AFRL-HE-WP-TP-2006-0086

Principles of Fit to Optimize Helmet Sizing

Catherine R. Harrison
Kathleen M. Robinette

May 2006

Interim Report for January 2004 to August 2004

20070103050

Approved for public release; distribution is unlimited.

Air Force Research Laboratory
Human Effectiveness Directorate
Biosciences and Protection Division
Biomechanics Branch
Wright-Patterson AFB, OH 45433-7022

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
May 2006	Interim	January 2004 – August 2005

4. TITLE AND SUBTITLE
Principles of Fit to Optimize Helmet Sizing

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62202F

6. AUTHOR(S)
Catherine R. Harrison
Kathleen M. Robinette

5d. PROJECT NUMBER
7184

5e. TASK NUMBER
02

5f. WORK UNIT NUMBER
08

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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
Biosciences and Protection Division
Biomechanics Branch
Wright Patterson AFB OH 45433-7947

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

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-HE-WP-TP-2006-0086

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; Distribution is unlimited. Cleared by AFRL/PA as WS-05-1711 on 20 July 2005.

13. SUPPLEMENTARY NOTES
Published in proceedings of the NATO RTO Human Factors and Medicine Panel Symposium, Oct 05.

14. ABSTRACT
The present 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 African0American subjects were specifically included in order to examine the effects of racial anthropometric variability on fit. While the ranges of accommodation for the initial design was broad, it encompassed only a portion of subjects who fell within 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 sized, 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.

15. SUBJECT TERMS
fit, accommodation, fit mapping, size roll, helmet

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

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

Principles of Fit to Optimize Helmet Sizing

Dr. Catherine Harrison and Dr. Kathleen Robinette
2800 Q Street, Bldg. 824
Biomechanics Branch
Air Force Research Laboratory
Wright-Patterson Air Force Base, OH 45433
USA

catherine.harrison@wpafb.af.mil, kathleen.robinette@wpafb.af.mil

ABSTRACT

The present 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 two 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.

1.0 INTRODUCTION

Next-generation aviator helmets will incorporate helmet-mounted displays (HMDs) that serve as primary flight reference and more. As such, maintaining HMD eye-reference now surpasses in priority the more traditional aviator helmet requirements of supporting communication and oxygen systems, and providing impact, penetration, and hearing protection. Ensuring the existence of all these capabilities, plus safe ejection/crashworthiness and comfort for all occupants, in a logistically feasible package requires the development and use of performance-based methods to evaluate fit. Methods that can be implemented early in the development lifecycle rather than applied at the end to verify fit of a fully designed size roll will permit the design to be optimized for maximum accommodation with minimum sizes.

Common methods used in helmet design often do not take into account basic principles of fit, including the need to test a system on live human subjects in order to assess actual fit versus planned fit. Actual fit is determined by many factors, most of which are not currently captured by the CAD tools and head forms

Harrison, C.; Robinette, K. (2005) Principles of Fit to Optimize Helmet Sizing. In *Strategies to Maintain Combat Readiness during Extended Deployments – A Human Systems Approach* (pp. 6-1 – 6-16). Meeting Proceedings RTO-MP-HFM-124, Paper 6. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

commonly used in design. Important principles of fit include the fact that sizes are by nature a compromise; each human is shaped differently, and sizes at best capture a range of wearers, some of whom will be well fitted by the size and some of whom will not. Another important principle is that people are made up of a variety of uncorrelated dimensions. Not all narrow heads are short in height; not all wide faces come with wide heads. A design using a theoretic head shape made up of the average of all relevant dimensions will tend to accommodate no one well. This can be verified by thinking of the individual with the widest head one can picture, combining that with the tallest head, and then the deepest. Such a person would have a head that is unnaturally large and extremely rare. The combination of averages of all dimensions is just as unlikely to occur in a population. Designing to the average head and then simply scaling that head larger of smaller in all dimensions will produce a size roll that fails to accommodate large segments of the population.

Helmet designers have used a variety of methods to develop accommodation parameters and size rolls for new helmet designs. Often a shape is fabricated by a designer as a modification of an existing design, and the fit is tested on a variety of standardized mannequin heads. More recently, helmet concepts are designed in 3-D computer-aided design (CAD) software, and the shape of the helmet can then be tested on imported 3-D scans of actual human heads. The former method does not take into account tissue properties of the head that impact fit or the fact that helmet orientation during wearing by humans reflects wearer feedback as to the proper positioning of the helmet, with the result that helmets designed to fit mannequin heads do not necessarily provide an equivalent fit on human heads. The method of using CAD to test the positioning of a helmet concept on the head is also problematic, in that current technologies do not provide empirically-based tools to verify accurate orientation and placement of the helmet on the head, potentially misleading designers early in the design process. Development of accurate models relating CAD orientation and placement to actual fit on human wearers would greatly enhance designers' ability to develop helmets that fit and are sized to maximize accommodation. The present work contributes to an ongoing effort to develop such linkages between design tools and human accommodation data.

Equipment designs must be tested on actual human subjects in order to determine the ranges of population that are accommodated by each size. Mapping the fit of a helmet system onto the population by using a planned subject sample often reveals that the sizes designed actually accommodate more of the population than predicted or a different segment of the population than was intended, sometimes leaving large segments of the population not accommodated or resulting in redundant sizes with overlapping accommodation regions.

