AMSSB-RSS-E (N) 12 June 2002

MEMORANDUM FOR RECORD

SUBJECT: Anthropometry Research in Support of Accommodation Estimates for the UH-60M

1. Background:

Using the Jack man model, ARL/HRED has the capability to model reach, clearance, and field of view characteristics of virtual human subjects in virtual cockpits. Recently Natick anthropologists provided ARL/HRED with body dimension specifications for several sets of Jack man-models located on the periphery of accommodation envelopes capturing various percentages of the Army population. These boundary forms represent "worst case" extremes of body size and body proportions that must be accommodated in order to capture a certain percentage of users. They can thus be helpful in establishing performance – based design and exit criteria for systems that are required to accommodate a certain percentage of users. While virtual models can never substitute for testing properly clothed and equipped human subjects in real cockpits or mock-ups, virtual testing can give important quantitative feedback that helps to shorten development and fielding times, reduce testing and evaluation costs, and minimize costly human factors failures in operational testing.

2. Anthropometric Specifications of the Models:

Body dimension specifications for the Jack man models describing various theoretical accommodation envelopes were derived using multivariate statistical methods because cockpit controls and adjustment mechanisms must accommodate many critical body dimensions ***simultaneously.*** When simultaneous accommodation of multiple body dimensions (e.g.sitting height, leg segment lengths, and arm segment lengths) is required, univariate percentile ranges cannot be used to establish design and testing criteria because a) body dimensions are not perfectly correlated with one another, so different people may be outside the 5^{th} –95^{th} percentile ranges for different variables (Moroney and Smith, 1972); b) because uniformly large and uniformly small models do not necessarily describe the engineer's worst case scenario – combinations of extremely large and extremely small values in the same subject may be critical to design (Roebuck et al., 1975; Bittner et al., 1987; Hendy, 1990; Zehner et al., 1992); and 3) because percentiles are not additive, human models created from percentile segments are unrealistic in both size and shape (Churchill, 1978; Robinette & McConville, 1981; Annis & McConville, 1990).

In order to validly describe extremes of both body size and shape in user populations, multivariate statistical analyses such as Principle Components Analyses (PCA) have been used. PCA reduces the dimensionality of the accommodation envelope from *n*-space (where *n* is the number of body dimensions that are critical for design accommodation) to a smaller number of dimensions (say 2 or 3) that account for a large proportion of the original variation by using linear combinations of the original measurements. Further, PCA identifies important "large-small" body dimension combinations when they are important in the covariance structure, and the method generally creates one or more principal components that actually measure such extremes of shape.

Table 1 illustrates a Principal Components Analysis (PCA) conducted on 6 critical cockpit geometry variables for the UH-60: Acromion Height Seated, Buttock-Popliteal Length, Eye Height Seated, Popliteal Height, Sleeve Outseam, and Thigh Clearance. Acromion Height Seated and Sleeve Outseam are related to hand control reaches; Eye Height Seated is related to field of view; Buttock-Popliteal Length and Popliteal Height are related to foot operated control reaches; Thigh Clearance is included because Blackhawk pilots generally rest their forearms on their thighs to achieve greater stability and control of the Cyclic. Sleeve Outseam was chosen for the PCA analysis instead of Thumbtip Reach in order to take advantage of existing anthropometric and reach data on actual female pilots (Gordon & Licina, 1999).

The PCA was conducted on U.S. Army females measured in the 1988 ANSUR Survey (Gordon et al., 1989), with subjects weighted to match contemporary Army female age & race distributions. All analyses were conducted using Stata 6.0 (Stata Corp, 1999).

Table 1. Principal Components Analysis of US Army Females (n=3470)

PC	Eigenvalue	Difference	Proportion	Cumulative
1	3.14090	1.74402	0.5235	0.5235
2	1.39688	0.43683	0.2328	0.7563
3	0.96005	0.74640	0.1600	**0.9163**

Variable	PC 1	PC 2	PC 3
ACRHTST	0.36320	0.61077	-0.03726
BUTTPLTH	0.46269	-0.36279	0.08979
EYEHTSIT	0.38267	0.57796	-0.08664
POPHGHT	0.46886	-0.27986	-0.32614
SLOUTSM	0.48953	-0.28774	-0.09446
THGHCLR	**0.21931**	**-0.01401**	**0.93153**

As can be seen above, the three PC's together account for 91.6% of the variation present in the original 6 variables. PC1, which captures 52% of the original variation, describes overall body size: the largest values of PC1 occur when all body dimensions are large. PC2, which accounts for an additional 23% of the original variation, contrasts limb lengths with torso height: the largest values of PC2 occur when a soldier has a long torso and short arms & legs. PC3, which accounts for an additional 16% of the original variation, primarily describes variation in thigh clearance height, and contrasts it with popliteal height. The largest values of PC3 occur when a soldier has large thighs and short lower legs.

