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Maximizing Anthropometric Accommodation and Protection

Kathleen M. Robinette

Biosciences and Protection Division
Biomechanics Branch

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Final Report for April 2002 to August 2007

Air Force Research Laboratory
Human Effectiveness Directorate
Biosciences and Protection Division
Biomechanics Branch
Wright-Patterson AFB OH 45433-7947

NOTICE AND SIGNATURE PAGE

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KATHLEEN ROBINETTE Work Unit Manager Biomechanics Branch	MARK M. HOFFMAN Deputy Chief, Biosciences & Protection Division Human Effectiveness Directorate Air Force Research Laboratory

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14. ABSTRACT

This document summarizes in-house anthropometric research done over a 5- year period with three primary objectives: 1) worldwide anthropometry resource development; 2) understanding the impact of anthropometry on fit and performance; and 3) transitioning fit, accommodation, and anthropometric technologies to the engineering and safety communities. It is a companion to a contractual effort entitled "Adaptive Anthropometric Accommodation."

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PREFACE

This summarizes the work done under work-unit 71840207, Maximizing Anthropometric Accommodation and Protection managed by Kathleen M. Robinette. The work-unit covered a broad range of anthropometry related efforts aimed at improving accommodation and protection of Air Force and military personnel. The scope of the research focused on three primary objectives: 1) worldwide anthropometry resource development; 2) understanding the impact of anthropometry on fit and performance; and 3) transitioning fit, accommodation, and anthropometric technologies to the engineering and safety communities.

We would like to thank Tina Brill for her careful editing and data formatting of this document as well as all of the people who contributed to the work summarized here. This includes: 1) Greg Zehner, Scott Fleming, Cate Harrison, Julia Parakkat, Joseph Pellettiere, John Plaga, and Huaining Cheng from the Biomechanics Branch, 2) Jeff Hudson, Dennis Burnsides, Sherri Blackwell, Cecelia Mitchell, Dave Hoeferlin and Mark Boehmer from General Dynamics, 3) Hein Daanen and Aernout Oudenhuijzen from TNO Human Factors, 4) Marc Rioux and Eric Paquet from the National Research Council Canada, and Hyeg joo Choi from the Oak Ridge Institute for Science and Education (ORISE).

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SUMMARY

This document summarizes the anthropometric research conducted over a 5-year period under the work-unit titled, Maximizing Anthropometric Accommodation and Protection. It is a companion summary to contractual research efforts under the Adaptive Anthropometric Accommodation contract which also has a final report. The research area includes anthropometry, methods for measuring the quality of fit, and methods for relating the two. Applications include hearing protection, helmets, oxygen masks, workstations, and manikin proportioning for safety testing

CHAPTER 1: INTRODUCTION

The research under this work-unit and summarized here had three primary objectives: 1) to develop the capability for a web accessible anthropometric information system with the latest anthropometric imaging and fit/accommodation mapping information made accessible to the US and our allies from any location in the world; 2) to understand the effects and interrelationships between equipment fit, workload, marginal anthropometry, physical capability, cognitive capability, and increasingly equipped states on pilot performance; and 3) to devise ways to transfer the latest anthropometric technologies to engineering practice through both the Department of Defense and civil sector channels. This report provides an overview of the work accomplished. Each chapter describes the work under one of the three objectives.

CHAPTER 2: WORLD ANTHROPOMETRY INFORMATION SYSTEM

The anthropometry information system was intended to include not only the latest 3-D surface anthropometric data from all over the world, but also traditional anthropometric data, mass distribution data, human performance and preference data, fit and accommodation information, analytic and software tools, and guidance or intelligent agents for using the information effectively. It is also intended that it be able to be continually updated by registered users, and the information contained in it distributed throughout the world. This would enable it to be frequently and quickly updated, and the cost to any one organization for maintenance would be minimized.

The approach for the information system was to bring together experts from different fields and from around the world to develop a general system concept and make recommendations for the creation of an on-line world-wide information system for utilizing the latest anthropometry databases in engineering environments. This includes identifying and developing data models, software tools, and theoretical constructs and principles for the system and addresses any worldwide sharing issues. Current users of engineering anthropometry evaluated user interface concepts and other information system requirements. In-house experts determined the best potential technologies for replicating the experts in the system.

Volunteers from around the world were assembled for the working group which was named World Engineering Anthropometry Resource (WEAR). The first meeting of this group occurred in Paris, France in 2002, with subsequent meetings in the United States, South Korea, South Africa, Brazil, The Netherlands, Australia, Canada, Japan, and China (Robinette and Lee 2003). The stated goal of WEAR is to contribute actively to the diffusion and the advancement of knowledge of anthropometry, ergonomics and human factors engineering for health, safety and well-being for all people.

The technical challenges to a world anthropometry network include: 1) methods to search and analyze 3-D shapes, 2) alignment and standardization of data with organizational, national and language differences, and 3) quality assurance for data from diverse sources. Research was accomplished addressing each of these challenges. In addition, new databases to be included in the system were developed.

3-D Shape Descriptors and Search Methods

Methods for mathematically coding 3-D human shapes for searching in large databases is called shape description and the codes themselves are called shape descriptors. The measure of effectiveness of the shape descriptors is the ability to locate a different copy of the same person from amongst a database of thousands. An evaluation of the effectiveness of different types of 3-D human shape descriptors for database searching was completed. This compares traditional measurement descriptors, landmark based descriptors, and the descriptor developed by Paquet et al (2000), which is referred to as the Paquet Shape Descriptor or PSD. The PSD is different from the others in that it characterizes the entire object with no pre-selection of locations, and it represents the locations of areas with a large amount of surface contour change.

The results indicated that the PSD is very effective for finding subjects with similar shapes, and more useful for finding soft tissue contour differences than traditional or landmark methods. For example, PSD should be more effective for separating fatty tissue from muscle tissue, for identifying physical fitness, or for determining mass distribution, than landmarks or traditional methods. More than 91% of the time PSD identified a second scan of the same subject as the closest match out of thousands of subjects, regardless of the scanner used. It performed as well or better than all of the traditional and landmark methods against which it was compared for within-scanner searching. Examination of the closest matching subject who was not the same subject indicates PSD matches contour changes regardless of size. Therefore, it appears to be a pure shape descriptor.

The PSD also has the advantage of being very compact. It requires only 256 bits. This makes it very useful for searching large databases over the internet. However, some posture and scanner standardization and calibration will be necessary to make it ideal for searching across surveys. For example, things that are not part of the body, such as the standing platform or the chair must be removed from the scan or they will influence the result. This research suggests that PSD excels in searches when body contours are the most important criterion, and offers a viable alternative when key measurement or landmark data are not available. When underlying skeletal structure is more important than surface contours, other search methods may still be preferable when available. Detailed results were reported in an article by Robinette (2005).

A second iteration of the new 3-D shape search engine, Nefertiti was delivered and is being tested. This version runs directly off a USB drive so there is no need to install software and the descriptors are output into an excel spreadsheet.