The Air Force Research Laboratory Computerized Anthropometry Research Laboratory (CARD Lab) used a commercially developed one-size concept helmet to develop and test a method of predicting the portion of the Joint Strike Fighter (JSF) military population that would be accommodated in a commercially developed one-size concept helmet. This helmet fit assessment anthropometrically characterized the portion of the U.S. naval aviation and JSF populations who would get a good fit in the concept helmet and provided information on design modifications to fully accommodate this population.

2.0 METHODS

The fit mapping and size optimization employed the following steps:

- Selected a subject sample that represented the U.S. naval aviation / JSF populations
- Documented head-neck alignment of each subject wearing the concept helmet in a seat-back simulation in order to determine number of sizes needed, and used experimenter and subject assessments of the helmet's fit and comfort to further refine design recommendations.

- Digitally and mathematically compared key helmet features and related human features in order to determine the variability of positioning depending on each wearer's unique head shape.
- Plotted the subjects by passing or failing fit based upon head-neck alignment on the two dimensions that best correlated to overall fit (head length and head breadth) to determine the range over which the existing concept helmet provided acceptable fit. This was the region of fit for the existing design.
- Transposed this region of fit so that it was positioned over the desired population. Copied the region and pasted it over the remaining unaccommodated portion of the population as necessary to accommodate the entire population range required.
- Determined from the locations of the new size regions what dimensional changes to the helmet concept would be needed in order to modify the helmet to create each new size.

Data collection for this study was completed over a three-week period in the spring of 2004. Data were collected by personnel from the Air Force Research Laboratory Human Effectiveness Directorate (AFRL/HE), their support contractors (General Dynamics, Beavercreek, Ohio), and life support technicians trained by the manufacturer in fitting the concept helmet.

2.1 Test Article Description

The test helmet consisted of a two-part modular inner and outer helmet concept. The inner helmet allowed for a personal fit referenced to the location of each wearer's eyes. An assortment of outer helmets would allow the wearer to tailor the helmet configuration for specific missions. This evaluation included only one size of helmet.

For tactical jet use, the helmet concept included bayonet fittings to attach an oxygen mask. The MBU-20/P oxygen mask was included in this evaluation since it is approved and available for use by the U.S. military aviators. The MBU-20/P is available in five sizes (Extra Small Narrow, Small Narrow, Medium Narrow, Medium Wide, and Large Wide), but the smaller two sizes were not available for this study.

2.2 Subject Selection

Subjects were selected in a stratified sample drawn to represent head size / shape across the JSF population (Hudson, Zehner and Robinette, 2003), after first determining that the JSF population encompasses the anthropometric range of the U.S. naval aviation population (747 heads surveyed in 2002). This subject selection approach is critical to understanding how the helmet will fit and perform across the target population and not just the "middle of the bell curve" for the populations. Tables 1 and 2 show the Subject Selection Matrices for females and for males. The matrices were constructed separately for each gender in order to create nine cells, each of which would contain an equal 11.1% of the population. First, the population was divided by head length into columns, each representing one-third of the population. Then, each of those head length columns was divided independently into thirds by head breadth. Notice that, in order to accomplish this, the range of head breadth is different within each column. Although this makes the range of each cell in the matrix a different size in terms of head length and head breadth, it allows each cell to represent the same percentage of the population.

Head Length 179-197 mm		Head Length 197-203 mm		Head Length 203-219 mm	
Head Breadth	**Subject**	**Head Breadth**	**Subject**	**Head Breadth**	**Subject**
138-151 mm	*3, 23*	**142-152 mm**	*4, 5, 10*	**141-152 mm**	
151-156 mm	*8, 16*	**152-156 mm**	*1*	**152-156 mm**	*27*
156-175 mm	*2, 20, 26*	**156-174 mm**	*6, 12*	**156-168 mm**	*25*

Table 1: Subject selection matrix for males. Subject numbers in italics indicate which subjects were sampled in each cell.

Head Length 166-185 mm		Head Length 185-191 mm		Head Length 191-206mm	
Head Breadth	**Subject**	**Head Breadth**	**Subject**	**Head Breadth**	**Subject**
131-143 mm	*24*	**133-143 mm**	*14*	**135-145 mm**	*9, 17*
143-148 mm	*15*	**143-146 mm**	*13*	**145-147 mm**	*21*
148-170 mm		**146-159 mm**	*7, 11, 19, 22*	**147-163 mm**	*18*

Table 2: Subject selection matrix for females. Subject numbers in italics indicate which subjects were sampled in each cell.

A total of 27 subjects were tested, 15 male and 12 female, in order to fill the cells of the subject selection matrices for each gender. Although at least one subject per cell was sought, ultimately there was one empty cell each in the male and female matrices, despite over-sampling.

2.3 Procedure

2.3.1 Helmet Fitting

A life support technician custom fitted the helmet to each subject. The helmet was then adjusted to fit snugly to the head while the subject continued to maintain the optical focus and convergence through the optical device. In other words, the fitting procedure was optics-centered.

The life support technicians recorded objective information about which settings were used for the helmet in all adjustments, how long it took to fit the helmet and the mask, which size mask was used, and other factors. In addition, the life support technicians recorded comments about the quality of fit or particular difficulties or aspects of the fit of each subject on a Helmet Fitting Form.