Once the PCA is completed, database subjects are scored on the new composite variables (PC's), which now describe the most important components of variation in both size and shape. Subject PC scores are plotted in 3-dimensional PC space (see Figure 1), and an ellipsoid capturing a specified percentage of subjects is fit to their distribution. The surface of the ellipsoid represents the accommodation envelope associated with the percentage of subjects chosen. Twenty-six boundary forms located on the surface of the ellipsoid at major axis intersections and midpoints between intersections can then be used to represent extremes of both size and shape present in a certain percentage of users for the original *n* body dimensions considered ***simultaneously***. The central form, located at the intersection of the 3 PC axes, represents a multivariate "average" body form.

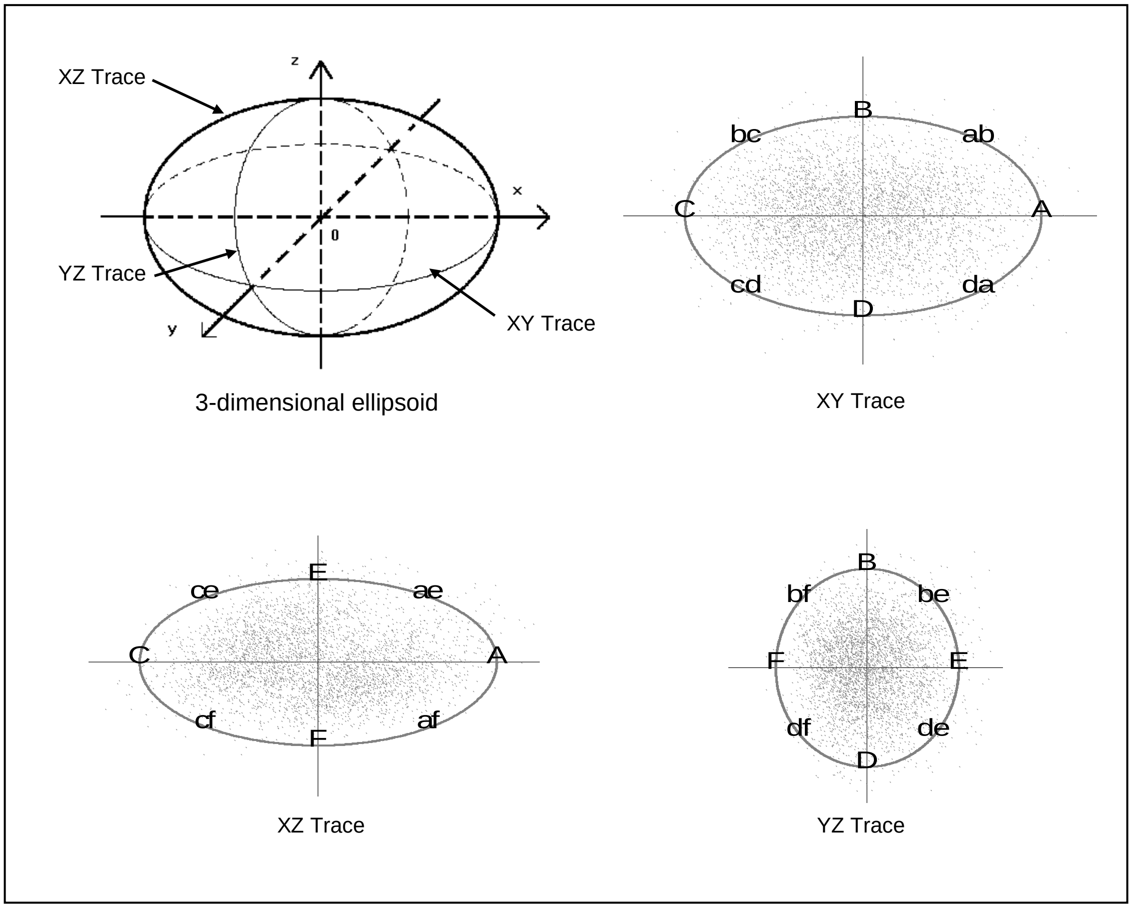

Figure 1. A 90% Ellipsoid Capturing Variation in 3 Principal Components.
(boundary forms are identified by letter)

3. Application of PCA Forms in Design & Testing

The Central and Extreme boundary forms illustrated above can be used in several ways. Central forms are helpful when design concepts are first being explored, to ensure that system components are properly integrated and to establish the ranges of body dimensions that a proposed system can accommodate successfully without additional sizes or adjustments. Extreme forms can be used as both design limits and exit criteria for multivariate designs such as cockpits and integrated protective clothing ensembles because they capture the worst-case scenarios for the critical design variables considered simultaneously. They can also be used to guide test subject sample selection, and provide anthropometric specifications for digital human models (such as Jack) in virtual testing environments.