Data Coordination and Standardization

Anthropometric data are used by numerous types of organizations for health evaluation, ergonomics, apparel sizing, fitness training, and many other applications. Data have been collected and stored in electronic databases since at least the 1940s, and while there are many standards, few anthropometric studies are alike in terminology, procedures or measurement set. Two studies may collect the same measurement but label it differently or refer to different measurements by the same name. For example, the measurement called waist circumference is taken by some at a location that is referred to as the minimum indent of the torso and by others at the location where people prefer the waist of their clothes. These locations can be 100 mm or more apart and the resulting measurements can be quite different. Add different languages in the country of origin to the mix and it is easy to see that organizing worldwide anthropometry data into a single database architecture could be a daunting and expensive undertaking. Fortunately, XML schema and webservices provide an alternative method for networking databases, referred to as a Loose Distribution Method. A standard XML schema is defined and used as a type of Rosetta stone to translate and a webservices system is set up to link the translated databases together. In this way the originators of the data can keep their data locally along with their own data management system and user interface, but their data can be searched, accessed as part of the larger data network, and even combined with the data of others. Robinette and Cheng (2006) drafted an XML schema for standardized anthropometry data description with web services concept was completed and presented to the World Engineering Anthropometry Resource (WEAR) group partners as a model for implementation in WEAR.

Anthropometric Quality Control

The accuracy of the scanner-derived 1-D dimensions from the Civilian American and European Surface Anthropometry Resource (CAESAR) survey was investigated (Robinette et al 2002 and Blackwell et al 2002). Two combinations of scanning teams with 3-D whole body scanners were compared, one called the US team and the other the Dutch team. Twenty subjects were measured following the CAESAR protocol, three times by one scanner and one team, and three times by the other combination. The Mean Absolute Differences (MAD) of the repetitions was calculated and these were compared to reported errors in manual measurements from the U.S. Army's ANSUR survey when similar measurements were available (Gordon et al 1989). The Coefficient of Variation (CV) was also calculated for all measurements. The results indicate that more than 93% of the MAD values for CAESAR were significantly smaller than the ANSUR survey reported allowable errors. The CAESAR scan-extracted measurements are highly reproducible; in most measures the error was less than 5 mm. While the US Team came fresh from the Italian portion of the CAESAR survey and was well-practiced, the Dutch team had not done any CAESAR data collection for almost two years. In other words, they were out of practice and should be considered comparable to the team the ANSUR project used. Therefore, it is concluded that the type of scan extracted measures used in CAESAR are more reproducible than comparable manual measurements. All of the CAESAR scan extracted measurements were linear distances using pre-marked landmarks. There were neither arcs nor circumferences in the set. Measurements extracted from scans that do not use landmarks or that follow along the body surface rather than being straight-line distances are not represented here and additional studies would be needed to verify their accuracy. Detailed results were reported by Robinette and Daanen (2006).

The same data were used for a study comparing the 3-D results from the two competing 3-D scanners used to collect the data, one manufactured by Vitronics, Inc. and the other Cyberware, Inc. Systematic differences between the scanners, as well as consistency within each scanner, were quantified by this study. In addition, the data collected permitted an analysis of the degree to which anatomical landmarks on the human thorax are shifted by tissue deformation between different scanning poses. Harrison and Burnsides (2003) used the data to develop and demonstrate a method for comparing the 3-D quality of scanners for anthropometry that they presented at the Society of Automotive Engineers Digital Human Modeling Conference. 3-D image data were segmented, aligned and compared using a difference mapping algorithm. The analysis of the scan data points to differences in the variability of the two scanners. The method developed here may also be useful to characterize soft tissue deformation effects between seated and standing postures.

New Anthropometric Databases/Samples

A sample was created to represent the Joint Strike Fighter (JSF) aircrew population for the purpose of design and sizing of pilot clothing and life support equipment for the JSF (Hudson et al 2003). The JSF anthropometric requirements were to accommodate the full range of people for eight cases derived from the Joint Primary Aircrew Training System (JPATS) sample. These eight were developed to ensure cockpit accommodation, and were not intended to represent a statistical description for the variation important in the design of personal clothing and equipment. They contain too few measurements to sufficiently characterize the variability of the body for apparel and protective equipment and they do not represent the variability of the population for the relevant measures. The statistical process of constructing representative cases used in the design of clothing and gear require an entirely different multivariate approach, and therefore a sample from which to draw these cases was needed. This new sample addresses this need.

Summary statistics for the civilian populations of Italy and The Netherlands were calculated and reported in two volumes by Hudson and Robinette (2003a and 2003 b). The samples collected for these countries were collected using a stratified sampling scheme by gender, age and ethnicity (Robinette et al 2002). Therefore to have representative summary statistics the samples needed to be weighted to reflect the current population. Census data from the countries were used to create the sample weights.

CHAPTER 3: IMPACT OF ANTHROPOMETRY ON FIT AND PERFORMANCE

Task performance or the potential for injury (either acute or by repetitive stress) may be impacted by how well a person is accommodated by his or her work environment or life support equipment. A review of the literature indicates that previous work has tended to be narrow in scope, demonstrating linkages of one measure of performance or type of injury to fit of one particular aspect of a work environment, or even one portion of a task. Such work has had a positive impact in helping individual task or equipment elements to be modified to improve performance and/or reduce injury. What remains to be quantified, however, is the cumulative, synergistic effect of the type of assemblages of different types of equipment and environmental elements that an individual contends with in his or her job. For example, how much gear can we place on the pilot before we begin to seriously affect mission effectiveness? How well do pilots of marginal size perform? What is the combined effect of poor fitting equipment and marginal anthropometry, in terms of workload and pilot performance?

Fit mapping is a method developed to relate body size to performance. It uses performance criteria determine the range of fit accommodated in a single size, and subsequently the number and assortment of sizes and adjustments needed to accommodate a target population with a design concept. Fit mapping involves using prototypes or mock-ups and performance testing in conjunction with anthropometric measurement. Fit effectiveness means that the desired population is accommodated without wasted sizes or wasted accommodation regions. Because most performance-based fit tests cannot be done on digital models, fit mapping involves using human subjects to do the assessments. Several different types of fit mapping studies were completed and are summarized below.

Fit Mapping Using Sound Attenuation Performance

Fit mapping was used in a series of studies aimed at improving passive hearing protection, and the measure of fit effectiveness was sound attenuation testing in a Microphone-in-real-ear (MIRE) facility. Permanent hearing loss is the most prevalent DOD disability - accounting for more than $6B in compensation payments as a primary disability since 1977 ($633.8M in 2004 alone) (Liewer 2006). DoD Instruction 6055.12 sets a noise exposure criterion of 85 dB (A) (with 3 dB doubling) for 8 hours of unprotected exposure followed by quiet recovery. But today's high performance military aircraft frequently generate noise levels ranging from 130 to over 150 dB at the worst case aircraft maintenance / handler locations and from 110 - 120 dB at cockpit pilot locations. Current earplug-earmuff combinations used by military aviation personnel provide approximately 30 dB of protective attenuation. This inadequate level of protection coupled with generally long daily exposures to extreme noise levels has contributed to a high incidence of noise induced hearing loss among military personnel.

For this research the Air Force Research Laboratory (AFRL) and Naval Air Systems Command (NAVAIR) initiated Defense Technology Objective HS.33 "Improved Aviation Personnel Hearing Protection". HS.33 is a 7 year joint development plan to provide military aviation crews with effective, affordable, reliable, easy-to-use hearing protection that will allow safe, extended exposures in up to 150 dB of aviation related noise.

