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Design and Development of Anthropometrically Correct Head Forms for Joint Strike Fighter Ejection Seat Testing

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NOTICES

TECHNICAL REVIEW AND APPROVAL

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

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

FOR THE DIRECTOR

//SIGNED//

MARK M. HOFFMAN
Deputy Chief, Biosciences and Protection Division
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14. ABSTRACT

Anthropometric test manikins are commonly used in the assessment of head/neck injury potential of helmet systems during aircraft crashes or ejections. Current ejection test manikins use rudimentary heads developed long ago. Heads that are more representative of military aviators in the areas of shape, size, and inertial properties are required so that the helmets can be properly fit and evaluated. Surface scan and traditional anthropomorphic data were analyzed from the Civilian American and European Surface Anthropometry Resource (CAESAR) database to determine typical head sizes of people representing Case 1 and Case 6 anthropometries. Human cadaver head studies were also reviewed, and data were analyzed to estimate head mass property relationships for different sized heads. Representative mass properties were determined to characterize a 5^{th} percentile female head weight, a 50^{th} percentile small female head weight, and a 95^{th} percentile male head weight. Representative heads were then chosen from the CAESAR database from which anthropometric manikin heads were developed and produced to better evaluate helmet systems.

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PREFACE

This report serves as the documentation for the development of anthropometrically representative manikin heads for use in Joint Strike Fighter (JSF) ejection seat testing. The work described in this report was funded under Work Unit 71840204 and by the Joint Strike Fighter Office. This work was performed by personnel in the Biomechanics Branch, Human Effectiveness Directorate of the Air Force Research Laboratory at Wright-Patterson AFB, Ohio. Technical support for this effort was provided by General Dynamics AIES Corporation under contract F41624-97-D-6004. First Technologies Safety Systems (FTSS) was subcontracted by General Dynamics for the development and production of the head forms. The progress of the design, development, and production of the head forms was continuously reviewed by what became known as the Head Case Team. This team consisted of Biomechanics and Anthropometry experts from AFRL, a helmet systems expert from ASC/EN, and Escape Systems Engineers from NAVAIR.

The findings and conclusions in this report/presentation have not been formally disseminated by the Air Force and should not be construed to represent any agency determination or policy.

ACKNOWLEDGEMENTS

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INTRODUCTION

The first flight of a powered aircraft was in December 1903, and the first fatality from an airplane crash occurred in 1908 in which US Army Lieutenant Thomas Selfridge died from a fractured skull. This event was the impetus for head protection in aircraft. At first the aviator's helmet was nothing more than a leather football helmet, but over time the military aviator helmets evolved into the complex systems that we have today.

When radio communications systems were put on aircraft, the helmets were modified to include ear cups with speakers so that the pilot could hear over the aircraft noise. When aircraft started flying at altitudes where supplemental oxygen was required, the helmet was modified to be a platform to hold oxygen masks. When the crewmembers needed to see at night, the helmet was again modified to hold night vision goggles. When the pilots wanted a "look and shoot" capability, a cueing system was also added to the helmets. Now, the latest concept for helmet-mounted systems is an "all-in-one" concept which will allow the pilot to not only see at night and "look and shoot," but also allow the pilot to see critical aircraft instrument readouts as well as being able to see "through" the aircraft. This is the goal for the Joint Strike Fighter (JSF) helmet system.

Background

During ejection from an aircraft, the crewmember experiences high accelerations as the ejection seat is catapulted out of the aircraft and then decelerated to a safe speed for the crewmember's recovery parachute to deploy. During a high-speed ejection, the crewmember also experiences large aerodynamic loads, particularly on the limbs and head. Both aerodynamic and inertial loads that are encountered during ejection can be injurious to the crewmember's neck, and the injury potential is related to the fit, aerodynamic characteristics, and inertial properties of the helmet being worn. Whenever additional equipment is mounted on crewmember helmets, additional weight is also added to the helmet system that needs to be borne by the crewmember both during high-g maneuvers and during ejection. The added weight also changes the helmet center of gravity, usually moving it forward. This can also have a significant impact on potential injury to the crewmember, especially during ejection.

Ejection seats historically have been designed for $3^{rd}/5^{th}$ percentile through $95^{th}/98^{th}$ percentile males, and tested to verify safe operation using manikins representative of these sizes. Since females were recently cleared to fly in combat aircraft equipped with ejection seats, much research has been conducted to study how injury potential differs between the traditional aircrew population and this new, lighter and smaller population. There is great concern about the ability to safely eject crewmembers who weigh less than the original ejection seat qualification weight, which equates to approximately 140 lbs nude weight. Approximately 86% of the females in the US Armed Services weigh less than 140 lbs.[1] The expanded aircrew population was first addressed in the Joint Primary Air Training System (JPATS) or T-6A aircraft. The aircraft and ejection seat, the Martin-Baker MkUS.16L, was designed to accommodate crewmembers with weights between 116 lbs and 245 lbs. The lower weight limit was later reduced to 103 lbs. The 103 lbs to 245 lbs limit was adopted in the Joint Model Specification for the Joint Strike Fighter.

Figure 1. JPATS Case 6 (left) and Case 1 (Right) Manikins

The approach to manikin sizes was also revisited during the JPATS program. Traditionally, manikin sizes would be determined by using regression curves generated for each major body part using an anthropometry database of human subject measurements such as weight, stature, leg length, etc. A manikin would be defined by selecting a specific percentile, such as 5th percentile, and then all of the body parts would be designed to match those specific 5th percentile dimensions. In reality, it is almost impossible for a human to be the same percentile with respect to all anthropometric measurements. A human may have a 5th percentile arm length but a 50th percentile leg length. Similarly, a human may have a 95th percentile sitting height but a 50th percentile leg length. There is also very little correlation between body size and head size.[2] These variations in human anthropometry make it difficult to fully assess crew accommodation issues. Rather than defining a certain overall percentile size of a manikin as was traditionally done, specific "Cases" were defined.[3] The chosen Cases were based on anthropometry that was especially difficult to accommodate in aircraft cockpits. A general description of these Cases is shown in Table 1. Hybrid III Automotive Manikins were modified to represent Case 1 and Case 6 sizes (Figure 1) for the assessment of the JPATS ejection seat.

Specific dimensions for parameters such as sitting height, knee height, thumb-tip reach, etc., are shown for each Case. However, there are no dimensions or specifications given explicitly for the heads for any of the Cases. There are also no specific overall weights or statures defined, but only a weight range of 103 lbs to 245 lbs for any of the Cases. This implies that the head sizes and weights of the specific Cases are independent variables.

Table 1. Case Descriptions

	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7	CASE 8
Descriptor	Small	Medium Build Short Limbs	Medium Build Long Limbs	Tall Sitting Height Short Limbs	Overall Large	Longest Limbs	Overall Small	Largest Torso
Thumb Tip Reach	27.0	27.6	33.9	29.7	35.6	36.0	26.1	33.3
Buttock-knee Length	21.3	21.3	26.5	22.7	27.4	27.9	20.8	25.4
Knee-height Sitting	18.7	19.1	23.3	20.6	24.7	24.8	18.1	23.2
Sitting Height	32.8	35.5	34.9	38.5	40.0	38.0	31.0	41.0
Eye Height Sitting	28.0	30.7	30.2	33.4	35.0	32.9	26.8	35.9
Shoulder Height Sitting	20.6	22.7	22.6	25.2	26.9	25.0	19.5	27.6
Shoulder Breadth Range	14.7-18.1	16.4-20.6	16.2-21.2	16.8-21.7	16.9-22.6	16.8-22.5	14.2-18.0	16.9-22.6
Chest Depth Range	7.4-10.9	6.9-10.6	7.2-11.3	7.1-11.0	7.3-12.1	7.4-12.2	7.2-10.2	7.4-12.4
Thigh Circumference Range	18.5-25.0	17.1-25.0	20.2-27.6	17.6-26.3	18.6-29.2	19.1-29.7	17.8-25.2	18.6-29.1
Weight Range	103 lbs to 245 lbs							
NOTE: Units are in inches unless otherwise indicated								

Since there were no specifications for head sizes when the original manikins were built, existing manikin heads were chosen for the Case 1 and Case 6 manikins that were developed for the JPATS program. The Case 1 manikin was delivered with a 5th percentile female VIP head (Figure 2). This head is an Alderson Research Laboratory development that appears to match closely to the 1964 Stoudt *et al* anthropometry in "The Human Body in Equipment Design," republished in 1970[4]. The Case 6 manikin was delivered with the shape and physical size of a 50th percentile Hybrid II head (Figure 3) ballasted to a total weight of 10.95 lbs. The Hybrid II was a modification of a Sierra Engineering design modified by General Motors for National Highway Traffic Safety Administration (NHTSA) in 1972, released in 1973.

The basis for this head was Society of Automotive Engineers (SAE) J963, "Anthropomorphic Test Device for Use in Dynamic Testing of Motor Vehicles."[5]

Figure 2. Case 1 5% VIP Head

Requirements for safe emergency ejection from the Joint Strike Fighter are the strictest of any aircraft to date. This is particularly true for neck load limits encountered during ejection from the aircraft. These neck load limits will be verified by conducting a series of ejection seat tests from rocket sleds and aircraft using instrumented test manikins. In the past, head size and weight were not critical in the evaluation of the ejection seat performance since neck load limits had not been defined and neck loads were not routinely measured during the tests. The heads were merely a prosthetic to hold the helmet and add to the total weight of the manikin. In order for the manikin heads to realistically respond similar to a human head during ejection and enable meaningful loading parameters to be measured to evaluate neck injuries, the heads needed to adequately represent their human counterparts. The primary areas in which the heads need to be representative of humans of similar size to the manikins are head size and shape to ensure proper helmet fit, and inertial properties (weight, center of gravity, moments of inertia) so the heads respond similarly to human heads under the forces and accelerations encountered during ejection. The objective of this study was to define these parameters so that three manikin heads could be designed and produced that are more representative of humans than current manikin heads. This report describes the methods used to determine those representative heads and the results of the study.

Figure 3. Case 6 Hybrid II Head

METHODS

Traditional anthropometry databases contain limited linear dimensions such as head breadth, length, circumference, and face length, but they do not give any detail to the overall shape of the head. Also, there is no standard measurement that identifies the overall height or volume/weight of the head. Although several references exist that relate a few head dimensions and sometimes body weight to estimated head weight, the accuracy of these correlations was poor.

The Civilian American and European Surface Anthropometry Resource (CAESAR)[6] is an anthropometry database that not only contains traditional measurements but also includes three-dimensional digital surface scans of the subjects' entire bodies. These scans were critical in determining head volume and shape, and were used to create the actual manikin head shapes. This was the primary database used for this study; however, since this database contains civilians, caution was required since the population in which JSF is interested in varies from the general civilian population.

The North American database was selected from the overall CAESAR database. This database contains 1255 female subjects and 1120 male subjects. Since the military has strict weight and height limitations, subjects in the database such as a 60 in. stature female with a weight of 200 lbs needed to be screened out prior to the data analysis. The screening criteria were extracted from Air Force Instruction 48-123, *Aerospace Medicine, Medical Examinations and Standards,* Table 3, "Height and Weight Tables."[7] These tables are used to screen potential Air Force candidates and to assure that weight standards are adhered to during service. These tables list minimum and maximum weight ranges for males and females with statures between 58 in. and 80 in. The JSF Model Specification further restricts the flying population weight to be between 103 lbs and 245 lbs. Applying these screening criteria resulted in a total of 716 males and 739 females being used for data analysis.

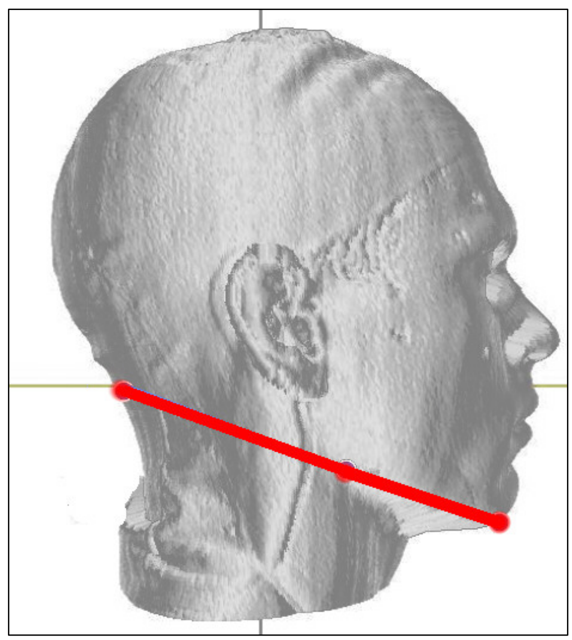

Figure 4. CAESAR Head Sectioning

Since traditional anthropometric measurements of the head cannot be used to adequately determine head size, the head sizes were calculated by using the three-dimensional surface scan data contained in the CAESAR database. However, since the CAESAR database contained whole-body scans of each subject, an automated routine was developed to section the subjects' heads at predefined head landmarks (Figure 4). These head landmarks are the nuchale, the gonion, and the menton. The head volume and center-of-volume were also calculated. Head weight for each subject was then calculated using an average density of 1.06 g/cm^3.[2, 8] These values were compared using regression calculations[9, 10] to verify that the head volumes and weights were reasonable.

Weibull distributions were generated for head weight for the sample female population, the sample male population, and the sample combined male/female population. Head weight information from human subjects with stature ranges of 60 in. ± 2 in. and 74 in. ± 2 in. (Appendix B, Section 5) were extracted from the sample population to represent Case 1 and Case 6 subjects respectively. Additional Weibull distributions were generated (Appendix B, Section 2) for head weight for these two populations. These data are presented in Table 2.

Once the head mass distribution was determined and the particular head weights were decided upon, the database was then searched for subjects with those particular head weights. These heads were then reviewed to rule out any heads that had anomalies or incomplete data, and then specific heads were chosen to be used to develop the manikin heads.

To determine human head inertial properties, three human cadaver head reports were reviewed. Walker[11] measured inertial properties of 20 male heads, Beier[12] measured the inertial properties of 19 male and 2 female heads, and Albery[13] measured the inertial properties of 8 male and 7 female heads. The head specimens in all three studies were sectioned from the body as shown in Figure 5, which is similar to how the CAESAR subject heads were sectioned to calculate the head volumes.

These head cadaver references related the head center of gravity (CG) with respect to an anatomical coordinate system (Frankfort plane). The data required for this study needed to be referenced with respect to the Occipital Condyle (OC), which is where the head and the neck intersect, since this is a precisely defined location on the manikin head. The Albery data was the only resource that contained data on the subjects' OC location. The Albery data also contained measurements of head circumference, breadth, length, digitized locations of 32 features, and markers that identified the Frankfort plane.

Since the Albery study was the only study that made measurements of the OC location, the data from this study were used to estimate the distances between the head CG and OC for the other two studies.

Head inertial data from each of the aforementioned studies were separately tabulated, converted to consistent units, and transformed from the Anatomical Reference System, shown in Figure 6, to the OC. The origin of the Anatomical Reference System is at the midpoint of the left and right tragion, with the X axis passing through the midpoint of the line between the left and right infraorbitale. The data were sorted by head weight, and regression analysis was conducted to determine if there was any kind of relationship between head weight and CG with respect to the OC.

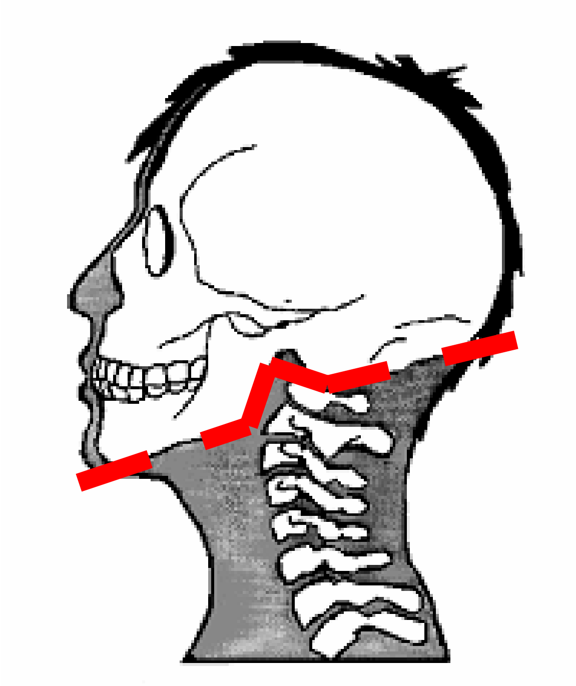

Figure 5. Cadaver Head Sectioning Scheme

The Beier head principal moments of inertia data were analyzed and correlated against the head weight data using the least-squares method. The inertial properties of existing manikin heads were also measured and tabulated. Inertial properties for three head sizes[14] were identified for Case 1 and Case 6 ejection test dummies.