It is important to realize that the multivariate center and boundaries of a particular accommodation envelope do not necessarily tell the designer how to successfully accommodate the users in between. In design problems involving clothing with multiple sizes, workstations with adjustments affecting two dimensions simultaneously, or clothing and workstation adjustment features with pre-determined adjustment "stops", knowledge of the sizes and shapes of boundary forms *alone* is not enough to complete a successful design. Additional statistical analyses are needed to optimize the sizing system, adjustment slopes, and/or adjustment stops to ensure that everyone inside the ellipsoid is properly accommodated by the design. This may seem obvious in the case of developing a new aircraft, however it has critical and often overlooked consequences for evaluating and retrofitting existing aircraft designs.

In the case of an aircraft cockpit, because the accommodation of subjects inside the design envelope depends in part on the geometry of the seat adjustment mechanism, one needs to be careful in drawing conclusions from boundary form tests alone when working backwards from an existing cockpit to an estimated accommodation rate. Failure to accommodate a boundary form of a particular (say 90%) ellipsoid ***is*** sufficient evidence to suggest that the cockpit does not meet a 90% accommodation requirement. However, accommodation of all the 90% boundary forms ***is not*** a guarantee that the 90% requirement will be met, because there may be subjects inside the design envelope who cannot be fit because the seat adjustment stops are too far apart and/or because the geometric relationships of the adjustment mechanism(s) do not accommodate their body proportions. For this reason, cockpit checks with live subjects whose body dimensions are distributed throughout the required design envelope are always desirable.

4. Cockpit Evaluation Data on Female Pilots in the UH-60A

In the current evaluation of UH-60M accommodation, we are fortunate to have access to complete study data on 71 Army pilots who were tested in the UH-60A cockpit while participating in the 1995 U.S. Army Female Anthropometric, Clothing, and Cockpit Compatibility Study conducted at USAARL, Ft. Rucker, AL under the direction of Mr. Joseph Licina. The anthropometry of the USAARL pilot sample is reported in Gordon & Licina (1999), and compared to that of "Pilot Eligible" Army females from the ANSUR survey (Donelson & Gordon, 1991). In this and other studies by the author, the term "Pilot Eligible" refers to Army females whose body dimensions meet Initial Entrance Rotary Wing anthropometric criteria

(Chase, 1990). Population estimates for the Pilot Eligible subset of Army females always incorporate demographic (age, race) matches to the actual female pilot population.

Figure 2 illustrates the distribution of the USAARL pilot sample relative to 90% ellipses for female pilot eligibles and the general female army population, using scores from the Blackhawk PCA reported in Table 1.