First, the effectiveness of custom shaping an ear cup seal was studied. Custom or individual size and shaping of a product should be the best fit scenario. If a custom-shaped fit does not improve attenuation then no sizing or shaping solution will improve fit. If shaping does improve attenuation then non-custom sizing and shaping solutions may be possible.

This study used Cyberware head scans of subjects to custom shape the hard interface of the ear cup to the subjects exact head contour. Then, using MIRE hearing tests, the hearing protection afforded by standard and custom-fit ear-cup were compared. In 2003 it was demonstrated that increased passive hearing protection over 4 dB was possible by custom shaping the ear cup. This doubles the length of time an individual can be exposed to 105dB pink noise.

Next, a fit mapping study using sound attenuation as the fit criteria was conducted to evaluate alternative urethane materials with different durometers in an attempt to identify a field-able seal material. Some potential materials were identified.

A study of “summary shapes” derived from the median and mean shapes of ten test subjects indicated no improvement over the standard ear-cup alternative. Other methods for deriving more effective summary shapes will be explored in follow-on research.

The final fit mapping study to use sound attenuation as a fit criterion was a study of the Navy Flight Deck Crewman’s Standard Helmet Assembly, shown in figure 1, which is referred to as the cranial. This assembly holds the ear cup in place. Other fit criteria in this instance included comfort and movement or slippage. All of these need to be assessed simultaneously because they interact. For example, the most comfortable cranial may be the loosest, but the most sound attenuation is achieved with a tight fit.

Prior to fit mapping the cranials and patterns were measured. This led to the unexpected discovery that three of the four sizes had little or no actual difference between them. Inspection of the specifications revealed that the impact plates which attach to the cranials for all sizes are identical (interchangeable). The same is true of the cloth side panels that hold the earcups in the cranial. Measurements of the rest of the cloth cranial are shown in Table 1. As can be seen sizes 6.75, 7.0, and 7.25 are essentially the same size for all practical purposes. Size 7.5 represents a larger size by 1-3 cm for four of the six dimensions measured.

Table 1. Cloth Cranial Measurements

Size	Front Edge	Sleeve Snap	Back Center	Back Bottom	Back Bottom Stretched	Length
6.75	15.5	17.5	16.0	12.5	13.5	38.5
7.0	15.0	18.0	16.5	12.5	13.5	39.0
7.25	15.5	18.0	16.5	13.0	14.5	39.0
7.5	16.5	19.0	19.0	13.5	16.5	39.0

- Measurements are in centimeters
- Front Edge, Sleeve Snap, Back Center, Back Bottom, Back Bottom Stretched are widths
- All widths measured between the seams that connect the side panels to the center section of the cranial
- Length measured along the center seam

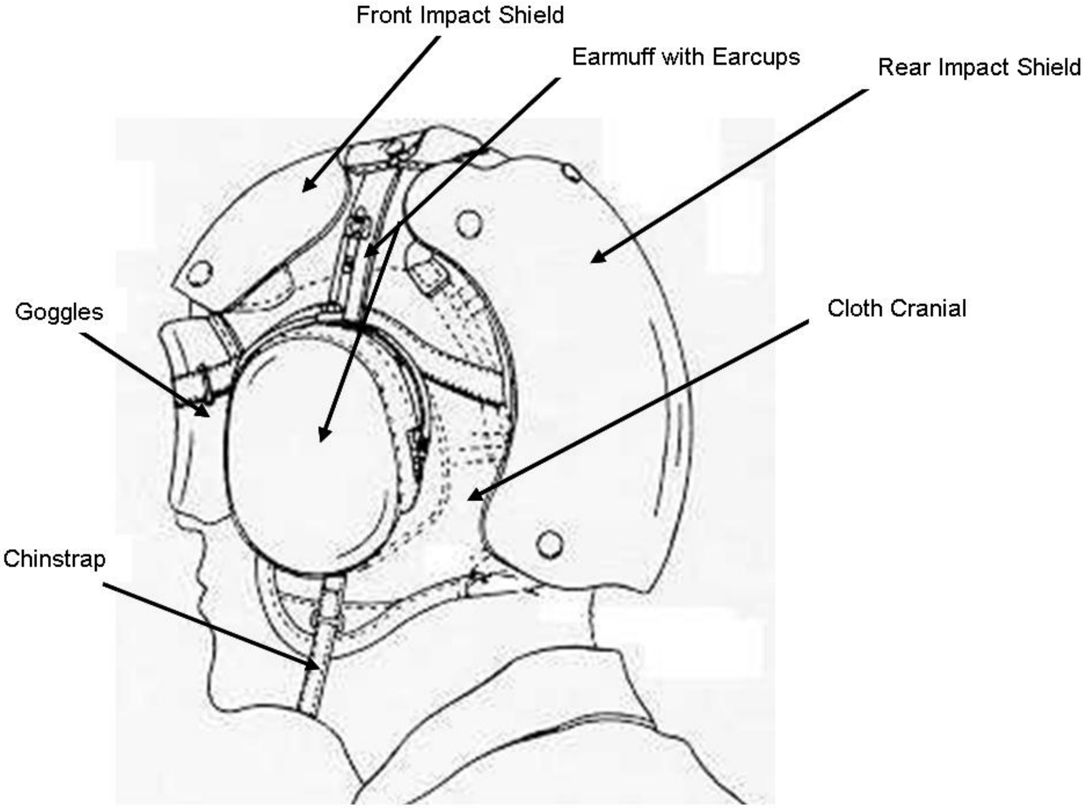


Figure 1. Navy Flight Deck Crewman's Standard Helmet Assembly.

Since the goal of fit mapping is to determine the range of accommodation within one size, only one size is needed for the test. Prior studies had indicated that the size 7.5 provided worse sound attenuation than the other sizes. Therefore the size selected for testing was size 6.75.

MIRE attenuation testing results indicate that males consistently achieve a higher attenuation score than females by 5-10 dB and the addition of the cranial does not add significant hearing protection. The different response for females seems to be explained by examination of the common element of the three devices, the earmuff. Examination of the earmuff band lengths among males and females indicates the band is not adjustable for most females. Most women needed to have a smaller band but were unable to adjust it to the needed length whereas most if not all men were able to adjust the band for their head size. Lower MIRE attenuation scores and minimal adjustment are most common among women, and some men, with bitragion-coronal arcs less than 340 mm. Increasing the band adjustment limits by 20 mm would provide enough adjustment to accommodate all the females and the few males who required a smaller band length than the current configuration allows.

The band length caused all of the critical fit failures indicating that with the added adjustment the male and female Navy population could be accommodated in one size without slippage, without significant discomfort, and with maximal sound attenuation. However, there was one important fit issue identified that was not part of the concept of fit for the fit mapping. The current configuration of the front impact shield of the cranial does not allow simultaneously the proper earcup positioning and the proper impact shield location on the forehead. The design requires the earcups to rotate off the ear as the impact shield is rotated forward and down over the forehead. Analysis of the 3-D scans indicates a 33 mm maximum forward rotation would be necessary to protect the forehead. Rotation of the head band to allow the earcups to remain in place on the ears is not possible. The proximity of the sleeve snap to the front impact shield only allows for 1 mm forward rotation before the head band contacts the impact shield. The front impact shield would need to be adjusted forward 32 mm to accommodate forehead protection while maintaining hearing protection.