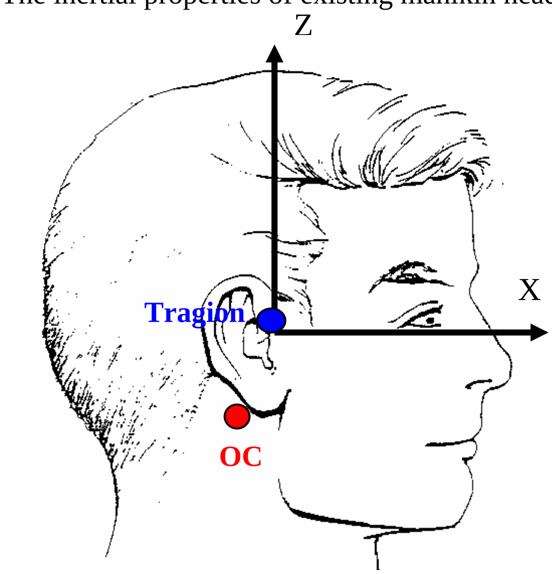

Figure 6. Anatomical Reference System

The cadaver head studies and the CAESAR database heads used similar segmentation techniques to determine the head weights (Figures 4 & 5). These sectioning techniques resulted in obtaining data that would replicate the weight of the head that reacts into the first cervical vertebra (C1) as a subject is exposed to vertical acceleration. For example, a 10-pound head undergoing a 10g acceleration would result in a 100-pound force between the head and C1. Since a neck load sensor in the manikins is at the C0/C1 location, one of the goals in designing the heads is to insure that the head with a designated weight results in applying an inertial force proportional to its designated weight. A problem with obtaining this objective is that, while human neck tissue is distributed and secured throughout the neck, the manikin neck skin is attached to the head. The manikin neck skin is needed to support the chin strap and nape straps of the helmet.

This lead to the specification that the manikin head weight should be the total force that acts into the load cell. This means that the head skin, skull, head mounted sensors, cabling in the head, sensor block, ballast, and part of the upper neck load cell above the sensing elements should all add up to the specified head weight. Similarly, the head CG should also be met with this configuration since the entire head mass moves together. In the past, many of these items had not been clearly defined, and the designation of the head weight included the entire upper neck load cell weight. Since the lower part of the upper neck load cell does not contribute to the mass acting into the strain gauges that measure the head force, this weight (0.6 pounds of the total 1.6 pounds) and the resulting change in CG is subtracted out.

The current manikin heads were reviewed to determine if these heads were representative of humans similar to the Case 1 and Case 6 sizes. The areas needing to be representative include head inertial properties, dimensions, and shape. Representative head volumes and dimensions (head length, width, height, circumference), and overall shape are important for proper helmet fit, which also affects the forces acting on the head.

The current manikin heads were scanned and digitally sectioned in a manner similar to the CAESAR subject scans and the human cadaver studies. This was done to determine head volumes comparable to the methods used to determine the human head volumes, and then to estimate the head weight that a human with the same head volume would have. Similarly, the manikin head weights were used to estimate what a comparable human head volume would be.

The inertial properties of at least one of each type of manikin head currently used (legacy heads) on the Case 1 and Case 6 manikins had been previously measured. However, incomplete or ambiguous documentation of these measurements resulted in some question as to what items were included in the measurements (e.g. accelerometer, sensor mounting block, cabling). In order to get a consistent comparison between the current manikin heads and what was being proposed for the JSF heads, several of the legacy head inertial properties were remeasured using the proposed JSF head instrumentation. In examining the inventory of the legacy JPATS and 95% Aerospace manikin heads, discrepancies in the inertial properties of the various heads were discovered. Tables 4 and 5 show the relative weight and CG values for different types of heads for both configurations (with traditional full load cell weight and with partial weight of just the upper part of the load cell).

The adequacy of the shape of the current manikin heads was assessed by examining the cross-sectional views of the current manikin heads and comparing them with cross-sectional views of human subjects from the CAESAR database with similar head breadth, head length, and head circumference measurements.

RESULTS

Calculated head weights versus stature and total body weight of the CAESAR subjects are plotted in Figures 7 through 10 below. The plots indicate a wide range of possible head weights for any given body weight or stature and a large range in body weights or stature for any given head weight. There is a low correlation between head weight and body weight (r = 0.48 and 0.37 for males and females respectively) and between head weight and stature (r = 0.37 and 0.34 for males and females respectively).

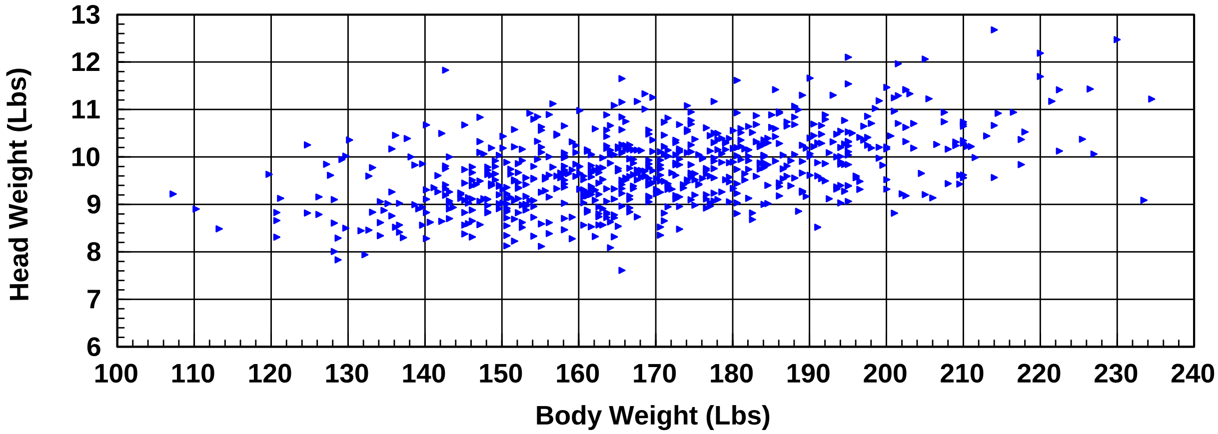

Figure 7. Male CAESAR Subject Head Weights vs. Body Weight

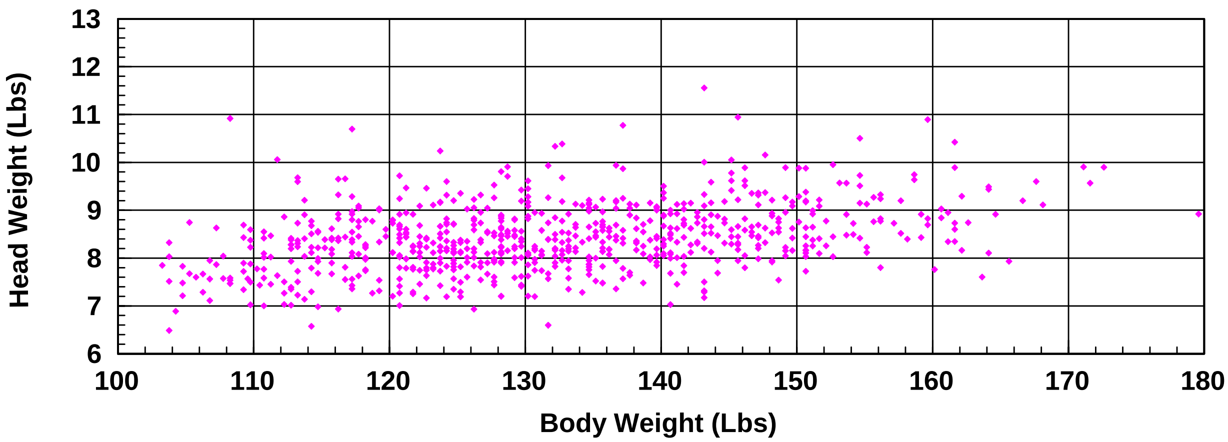

Figure 8. Female CAESAR Subject Head Weights vs. Body Weight

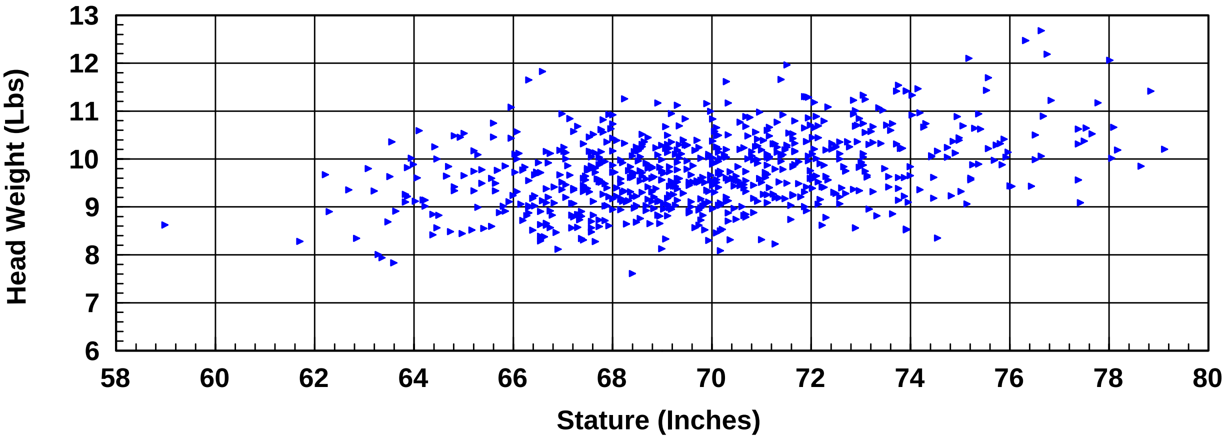

Figure 9. Male CAESAR Subject Head Weights vs. Stature

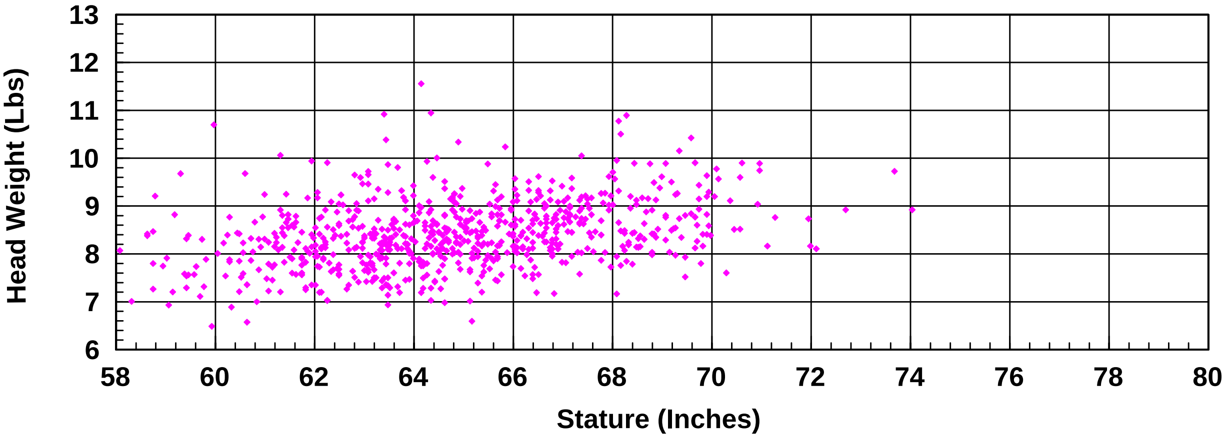

Figure 10. Female CAESAR Subject Head Weights vs. Stature

The results of the Weibull distribution analysis for human head weight are listed in Table 2 below. For a detailed explanation of the Weibull distribution analysis, see Appendix B.

Table 2. Weibull Distribution Results

Head Percentile	**Head Weight (lbs)**				
	Male	**Female**	**Combined**	**Small Female**	**Large Male**
1	8.2	7.1	7.2	-	-
5	8.5	7.4	7.6	7.1	8.8
50	9.7	8.4	9.0	8.1	10.1
95	11.0	9.6	10.8	9.2	11.3
99	11.4	10.1	11.5	-	-

A data plot of the human head CG values for all three of the cadaver studies is shown in Figure 11. The CG values are with respect to the OC, in the coordinate system shown in Figure 6. The average, standard deviation, minimums, and maximums for each of the three human head studies are listed in Table 3. Figure 12 shows a 95% probability ellipse for the head CGx and CGz locations from the three human cadaver head studies.

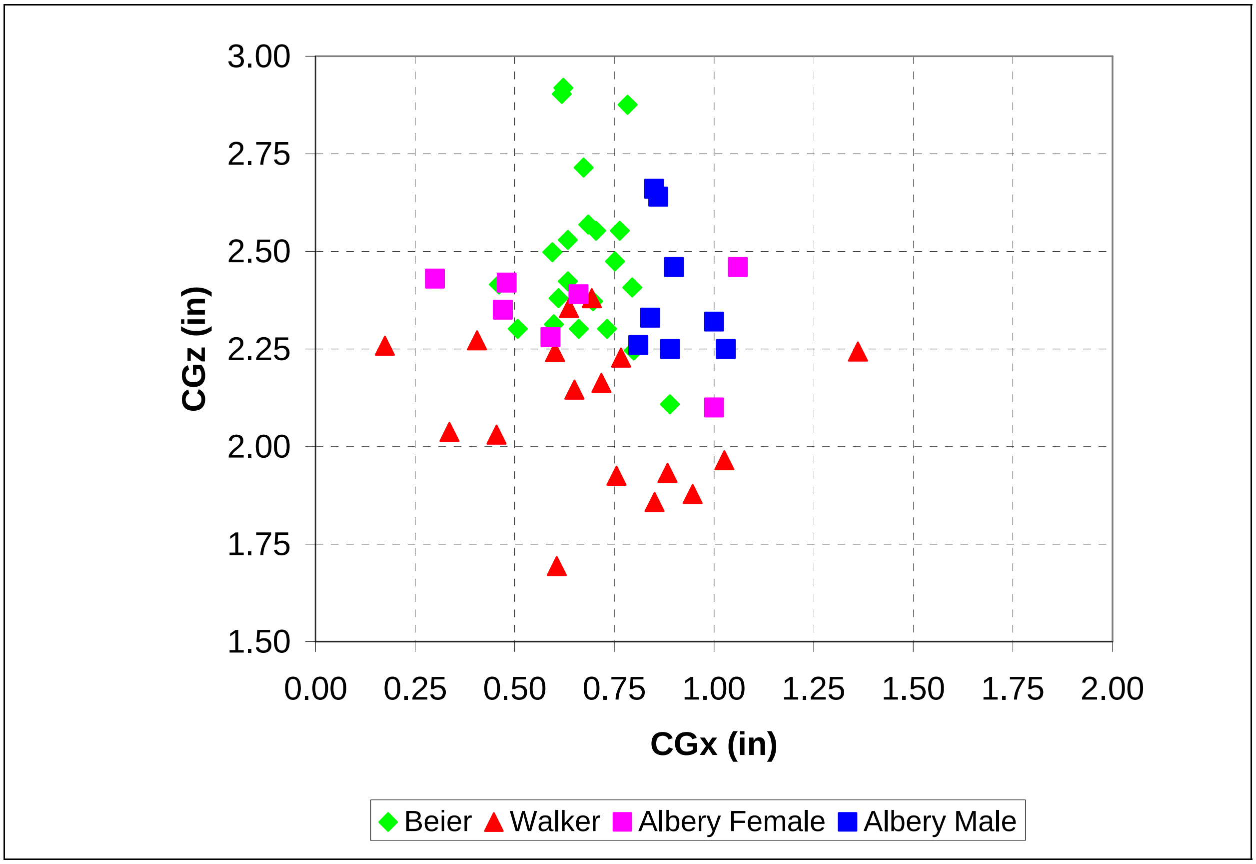

Figure 11. Human Head CG's with Respect to OC

Table 3. Average Human Head Inertial Properties

		Walker	Beier	Albery	All
Weight (lbs)	Weight	9.83	9.47	7.27	8.96
	SD	1.02	0.88	1.27	1.49
	Min	8.65	8.09	6.06	6.06
	Max	12.66	11.57	9.81	12.66
CGx (in.)	CG	0.70	0.68	0.78	0.71
	SD	0.28	0.10	0.23	0.21
	Min	0.17	0.46	0.30	0.17
	Max	1.36	0.89	1.06	1.36
CGz (in.)	CG	2.09	2.48	2.37	2.33
	SD	0.20	0.22	0.15	0.25
	Min	1.69	2.11	2.10	1.69
	Max	2.38	2.92	2.66	2.92