2.3.2 3-D Anthropometry and Scanning

Each subject was measured by a trained anthropometrist, and 22 important bony landmarks of the face and head were marked with stickers in order to be visible on 3-D digital scan data collection. Four scans were made for each subject in the following order:

- "Nude" (no helmet on) scan performed with landmarks but no helmet
- Helmet-only scan prior to the slippage test (i.e., before head shaking and nodding)
- With helmet and mask, prior to the slippage test
- With helmet only, after slippage test

Using landmarked subject nude head scans, the scan of the helmet, and the scan of the subject wearing the helmet and mask, the locations of the head contours and landmarks within the helmet were obtained by subtractive image analysis. 3-D scans were aligned so that the nude head was positioned in the helmeted scan, revealing each subject's actual head position in the helmet.

2.3.3 Helmet Slippage

To measure helmet slippage, three helmet landmarks were used in conjunction with three facial landmarks to obtain five distance measurements. The three facial landmarks were glabella, which is the center of the eyebrow ridge bone, and the left and right frontotemporale, which are the front parts of the left and right temple. The five distance measurements were taken with callipers before and after a simple head shake and nod test, and the measurements were recorded and compared by subtraction. The head shake and nod test consisted of having subjects nod their heads up and down to the anthropometrist's count of ten, and then shake their heads side to side to the anthropometrist's count of ten. The purpose of these head movements was to challenge the stability of the helmet platform, particularly for eventual HMD viewing stability. There was variability in both the range of motion and the severity of each subject's head shakes and nods.

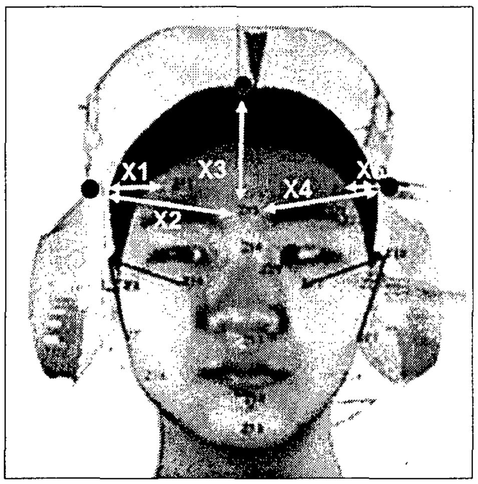

Figure 1: Head slippage landmarks and measurements. Arrows connect three landmarks placed on the helmet with landmarks identified on the face, and represent the five distances measured before and after head shakes and nods in order to quantify slippage.

Figure 1 illustrates the locations of the helmet points and labels the five measurements as X1 - X5 as they were positioned for the facial landmarks of one particular subject. The numbering represents the order in which these measurements were taken for each subject, regardless of the relative location of the landmarks. The exact orientation of the vectors of measurement varied with each subject's facial morphology, as well as the positioning of the helmet on the head pre- and post-slippage.

2.3.4 Neck Offset

One objective fit criterion was neck offset, which was defined in this study as the distance from a mock-up ejection seat back to the subject's neck. Neck offset is important since poor head position caused by the helmet against the seat can cause neck fatigue / discomfort and, worse, misalignment and spinal injury during any and all portions of an ejection seat sequence. For this test, a flat-backed seat mock up was adjusted to mimic the F/A-18 aircraft ejection seat back tangent of 18 degrees. Subjects wore the properly fitted helmet in this seat, and looked straight ahead in a gaze direction parallel to the ground. While the subjects were in this position, the anthropometrist measured the distance from where the back of the helmet contacted the seat to the back of the subject's neck on a horizontal plane.

2.4 Scoring

Fit issues fell into five categories: neck offset, adjustment, position, ear cups, and mask. Table 3 summarizes the criteria by which a subject scored a failure in any of these categories. There were multiple fit criteria in some categories. Failures were binary pass-fail, scored as 0 for failure and 1 for pass.

3.0 RESULTS

3.1 Neck Offset

The scans in Figures 2 through 5 illustrate why neck offset is a problem. Seven of 12 females failed on this criterion at a level of neck offset >= 6 cm, as did 2 of 15 males. Subject numbers and measured neck offset are provided below each figure. Although scans are made with the subjects holding their heads unsupported, it is easy to visualize from the scans that larger offsets will correspond with larger neck angles (i.e., a larger angle of cervical spine to thoracic spine) when the subjects are sitting with their heads pressed back against a flat seat back. Note the lines drawn on each of these scans from the infraorbitale landmark (below the pupil) to the top of the ear to the bottom of the ear. Those lines are extracted to compare multiple subjects in further visual analyses.