Fit Mapping Using Reach Under Adverse Accelerations

A study in the centrifuge was completed to simulate pilot ability to reach controls under adverse accelerations. Test subjects were spun at –1, +1, +2, +3, and +4 Gz, and compared their reach capability with locked and unlocked harness restraint systems. Results for the ACES II ejection seat show that pilots have the ability to reach several inches farther under positive G in the Zone 3 restraint condition than the Zone 2 condition. However, the speed with which they reach is greatly reduced. Under negative accelerations, Zone 3 reach is similar to Zone 2, and shoulder displacements averaging over 3 inches (~ 8 cm) were found. This greatly reduces reach and overhead clearance with the canopy. These results were reported at the SAFE conference in 2003 (Albery et al 2003).

Joint Service Aircrew Mask (JSAM) Fit Mapping

New production prototype assets of the new JSAM mask was fit tested in late 2006 and early 2007 and by January 24, 2007 significant problems had been detected that indicated the mask required re-working. Fit assessments had been performed on 19 male and 7 female subjects using the M41 Protection Assessment Test System (PATS). All subjects were tested in each JSAM size, unless they are unable to wear a size due to unbearable discomfort or inability to breathe. The results to this date indicated:

- Of 19 male subjects, all 19 were able to pass the PATS test in at least one JSAM size; however 5 could not valsalva in any of the five JSAM sizes. This is a 26% failure rate.
- Of 7 female subjects, 6 were able to pass the PATS test in at least one JSAM size and all 7 were able to valsalva in at least one size.
- One female subject was unable to pass the PATS test in any size.
- Of the female subjects, 2 were able to pass the PATS tester in one size only and in each case the fit of the mask in which they passed on PATS was unacceptably tight by the evaluator's rating, and had intolerable pressure by subject rating. In other words, 3 female subjects out of a sample of 7 (i.e. 43%) are not acceptably accommodated by any of the current sizes of JSAM mask.
- Of 7 female subjects, 3 have been unable to test in one or more sizes due to the air-guide applying downward pressure to the nostrils that makes breathing impossible when looking up or to the side, or due to unbearable downward pressure of the air-guide to the bridge of the nose.

These results were surprising because they were not observed in earlier studies. A fit mapping study was conducted with a Quantitative Fit Factor facility in 2004, using a different vendor's assets and none of the subjects experienced these problems.

Preliminary Observation 1: There is a problem with the ability of the JSAM mask to accommodate female aircrew. One preliminary hypothesis suggests that the shape of the current masks better accommodates the more massive brow and jaw structure of males. The current hood ring may not be shaped to be supported adequately by finer facial bone structure, which in turn distributes force disproportionately to the most prominent available boney structure. In some cases, the air-guide supports the mask by resting on the bridge of the nose.

Preliminary Observation 2: The valsalva arms are too short within the air-guide, and angled too high to be effective when the air-guide fits properly. This accounts for our observations that females are more consistently able to valsalva, and simultaneously the air-guide tends to rest too low on females' noses.

Summary: While the test plan called for 45 male and 45 female subjects to be run in this study, the findings to this date were sufficient cause for concern. The testing was halted pending changes to the product.

Impact of Workstation Accommodation on Fatigue and Performance

The development of a man-machine interface with component adjustability for Unmanned Aerial Vehicle and other remote workstations that the Air Force employs is important and necessary due to the size variability of the operators. In order to provide the range of operators the optimum interface, good ergonomic principles must be applied to design for the adjustability that is required to simultaneously prevent discomfort and injury and promote performance. Appropriate performance measures must then be employed to delineate between optimum and sub-optimum workstation configurations. Toward this aim Parakkat et al (2006) conducted a baseline study examining postural performance effects relevant to Unmanned Aerial Vehicle control stations.

Methods: Thirty male and female subjects participated in this study which examined the impact of accommodation of a dual-monitor computer workstation. As a measure of performance, subjects performed a split-attention computer task. Surface electromyography was collected on the left and right trapezius and deltoid muscles. Cerebral oxygenation levels were monitored via non-invasive near-infrared surface sensors placed on the right and left sides of the forehead. Subjective comfort levels were recorded via a questionnaire at the start, middle, and end of the session.

Results: Trends in performance, oxygenation, and comfort corresponded with workstation configuration. Median frequency analyses of the electromyography signal gave an indication of muscular fatigue levels that were only evident in the task-controlling arm.

Conclusions: Though only low-level muscle activity was present, the cumulative effect resulted in higher fatigue and correspondingly higher subjective discomfort for the poor workstation configuration. Subjective responses regarding comfort of individual body parts corresponded well and quite accurately reflect workstation component adjustments. Objective methods were developed for using electromyography and oxygenation to predict declining operator mission effectiveness due to poor workstation fit. These results will be utilized in follow-on workstation parameter optimization investigations to ultimately aid in establishing performance-based workstation design guidelines and promoting universal man-machine interfaces.

CHAPTER 4: TRANSFERING ANTHROPOMETRY METHODS OUT OF THE LABORATORY

Methods developed in the other areas were transferred to engineering practice in two ways: 1) publication of methods and lessons learned and 2) real-world demonstrations. Several examples of each were completed and are summarized below.

Methods and Lessons Learned

The Civilian American and European Surface Anthropometry Resource (CAESAR) anthropometric survey was the world's first survey to successfully provide full-body, 3-D models and 3-D homologous landmarks. As such, many organizations around the world have an interest in replicating the study for their populations. Robinette and Daanen (2003) published and presented some lessons learned during the survey process to help people conducting future surveys avoid some of the difficulties encountered.

Robinette and Hudson (2006) published a book chapter about the use of anthropometry in engineering applications for one of the Wiley Press series on Human Factors. It includes sections on common pitfalls and examples of practical effective methods for incorporating the human body in design.

Advances in optics and computing science have made it possible to digitally capture the size, shape, and position of the different parts of the body in three dimensions in a few seconds. This can be thought of as a posture snapshot in addition to capturing size and shape. After all, what is posture really but the relative location in space of the parts of the body? New methods for tracking the change in posture in three dimensions are also being developed. The study of these three-dimensional snapshots and the tracking of changes in three dimensions is referred to as three-dimensional anthropometry. Robinette et al. (2004) published a chapter describing the most recent three-dimensional anthropometry methods including: (1) why and when to use three-dimensional anthropometry, (2) a general description of three-dimensional anthropometry measurement techniques, (3) data processing methods, and (4) issues with three-dimensional data acquisition and use.

Fit Mapping for Helmet Design and Sizing

Harrison and Robinette (2005) demonstrated fit mapping principles to teach the manufacturer and others about the benefits of the process. The research sought to apply underlying principles that determine helmet fit to develop a scientific design method for determining the minimum number of helmet sizes to accommodate the full anthropometric variability of the population. The method was tested on a prototype helmet concept using a stratified sample of males and females drawn to represent the Joint Strike Fighter population. Asian- and African-American subjects were specifically included in order to examine the effects of racial anthropometric variability on fit. While the range of accommodation for the initial design was broad, it encompassed only a portion of subjects who fell within the 99% probability ellipse for the target population, while accommodating a broad range of subjects falling outside the 99% probability ellipse, best meeting the fitting needs of a very small subset of the population. Applying a fit mapping method determined that two helmet sizes, sized and shaped differently than those initially proposed and with a modified fitting concept, would accommodate 99% of both males and females. The fit mapping process also provided specific, quantified feedback to the designers on size and shape modifications needed to make the helmet to provide better fit for the full range of the population. Determining the parameters that link anthropometric principles to fit of a specific piece of equipment permit design modifications to equipment to be made early in the design process using only a single size prototype, resulting in fewer sizes while ensuring accommodation of the desired population.

