0142). AFRL/HECP, Wright-Patterson AFB, OH.

Hughes, T. L. (1968) Cabin Air Requirements for Crew Comfort in Military Aircraft. Royal Aircraft Establishment, Farnborough, Hants, UK. Technical Report No. 68304.

Hursh, S. R., Redmond, D. P., Johnson, M. L., Thorne, D. R., Belenky, G., Balkin, T. J., Miller, J. C., Eddy, D. R. and Storm, W. F. (2003). The DOD Sleep, Activity, Fatigue and Task Effectiveness Model. *Proceedings of the 12th Conference on Behavior Representation in Modeling and Simulation (BRIMS 2003)*, 03-BRIMS-001, 14-15 May 2003, Mesa, Arizona.

Hursh, S. R., Redmond, D. P., Johnson, M. L., Thorne, D. R., Belenky, G., Balkin, T. J., Storm, W. F., Miller, J. C. and Eddy, D. R. (2004). Fatigue models for applied research in warfighting. *Journal of Aviation, Space and Environmental Medicine*, 75(3, Suppl.), A44-53

Jaschinski, W., Heuer, H., and Kylian, H. (1998). Preferred position of visual displays relative to the eyes: a field study of visual strain and individual differences. *Ergonomics*, 41, 1034-1049.

Jones, D. (1983) "Noise." Stress and Fatigue in Human Performance Hockey, G. R. J. John Wiley & Sons, New York, NY.

Laville, A. (1980). Postural reactions related to activities on VDU. In Grandjean, E. and Vigliani, E., (eds.) Postural problem Section 5 in *Ergonomics Aspects of VDU*. London: Taylor & Francis, pp. 167-174.

Liao, M.H. and Drury, C. G.(2000), Posture, discomfort and performance in a VDT task, *Ergonomics*, 43, 345-359.

Mark, L. S. (1995). Perceiving the preferred critical boundary for an affordance. In R. Bootsma, & B. Bardy (Eds.) *Studies in perception and action III* (pp 183-186). Hillsdale, New Jersey: Erlbaum Associates.

Mark, L.S., Nemeth, K., Gardner, D., Dainoff, M.J., Paashe, J., Duffy, M., & Grandt, K. (1997). Postural dynamics and the preferred critical boundary for visually guided reaching, *Journal of Experimental Psychology: Human Perception and Performance*, *23*, 1365-1379.

Meindl, R.S., Hudson, J.A. & Zehner, G.F. (1993). A Multivariate Anthropometric Method for Crew Station Design (Publication No.: AL-TR-1993-0054). Wright-Patterson AFB, OH: Crew Systems Directorate, Human Engineering Division.

Meindl, R.S., Zehner, G.F., & Hudson, J.A. (1993). A Multivariate Anthropometric Method for Crew Station Design (AL-TR-1993-0054). Wright-Patterson AFB, OH: Crew Systems Directorate, Human Engineering Division.

MIL-STD-1472F (1999). Department of Defense Design Criteria Standard: Human Engineering.

NIOSH (1972) Criteria for a Recommended Standard – Occupational Exposure to Hot Environments, Washington D.C.: National Institute for Occupational Safety and Health, USGPO – HSM 72-10269.

Oudenhuijzen A.J.K., Zehner G.F., Hudson J.A. (2002). Verification and Validation of Human Modeling Systems (Report TNO-TM-02-A007). Soesterberg, The Netherlands: TNO Human Factors.

Parakkat, J., Pelletiere, J., Reynolds, D., Sasidharan, M. and El-Zoghbi, M. (2006). Quantitative methods for determining U.S. Air Force crew cushion comfort. *Society of Automotive Engineers*, Paper Number 06 DHM-45.

Parakkat, J., Pellettiere, J., and Harrison, C. (2005). Impact of workstation accommodation on fatigue and performance, RTO-HFM-135-P05.

Pheasant, S. (1995). Bodyspace : Anthropometry, Ergonomics and Design. Taylor & Francis, Bristol, PA.

Psihogios, J.P., Sommerich, C.M., Mirka, G.A., and Moon, S.D. (1998). The effects of VDT location on user posture and comfort: A field study, in *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting, Vol.2,* Santa Monica, CA: Human Factors and Ergonomics Society, 871-875.

Ramsey, J. (1983) "Heat and Cold." Stress and Fatigue in Human Performance Hockey, G. R. J. John Wiley & Sons, New York, NY.

Robinette, KM; Daanen, H; Paquet, E (1999) The CAESAR Project: A 3-D Surface Anthropometry Survey, in *Second International Conference on 3-D Digital Imaging and Modeling, 1999. Proceedings*, pp.380 – 386. IEEE Catalog Number: PR00062, New Brunswick, NJ.

Stins, J. F., Kadar, E. E. & Costall, A. (2001). A kinematic analysis of hand selection in a reaching task. *Laterality*, 6, 347-367.

Van Dieën, J. H., De Looze, M.P., and Hermans, V. (2001). Effects of dynamic office chairs on trunk kinematics, trunk extensor EMG and spinal shrinkage, *Ergonomics*, 44, 739-750.

Van Dieen, J.H., Nussbaum, M.A. (2004). Trunk. In Delleman, N.J., Haslegrave, C.M., Chaffin, D.B. (eds.) *Working Postures and Movements: Tools for Evaluation and Engineering*. New York, CRC Press, pp.109-141.

Weston, H.C. (1953). Visual fatigue with special reference to lighting. In Floyd, W.F., and Welford, A.T. (eds.) *Symposium on Fatigue*, London: Lewis, 117-135.

Whitmore, J., French, J., & Fischer, J. (2001) Psychophysiological effects of a brief nocturnal light exposure of selected frequencies and intensities. *Journal of Human Ergology*, 30, 267-272.

Wing, J. I. (1965) A review of the effect of high ambient temperature on mental performance. Aerospace Medical Research Laboratories, AMRL-TR-65-102.

Zehner, G. F. (1996). Anthropometric Accommodation and the JPATS Program, *SAFE Journal, 26*(3).

Zehner, G.F, Meindl, R.S., and Hudson, J.A. (1993) A Multivariate Anthropometric Method for Crew Stations Design: Abridged, (Publication No.: AL-TR-1992-0164), Armstrong Laboratory, Air Force Systems Command, Wright Patterson Air Force Base, OH

Zehner, G.F., Hudson, J.A. (2002). Body Size Accommodation in USAF Aircraft. (Publication No.: AFRL-HE-WP-TR-2002-0118). Air Force Research Laboratory, Human Effectiveness Directorate, Wright-Patterson AFB, OH.