Fit Category	Failure Criteria	Criteria description
Neck Offset Failure	> 6 cm Neck Offset	Neck offset
Adjustments Failure	Adjustments Failure	Life support technician-reported difficulty or problem adjusting helmet
Position Failure	Position life support technician Failure	Life support technician-reported position positioning problem
	Position - Hotspot	Subject-reported hotspot or intolerable pressure
	Forehead Failure	Experimenter-reported forehead position too high or low
Ear cup Failure	Ear cups Failure	Life support technician-reported ear cup problem
	Ear - Hotspot	Subject-reported ear hotspot or intolerable pressure
	Ear Fore-aft Failure	Experimenter-reported failure, helmet too far forward or back on ear
	Ear In-out Failure	Experimenter-reported failure, helmet not wide enough or narrow enough on ear
	Ear Up-down Failure	Experimenter-reported failure, helmet too high or too low on ear. Excluded "too high" failures when the only problem was helmet resting on earlobe, there was no discomfort, and life support technician reported good fit.
Mask Failure	Life support technician Mask Failure	Life support technician-reported failure of mask fit. Excluded failures due to proper size not available.
	Mask - Hotspot	Subject-reported hotspots from mask.

Table 3: Fit failure categories and criteria. Failure by any criterion in a category causes failure for that category.

Subject 15 (Figure 2) has a relatively small head overall. Although her ear cup, positioning, and mask fit criteria all achieved passing scores, the small size of her head caused her to have the largest neck offset seen in this study, 6.8 cm.

Subject 23 (Figure 3) has one of the lowest neck offsets, 3.6 cm. His head is large and fills the helmet cavity. He achieved passing scores in all fit categories except ear cups.

Subject 10 (Figure 4) received even better overall fit performance than subject 23, passing in each category; however, at 5.4 cm his neck offset is significantly greater than that of subject 23. This is due to the tapered shape of subject 23's head. In comparing the two scans, note that subject 23 has his gaze and chin tilted upward, which exaggerates the appearance of neck angle, while subject 10 is gazing straight ahead. Comparing the rightmost images for these two subjects, visually tilt subject 23's chin downward and you will see that the largest part of the protrusion on the back of the helmet, in his case, will not lie directly behind the back of his head against the seat back as it does for subject 10.

Figure 2: Subject 15, Offset 6.8 cm

Subject 19 (Figure 5) posed a number of fit challenges. Although her head length was in the median range overall, her ears are located very far back relative to nucale, a landmark on the back of her head. In addition, her eyes are located very close to the front of her face. It was necessary for the life support technician to fit her very far forward in the helmet in order to accommodate her anthropometry, which is typical for people of Asian descent people but unusual for people of Western European descent. It took the life support technician 60 minutes to fit this subject into the helmet. Mean time to fit the helmet over all subjects was 28.6 minutes.

The life support technician reported that with a thicker brow pad he might have been able to push this subject further back into the helmet. From this scan, however, it is clear that the helmet is also rotated backward on her head, perhaps due to the continuous degree of slope in this subject's brow.

Note that although these scans were made in an upright posture, the neck offsets were measured with the subject seated flat against a simulated ejection seat at an angle of 18 degrees, so the neck offset measurements presented represent a significant problem that we believe needs to be addressed with a shorter size of hard-shell helmet. The histogram in Figure 6 illustrates a tri-modal distribution of neck offset among subjects.

Figure 3: Subject 23, Offset 3.6 cm

Figure 4: Subject 10, Offset 5.4 cm

The variability in the location of ears is not less among the subjects who need a smaller helmet size. Head length, for example, had zero correlation to neck offset, so it would be incorrect to assume the shorter helmet is needed exclusively for very short heads. Rather, these data suggest that the relative location of the ears to the back of the head is a more important predictor of fit than overall head length. An example of the type of person who needs a shorter helmet is the Asian female, subject 19, illustrated in Figure 5. Her overall head length falls close to the mean head length for females. However, her ears are extremely close to the back of her head. In the new helmet size, her head would be centered within the helmet. If the new size were made by simply shrinking the existing size in all dimensions, this subject would still not achieve an appropriate fit. Notice also that her head width is accommodated well in the existing helmet. Subjects 10 and 19 demonstrate the need for a shorter size to accommodate ethnic variability among subjects.