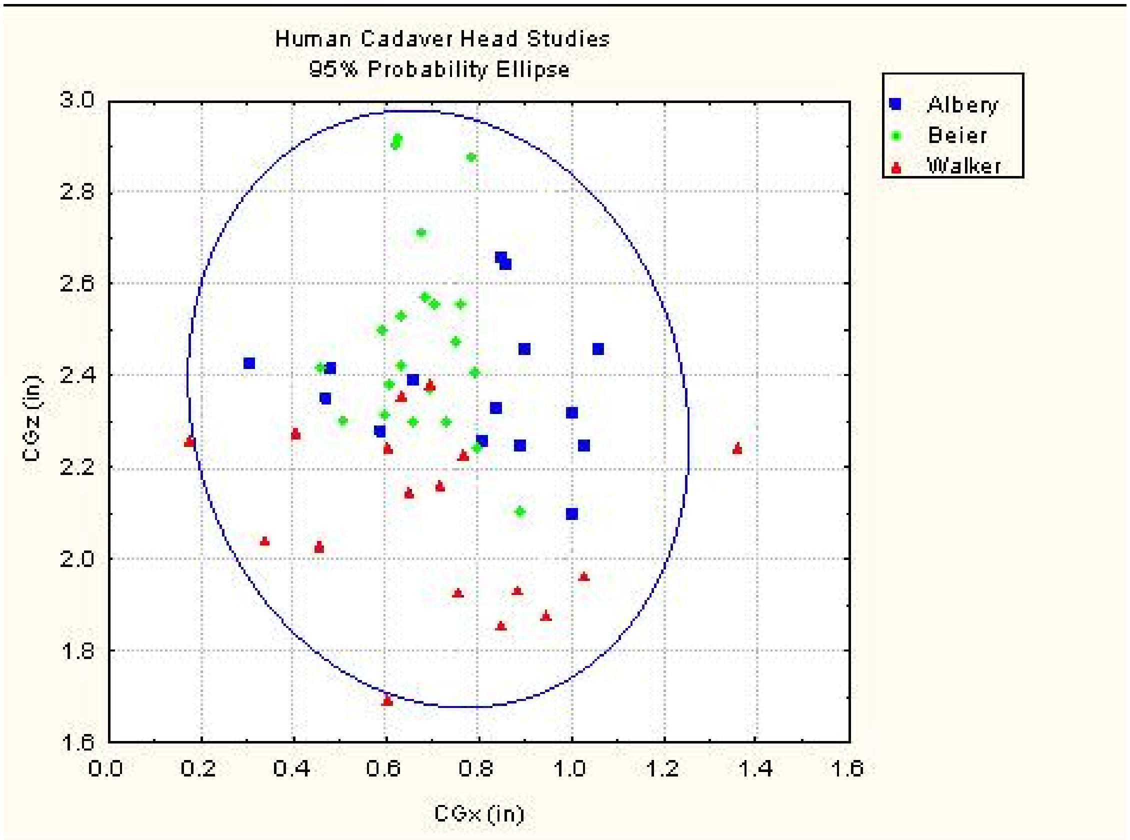

Figure 12. 95% Probability Ellipse for Head CGx and CGz (all studies)

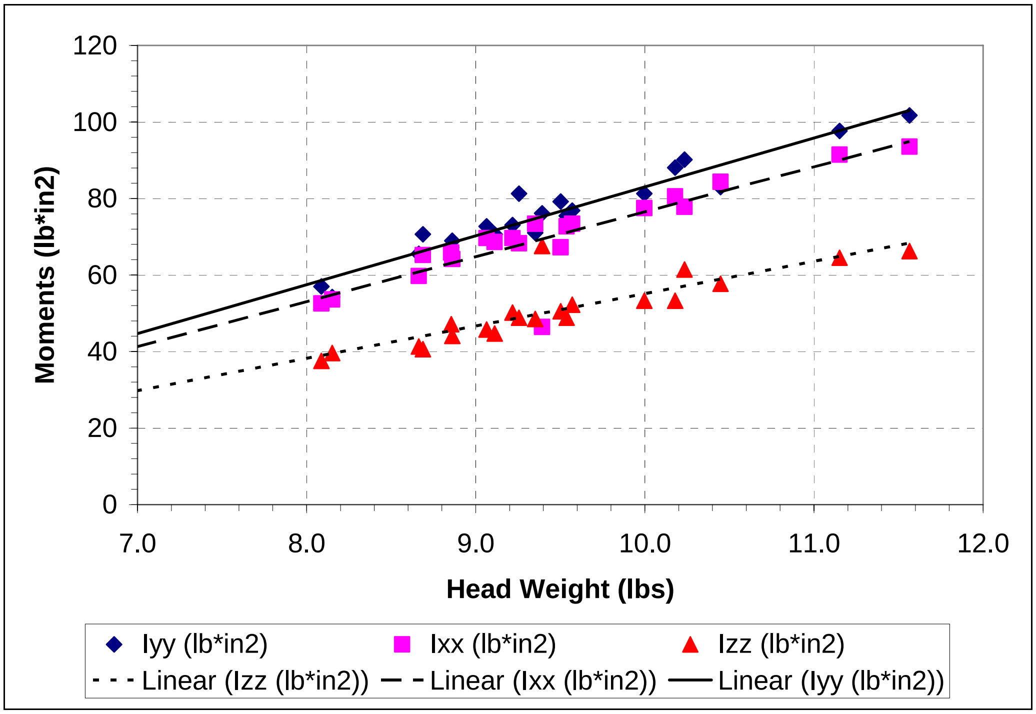

Figure 13. Human Cadaver Head Principal Moments of Inertia

A plot of human head principal moments of inertia and head weight is shown in Figure 13. The measured inertial properties of the manikin heads are shown in Table 4. The legacy Case 6 heads were found to have two discrete weights: approximately 10.8 pounds and 12.1 pounds. Discussions with the manufacturer (First Technologies Safety Systems) revealed that four of the Case 6 heads manufactured and delivered with Case 6 manikins were incorrectly ballasted to 12.1 pounds rather than to the specification of 10.8 pounds. Two of these heads were delivered to the US Air Force, and were subsequently reballasted to the correct 10.8 pound specification. Two other 12.1 pound heads were delivered to an ejection seat manufacturer in the United Kingdom, which was notified of this discrepancy.

Table 4. Current (Legacy) Manikin Head Inertial Properties

Subject	Weight (lbs)	CGx (in.)	CGz (in.)	Iyy lb-in.^{2}	Ixx lb-in.^{2}	Izz lb-in.^{2}
5% HB3 Female	8.2	0.78	1.7	52	34	50
Case 1	7.9	0.28	1.17	42	28	41
S. ADAM	9.0	0.27	1.78	73	69	49
L. ADAM	9.4	0.21	1.78	82	76	50
50% HB3 Male	10.0	0.77	1.99	74	49	71
95% HB3 Male	10.6	0.80	2.00	74	52	73
Case 6	10.8	0.31	1.71	98	88	63

Note: Weights include dummy load cell, neck pivot pin, 2 nodding washers (if used), accelerometer block & accelerometers and mounting screws.

Table 5 shows the measured inertial properties for manikin heads with the weight of the lower part of the load cell is subtracted out, along with data obtained from this study of select human sizes determined from the Weibull distribution analysis (head weight, Table 2) and average CG locations from the three human cadaver head studies (Table 3).

Table 5. Current (Legacy) Manikin Head Inertial Properties with Values Corrected for Partial Load Cell

Subject	Weight (lbs)	CGx (in.)	CGz (in.)	Iyy lb-in.^{2}	Ixx lb-in.^{2}	Izz lb-in.^{2}
5% Female*	7.4	0.71	2.33	49	46	32
SF-74	7.4	0.60	1.64	55	48	36
5% HB3 Female	7.6	0.84	1.84	50	32	49
Case 1	7.3	0.30	1.27	41	27	40
50% Small Female*	8.1	0.71	2.33	58	54	39
SF-81	8.1	0.71	1.96	59	52	38
S. ADAM	8.4	0.29	1.92	70	67	49
L. ADAM	8.8	0.22	1.91	80	74	50
50% HB3 Male	9.4	0.82	2.13	71	46	71
Case 6	10.2	0.33	1.82	96	86	63
95% HB3 Male	10.0	0.88	2.17	71	49	72
95% Male*	11.0	0.71	2.33	95	87	64
LM-110	11.0	0.74	1.84	99	79	70

* Average human data

Table 6 shows the measured weights and volumes of current manikin heads, and their corresponding calculated weights and volumes based upon the average human head densities. This indicates what an actual human head weight would be if it were the size of the manikin head and what the actual human head volume would be if it were the weight of the manikin head.

Table 6. Manikin Head Volumes and Weights

Subject	Measured Weight (lbs)	Measured Volume (in.^{3})	Weight Based on Volume (lbs)	Volume Based on Weight (in.^{3})
5% HB3 Female	7.6	192	7.3	199
Case 1	7.3	160	6.1	191
S. ADAM	8.4	228	8.7	220
L. ADAM	8.8	228	8.7	230
50% HB3 Male	9.4	-	-	246
Case 6	10.2	228	8.7	267
95% HB3 Male	10.0	-	-	261

An example of the head shape analysis is shown in Figure 14 below (manikin blue, human black). These figures show the typical differences between the manikin heads and their human counterparts. For a more detailed explanation, see Appendix B.

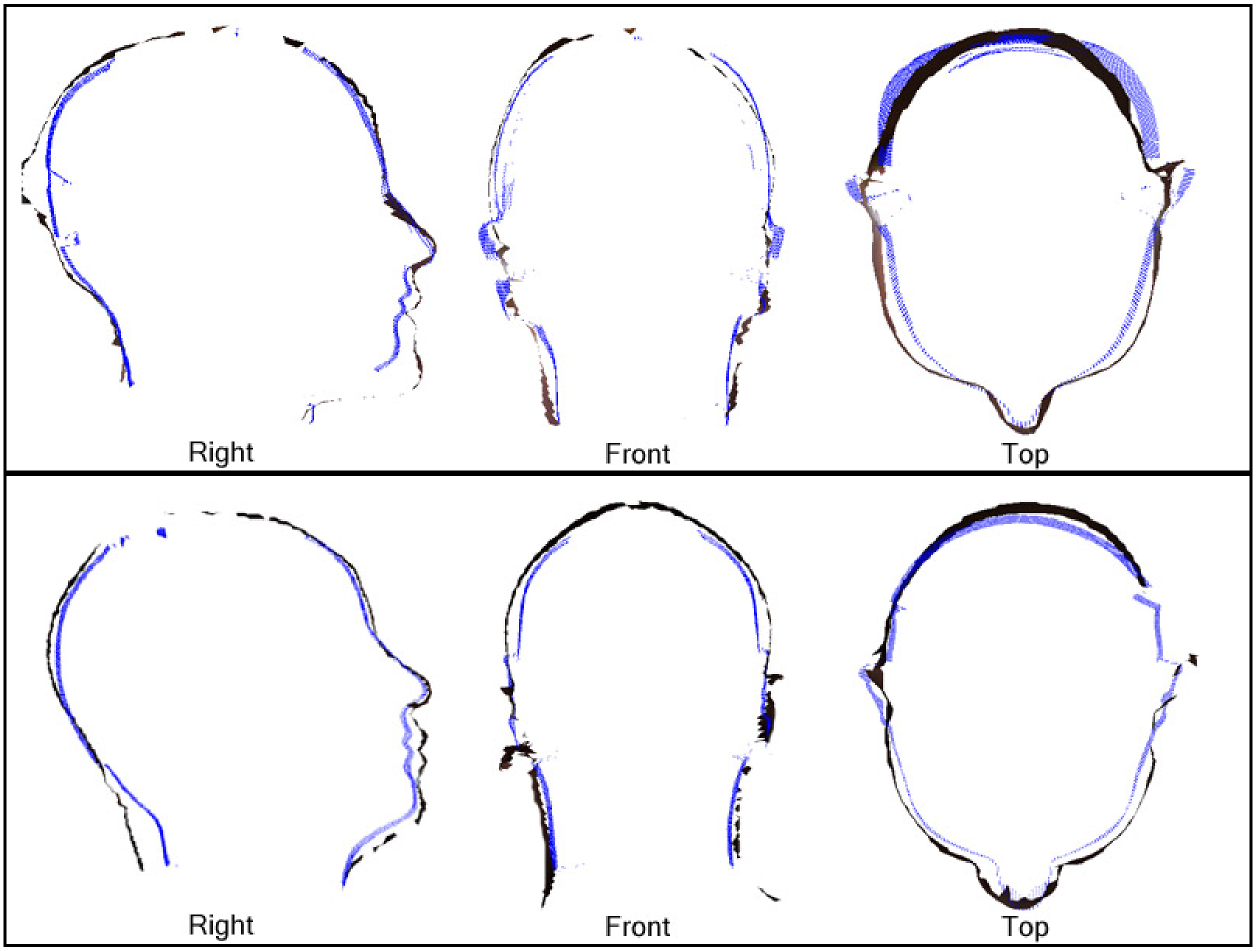

Figure 14. Case 1 Head Form vs. Subject 143 (top) and Case 6 Head Form vs. Subject 282 (bottom)

DISCUSSION

Prior to using the CEASAR surface scan data, traditional anthropometric measurements of the head were analyzed to determine if the head size and shape could be reasonably assessed. The key dimensions that were examined were Head Length, Head Breadth, and Head Circumference. Other head measurements such as Bizygomatic Breadth, Face Length (Menton-Sellion Length), Bigonial Breadth, Bitragion Breadth, Inter-pupillary Distance, Sellion-Supramenton Length are also available in various anthropometry studies.

Three bivariate plots obtained from a previous study were examined for relationships between head length, breadth, and circumference for a sample population. Typically, a confidence ellipse would be calculated and overlaid on the data to show an area which represents a certain confidence (i.e. 95%) that a population would fall within these head dimensions. This allowed the helmet manufacturer to examine the relationships between two head dimensions near this 95% ellipse. However, these plots were not sufficient to describe how the third dimension was related to the other two that were along the 95% ellipse. The three sample data plots were laid out orthographically (Figure 15) to try to better correlate all three dimensions, but this also did not relate the three dimensions very effectively. The other concern with using these three measurements was that the head circumference would be expected to be closely related to both the head breadth and head length since the head circumference measurement is taken around the breadth and length measurement areas. This essentially made the head circumference a function of the head length and breadth, which resulted in analysis of only two variables rather than three, which was inadequate data to provide information on the overall head size. This led to the idea of finding a third (vertical) head dimension that can be used to describe the volume. Unfortunately, there are no standard anthropometric measurements of the height of the head, so a combination of measurements was used to estimate this dimension. The equation used to estimate the head height was "sitting height" – "eye height sitting" + "face length". These data were then plotted on the three-dimensional (trivariate) plot shown in Figure 16. The goal was to take this information and use it to create ellipsoids (3-dimensional ellipse) that would encompass 95% of each gender, and use this information for the development of the head forms and design of the helmet sizes. This three-dimensional plot, although useful in demonstrating primary head dimensional relationship between genders, was ultimately leading towards the issue of head volume or weight. It was decided that a less complicated analysis could be done using a single dimension, that being head volume or weight.