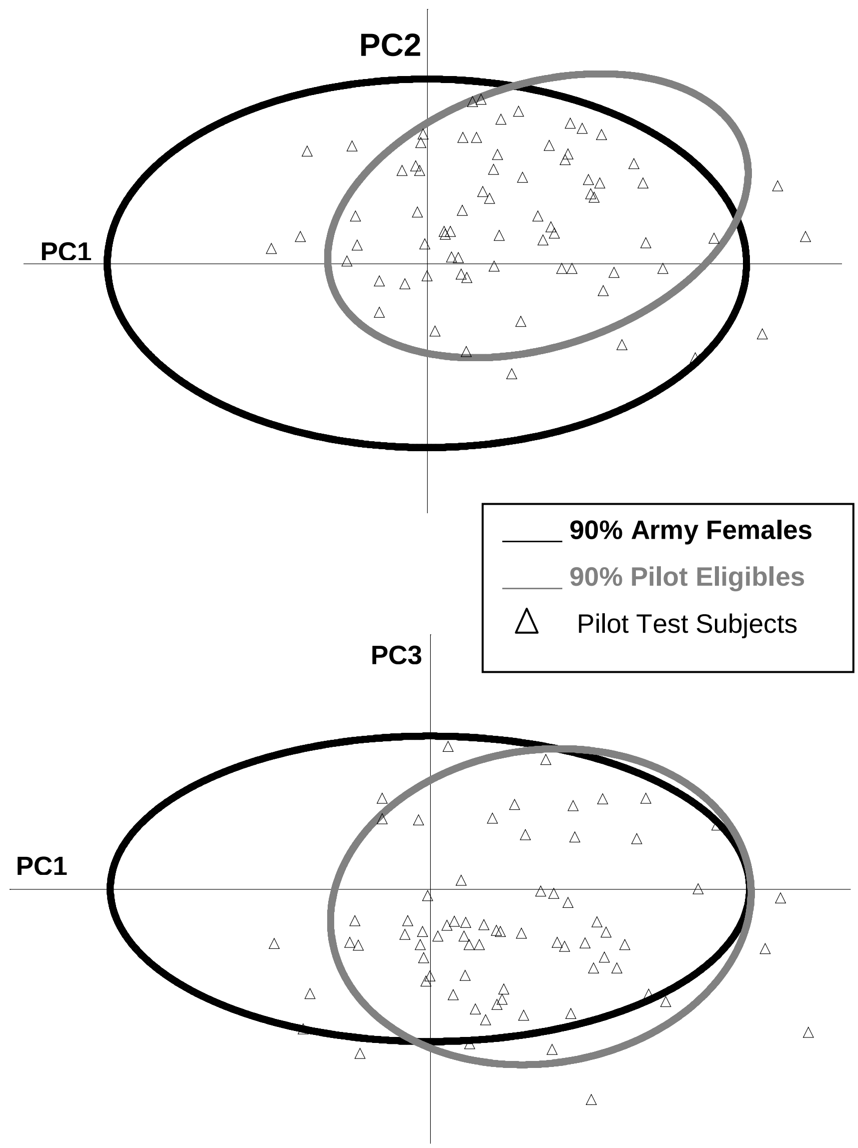

Figure 2. Distribution of USAARL Pilot Subjects Relative to 90% Ellipses of Army Females and Pilot Eligible Army females

As can be seen in Figure 2, the USAARL test subjects provide good coverage for most of the pilot eligible range of variation in PCA space. Thus the test subjects from the 1995 USAARL study of the UH-60A can provide a good sample for an exploratory study of female pilot accommodation in the UH-60 cockpit. Once plotted in PCA space, for example, test subject successes and failures in the UH-60A can be used to identify the critical region of body size/shape most in need of evaluation for the UH-60M. This approach reduces the number of Jack models that must be built and evaluated in order to estimate the accommodation boundary of the UH-60M.

5. Over the Nose Field of View in the UH-60A

Of the 71 pilots studied in 1995, none were able to achieve the 25-degree over the nose field of view requirement in MIL-STD-850B with their seats adjusted in preferred flying position. In all cases, the top of the glare-shield blocked the pilot's field of view. Figure 3 illustrates the distribution of forward field of views in the UH-60A. The median and mean forward fields of view are –15 degrees, with a range of –21 to –7 degrees; the distribution is skewed slightly to the right, compared to a normal distribution, however this difference is not statistically significant (Shapiro-Wilk W; *P* = .6463).

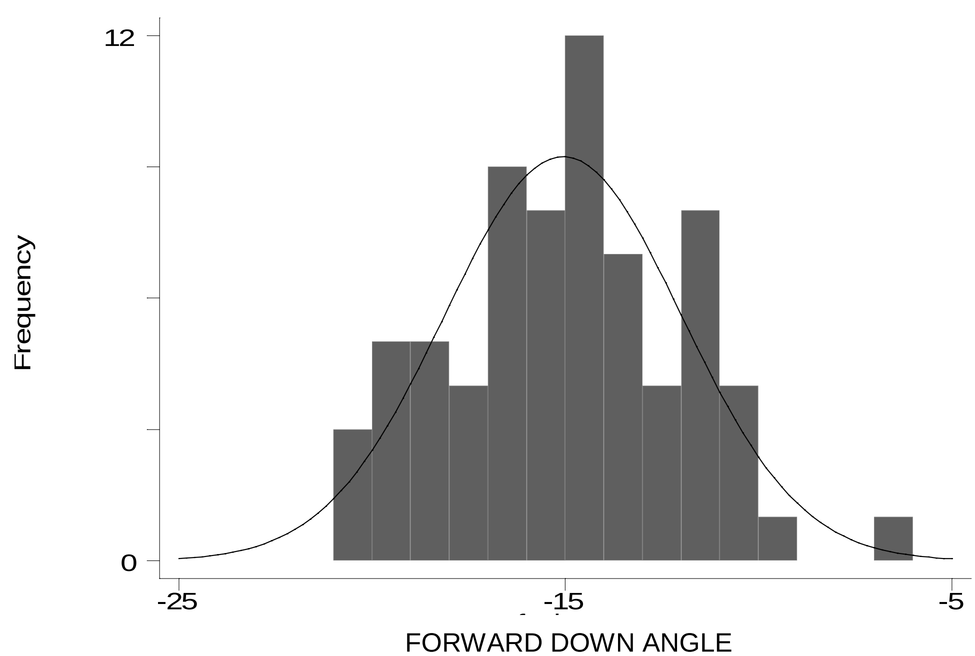

Figure 3. Over the Nose Field of View in the UH-60A with Seat at Pilot's Preferred Location