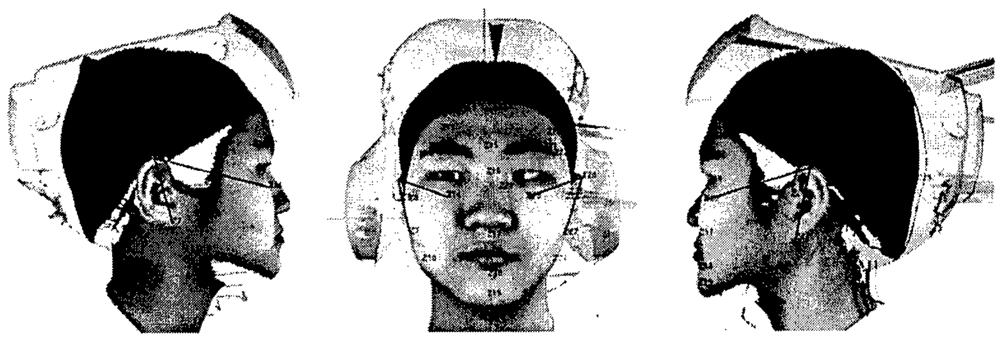

Figure 5: Subject 19, Offset 6.7 cm

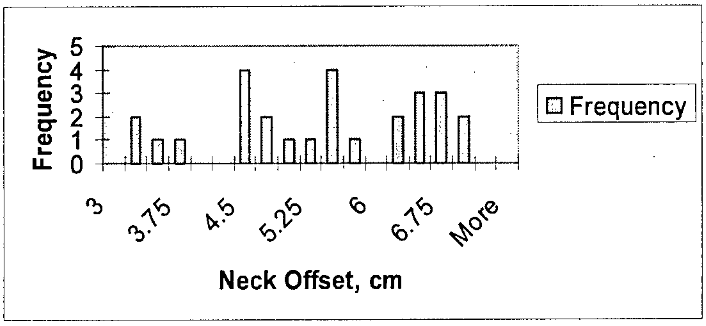

Figure 6: Distribution of neck offset

3.2 Adjustment

Examples of life support technician comments considered to indicate failures in this category included "[Setting] should have been 9 [clicks] but no clicks could be added on top front of pad" and "Couldn't reach bottom strap." Analysis of the life support technicians' comments pertaining to adjustment failures revealed areas in which the current adjustment system could be improved. Many adjustment failures had to do with accessibility and length of the adjustment straps. The current adjustment system adjustment tabs, for certain large head dimensions, are inaccessible, because the life support technician must reach inside the helmet to adjust the tab but is prevented by the lack of clearance. An additional finding that interior pads could overlap on small heads would be addressed by creating a smaller size for these wearers. For small heads, the crown and nape pads can overlap at the top rear portion of the head. This could cause injury to the wearer during an impact, and is a critical fit failure. The adjustment range of the new, smaller helmet size should be checked to ensure that it addresses this problem, and that the range of head sizes to be fitted by the large helmet is such that this failure cannot occur.

Subjects of both genders who received poor fit tended to be fitted with their ears closer to the front of the helmet, consistent with a less centered positioning within the helmet. This occurred for different reasons. In subjects whose heads were long or wide, the life support technicians had difficulty reaching the straps to make adjustments. In subjects whose heads were very small in some dimensions, the head was forced to be positioned very far forward in the helmet because the brow pad was thin, which caused some of the adjustment straps to be near the limits of their adjustment range and reduced flexibility of positioning.

3.3 Position

An example of a comment categorized to indicate a position failure was: "Head was really far forward in the helmet and her eyes were not deep set causing the position of the eyes to be in the wrong position (1 cm) with respect to the helmet. A thicker brow pad would have been helpful." Four subjects experienced a "forehead failure" (see Table 3) because the positioning of the helmet on the brow was either too high or too low. One of these was a female with a very narrow head and a very poor overall fit (subject 18, neck offset 6.7 cm). The other three were males. One of the males had the longest head and a marginal fit (subject 25, neck offset 4.4), and the helmet seemed to fit high on his forehead because it was, overall, small for his head. Cause of "forehead failure" in the other two males was not as clear: the particular shapes of their heads forced their helmets into an improper forehead height, despite expert fitting. Subject 19, Figure 5, experienced a "position life support technician failure" (see Table 3) due to the continuous slope of her brow, an anthropometric feature typical of people of Asian descent. In general, life support technicians suggested that the brow pad was not adequate to allow proper fore-aft fitting of the helmet on many subjects.

3.4 Ear cup Fit

Example of a comment considered to indicate a fail in this category: "Found ear cups to be painful at the tops but loose at bottoms." Many subjects experienced failures of ear cup fit because the ear cups were too tight at the top and too loose at the bottom. The scan of the front view of the helmet in Figure 1 reveals that the ear box of this helmet cants outward at the bottom and is much narrower at the top of the ear box, while human heads and ears are at their widest at approximately the region of the top of the ear.

Life support technician comments revealed that the most critical head dimensions for ear cup fit included the distance from the eye to the ear and the orientation of the ear. An ear that is positioned on the head with approximately a vertical orientation about an axis from top to bottom of the ear can be particularly problematic, when positioned very close either to the front or the back of the head, regardless of overall head length, due to the size limitation imposed by the hard ear box of the helmet.

3.5 Mask

An example of comments that were scored as failures in the mask fit criterion included "Bayonets pressing on cheek." Mask fit was scored as an automatic pass for any subject for whom the correct size was not available, which means that, because the extra-small narrow mask was not available throughout testing, mask fit problems for very small females were not captured. Nevertheless, one important observation was that for subjects with wide, flat faces, namely our Asian subjects, the bayonets tended to impinge upon the cheeks.

3.6 Slippage

Slippage was first assessed as a simple pre- and post-test difference in the measurements of the five lengths indicated in Figure 1. Absolute Motion was the sum of the absolute values of all five measured differences. The absolute value was used because directionality of motion was not taken into account. The slippage being measured was a difference between the location of the helmet on the head prior to head shaking and after head shaking. No measurement of motion during head motion was made during this test.

All subjects experienced helmet slippage in this study. Among 12 females, 10 experienced greater than 3 mm Absolute Motion slippage, and 6 experienced greater than 5 mm slippage. Among 15 males, all 15 experienced greater than 3 mm slippage and 6 experienced greater than 5 mm slippage. It is interesting that the two subjects who experienced the least slippage were females; however, that result may be confounded by the fact that some female subjects in this study tended to shake their heads less vigorously. Tables 4 and 5 present slippage for each subject along with the scores for each of the five categories of fit. Slippage did not correlate significantly with any of the other categories of fit, indicating that improving the fit of the helmet in these categories will not improve the stability of the helmet on the head in its current design.