Demonstration of the Use of 3-D Cases for Manikin Proportioning

Current test manikin heads were created using artistic concepts for shaping. The manufacturers of helmets, oxygen masks, etc. have complained that they have to create a separate size just to fit the manikins because the manikin heads are not human enough. Plaga et al (2005) demonstrated a method for using 3-D anthropometrically selected cases to create new manikin head "skins". The skins were produced using rapid prototyping technologies from 3-D head scans from the CAESAR database for use in the JSF program testing. The heads were selected based upon mass, estimated from volume, and other head dimensions. The candidate subjects' heads were then examined and compared against the existing manikin heads.

Human Modeling Methods for Cockpit Accommodation Evaluation

Work was done under prior efforts that documented some of the limitations of human models used in computer-aided-design (CAD). Work was done under the current effort to advanced human modeling and visualization methods for cockpit accommodation evaluation and to determine valid ways to use human models in CAD systems. This work was done in conjunction with colleagues at TNO in The Netherlands under an international project agreement. Two presentations of this work have been published. (Zehner et al. 2007 and Zehner et al. 2006)

3-D Anthropometry Summarization Methods for Helmet Applications

Anthropometric surveys have included 3-D scans for more than 2 decades and scientists are still struggling with methods for summarizing the scan data. Methods to summarize thousands of scans are needed in order to reduce the information for practical engineering applications. This effort examined simple methods for characterizing scans and described the trade-offs. Three orientations were used to explore the variability in 3-D head scans from 747 US navy personnel: 1) the Principal Axis System (PrinAx), 2) an approximate corneal plane alignment (Eye) and 3) a top-of-head alignment (TopHead). The first, PrinAx, provides an orientation that uniformly distributes variability, and as such is considered to be a baseline for examining head variability. The Eye alignment simulates a pupil location restriction condition that might occur with a helmet mounted display. The TopHead alignment simulates a helmet position restriction that might occur with a fixed helmet or liner size. Each of these orientations makes some assumptions about how a helmet would be situated. These gave a reasonable idea about the risks associated with the assumptions made, the limitations of any given alignment and error bounds.

Furthermore, they demonstrated how to use different alignment schemes in the design and evaluation of a helmet.

METHODS:

Prior to alignment the head was separated from the neck and all the holes were filled to make an electronic 3-D solid. This was necessary to create heads that have consistently defined volumes, surface areas, and estimated masses (assuming constant density). If one assumes constant density then the principal axis system represents the most balanced alignment scheme. The center, or origin, of the axis system is the center of gravity. The mass of the head is balanced about the center of gravity. In other words, there is the same amount of mass on each side of the center along each axis. It is hypothesized that the ideal location of a helmet would maintain this balance. As a result this axis system should be a good starting point.

The Principal Axis System (PrinAx) orientation was calculated as follows:

- Use all head surface points to define surface triangles (polygons)
- Center point of triangle used to define surface
- Area of each triangle is used as mass
- Center of “mass” is the origin

An illustration of the resulting PrinAx alignment is shown in figure 2 for one subject. Note that while they are mathematically derived using just the 3-D surface variability, the Principal Axes approximately correspond to what is commonly referred to as x, y, and z in an anatomical reference system. The x axis is the left-right axis, the y axis is fore-aft and the z axis is up-down. The y axis characterizes the greatest amount of variability, the z axis the second greatest that is orthogonal to y, and the x axis characterizes the next greatest amount of variability that is orthogonal to y and z.

Some helmets now have helmet mounted displays (HMDs). It is important to have the eyes in the right location to be able to use HMDs effectively. The Eye alignment (i.e., pupil or corneal plane) begins with the PrinAx and then moves all the heads to align at a pupil location defined as the midpoint of the line between left and right pupils. This simulates a helmet fit concept that used the helmet to adjust the position of the HMD position in front of the eyes. The effects due to changing from PrinAx to the Eye alignment will illustrate helmet design challenges for this fitting concept.

Blackwell and Robinette (1993) examined three different helmets that were equipped with Night Vision Goggles. One type adjusted the helmet fit based upon the eye location and the investigators found that this didn’t work very well. People are asymmetric so it was difficult to get both eyes in the correct place simultaneously. In addition, when the eyes were in the correct position with respect to the NVGs the helmet was pushed way off from the center of gravity making it seem heavier and unbalanced. Due to gravity helmets naturally will try to rest on the top of the head. The third alignment system, the TopHead alignment, attempts to simulate this condition. This alignment also begins with the principal axis system alignment then registers the subjects to the top most point on the up axis (z). This is only one of many possible top-of-the-head points. Another one is the top of the head as oriented to the Frankfurt Plane alignment, and another is the top of the head as oriented in a helmet. These all yield different points and different head orientations. The top of the head as oriented in a particular helmet may be the most useful if the helmet fit is similar to a helmet being designed. However, it requires knowledge of the location of the helmet with respect to the head which is generally unknown. The top of the head in the PrinAx system is related to the center-of-gravity of the head and can be thought of as a balance point. As such, it may have some value from a design standpoint for helmets intended for high-g environments or conditions.

RESULTS:

Two-dimensional (2-D) scatter-plots of the landmarks from the US Navy 3-D head scans in all three axis systems are shown from two different viewpoints, top-down and back-view in figures 3 and 4 respectively. PrinAx is in part a of each figure, Eye is in part b, and TopHead is in part c.

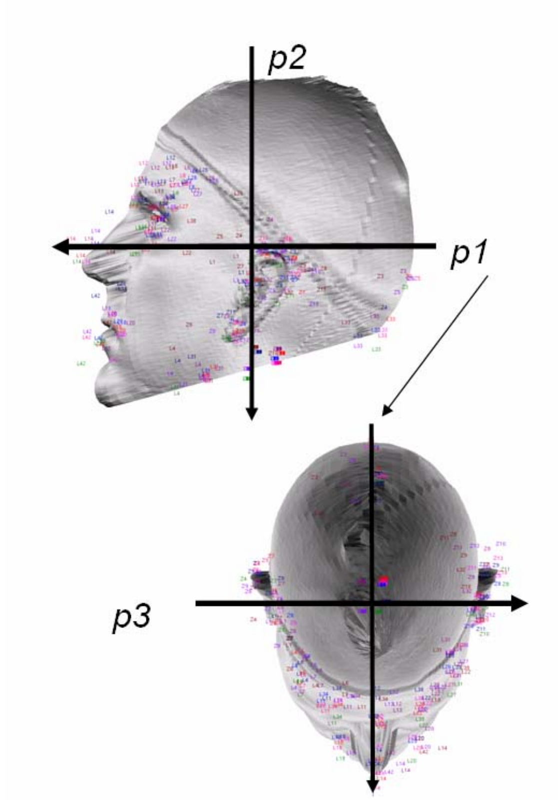


Figure 2. One head in Principal Axis System

The legend indicating which points belong to which landmark and gender is to the right of each figure. The head orientation for the plots is indicated at the bottom and the left of the figures. For example, the left to right direction is shown at the bottom of figure 3, and the forward direction is show to the left of the figure. In figure 4 the direction on the left axis is the up direction.