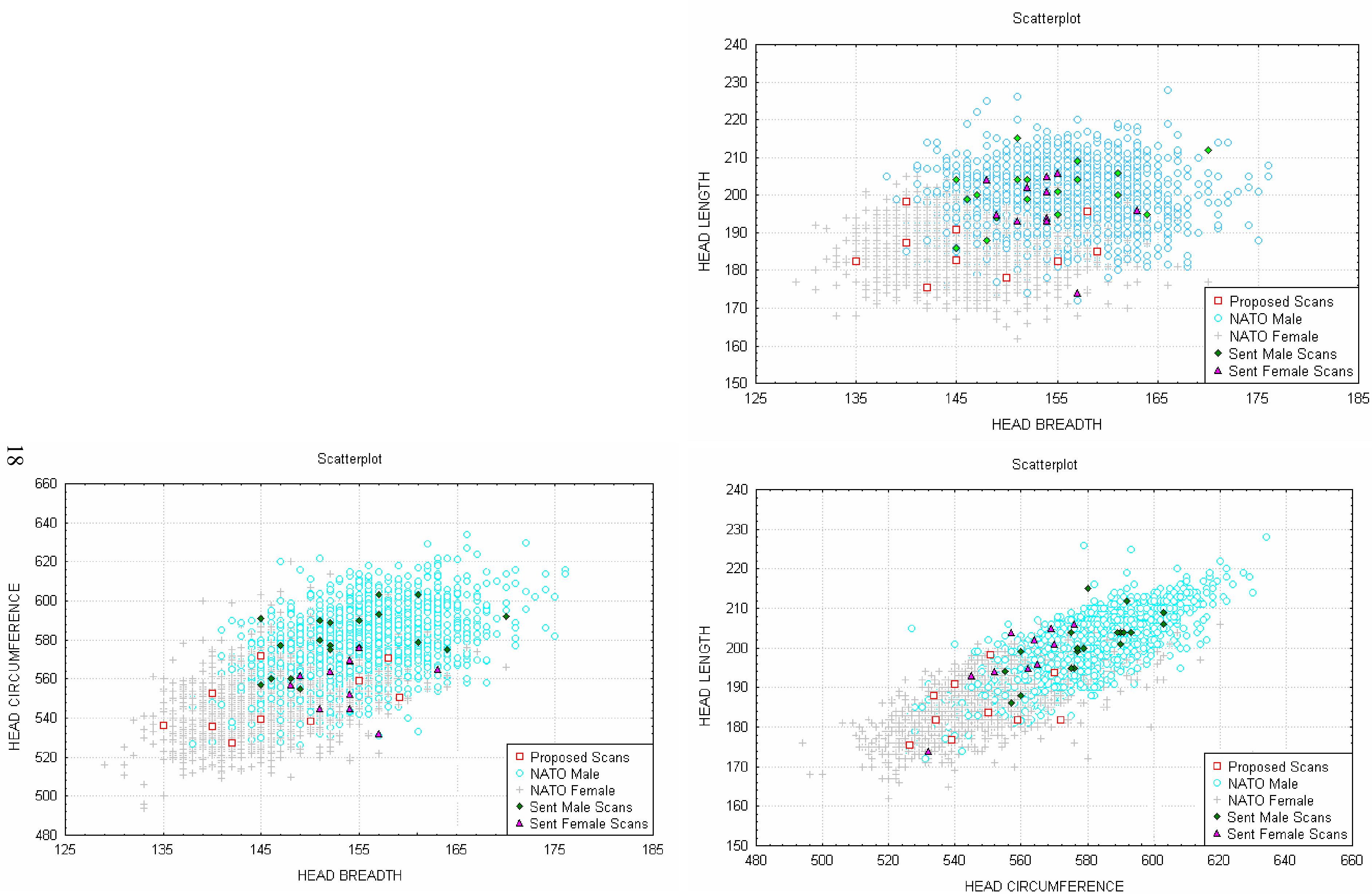

Figure 15. Example of Orthographic Presentation of Bivariate Data

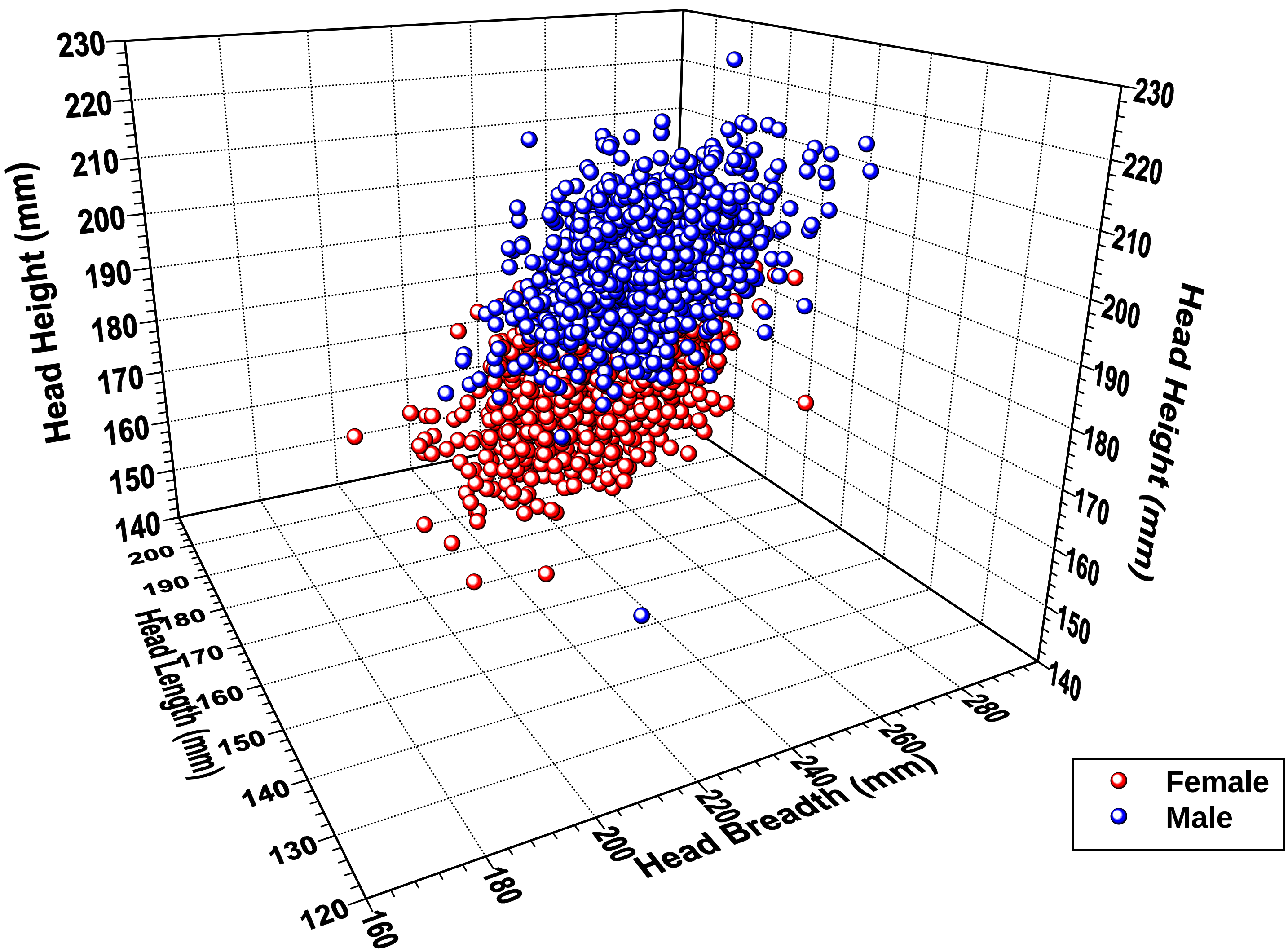

Figure 16. Head Height, Breadth, and Length 3-D Plot

Figures 7 through 10 above show that although there is a significant relationship between body size (vis-à-vis body weight and stature) and head weight ($p < 0.00001$), there are only low to moderate correlations between head weights and either of the two body measurements ($r^2 = 0.34$ to 0.48). This resulted in the theory that perhaps there was a stronger correlation between a generic body size, which encompasses both weight and stature, and the head weight. This theory was dispelled by standardizing the body size with respect to weight and stature and examining the head size distribution. The standardized data are shown in Figure 17. The "Body Size" vertical axis indicates the relative body size of each subject with respect to weight and stature.

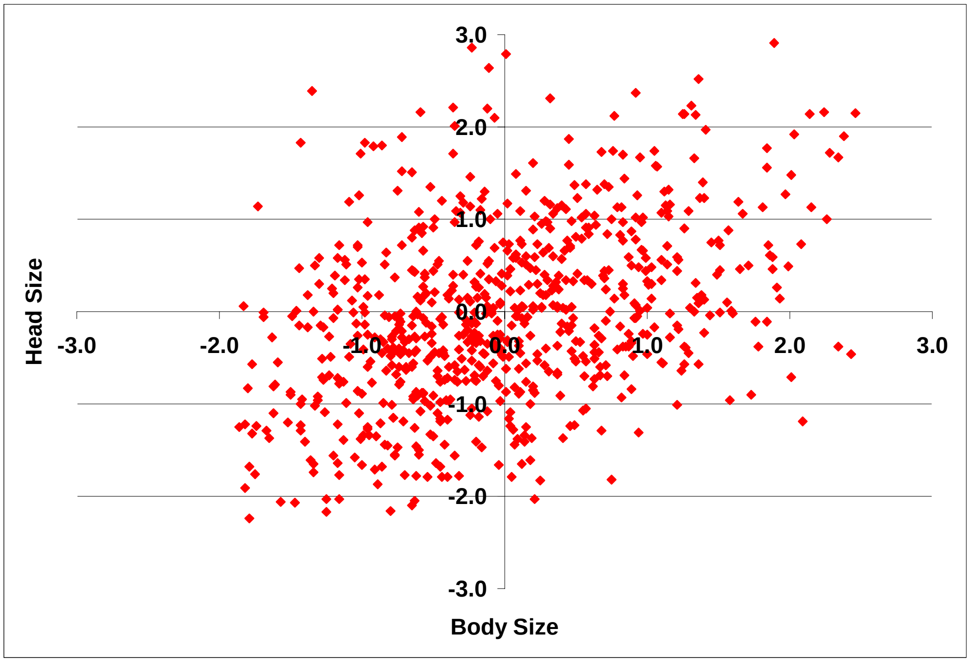

Figure 17. Standardized Female Head and Body Size Plot

For example, a person with an average weight and average stature would have a normalized Body Size of 0. A person with both above-average weight and stature would have a normalized body size greater than 0. A person with an above-average weight and below-average stature would be expected to have a body size near 0 unless one of the factors (either the stature or weight) was extreme. If there was a strong correlation between body size and head size, then Figure 17 would show a much greater distribution of subjects in the first and third quadrants (upper right and lower left) of the plot since this would indicate that an above-average body size has an above-average head size and vice versa. Although the plot indicates that there are a greater number of subjects in the first and third quadrants, there are also a large number of subjects in the second and fourth quadrants, which indicates small bodies with big heads and vice versa.

Defining Manikin Head Sizes

The criteria for choosing the head sizes, or defining what heads are representative of Case 1 and Case 6 manikins, needed to be defined. In the traditional sense, if a head were required for a 5^{th} percentile female manikin, then a 5^{th} percentile female head would have been chosen. Since the test manikins were based on Cases, not percentiles, it was not clear how to best choose a head appropriate for each manikin size. A plethora of dimensions and ranges of dimensions are used to define each Case. In theory, the database could be screened for subjects who met all of the specified dimensions within a certain tolerance. However, this would greatly reduce the number of subjects that could be used to determine a head size distribution or require large tolerances from the Case specifications in order to obtain a good sampling of subjects, both of which would reduce the statistical significance of the results.

The other option would be to choose subjects based on the weights of the Case 1 and Case 6 manikins. However, the weight for the Cases is an independent variable. There are no specific weights associated with any Cases other than the 103 lbs to 245 lbs range for all. This in theory means that the Case 6 could weigh 103 lbs and the Case 1 could weigh 245 lbs.

The option selected was to choose subjects based on a stature range related to the Case 1 and Case 6 manikins. While there are no statures specifically associated with the Cases, and there are no direct ways to "add up" the specified dimensions to get a stature, the actual statures of the Case 1 and Case 6 manikins were used (60 in. and 74 in. respectively) along with a ± 2” variance, since the manikins were designed to meet all of the Case specifications. Since the CAESAR database had already been screened by using the AFI 48-123 height and weight tables, use of the subject stature would already be correlated with body weight.

The second issue was what head percentile to use for each Case manikin. The key element of percentiles being used for this study is that the percentiles are based on head volumes or weight rather than individual linear dimensions. Traditionally, manikins would have head sizes that “matched” the manikin size percentile, i.e. a 50^{th} percentile manikin would have a 50^{th} percentile head, a 5^{th} percentile female manikin would have a 5^{th} percentile female head, etc. This is also the philosophy that the automotive industry has adopted. As stated previously, there is not a strong correlation between human head size and human body size. This method may not be the best method to use; in fact, it may be very flawed since the average head size of a 5^{th} percentile person is larger than a 5^{th} percentile head.

In order to address this issue, the objectives and philosophies of ejection seat test programs were examined. In an ideal world, one could run a multitude of rocket sled tests, varying the velocity, crewmember size, and even head size, and conduct a statistical analysis of the data. In reality, ejection seat tests are very costly and are usually limited to a minimum number of tests. As a result, traditional ejection seat testing has had to concentrate on testing the worst but reasonable scenarios. This resulted in testing the occupant weight extremes, which usually consisted of 3rd/5th percentiles and 95th/98th percentiles (based on weight of male population). These crewmember ranges would cover approximately 90-95% of the male military population. Similarly, using 103-lb Case 1 and 245-lb Case 6 manikins to qualify new ejection seats should result in the seat being qualified for approximately 90% of the total (male and female) anticipated future flying population.

Since head size is an independent variable with respect to body size, the question arises as to whether the head size should also be the worst case and, if so, what size would be the worst case. Traditionally, testing was done using manikin sizes to obtain a 90-95% coverage of the crew sizes. If we now put an extreme on top of an extreme (a small head on a Case 1 dummy), we may be representing a very rare situation. If the Case 1 dummy represented 1 in 20 females and the 5th percentile head represented 1 in 20 heads on this size person, then the Case 1 manikin with a 5th percentile head could represent 1 in 400 people, which represents a vary rare person and is much beyond the traditional testing philosophies.

Analysis of the effect of head size on neck loads revealed two areas where a head can be considered worst case, and these are poor fit and the dynamic loads encountered during ejection. Previous windblast and ejection testing indicate that a helmet that does not fit the head well (e.g. is too loose) allows air pressure to flow into the spaces between the head and helmet which results in high pressures under the helmet and large helmet lift loads. This can occur when the head size is on the small extreme size. The poor fit can also result in a decoupling of the helmet from the head (helmet slippage) which can exacerbate the neck loads. The other factor, dynamics, comes from the aerodynamic lift loads *over* the helmet and the head/helmet response to the accelerations encountered during the ejection event. The neck loads increase as the head (and helmet) size and weight increase.

The size and weight of the manikin can have a major effect on the dynamics in an ejection environment since a smaller manikin will experience higher accelerations and rotations than a larger manikin during an ejection which will result in higher neck loads. However, the effects of the head size on the *manikin's* (or seat/manikin) motion or dynamics during an ejection test are minor. Therefore, using a large head on the Case 6 manikin will not significantly increase the overall severity of the ejection with respect to assessing non-neck human injury potential, and the more stable large manikin will not result in exacerbating neck loads due to high accelerations on a large head mass. Therefore the head size chosen for the Case 6 manikin was a 95th percentile head based on male head weight. This follows traditional testing methodologies, and the smaller dynamics of a large manikin will not exaggerate the neck loads.

The head size for the Case 1 manikin involved more analysis. Putting a 95th percentile female head on the Case 1 manikin would be combining two worst cases, those being the larger dynamics due to the small manikin weight and the increase in neck loads due to larger head weight. Using a 5% female head on a Case 1 manikin may result in underestimation of the risk of neck injury since only 1 in 20 females the size of the manikin would have a head size this small. It was decided that a logical head size for the Case 1 manikin would be an average head size for a Case 1-sized person. This head size results in a moderate increase in weight over the previous Case 1 head, but does not go to an extreme. A second head, a 5th percentile head of the total female population head weight, was also chosen to be used on the Case 1 manikin for certain subsystem tests. This head will be used to verify proper helmet fit and neck loading under dynamic conditions such as windblast testing and catapult testing.

Since the designations for these heads were somewhat confusing due to the percentiles referring to either a head size on a Case or on a whole population, simplified designations relating to the head weights were developed. The head that represents the 5th percentile of all female head sizes was designated SF-74 (Small Female, 7.4 lbs); the head that represents the average head size of females that are the size of the Case 1 manikin was designated the SF-81 (Small Female, 8.1 lbs); and the head that represents the 95th percentile head of males was designated LM-110 (Large Male, 11.0 lbs).

Human Cadaver Head Centers of Gravity

All CG data, from the three studies, needed to be referenced from the OC for consistency and to provide meaningful information with respect to the pivot point. The Albery study was the only study that listed the location of the OC with respect to the Anatomical Reference System and the only study that listed CG data with respect to the OC. The Albery study showed that on average the OC was 0.35” forward and 1.25” below the origin of the anatomical coordinate systems that were used in the Beier and Walker studies. Therefore, the Albery data were used to translate Beier’s and Walker’s CG data with respect to the OC.

Table 3 summarizes the weight and CG data from all three studies. The average CGx and CGz values for all three studies were 0.71” and 2.33”, with standard deviations of 0.21” and 0.25” respectively. However, the CG values ranged from 0.17” to 1.36” horizontally, and 1.69” to 2.92” vertically (from OC). A 95% probability ellipse for the CGx versus CGz data from all three studies are shown in Figure 12 to take into account the dependencies between CGx and CGz. The CG values for the new manikin heads in theory should be within this 95% probability ellipse.

A comparison of the data from the three studies indicates that there are consistent results between the studies in the location of the head CG horizontally with respect to the OC, but there are some differences in the location of the head CG vertically with respect to the OC. An analysis of variance (ANOVA) indicated that there were no significant differences ($p = 0.314$) between the CGx positions for any of the three studies. There were significant differences between the CGz for the three studies, but no significant differences in the CGz between the Albery and the Beier studies ($p = 0.099$). Analysis of the Albery data indicated that there was no significant differences between gender for the CGs ($p = 0.034$ and 0.541 respectively for CGx and CGz).

The average Walker CGz data were approximately 0.4” lower than the average Beier data. These differences were noted by Beier in his report and Beier concluded, “Besides possible systematical differences due to different experimental procedures the reason may be a weight-loss of the soft tissue during fixation or fluid loss during the measurements of the embalmed specimens.” Although there were significant differences between the CGz of Walker and the other two studies, there was no decisive reason to believe that Walker data are invalid. As a result, the head center of gravity data from all three studies were used to determine the average and ranges of human head CGs. This is a change from the previously used method by Plaga and Albery in which only the data from the Beier study were used to determine average human head CGs.

The Albery data were unique since almost half of the subjects were females, whereas Beier’s study included only two female specimens and Walker’s study did not have any female specimens. When the head CG data are separated between the males and females, the average female CGx value is 71% of the average male CGx value, although the female standard deviation is 0.28 whereas the male standard deviation is only 0.08. These data (Table 3) were analyzed using a two-sample t-test and were found to be not statistically significant ($\alpha > 0.05$). The two female subjects from Beier’s data were examined and they fell in the lower values of the overall CGx range. Although comparison of seven to nine female heads to dozens of male heads may not result in a concrete conclusion, this trend should be noted and possibly be further investigated.

The data from all three human cadaver head studies indicate that there is no correlation between head weight and head CGx or CGz with respect to the OC. These data can be seen in Figure 18, which shows each head's relative weight (represented by relative-sized circles) and its center of gravity. This "bubble chart" indicates that there is no relationship between the head weights and the head centers of gravity with respect to the OC as can be seen by the fact that both large and small heads are scattered throughout the plot.