Pilot field of view with seat adjusted to the UH-60A Design Eye Position was also recorded in 1995 for 66 of the 74 pilots evaluated (see Figure 4). However, only 2 of the 66 pilots had a forward field of view 25-degrees or greater when at DEP. Figure 4 shows the distribution of DEP fields of view. These varied between –26 degrees and –5 degrees, with a median of -20 degrees. DEP field of view for this study group is not normally distributed (Shapiro-Wilk W; *P* = .0000), so a paired comparisons Sign test was used to test for significant differences between in the DEP and preferred seat position fields of view. Fields of view in DEP were significantly greater than in the pilot's preferred seat location for 63 of 66 subjects, with Binomial P=.0000. However, test subject interviews indicated that most pilots felt at DEP "that they were far too high up to conduct safe flight operations" (Hopf et al., 1996:10).

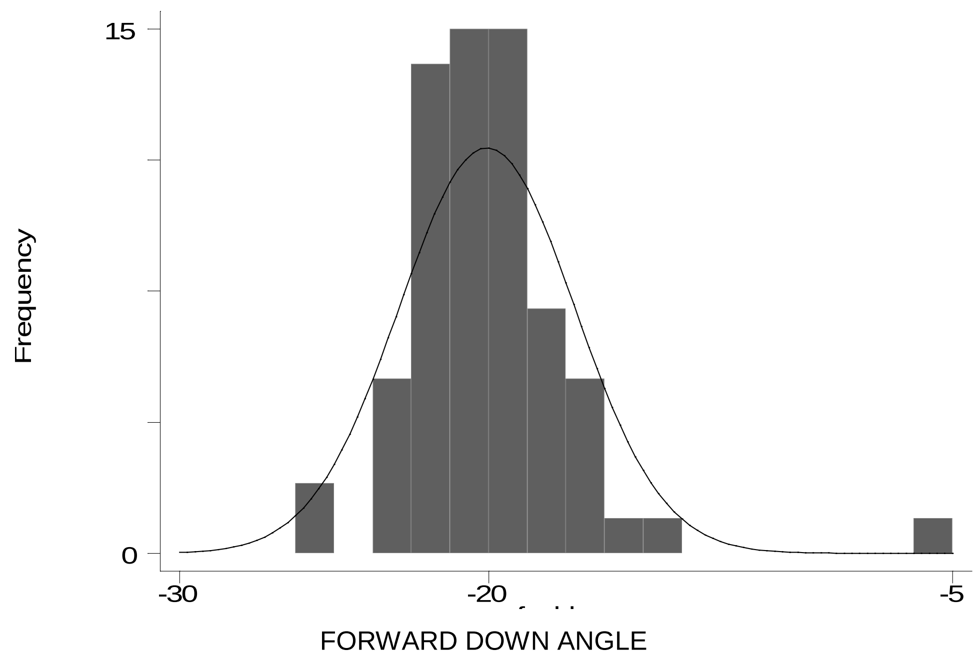

Figure 4. Over the Nose Field of View in the UH-60A with Seat at Design Eye Position

Since none of the pilots could achieve the required field of view from their preferred flying position, and only 2 could achieve the required field of view from DEP, the over the nose vision requirement was excluded from further analyses so that pilot reaches and control actuations in the UH-60A could be studied.

6. Critical Flight & Emergency Controls in the UH-60A

In this study, successful reach accommodation in the UH-60A cockpit was defined as being able to actuate all the controls listed in Table 2 with harness locked, wearing warm weather flight clothing, and with seat adjusted to the pilot's preferred flying position (Houy, 2002). Reach scores for each of the 71 pilots tested in the UH-60A cockpit during the 1995

USAARL study are given in Table 2. As can be seen below, only two controls required any of the pilots to unlock their restraint harnesses: Condition Lever 1 (also known as a Power Lever) and Fire Handle Number 1. Both controls are located on the overhead console of the UH-60A.