Subject	Absolute Motion, cm	Neck Offset	Adjustment	Position	Ear cup	Mask
1	0	1	0	0	1	0
2	0.6	1	1	0	0	1
3	0.7	1	1	1	0	1
4	0.8	0	0	1	0	0
5	1.8	0	1	1	0	1
6	0.7	1	1	0	1	1
8	0.3	1	1	1	1	0
10	0.7	1	1	1	1	1
12	0.3	1	1	0	1	1
16	0.6	1	1	0	0	0
20	1	1	1	1	1	0
23	0.7	1	1	1	0	1
25	0.7	1	0	0	0	0
26	0.6	1	1	0	1	1
27	1.8	1	0	0	1	1

Table 4: Slippage data and fit scores for male subjects. Fit scores: 0 = failure, 1=pass.

4.0 DISCUSSION

Using the specific findings of the data collection, and using the 3-D data collected in the study, it is possible to develop a size roll for this helmet based upon empirical data. This method of size roll development for helmets represents a departure from approaches to size roll development customarily used by helmet manufacturers currently supplying the U.S. government.

In order to develop new size rolls for the helmet, subject data were first plotted for head length versus head breadth. Subjects were shown as larger squares superimposed over the distributions of the Joint Strike Fighter and Navy head survey samples, with an ellipse drawn about the distribution to indicate the 99% accommodation range specified for the helmet. These plots were drawn separately for each fit criterion category, so that a color code could clearly indicate subjects who passed or failed in that category on that plot. A rectangle was then drawn around the subjects who achieved a passing fit for that category. This rectangle describes the actual region of fit of the helmet as defined by that particular fit criterion. The regions of fit for these categories can be superimposed to provide a quick view of the regions in which the present helmet size and shape provides best accommodation.

When the current regions of fit had been determined in this manner, the range of accommodation that could be made with one size of helmet could be deduced by the range being presently well accommodated. This range of accommodation was then shifted so as to accommodate a range of population more appropriate to the desired accommodation range, and a determination could be made as to what additional size or sizes might be needed in order to accommodate the remaining population, again using that range of accommodation as a guide. Figures 7 through 12 illustrate this process.

Subject	Absolute Motion, cm	Neck Offset	Adjustment	Position	Ear cup	Mask
7	0.3	0	1	0	0	1
9	0.2	0	1	0	1	1
11	0.2	0	1	0	1	1
13	0.4	1	1	0	1	1
14	1.6	0	0	1	1	1
15	0.6	0	0	1	1	1
17	2.4	1	0	0	1	0
18	1.1	0	0	0	1	0
19	0.9	1	0	0	0	0
21	0.9	1	0	0	1	0
22	0.5	0	0	1	1	1
24	1.1	1	0	0	1	1

Table 5: Slippage data and fit scores for females. Fit scores: 0 = failure, 1=pass.

4.1 Neck Offset

Subjects who achieved a passing fit score in the criterion of neck offset (i.e., neck offset <= 6 cm) are illustrated in Figure 7 by black diamonds. A grey rectangle is drawn in Figure 7 to encompass the majority of passing subjects. This box defines a region of accommodation for the concept helmet. The subjects receiving passing versus failing scores for neck offset had wider head breadths, to the extent that the present size accommodates two subjects on the outer boundaries of the 99th percentile ellipse and one that lies far outside the desired accommodation region described by that ellipse.

The other criteria (adjustment, position, and ear box) are related to aspects of the helmet design other than overall size, although size is probably implicated in fit or failure based on these criteria. Therefore, the size adjustments for a new size roll were based upon the neck offset accommodation.

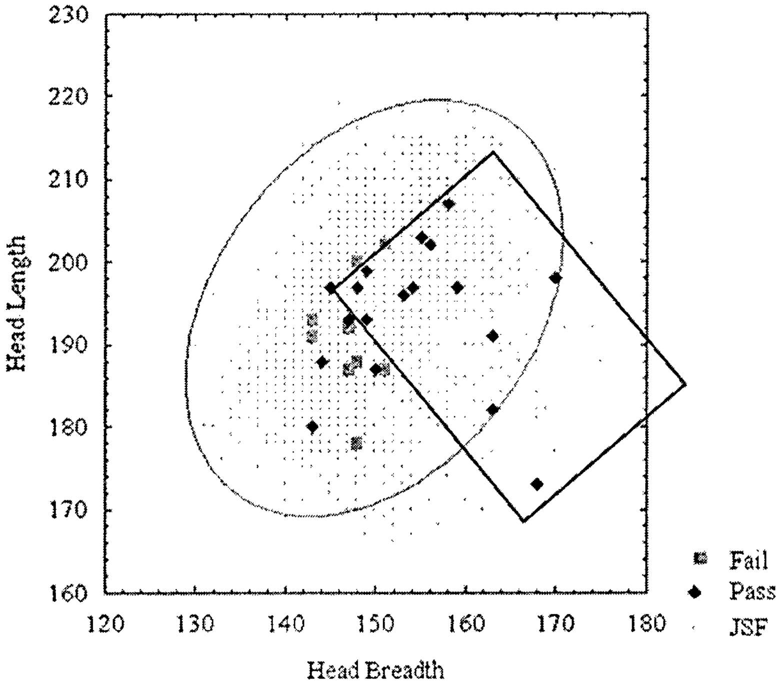

Figure 7: Neck offset accommodation region shaded.