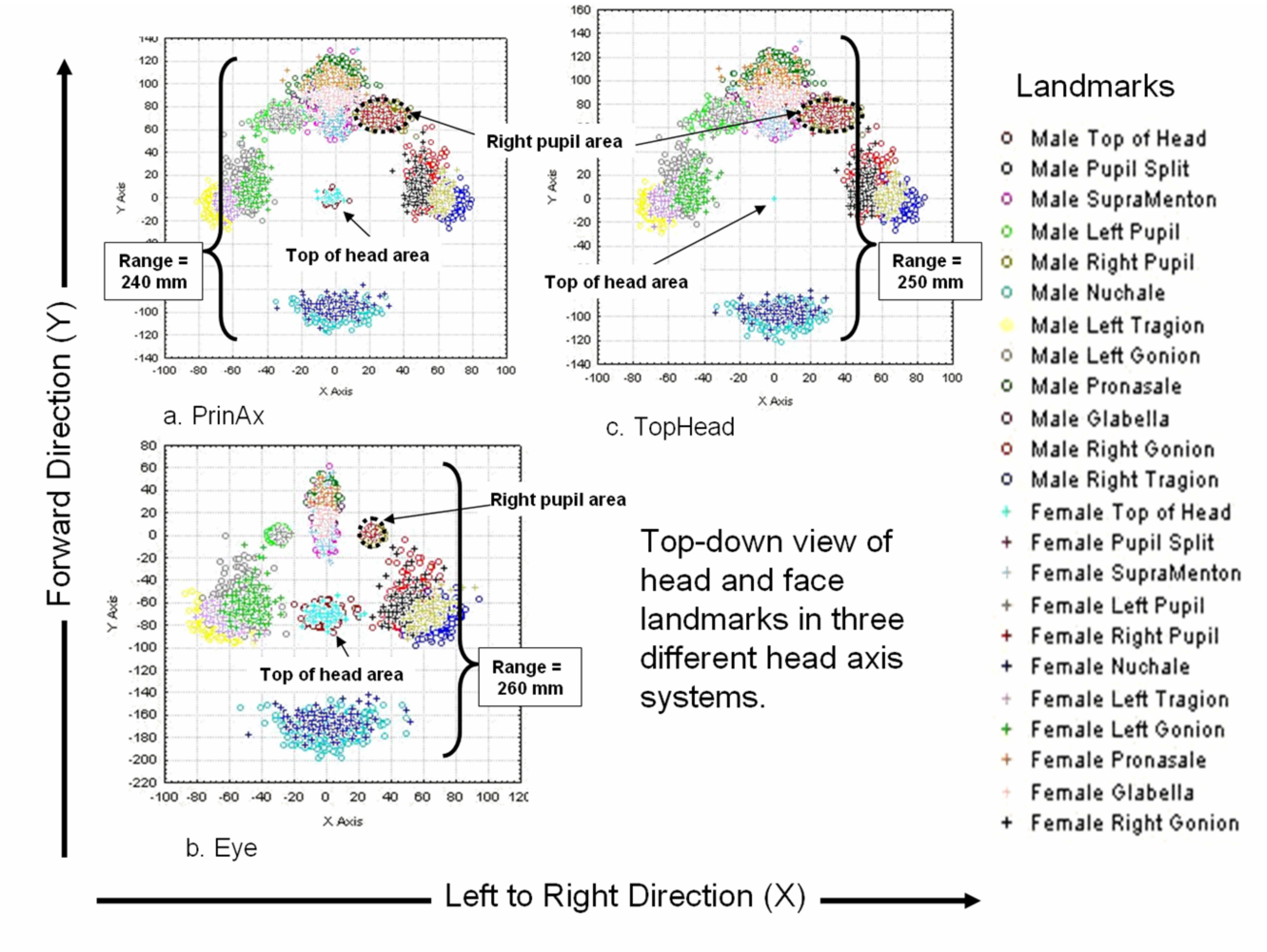
The spread of the landmark points in each axis system reveals the differences between them and the trade-offs for using them. The PrinAx can be viewed as a sort of mean spread of all points on the surface. The center of the PrinAx axis is also an estimate of the center of mass if you assume constant density. This is a type of balance point. As you diverge from the PrinAx by minimizing the spread of one point you will increase the spread of another and you will unbalance the mass distribution accordingly. However, this may be necessary when designing a helmet system, because the adjustment mechanisms for accommodating the spread of the landmarks must be taken into account.

For example, the Top of Head landmark spread in figures 3 and 4 is barely visible in the TopHead axis system because the points are all in the same exact location by definition. On the other hand, the spread of the right pupil landmark in the TopHead axis system is much wider than the other two. The spread of the right pupil in the Eye axis system is smaller than the other two, but the spread of the Top of Head landmark is larger. The vertical pupil range for approximately 99 percent accommodation in this PrinAx system is about 60 mm (2.4 inches). This is similar to the vertical range of pupils for Air Force pilots in the HGU-55/P helmet as measured in the Air Force head study done in 1989 (Whitestone and Robinette 1997). On the other hand the spread of the right pupil in the Eye axis system is about 10 mm (0.4 in).

It is important to note that the two-dimensional planar views of the points shown here may not provide the complete picture of the true underlying distribution of the points. In two dimensions paraboloid or cup-shaped distributions will appear to be ellipsoidal (like footballs) or spherical. In this instance, the spread of some the points may be rotating around the mean center of mass which could result in a cup-shaped spread. If so, a 99 percent accommodation range should be calculated using a quadratic rather than a linear function, and accommodation would be better accomplished using angular/rotational adjustments rather than linear. For example, the left and right pupil clouds in the top views appear to be curved toward the front and flat toward the back. This indicates they may be cup-shaped with an indent in the center in the positive p1 direction. If so, the amount of optical hardware adjustment needed can be reduced by using a rotational left-right and up-down adjustment mechanism and accommodating the small amount of fore-aft adjustment that remains with a custom-brow pad. In other words, instead of inter-pupillary distance, IPD, use the pupil angle from the center of rotation.

Another way to visualize the head variability is to examine cross-sectional slices. While they can be used to view rotational aspects of the point spread, they can only be viewed effectively in groups of ten or fewer subjects. Ten of the subjects who appear in figures 3 and 4 are shown in figure 5 in a transverse plane (a top view) cross-section and in figure 6 in a mid-sagittal plane cross-section (a side view). The straight line at the bottom of each subject in figure 6 is the cut-plane for separating the head from the neck. The back corner where this line meets up with the head contour is the nuchale point, or nape. A few selected landmarks are also shown as letters. There is a bright cluster of points at the eyes in the middle image of the three figures. That is the cluster of landmarks representing the point mid-way between the pupils and is due to the close alignment of the pupils in that axis system.

Cross-sectional slices are important for understanding the range of variability in the surfaces, in addition to the landmarks. The surface of the cranium is the part that interfaces with the helmet and it will importantly affect the helmet fit. They enable us to see the effect of the different alignments to predict or anticipate adjustment or sizing needs. Some of this adjustment can be done using multiple sizes if multiple sizes are an option.



Top-down view of head and face landmarks in three different head axis systems.