Table 2. Results of Task Analyses in the UH-60A for 73 Female Pilots

	Reach Required[1]			
Control Task	Zone 1	Zone 2	Zone 3	Zone 4
Full Cyclic Travel at 0 Degrees (full forward)	68	3		
Full Cyclic Travel at 45 Degrees	69	2		
Full Cyclic Travel at 90 Degrees	70	1		
Full Cyclic Travel at 135 Degrees	71			
Full Cyclic Travel at 180 Degrees (full aft)	71			
Full Cyclic Travel at 225 Degrees	69	2		
Full Cyclic Travel at 270 Degrees	67	4		
Full Cyclic Travel at 315 Degrees	45	26		
Full Collective Travel – up	70	1		
Full Collective Travel – down	70	1		
Neutral Cyclic with Full Left Pedal	69	2		
Neutral Cyclic with Full Left Pedal & Brakes	53	18		
Neutral Cyclic with Full Right Pedal	69	2		
Neutral Cyclic with Full Right Pedal & Brakes	52	19		
Full Aft Cyclic with Full Left Pedal	69	2		
Full Aft Cyclic with Full Left Pedal & Brakes	54	17		
Full Aft Cyclic with Full Right Pedal	68	3		
Full Aft Cyclic with Full Right Pedal & Brakes	51	20		
Condition Lever 1	43	24	4	
Condition Lever 2	67	4		
Auxiliary Power Unit Handle/Panel	70	1		
Fire Handle Number 1	15	42	14	
Fire Handle Number 2	71			

[1] **Zone 1**: Restraint harness is locked; subject actuates control without stretching the arms, shoulders, and/or leg muscles, and without forward movement of the torso or hips. **Zone 2**: Restraint harness is locked; subject actuates control but requires stretching and/or forward movement of the torso or hips. **Zone 3**: Restraint harness must be unlocked for subject to actuate control. **Zone 4**: Subject cannot actuate control even with restraint harness unlocked.

Table 3. Cross-Classification of Pilots Failing at Least One Task in the UH-60A

Condition Lever 1	**Fire Handle 1** fail	pass	Total
fail	3	1	4
pass	11	56	67
Total	14	57	71

Table 3 cross-classifies those pilots who required a Zone 3 reach to actuate Condition Lever 1 and/or Fire Handle 1. Only 3 of the 71 pilots (4.2%) failed both controls, however 15 of 71 pilots (21.1%) failed to actuate at least one control in the locked harness condition. Figure 5 illustrates the multivariate anthropometric distributions of the 15 subjects who failed to reach at least one critical control in the UH-60A.