4.2 Adjustment, Position, Ear Cup and Slippage

The distribution of subjects receiving passing versus failing scores for adjustment also favored wider head breadths, again accommodating two subjects on the outer boundaries of the 99th percentile ellipse and one that lies far outside the desired accommodation region described by that ellipse.

Relatively few subjects received passing scores for position, and these subjects were clustered toward the center of the desired population. This indicates the degree to which it is difficult to center subjects with either small or large heads using the existing system.

These findings indicate that the adjustment system should be improved to permit more flexible fore-aft positioning so that all wearers may be brought to the same neck offset, allowing proper head positioning for all wearers in the same ejection seat. In addition, a conformal brow pad of customizable thickness and shape would permit proper centering of the head in the helmet. Because helmets are now called upon to support critical optical systems, stability in the front of the helmet is particularly important. The conformal brow pad would also be expected to ameliorate slippage and address the stability demands of helmet-mounted optics. The brow pad designs should wrap around the sides of the forehead toward the temples in order to provide lateral stability. Mass customization by scanning and central rapid prototyping is now feasible and may be worth the cost if needed to provide the stability necessary for the optical performance the helmet system requires. Foam-in-place pads are another option. Finally, recent research in the custom hearing protection program suggests that scanning and fit mapping methods may permit development of a small fixed number of well-designed shapes that will provide a custom-like fit to a large percentage of the population.

Data indicated that redesigning the shape of the ear box to be wider at the top than the current design would improve fit. The ear box must also be made somewhat roomier to allow the ear cups to be moved forward and backward when the ear cup is oriented vertically; the current shape of the ear box permits fore-and-aft adjustments only with the ear cup canted backward about the axis of the ear.

4.3 New Sizes

Based on the size and shape of the region of accommodation of the existing helmet, two new sizes were created to accommodate the same range of accommodation, but shifted to cover the entire population of interest. Only two "size boxes" were needed to cover the entire region, meaning that two sizes comprise a sufficient size roll The size roll development process begins by defining the size and shape of the accommodation region for the existing helmet. The box represents neck offset failures, which are the failures that most closely relate to the overall size of the helmet. As stated previously, this box fails to cover much of the desired population, and does cover a large area that is outside the desired population. However, the box does describe the range that one helmet size can accommodate. Therefore, a helmet that is modified in size should also be accommodated by this size and shape of range.

For the proposed new large size, the helmet should be longer by 10 mm and narrower by 8 mm. Figure 8 shows the accommodation region for this new size, obtained by shifting the existing accommodation region (Figure 7) up and to the left to accommodate a region within the ellipse encompassing 99% of the population. The specific dimensional adjustments required to create the new size can be read directly from the plot in Figure 8 after visually shifting the accommodation region. A second size is then created, again covering the same size and shape of range, but shifted down and to the left (shortened by 30 mm), to cover the remaining portion of the population not accommodated by the proposed new large size. The 30 mm would be achieved by eliminating a backward bump-out on the existing concept shape (see Figure 9) in order to reduce the neck offset. Figure 10 shows both of these sizes superimposed over the population to be accommodated. These two sizes can accommodate approximately 99% of the population.

5.0 DISCUSSION AND CONCLUSIONS

Fit testing the concept helmet on live subjects revealed that the shape of the actual accommodation region failed to accommodate many subjects who were within the 99% probability ellipse for the target population, while encompassing a broad area that fell outside the 99% probability ellipse and held few subjects. In other words, while the range of accommodation was broader than predicted, it did not coincide well with the desired JSF accommodation distribution and would in fact fail to fit a large number of subjects within the desired accommodation region while accommodating well a size-shape combination that is rare in any population. Testing also revealed that the current design and adjustment system accommodated a sufficiently broad range of head sizes that it would be possible to accommodate all subjects within the region of desired accommodation with only two sizes. The results of this study indicated that two helmet sizes would likely accommodate 99% of both males and females with specific shape and size modifications, and a new fit adjustment concept. This two-size prediction was a significant finding since the manufacturer's design approach predicted as many as five sizes might be needed. This information can only be obtained by fit testing on live human subjects, appropriately sampled to represent the population of interest.

Broad implementation of the method described here would produce a significant cost savings to equipment purchasers in acquisition lifecycle costs by optimizing the number of sizes and reducing equipment modifications due to fit problems currently often discovered after a new system has been fielded. Cost savings would also accrue to both designer and customer by reducing late-cycle design modifications (with attendant penalties) as well as optimizing the number of sizes and reducing redundant sizes that are costly to develop and costly to field and support. Finally, in addition to evaluating fit of an existing concept helmet, this method also generates specific recommendations for design modification based upon empirical data, making it a valuable tool to be used early and iteratively during the design process.