Figure 3. Plots of landmarks for all subjects in top-down view (mm)

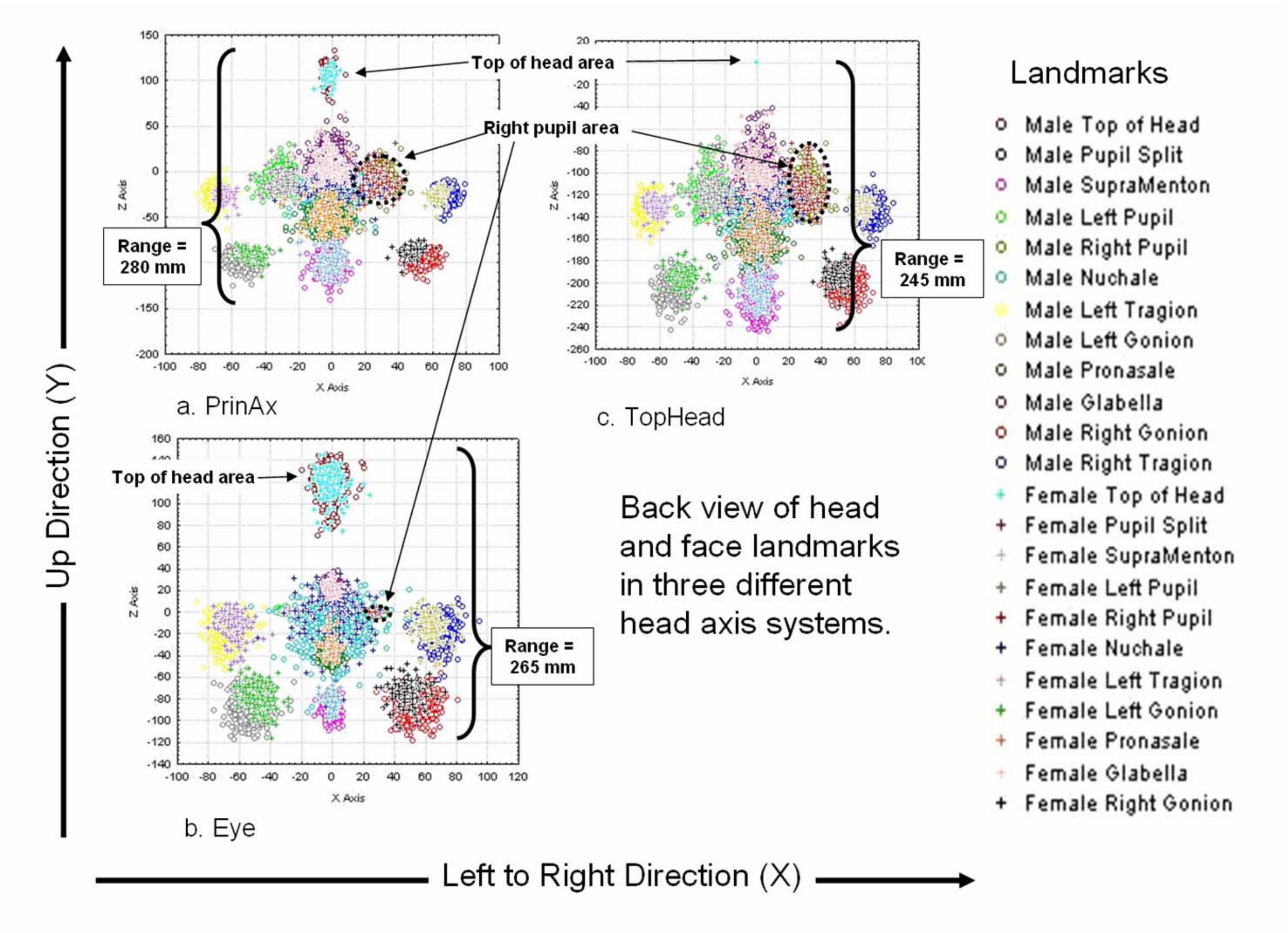


Figure 4. Plots of landmarks for all subjects in back view (mm)

The PrinAx system minimizes the overall spread or range of the head surface so it will have the smallest spread of these slices. It might be used for a helmet that has separate adjustability for: 1) cranial liner size and shape adjustability of 40 mm all around, 2) mechanical optical up-down adjustment of 60 mm, 3) a nape strap angular adjustment of about 45 degrees, 4) earcup placement vertical adjustment of 40 mm, and 5) oxygen mask placement adjustability of 80 mm. For this kind of helmet concept the outer contour of the combined set of subjects could be smoothed to create the outer contours of the helmet.

PrinAx would not be the ideal set of adjustments for the helmets with helmet mounted displays because the optical adjustments are so large. The use of angular adjustments, rather than linear may help, but the spread is still quite large. Alternative adjustability concepts can be explored by adjusting the data to alternative axis systems that correspond to the design adjustments being considered.

The Eye alignment minimizes eye location variability to less than 2 mm. This might be useful for a system that has no mechanical optical adjustment. However, the cost is a large additional variability in other regions. It will more than double the amount of adjustment needed at the top and back of the head, the forehead, as well as the nape strap angle. In addition, the ear locations have spread out more, which means the outer helmet shell will have to be enlarged quite a bit to accommodate earcup locations.

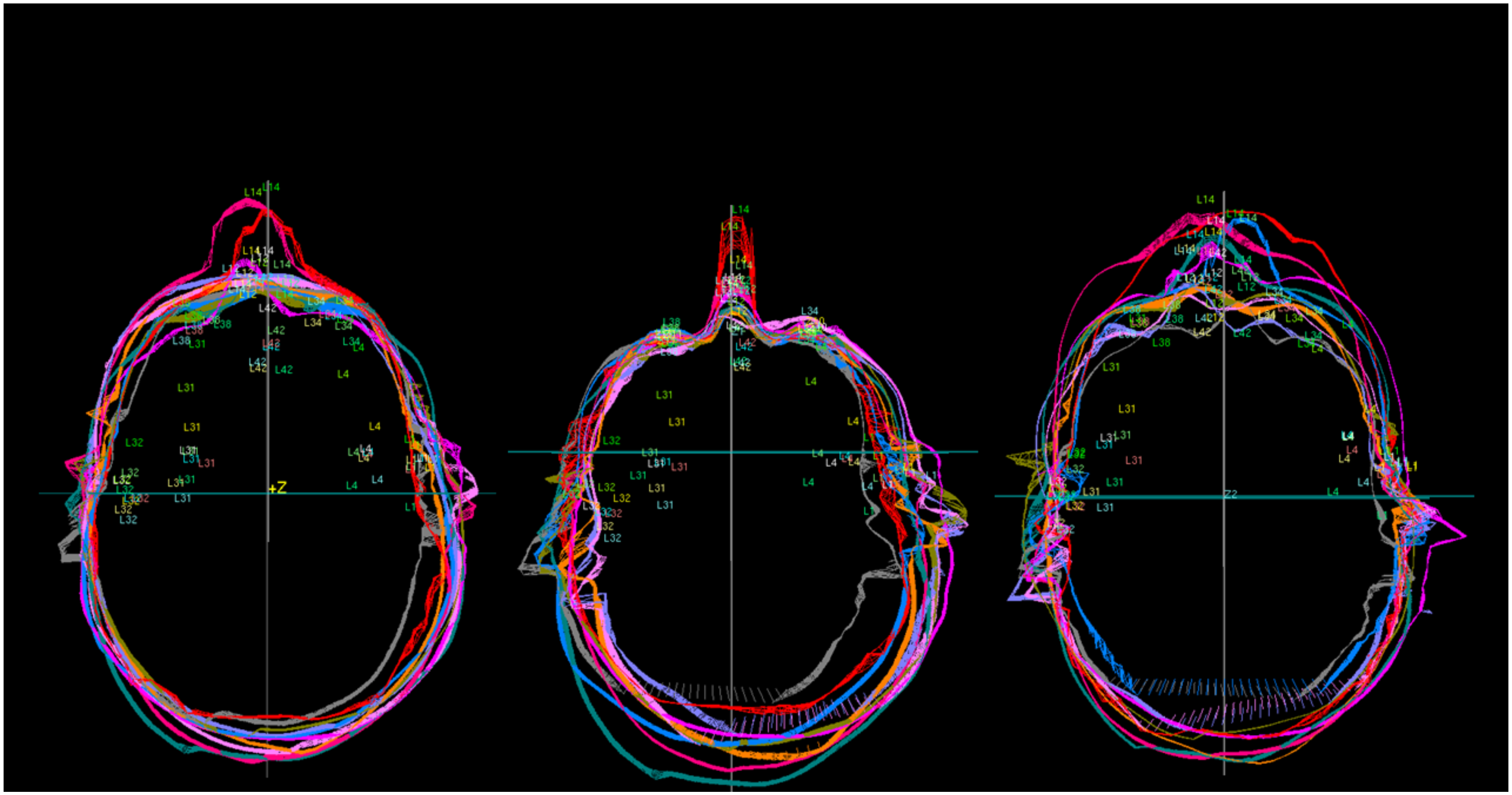
SUMMARY:

Three orientations were used to evaluate the 747 US navy 3-D head scans: 1) the Principal Axis System (PrinAx), 2) an approximate corneal plane alignment (Eye) and 3) a top-of-head alignment (TopHead). These three alignments characterize the range and variety of design/fit challenges in order to accommodate the population. It was demonstrated that each of the three alignments has advantages and disadvantages depending on design goals and each could be used if the design/fit concept could accommodate the particular variability they present. These are just three out of an infinite number of other alignment options, and they illustrate the ranges that an alignment tailored for the particular product's design goals will provide a better solution. Therefore, it is recommended that these be used only as a guide and that accommodation mechanisms for the new/evolving helmets are taken into account to arrive at an alignment specific to the system. In this manner the solution is optimized and the risk reduced as the design matures toward flight testing. Specifically the recommendations are:

1. Prioritize head mounted equipment design goals and establish tolerances for each.

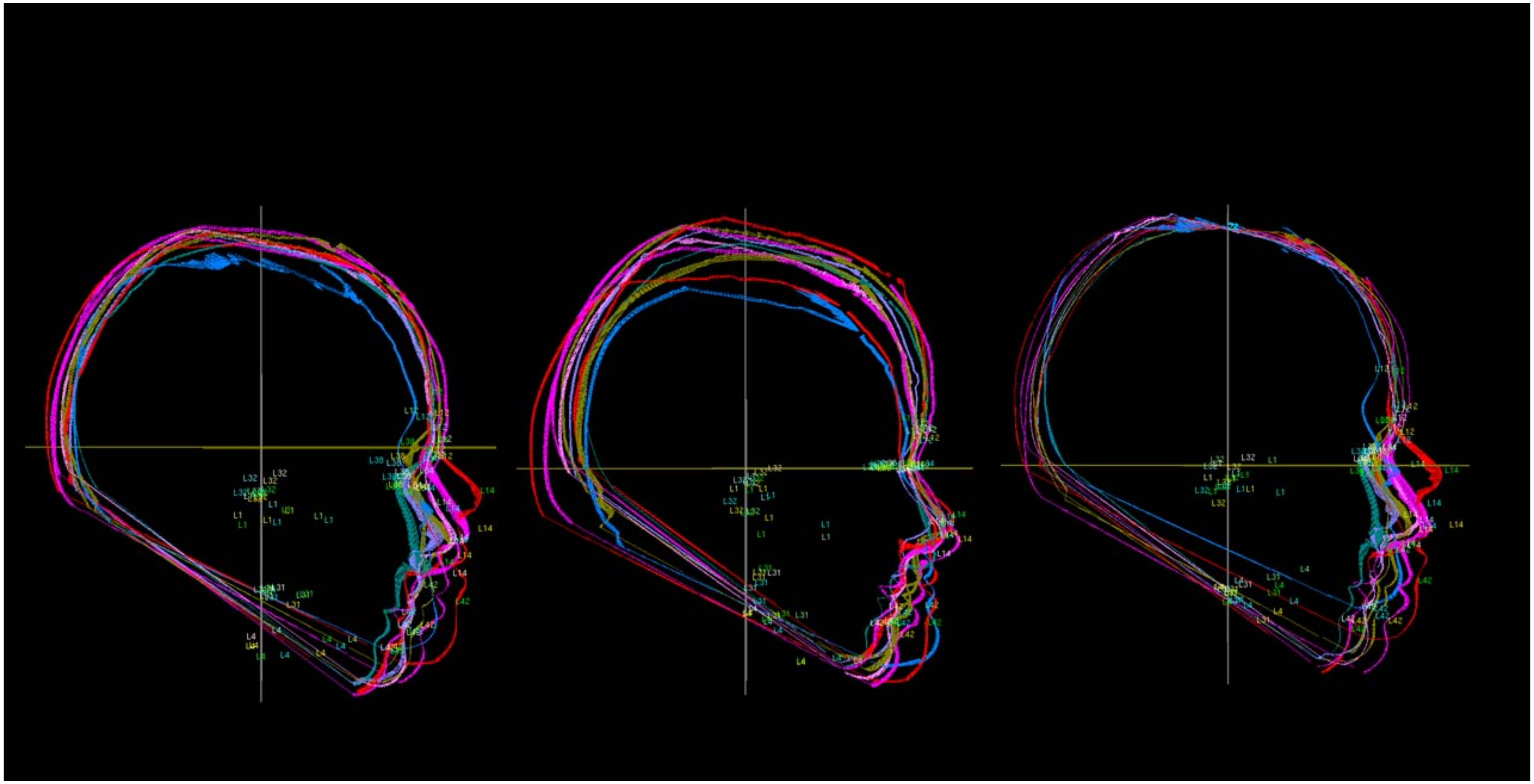
2. Determine design related orientations that minimize variability in the highest priority regions.

3. Explore design trade-offs related to each orientation using scatter plots and cross-sectional views.



a. PrinAx b. Eye c. TopHead

Figure 5. Top view cross-sections of ten subjects with landmarks in three different alignments.



a. PrinAx b. Eye c. TopHead

Figure 6. Right view cross-sections of ten subjects with landmarks in three different alignments.

Chapter 5: Summary

Each of the efforts under this program developed or used new engineering anthropometry methods to accommodate the broadest possible range of people in both military and civil sector products. Some ground-breaking methods for employing the use of anthropometric cases were demonstrated, as were the latest fit mapping technologies. New ways for networking and sharing anthropometry were also explored. These accomplishments are already having an impact in both the aerospace and automotive industries.

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