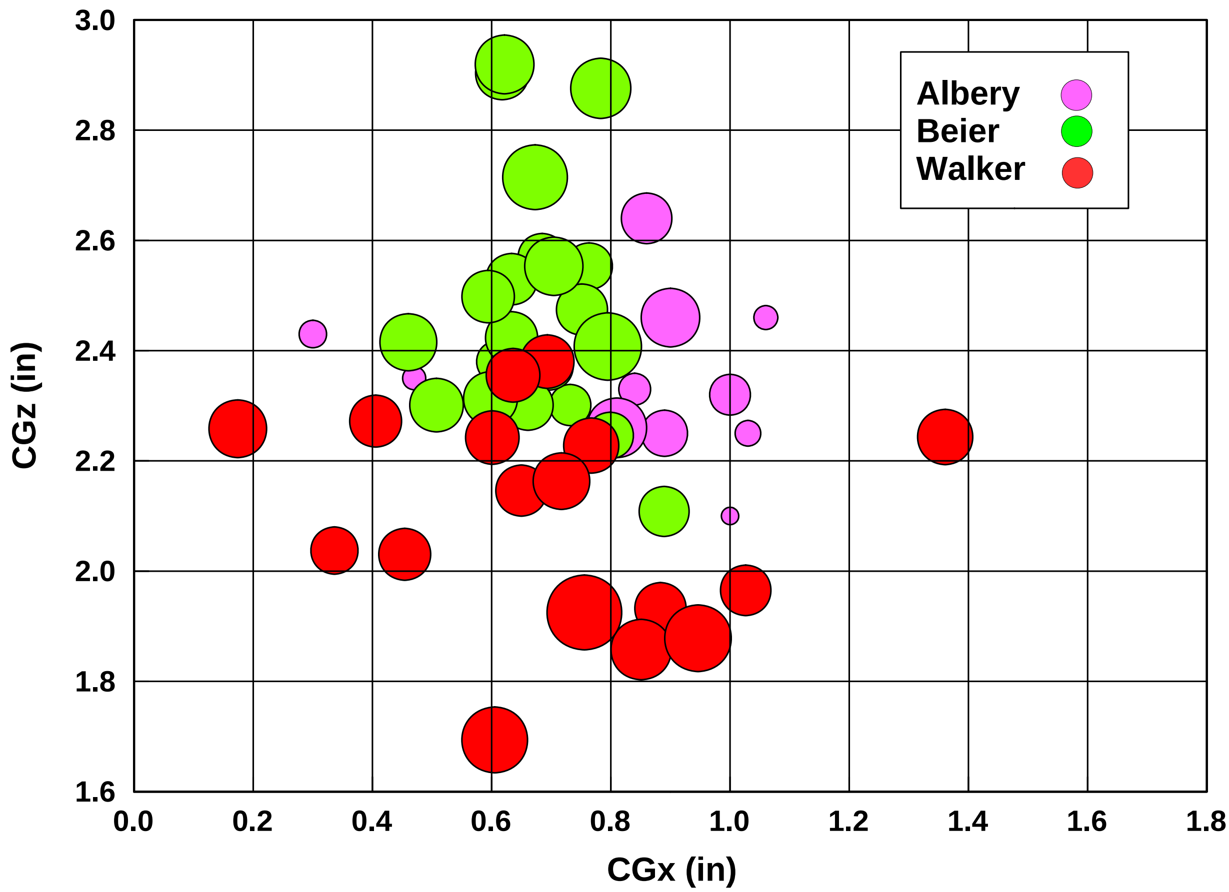

Figure 18. Cadaver Head Weight/CG Bubble Chart

When the actual manikin head CG data (Table 4) are compared to the average human head cadaver study data, most of the manikin head CGx values are aft of the cadaver head data. Two of the manikin heads, the Small ADAM and the 50% Hybrid III, closely match the CGx data the average cadaver head data (0.70 in. versus 0.71 in.). The Large ADAM manikin head CGx value (0.51 in.) is just within the range of the CGx measurements of human heads (minimum of 0.46 in.) and is within two standard deviations of the mean. The Case 1 CGx value (0.28 in.) is outside the limits that Beier measured, but it is within the range of measurements that Walker measured (0.17 in.) and just outside the range that Albery measured (0.30 in.). The Case 6 head CGx measurement of 0.07 in. is considerably further aft than any of the studies measured.

Not only were all of the manikin head CGz data lower than Beier's average of 2.48 in., they were also lower than his minimum CGz measurement of 2.11 in. By comparison, Albery's mean and minimum CGz measurements were 2.37 in. and 2.10 in., respectively, both of which are higher than all of the manikin CGz locations. Walker's mean CGz is 2.09 in. with a standard deviation of 0.20 in. and a lower range of 1.69 in. This puts the 50% Hybrid III head just within one standard deviation of Walker's mean, and all of the others except for the Case 1 head (CGz = 1.17 in.) within the range of CGz values that Walker measured.

Human Cadaver Head Moments of Inertia

Data from Beier indicate that there are good correlations (R^2 = 0.77, 0.93, and 0.74 for Ixx, Iyy, and Izz respectively) between head principal moments of inertia and head weight (figure 13). The predictive equations for mass moment of inertia as a function of head mass is given in equations 1-3 below.

Equation 1: $I_{xx} = 11.746W - 40.964$

Equation 2: $I_{yy} = 12.788W - 44.826$

Equation 3: $I_{zz} = 8.4519W - 29.386$

Where W = the weight of the head in lbs, and I is the mass moment of inertia in $lb*in^2$.

Comparison of Human and Manikin Head Mass Properties

The Case 1 head CG locations vary greatly from the human cadaver head CG data. Examination of the head reveals that the OC is much higher on the Case 1 head than on humans or the other manikin heads (eye level rather than lower nose level). The Case 1 head was an off-the-shelf head that was developed for eyeglass assessment and was later put on a 5^{th} percentile VIP manikin. This head was never designed to be used with a flexible Hybrid III-type neck. When the head was modified to accept the Hybrid III neck and 6-axis load cell, the neck and load cell were mounted directly to the bottom surface of the existing skull structure. The location of the bottom surface was higher than Hybrid II or III heads, which were specifically designed to be mounted to the flexible necks and load cells. This explains why the Case 1 head CG is much lower than the human head CG.

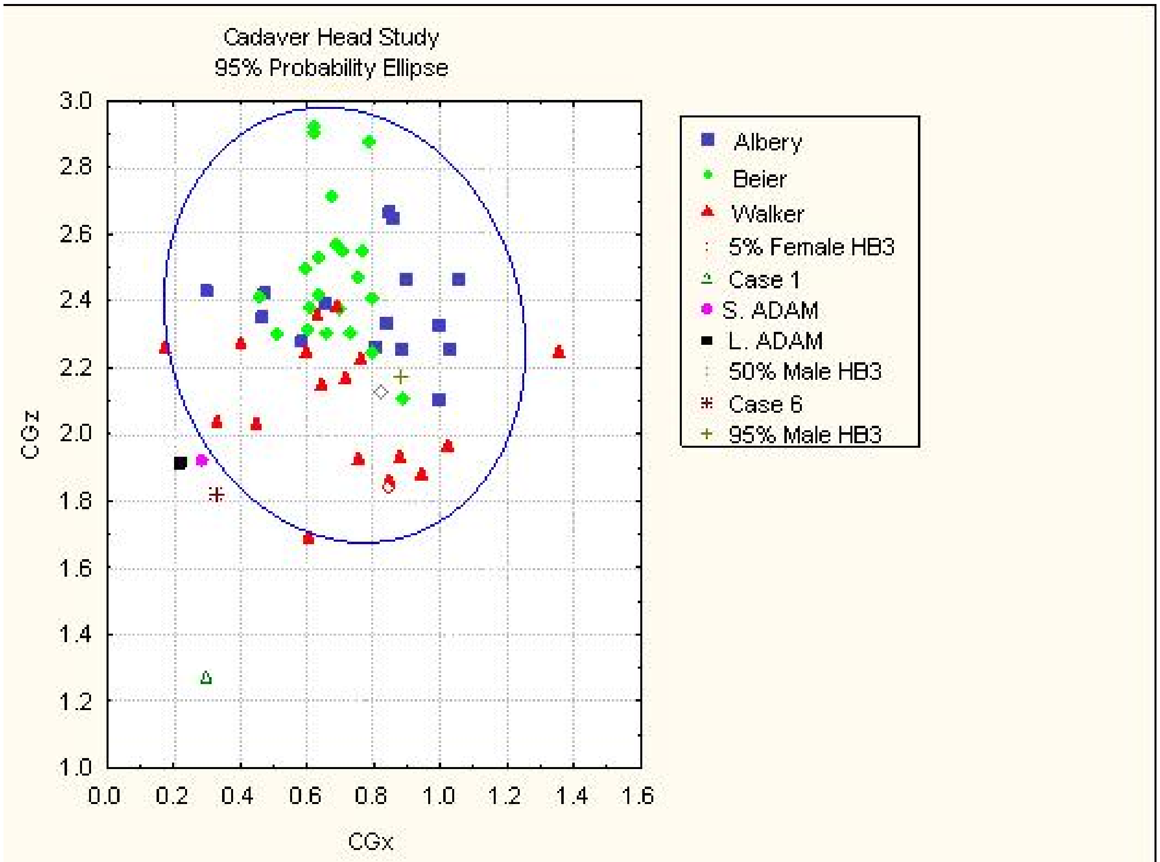

Figure 19. Cadaver Head CG 95% Probability Ellipse Showing Manikin Head CGs

The Small and Large ADAM heads and the Case 6 head are all derived from the 50% male Hybrid II-type heads. All three of these heads have the same external geometries. The Small and Large ADAM head specifications were for a 3rd and 97th percentile head respectively, based on the 1988 male tri-service aviator anthropology database[15]. The weight of the standard 50th percentile Hybrid II head was reduced to make the Small ADAM by impregnating the vinyl skin with foam, and the weight was increased to make the Large ADAM head by adding ballast in the skull cap area. The Case 6 head weight was increased using a distributed ballast.

The 50th percentile male Hybrid III head is listed as a comparison with the human data. Since the Hybrid III heads do not have human-like features and do not have full chins and napes, these heads are not acceptable head forms for testing helmets. However, these heads were developed for automotive testing to represent the weight, inertial properties, and gross size of the human head. In 1974, Hubbard and McLeod[16] analyzed human head cadaver data to determine the size, weight and CG for the 50th percentile male Hybrid III head. This head was ultimately used as the standard head on automotive crash test dummies, and thousands of these heads are in existence and being used today for testing. However, Hubbard used the Walker head cadaver data to determine the head weight and CG location for the Hybrid III head, which had a CG of about 0.4" lower than the Beier data. In addition, examination of Hubbard's head coordinate system shows the distance between the OC and the origin of the anatomical coordinate system to be 0.2" lower than what was seen on the Albery cadaver landmark data. This results in the CGz on the Hybrid III head being 0.6" lower than the Beier cadaver head data (1.9" versus 2.48" with respect to the OC).

The human and manikin head principal moments of inertia were also compared. Since the manikin Hybrid III necks were designed primarily for flexion/extension response, the pitching moment (Iyy) is the most critical moment to match. All of the manikin heads except for the Case 1 head have less than a 10% difference from the estimated human Iyy values. The Case 1 head Iyy was 25% less than the estimated value for a similar weight human head. This is due to the fact that the Case 1 head volume is much smaller than a comparable weight human head.

Comparing the head roll principal moment of inertia (Ixx) and the head yaw principal moment of inertia (Izz) of the human subjects to the principal moments of inertia of the manikin heads reveals that the Hybrid II-based heads (Large & Small ADAM and Case 6) have less than a 10% difference from the human head data, whereas the Case 1 and 50% Hybrid III head had a difference of 46% and 34% respectively in Ixx and 11% and 29% respectively in Izz. The differences in the Case 1 head are again most likely due to the very small head volume, and the differences in the Hybrid III head are due to the head not having an overall shape representative of the human head.

Using the average human cadaver head CG data and the regressions for the head principal moments of inertia from Beier, approximate (average) human head mass property data were generated for the three head sizes chosen to be developed and produced for JSF manikin heads as described above (Table 7).

Table 7. Average Inertial Properties for Various Human Head Sizes

Subject	5% Head Females	50% Head Small Females	95% Head Males
Weight (lbs)	7.4	8.1	11.0
CGx (in.)	0.71	0.71	0.71
CGz (in.)	2.33	2.33	2.33
Iyy ($lb*in^2$)	49	58	95
Ixx ($lb*in^2$)	46	54	87
Izz ($lb*in^2$)	32	39	64

Current Manikin Head Shape and Size

After defining the human head properties, the current manikin heads were reviewed to determine if they were representative of human heads in the areas of shape, size, and inertial properties. The shape and size are critical issues for proper helmet fit. As shown in Figure 13, the manikin head shapes were not entirely similar to human head shapes. The manikin lips and chins were more receded than their human counterparts, and the upper foreheads were less pronounced on the manikins than on the humans. There are other shape differences, such as in the nape area, that can be seen in the figures. Appendix A provides a more detailed analysis of the differences between the human and manikin head shapes. The size or volume of the manikin heads also differed from humans. The legacy Case 1 and Case 6 heads are 20% and 18% smaller, respectively, than human heads with equivalent weights to the manikin heads. The manikin head volumes were used to calculate what their weights would be for a comparably-sized human head.

CONCLUSIONS

Current manikin heads do not represent human heads in the areas of shape, size, and inertial properties as demonstrated in this report. Surface scan and traditional anthropomorphic data were analyzed from the Civilian American and European Surface Anthropometry Resource (CAESAR) database to determine typical head sizes of people representing Case 1 and Case 6 anthropometries. Human cadaver head studies were also reviewed, and data were analyzed to estimate head mass property relationships for different-sized heads. Representative mass properties were determined to characterize a 5^{th} percentile female head weight, a 50^{th} percentile small female head weight, and a 95^{th} percentile male head weight. Representative heads were then chosen from the CAESAR database so that anthropometric manikin heads could be developed and produced to better evaluate helmet systems.

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APPENDIX A. HEAD SHAPE ANALYSIS

Three functional manikin heads at Wright Patterson Air Force Base were scanned for practicality and realistic design improvements. These three manikin heads were LOIS (Lightest Occupant in Service), ADAM (Advanced Dynamic Anthropomorphic Mannequin), and the VIP 95% (Very Important Person) manikin.

After reviewing the scans and the listed head dimensions for the manikins in the areas of head breadth, head circumference, and head length, several measurements were found to be inconsistent with the manual measurements performed on the same manikin heads using CAESAR anthropometric techniques. The recorded head breadth measurement was taken over the manikin's flattened ears, while CAESAR techniques practice finding maximum head breadth above the ears, perpendicular to the mid-sagittal plane. The head circumference had been found either over the ears or over a very vertical plane. CAESAR head circumference measurements are found using the largest value above the brow ridge at a near-horizontal plane, and <u>not</u> over the ears. The head length measurement was measured on a horizontal plane from the glabella to the back of the head. The head length measurement for CAESAR does not have to be horizontal, but rather a straight line between the glabella and rear-most point of head.

The following differences are noted:

The LOIS manikin represents the smallest 5% of the military force or a person weighing approximately 103 pounds. The listed value for head length is 173mm. The measured value was 179mm. The listed value for head breadth is 148mm. The measured value was 142mm. The measured value for head circumference was the same as the listed value of 525mm.

ADAM represents the largest 97% of the male military population or a person weighing approximately 218 pounds. The listed value for head length is 200mm. The measured value was 202mm. The listed value for head breadth is 178 mm. The measured value was 156mm. The listed value for head circumference is 588mm. The measured value was 585mm.

The VIP 95% manikin is still commonly tested, although it is an older manikin than the ADAM. It is assumed to represent 95% of the male population since it has the same head breadth, head length, and head circumference measurements as the ADAM manikin. The only difference between the ADAM and VIP manikin is the age and longer face on the VIP manikin. No previously listed dimensions were found.

After the three manikin heads were scanned, the scans were compared to actual human scans with similar head breadth, head length, and head circumference measurements. What is shown below are the manikin scans (blue) transposed on top of comparable subject scans (red).