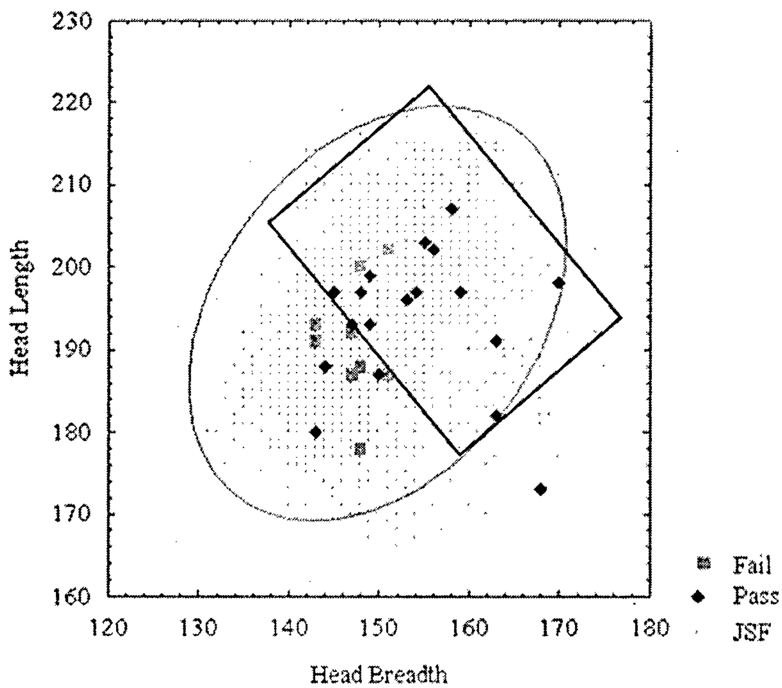

Figure 8: New large size, obtained by translating the existing region of accommodation based on neck offset (Figure 7) to a position accommodating a large percentage of the population of interest.

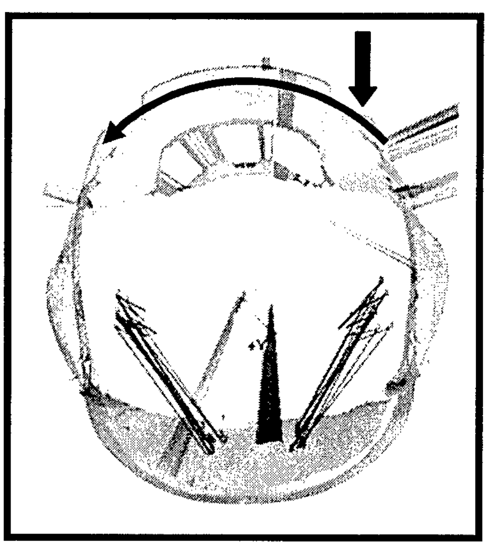

Figure 9: Arc represents recommended shape modification to create shorter helmet size.

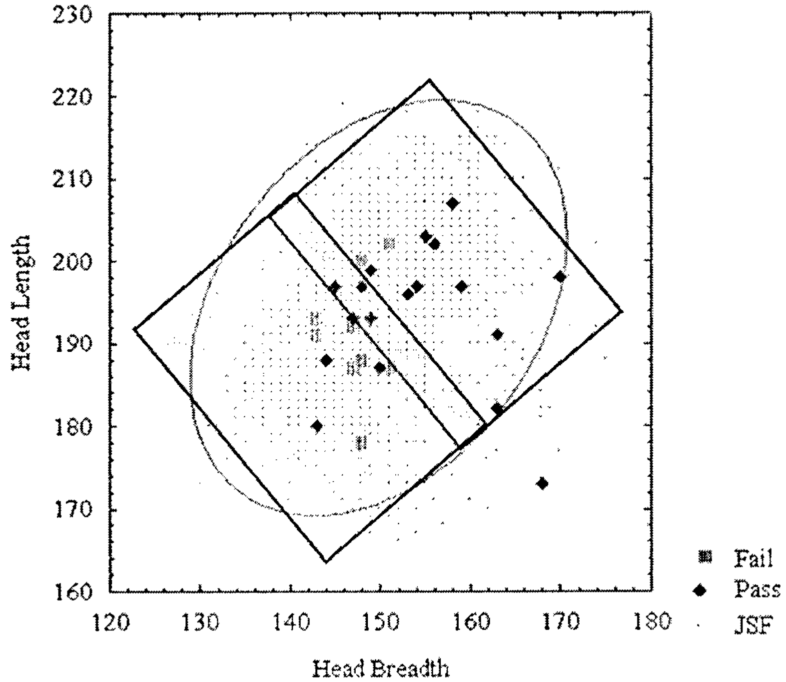

Figure 10: New small size.

[1] Brinkley et al ("Vertical Impact Tests of a Modified F/FB-111 Crew Seat to Evaluate Headrest Position and Restraint Configuration Effects," AFAMRL-TR-82-51)

[2] Burnsides, Dennis B., Files, Patrick, Whitestone, Jennifer J. (2000) Integrate 1.28: A Software Tool for Visualizing, Analyzing and Manipulating Three-Dimensional Data (U), Technical Report AFRL-HE-WP-TR-2000-0100, Human Effectiveness Directorate, Crew System Interface Division, 2255 H Street, Wright-Patterson AFB, OH.

[3] Hudson, J. A., Zehner, G. F., and 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, Human Effectiveness Directorate, Crew Systems Interface Division, Wright-Patterson Air Force Base, Ohio, AFRL-HE-WP-TR-2003-0142.