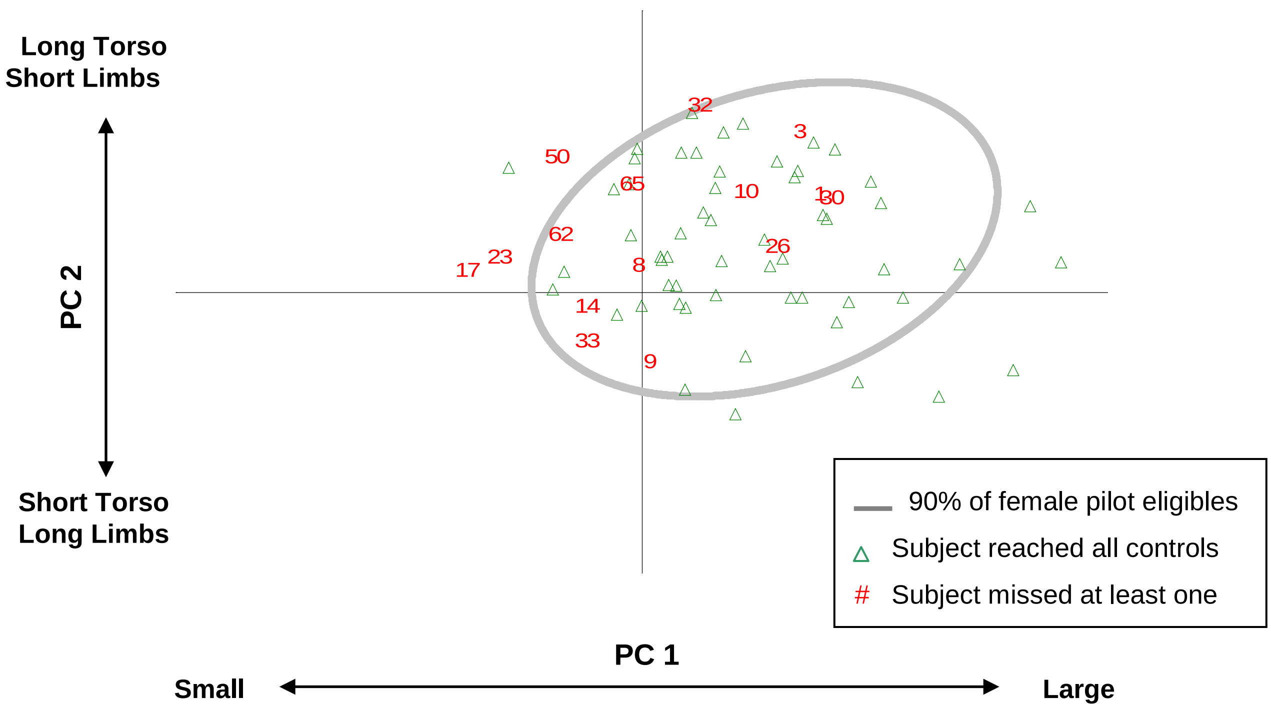

Figure 5. Reach Results in the UH-60A USAARL Study

It is important to remember that the distribution of reach failures in Figure 5 represents test subjects evaluated in the UH-60A (not UH-60M) aircraft, and that the subjects were allowed to position their seat to a location of their choosing. Although all test subjects were Army pilots, only 15 of the 71 (21%) were qualified in the UH-60A aircraft at the time of testing. Therefore it is possible that some test subjects' chosen seat positions were not optimal for the aircraft because they were not experienced UH-60A pilots. Of those test subjects failing to reach at least one control, 13 were not qualified in the UH-60 and 2 (13%) were qualified in the aircraft.

7. Using Jack Models for Virtual Reach Testing in the UH-60M Cockpit

Review of the 1995 USAARL study data suggests that most pilots with "above average" (PC1>0) female body size can reach all primary flight and emergency controls in the UH-60A. Although minor, there have been some changes in control locations between the UH-60A and UH-60M, so it was decided to test models representing all 15 subjects who failed to reach critical controls in the UH-60A, as well as the 5 smallest subjects who were successful in reaching UH-60A critical controls. Four additional models, representing the lower boundaries of a 40% accommodation envelope for Army females in Comanche PCA space (Kozycki & Gordon, 2002), were also tested in the virtual UH-60M cockpit since they were readily available.

Anthropometric specifications for all Jack models were derived using actual dimensions for those variables included in the PCAs, and by using the median values of nearest neighbors in PCA space for Jack dimensions not included in the PCA. Before reach tests were conducted, each figure's seat was positioned so that they could operate foot controls while simultaneously resting their forearm on their thigh for cyclic operation. As indicated earlier, these cockpit tests focused on reach issues and so visual field was not assessed, nor was it considered in seat positioning.

The results of virtual testing with the Jack human digital model are illustrated below in Figure 6. Subjects able to reach all controls are in green; subjects who failed at least one critical control are in red; subjects who barely reached all critical controls are in black. These results indicate that the UH-60M accommodation boundary is probably in the vicinity of the PC1=0 axis. In fact, if we assume that the boundary is approximated by the location of subjects 65, 8, and 9, then we can use Blackhawk PC1 scores that are less than or equal to -.1 as a predictor of which subjects can/cannot reach all controls in the UH-60M. Applying this criterion to the general Army female population results in an estimated *reach* accommodation rate of 51% of all female soldiers for the UH-60M, and an estimated reach accommodation rate of 90% for the pilot eligible sub-population (see Table 4).