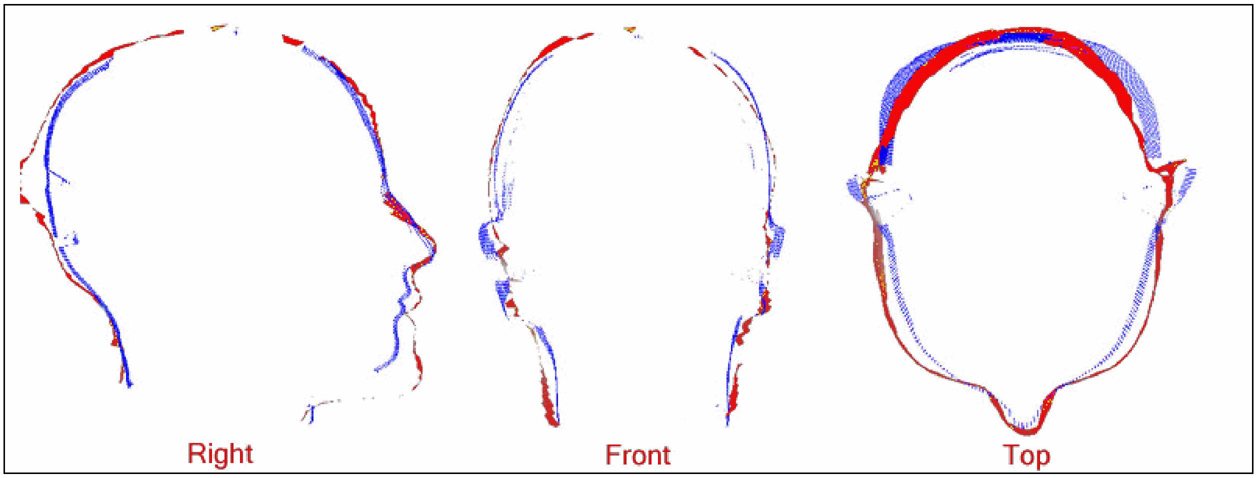


Figure A-1. LOIS Head (blue) and CAESAR Subject 143 (red)

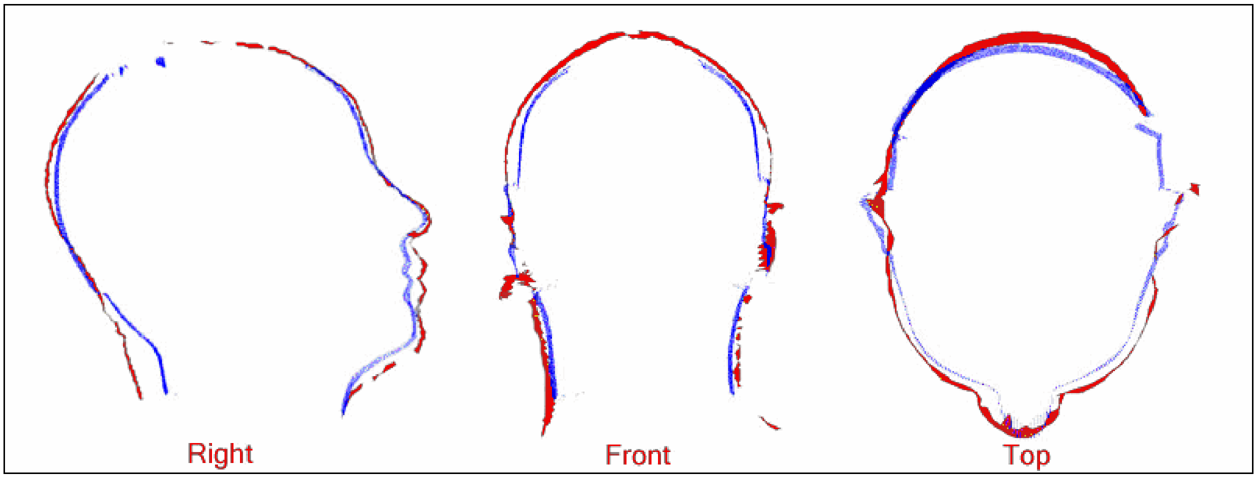


Figure A-2. ADAM Head (blue) and CAESAR Subject 282 (red)

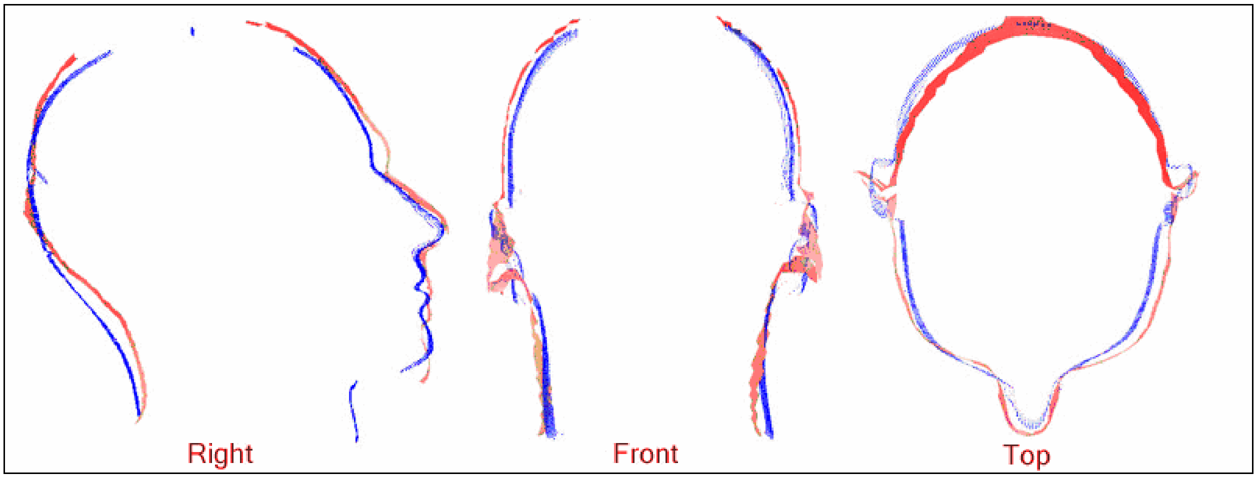


Figure A-3. VIP Head (blue) and CAESAR Subject 6008 (red)

When comparing the LOIS head scan with the 5% CAESAR population, and the ADAM/VIP scans with the 95% CAESAR population, the differences were great, especially in the face structure. What is shown below are the differences between the manikin scans (blue) transposed on top of the ~5% or ~95% CAESAR subject scans (red).

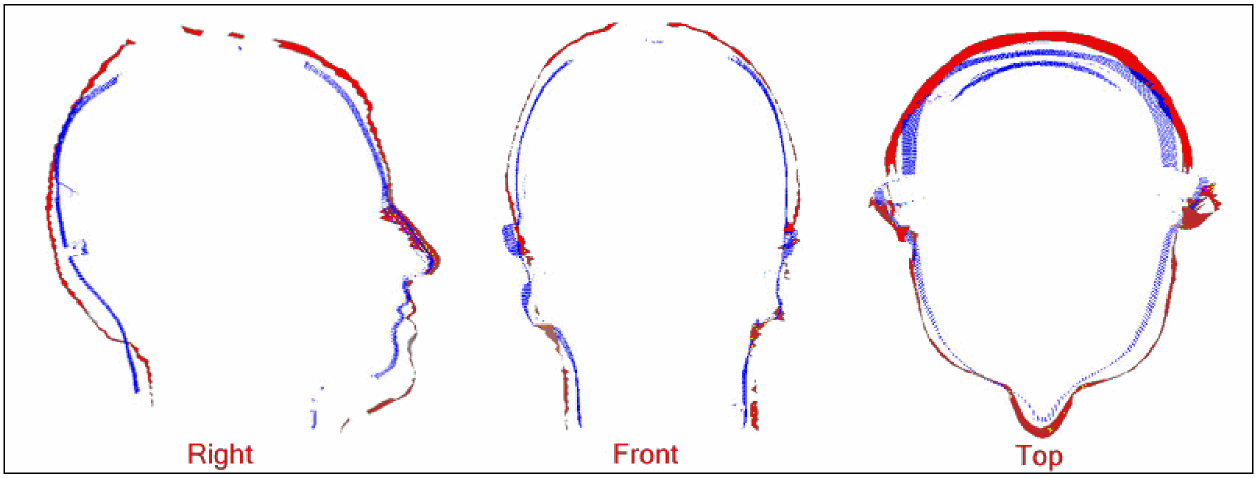


Figure A-4. LOIS Head (blue) and ~5% CAESAR subject (red)

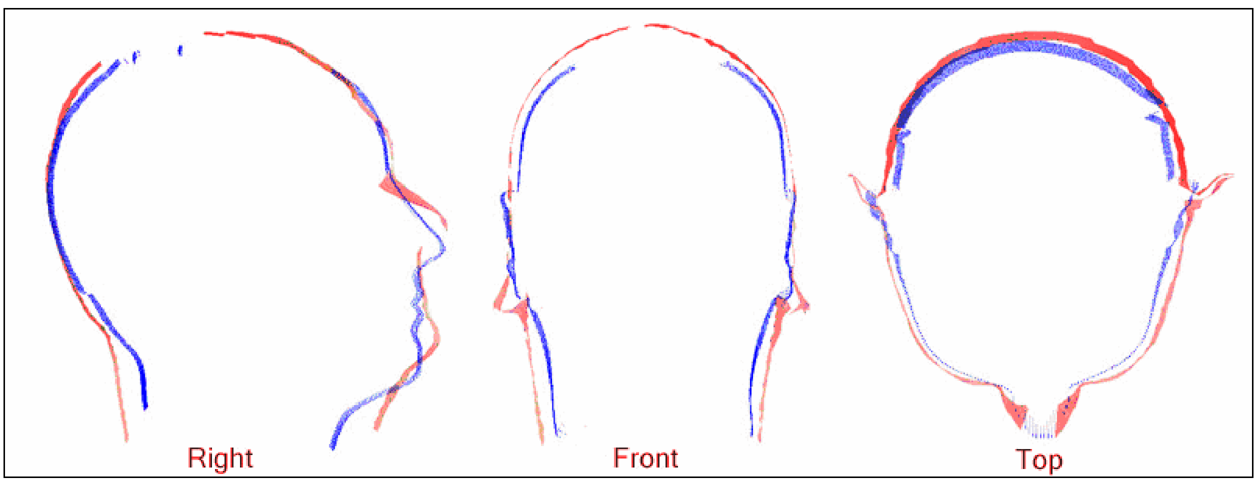


Figure A-5. ADAM Head (blue) and ~95% CAESAR subject (red)

The following graphs show how the LOIS head compares to the 5% CAESAR population and how the ADAM/VIP manikin heads compare to the 95% CAESAR population in the measurements of head length, head breadth, and head circumference.

Note that the subjects in the gray area are not being represented by choosing a range of 5% through 95% for the manikin design. Although this range eliminates only about 223 subjects for the smallest 5% and 223 subjects for the largest 5% (a total of 446 subjects eliminated), up to 892 subjects are possibly eliminated (20%) just by cross-referencing two variables. Already, the manikin design is satisfying just over 80% of the population.

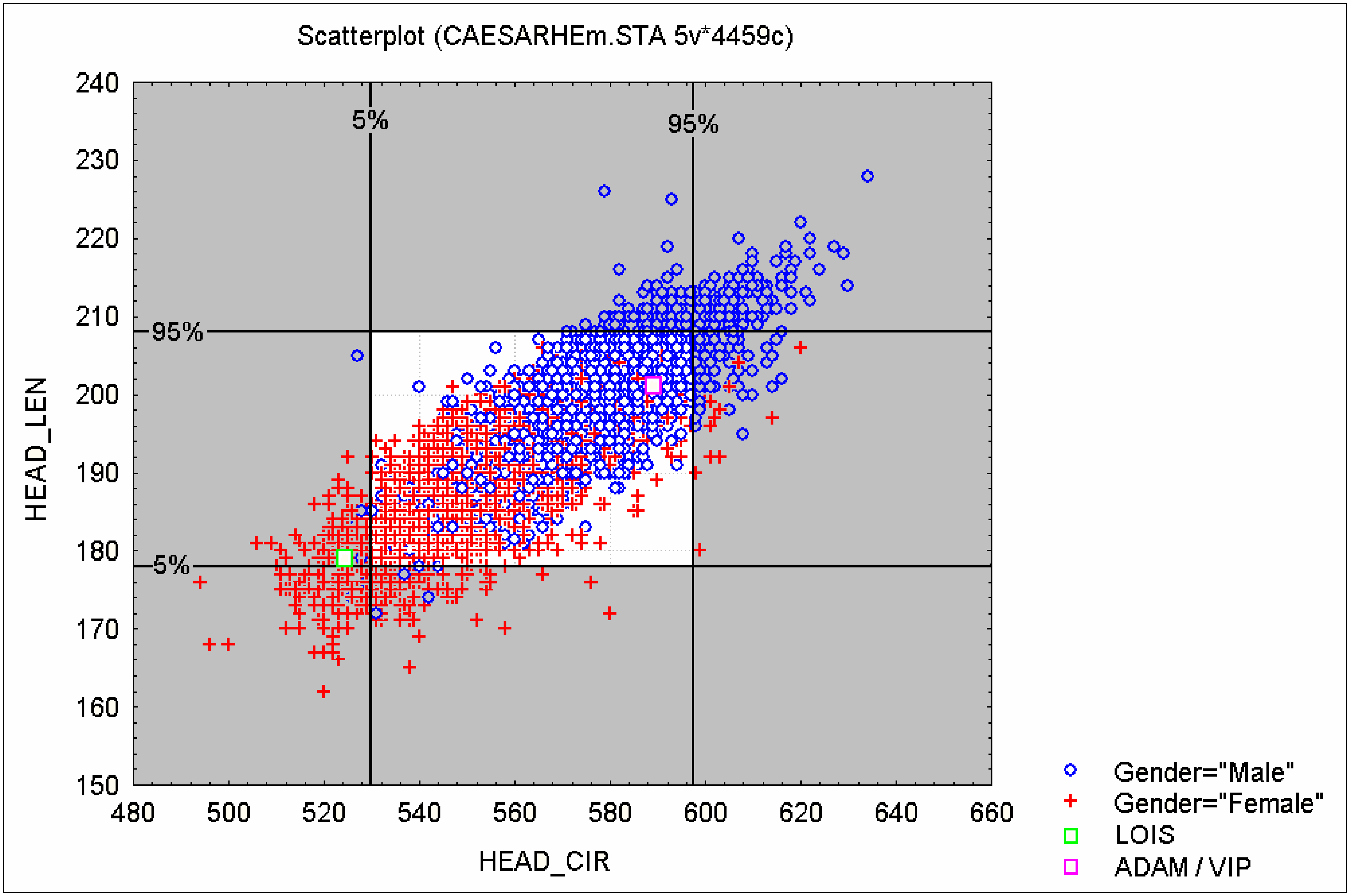


Figure A-6. Head Circumference vs. Head Length Bivariate Plot

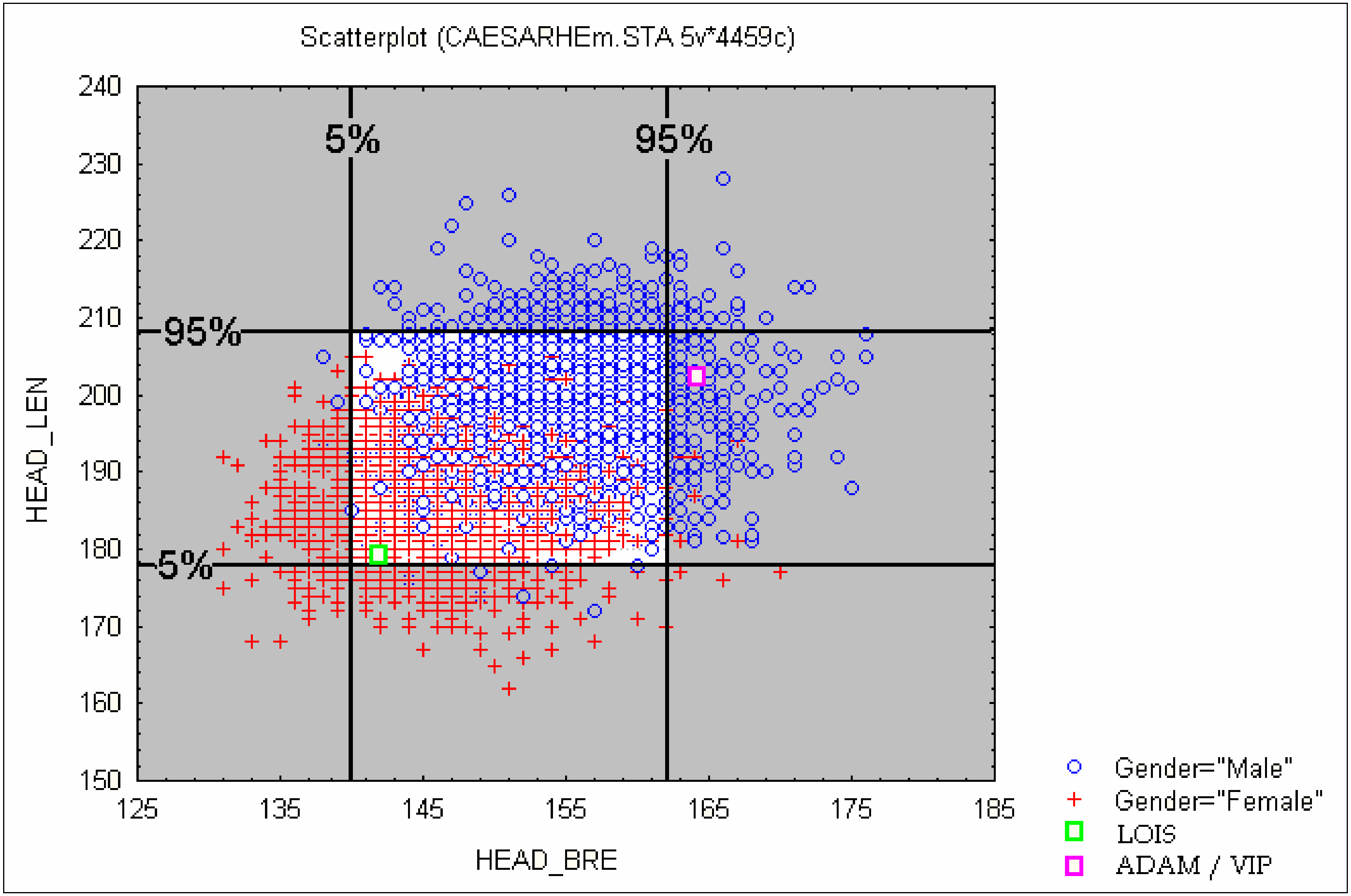


Figure A-7. Head Breadth vs. Head Length Bivariate Plot

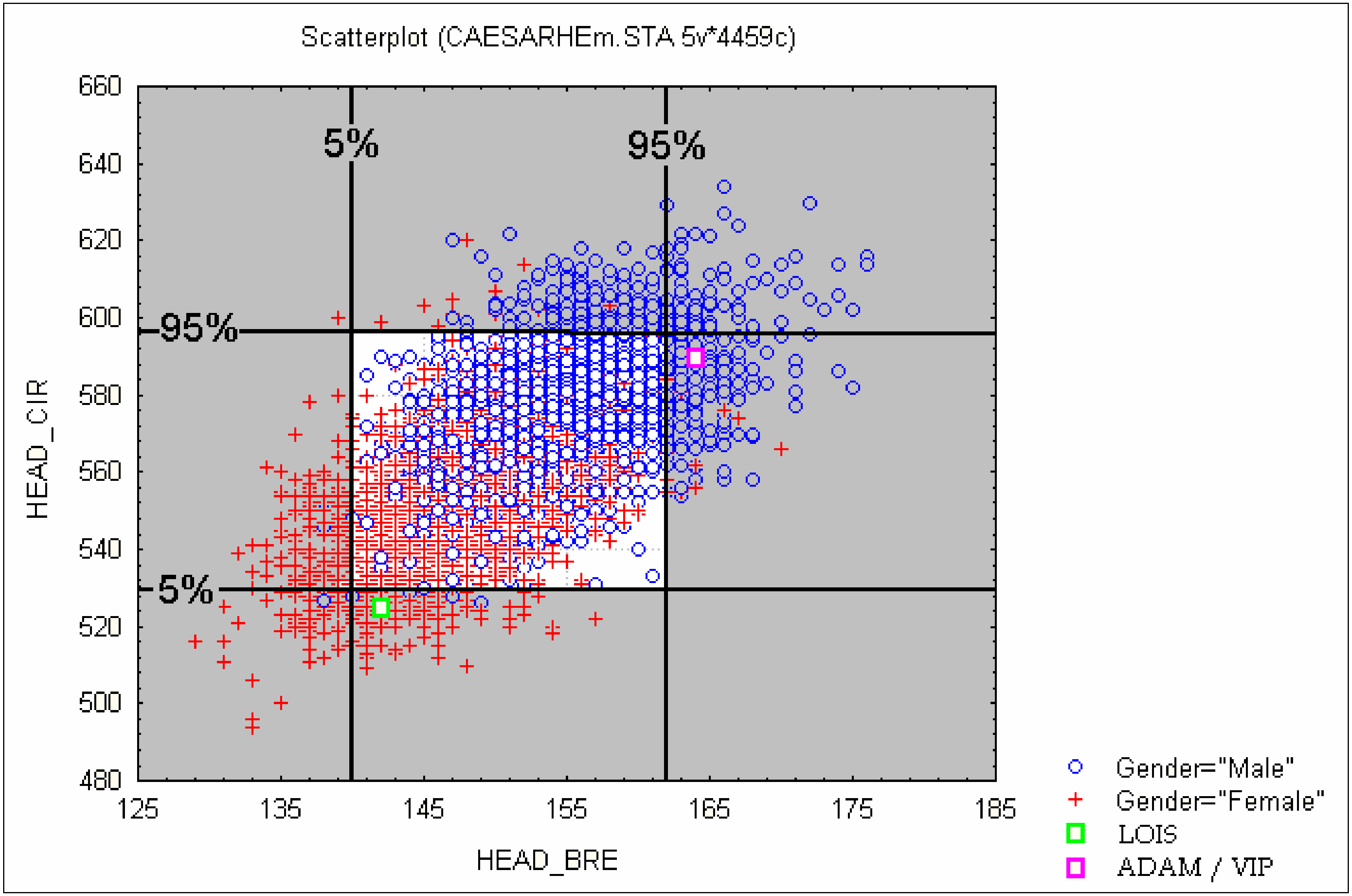


Figure A-8. Head Breadth vs. Head Circumference Bivariate Plot

APPENDIX B. WEIBULL DISTRIBUTION ANALYSIS

From the North American CAESAR data, all males and females were used that met height-weight requirements of Air Force Instruction 48-123 weight tables and who also met the following requirements for stature, sitting height, and weight:

58 in. ≤ stature ≤ 80 in.
31 in. ≤ sitting height ≤ 41 in.
103 lb ≤ weight ≤ 245 lb

Of the subjects meeting all height-weight requirements, 4 male and 4 female head masses were considered outliers and not used for any analysis. The number of subjects used was N = 716 for males and N = 739 for females. The Weibull cumulative distribution was used to fit the sample cumulative proportions of head mass for each set of subjects under consideration. Head mass was determined by multiplying the scanned head volume by the average head density (1.06 g/cm^3). Following is a description of the Weibull distribution.

Weibull Density Function: $f(x) = \left(\frac{\beta}{\alpha}\right)\left(\frac{x - x_o}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x-x_o}{\alpha}\right)^{\beta}}$ where $0 < \alpha$ and $0 < \beta$

α = scale parameter, β = shape parameter, x_o = lower bound (LB)

Weibull Cumulative Distribution: $F(x) = 1 - e^{-\left(\frac{x-x_o}{\alpha}\right)^{\beta}}$

Solving the cumulative distribution for X results in the following equation:

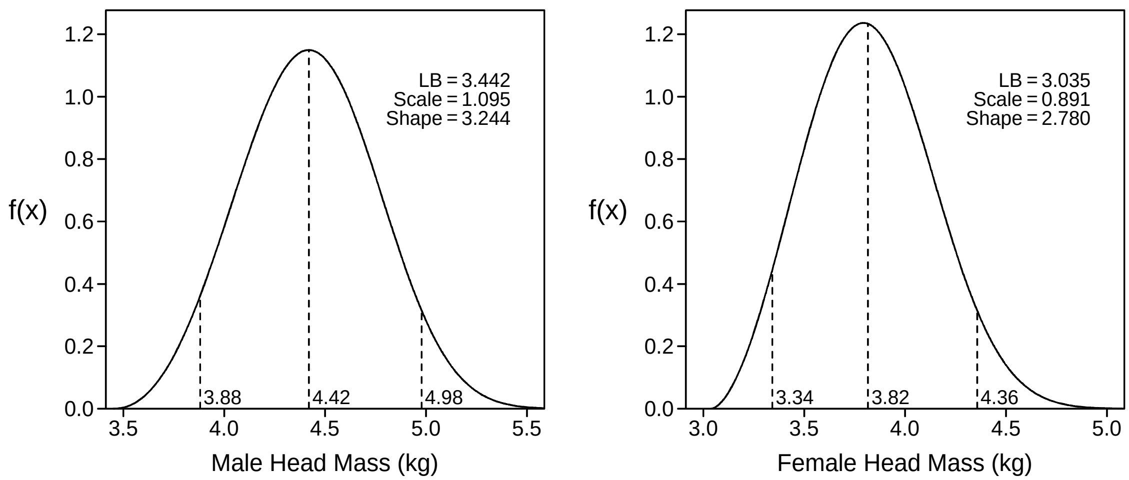
$$x = x_o + \alpha * \{-\ln[1 - F(x)]\}^{\frac{1}{\beta}}$$

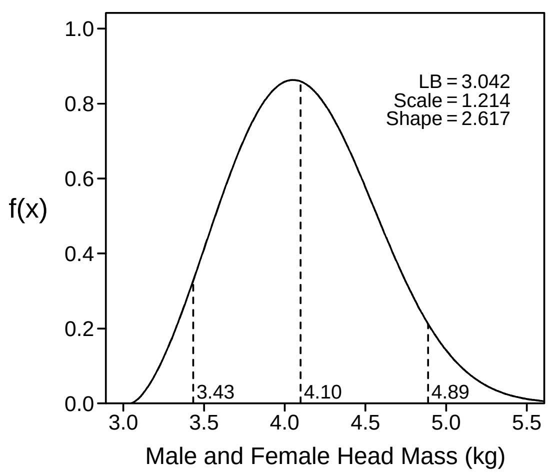
This report is broken into sections based on the set of subjects under consideration as follows:

Section	Description
1	Fit of all males, all females, and all combined males and females.
	Subjects within 0.01 kg of the estimated 5th percentile for all females.
	Subjects within 0.01 kg of the estimated 95th percentile for all males.
2	Males with 1828 mm ≤ stature ≤ 1930 mm (N = 146)
3	Males with 91 kg ≤ weight (N = 57)
4	Females with 1473 mm ≤ stature ≤ 1575 mm (N = 119)
5	Females with weight ≤ 54 kg (N = 142)
6	Estimated density functions from sections 2, 3, 4, & 5
7	Subjects within 0.03 kg of the estimated 5th percentile for short or light females
8	Subjects equal to the estimated 50th percentile for short or light females
9	Subjects equal to the estimated 95th percentile for short or light females
10	Subjects within 0.02 kg of the estimated 95th percentile for tall males
11	Fit of stature and weight for all males and females

Section 1

From estimated Weibull cumulative distributions, as shown on the following page, density functions and selected percentiles of head mass were determined and are shown in the following figure and table.





Percentile	Head Mass (kg)		
	Male	Female	Combined
1	3.71	3.21	3.25
5	3.88	3.34	3.43
10	3.99	3.43	3.56
25	4.19	3.60	3.80
50	4.42	3.82	4.10
75	4.65	4.04	4.42
90	4.86	4.24	4.71
95	4.98	4.36	4.89
99	5.20	4.58	5.22

Figure B-1. Estimated Weibull density functions. Referenced values are 5^{th}, 50^{th}, and 95^{th} percentiles. N = 716 for males, N = 739 for females.

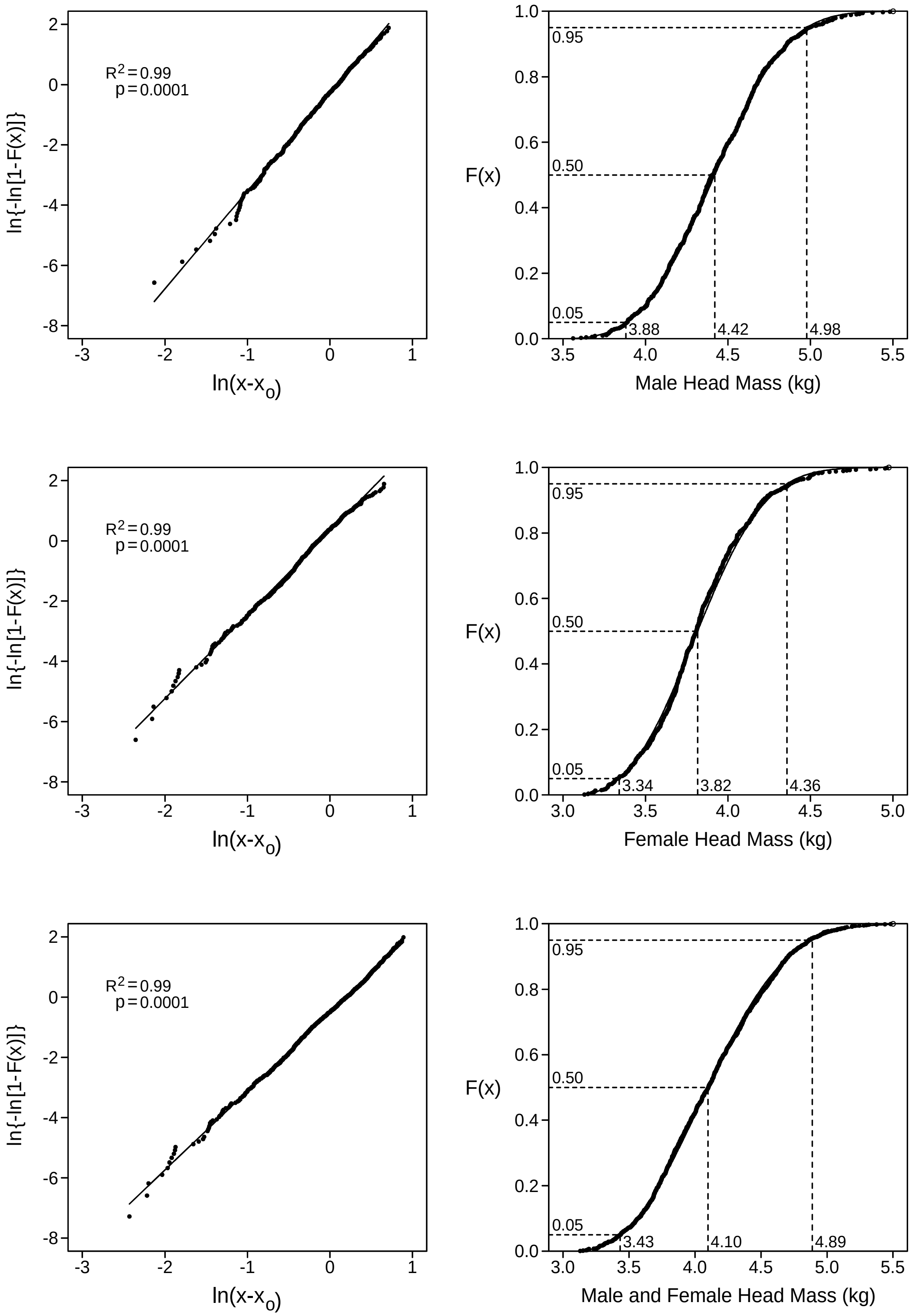


Figure B-2. Weibull fit of male (N = 716), female (N = 739) and combined cumulative proportions of head mass. Referenced values are 5th, 50th, and 95th percentiles.

The following table contains those male or female subjects who had a head mass after rounding within 0.01 kg of the 5th percentile (3.34 kg) for all females. Following this table is a bubble plot containing the same subjects where the size of the dot is relative magnitude of head breadth..

Table B-1. Subjects with head mass within 0.01 kg of the 5th percentile (3.34 kg) for all females.

Gender	Subject Number	Stature (mm)	Sitting Height (mm)	Weight (kg)	Head Circumference (mm)	Head Height (mm)	Head Length (mm)	Head Breadth (mm)	Head Mass (kg)
Female	2013	1517	821	54.2	527	217	178	141	3.33
Female	2902	1616	853	65.1	536	206	184	138	3.33
Female	2016	1611	870	49.7	535	221	186	142	3.34
Female	1237	1591	832	60.5	523	212	189	135	3.34
Female	2363	1574	842	56.7	525	203	170	152	3.34
Female	143	1572	841	51.3	525	221	177	142	3.34
Female	1810	1539	834	62.1	523	212	178	142	3.34
Female	2535	1610	868	53.3	528	198	185	136	3.35
					Mean	211	181	141	

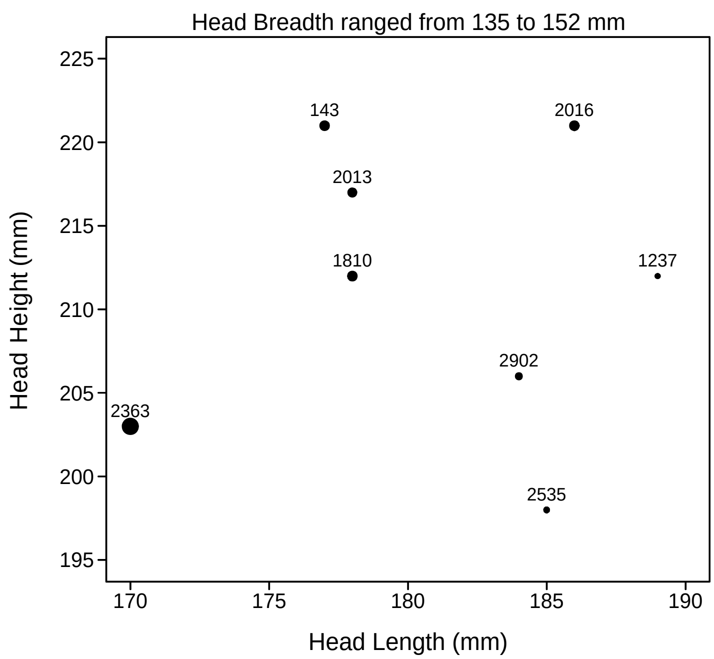


Figure B-3. Head height and length of subjects who had head mass within 0.01 kg of the 5th percentile (3.34 kg) for all females. Legend = subject number.

The following table contains those male or female subjects who had a head mass after rounding within 0.01 kg of the 95th percentile (4.98 kg) for all males. Following this table is a bubble plot containing the same subjects where the size of the dot is relative magnitude of head breadth..

Table B-2. Subjects with head mass within 0.01 kg of the 95th percentile (4.98 kg) for all males.