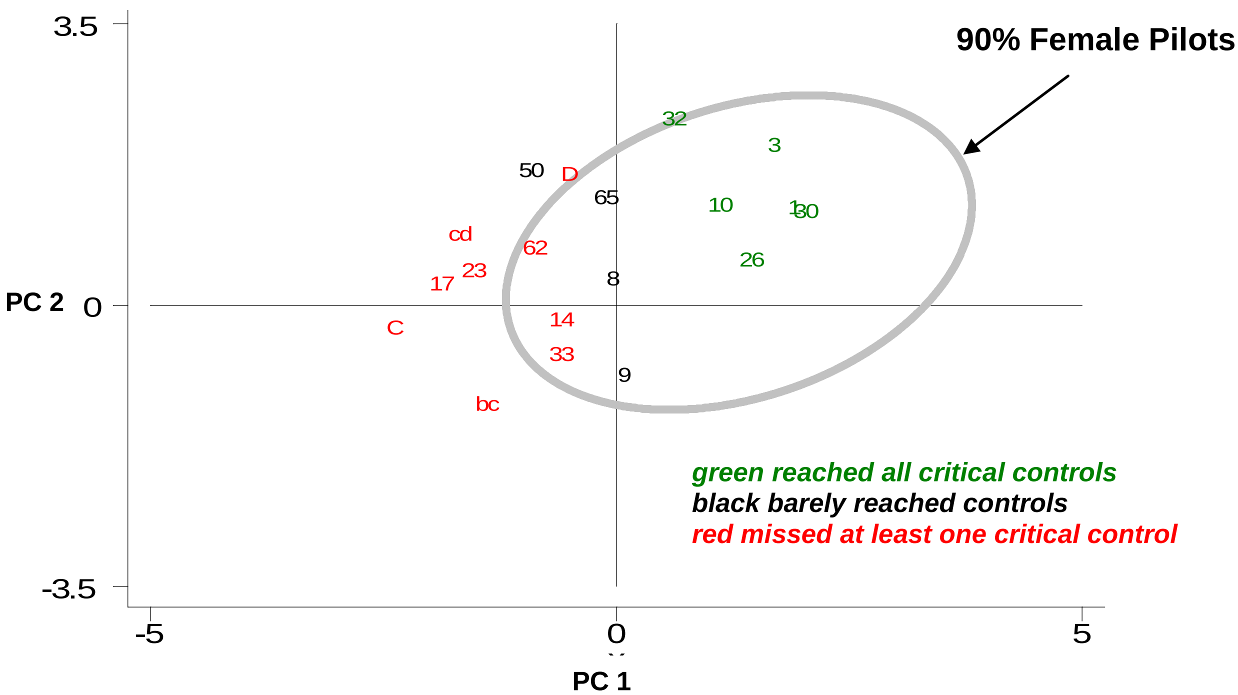

Figure 6. Results of Jack Model Reach Testing in a Virtual UH-60M Cockpit

Table 4. Estimated Reach Accommodation Rates for the UH-60M

	Able to Reach UH-60M Controls?	
	No	Yes
Pilot Eligible Females	36 (10.78 %)	298 (89.22 %)
All Female Soldiers	1693 (48.80 %)	1777 (51.20 %)

8. Overall Results and Discussion

The results of this study suggest that approximately 90% of female pilot eligibles (soldiers meeting minimum IERW anthropometric criteria) and approximately 51% of female soldiers overall should be able to reach critical flight controls in the UH-60M cockpit. However, it should be emphasized that *actual* reach accommodation rates in the female pilot population may be slightly lower than the 90% estimated in this study because substantial numbers of female Army pilots have been given exemptions to the IERW anthropometric criteria, and therefore the *true* female pilot anthropometric distributions may be somewhat smaller than those represented by a "pilot eligible" sample that assumes 100% enforcement of IERW criteria.

In addition, it should be noted that while the overall estimate of female pilot reach accommodation is relatively high (90%), it is not equally good in all population subgroups. Minority females who belong to a racial/ethnic group with average body size smaller than the majority of Army females will be disaccommodated at substantially higher rates than expected over all. Table 5 illustrates this problem using the general Army female population (n=3470).

Table 5. Estimated Reach Accommodation for Female Soldiers in the UH-60M by Race/Ethnicity

	Able to Reach UH-60M Controls?	
Race/Ethnicity	**No**	**Yes**
White	678 (49.4%)	695 (50.6 %)
Black	572 (42.2 %)	785 (57.8 %)
Hispanic	237 (72.0 %)	92 (28.0 %)
Asian/Pacific Islander	109 (79.0 %)	29 (21.0 %)
`Native American	26 (54.2 %)	22 (45.8 %)
Mixed/Other	137 (56.2 %)	88 (43.8 %)

Whereas reach accommodation is expected for 51% of the overall female soldier population, only 28% of Hispanics and only 21% of Asian/Pacific Islanders may be accommodated. This is an important consideration if the Army intends to continue encouraging minority groups to enter aviation careers.

Finally, it is important to understand that the multivariate modeling approaches used in this study provide only *estimates* of the actual UH-60M accommodation boundaries and rates. Some of the reasons that these results are inexact include the somewhat unpredictable impact of hardware adjustment relationships in cockpits that were not designed using multivariate anthropometric criteria to begin with; the need to utilize a "pilot eligible" database that assumes 100% compliance with IERW anthropometric criteria because the Army lacks a true female aviator database; the inherent limitations of digital man models to accurately represent clothing effects and true human motion; and the inability of mathematical and digital models to represent behavioral human adaptability – that is, the tricks that experienced pilots know in order to fly better, whatever their anthropometry is.

It is expected, however, that the results of this study have improved our understanding of the limitations of the UH-60A cockpit, provided better models for virtual testing of the UH-60M cockpit using Jack, and provided rough estimates of the percentage of female aviators who can fly the UH-60M as it is currently configured. It is always advisable, however, to validate our predictions by testing real pilots in real cockpit mock-ups.

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