Gender	Subject Number	Stature (mm)	Sitting Height (mm)	Weight (kg)	Head Circumference (mm)	Head Height (mm)	Head Length (mm)	Head Breadth (mm)	Head Mass (kg)
Male	1839	1813	935	84.6	610	252	218	153	4.97
Male	1306	1724	915	82.1	585	267	204	159	4.97
Male	1075	1849	954	94.3	592	245	208	154	4.97
Male	654	1913	998	98.4	595	253	211	150	4.97
Male	190	1700	909	79.4	582	246	203	156	4.98
Male	247	1756	893	84.6	590	253	197	166	4.98
Male	524	1883	971	91.4	586	245	208	150	4.98
Male	1927	1801	961	72.8	601	261	214	155	4.99
Female	1336	1633	821	66.2	601	232	192	147	4.98
					Mean	250	206	154	

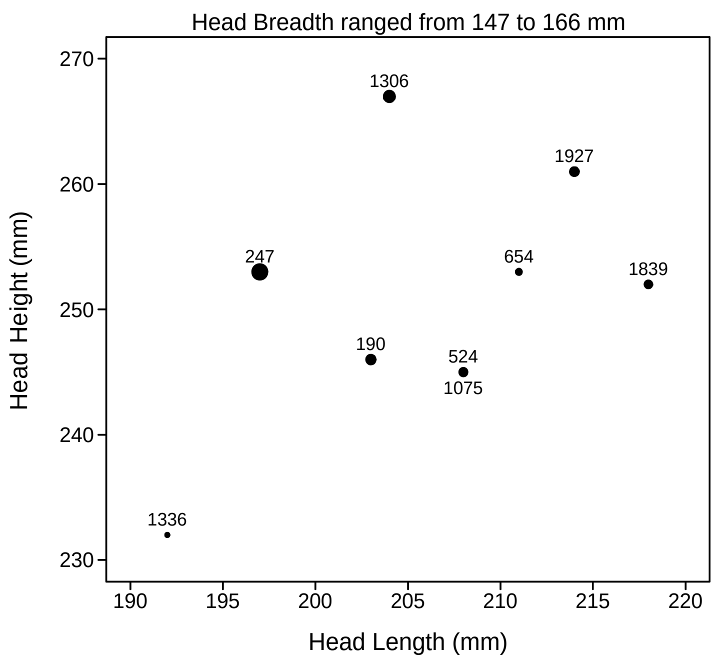


Figure B-4. Head height and length of subjects who had head mass within 0.01 kg of the 95th percentile (4.98 kg) for all males. Legend = subject number.

Section 2

The following figure shows the estimated Weibull cumulative distribution and density function for males with 1828 mm ≤ stature ≤ 1930 mm (N = 146).

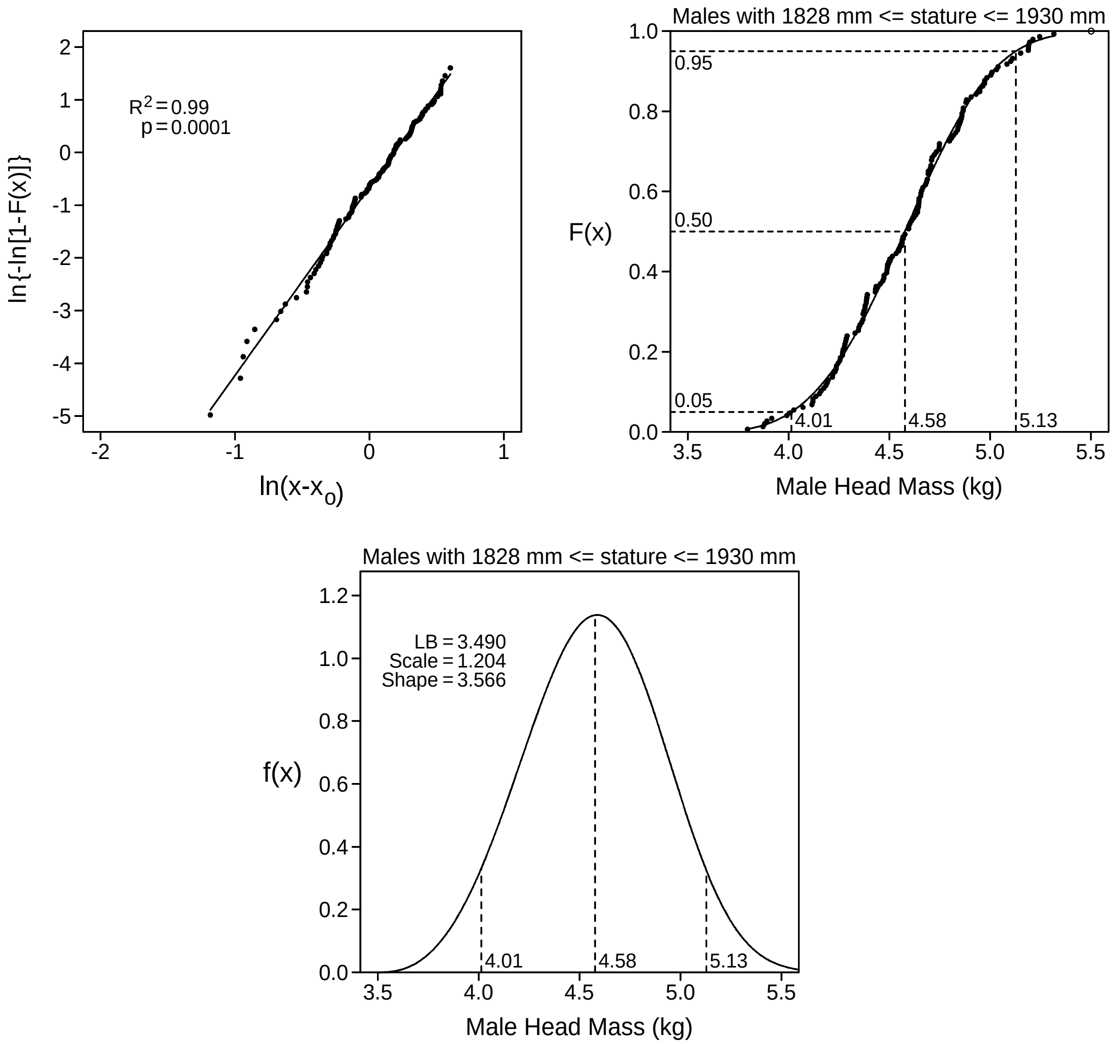


Figure B-5. Estimated Weibull cumulative distribution and density function. Referenced values are 5th, 50th, and 95th percentiles.

Section 3

The following figure shows the estimated Weibull cumulative distribution and density function for males with 91 kg ≤ weight (N = 57).

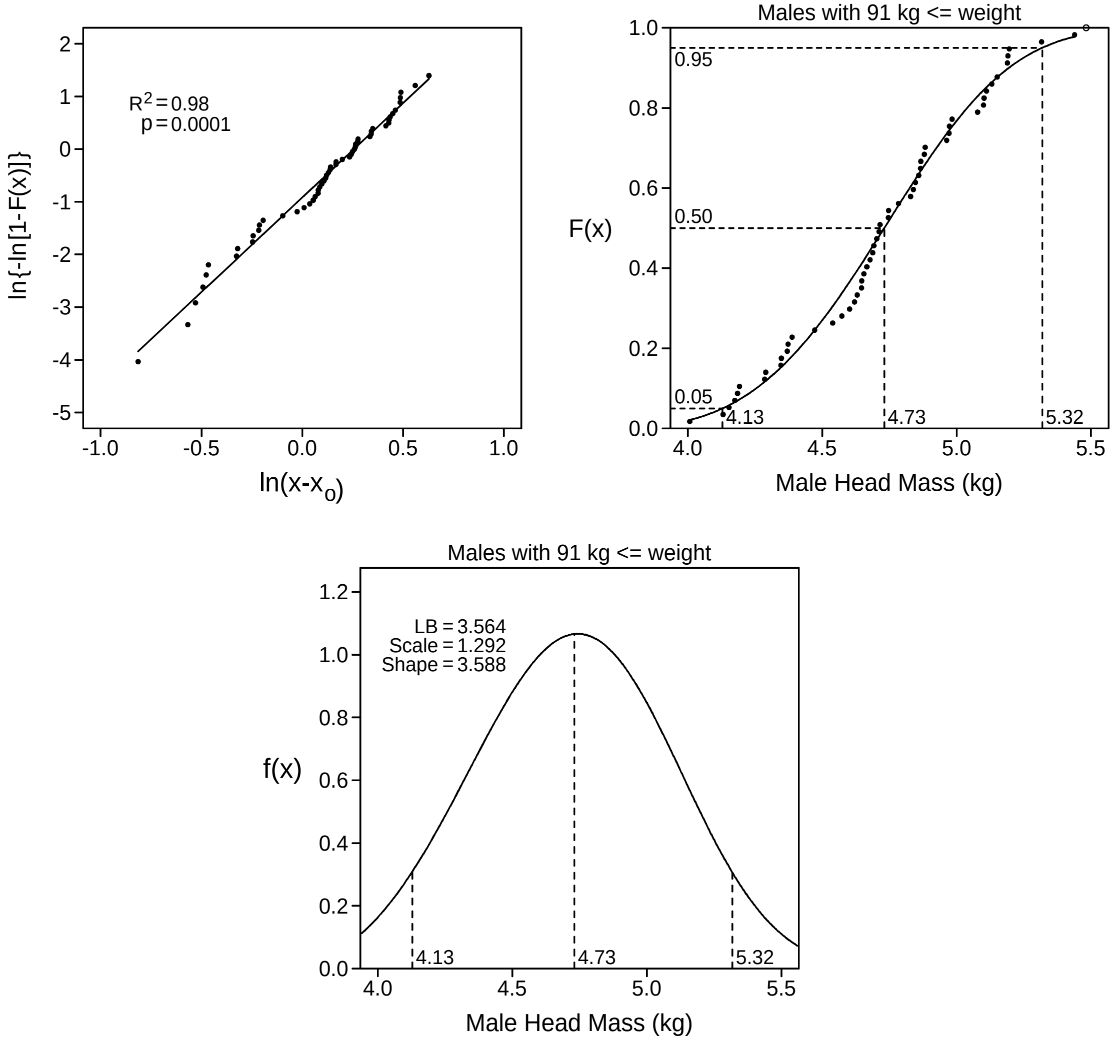


Figure B-6. Estimated Weibull cumulative distribution and density function. Referenced values are 5th, 50th, and 95th percentiles.

The following figure shows the estimated Weibull cumulative distribution and density function for females with 1473 mm ≤ stature ≤ 1575 mm (N = 119).

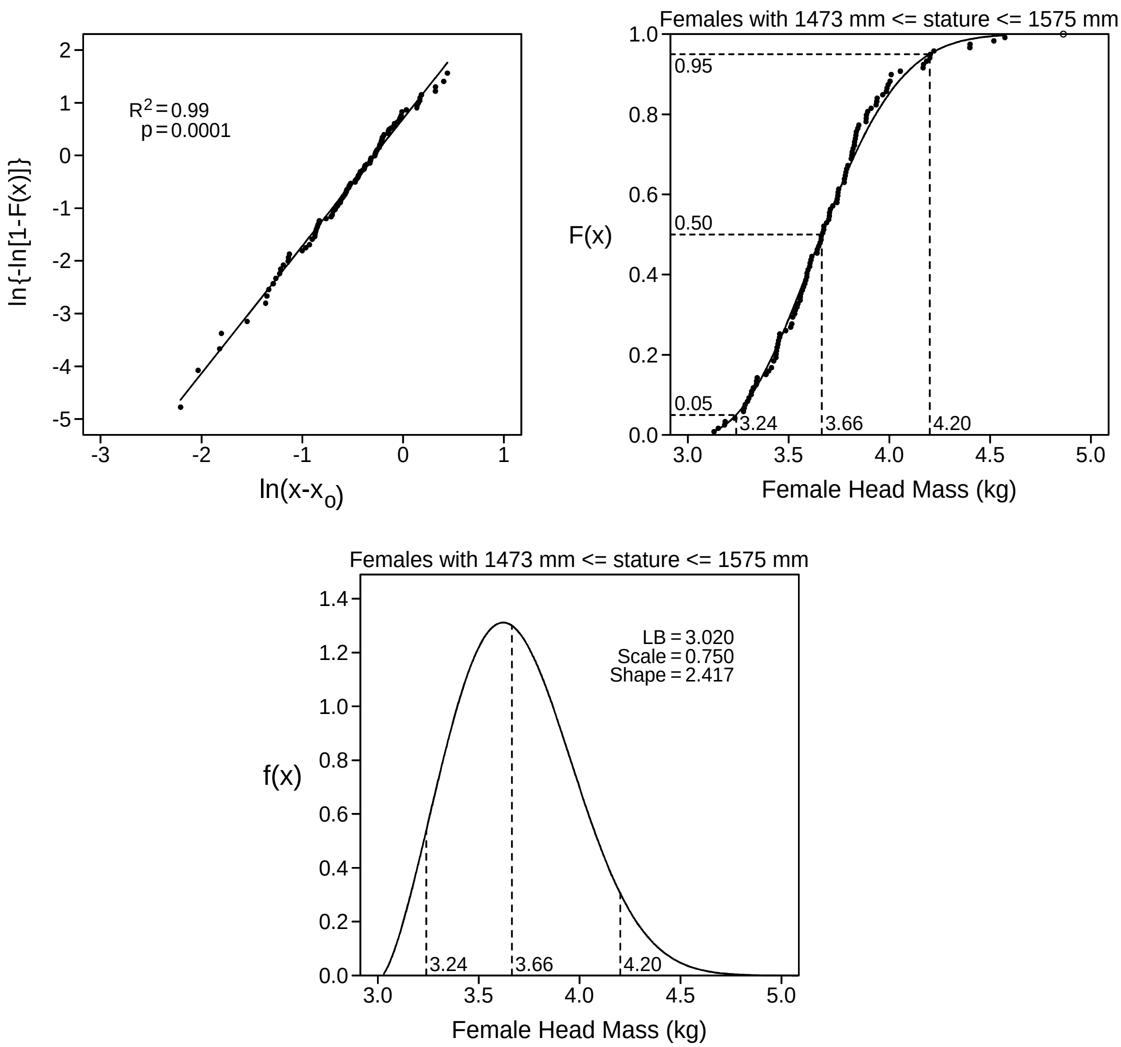


Figure B-7. Estimated Weibull cumulative distribution and density function.
Referenced values are 5th, 50th, and 95th percentiles.

Section 5

The following figure shows the estimated Weibull cumulative distribution and density function for females with weight ≤ 54 kg (N = 142).

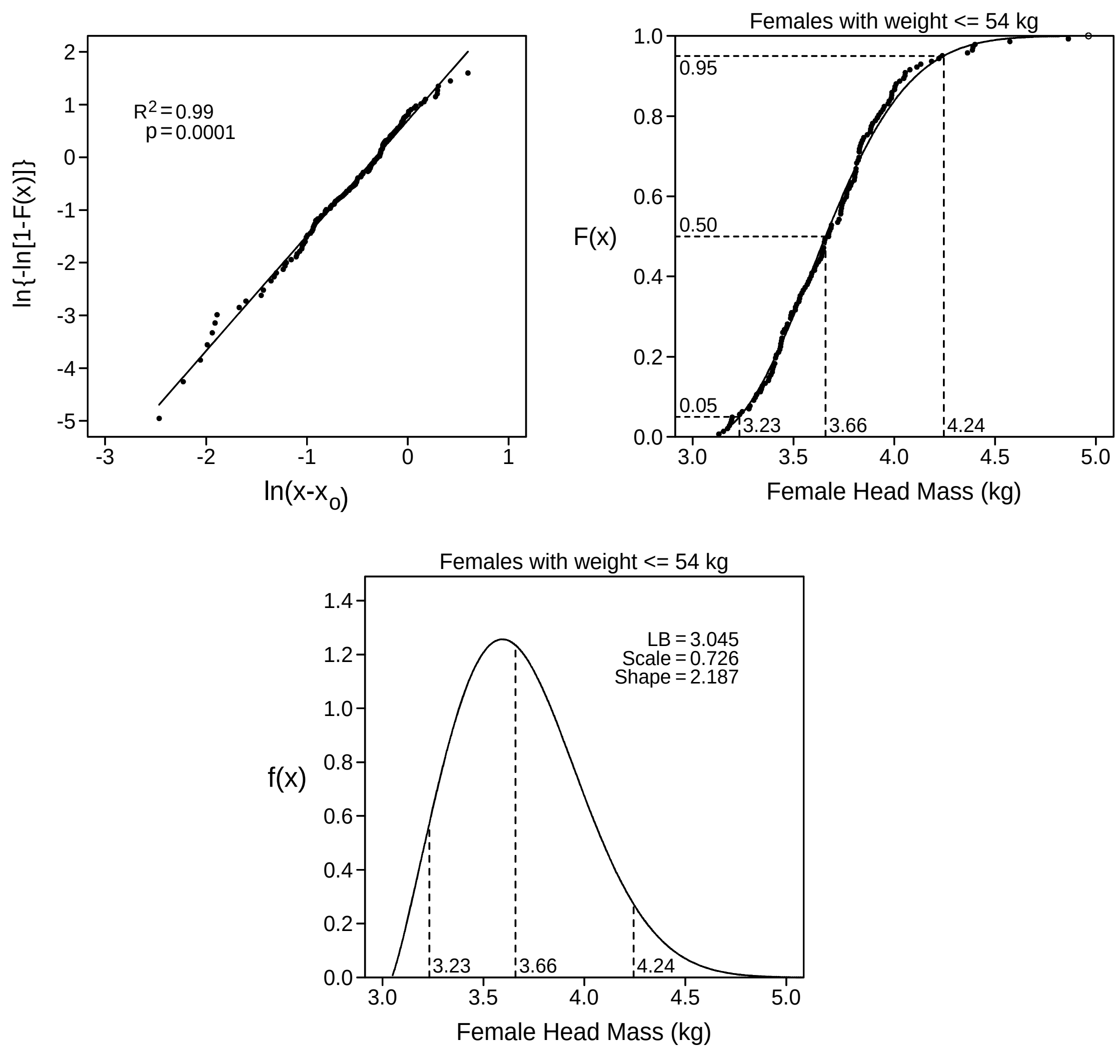


Figure B-8. Estimated Weibull cumulative distribution and density function. Referenced values are 5th, 50th, and 95th percentiles.

Section 6

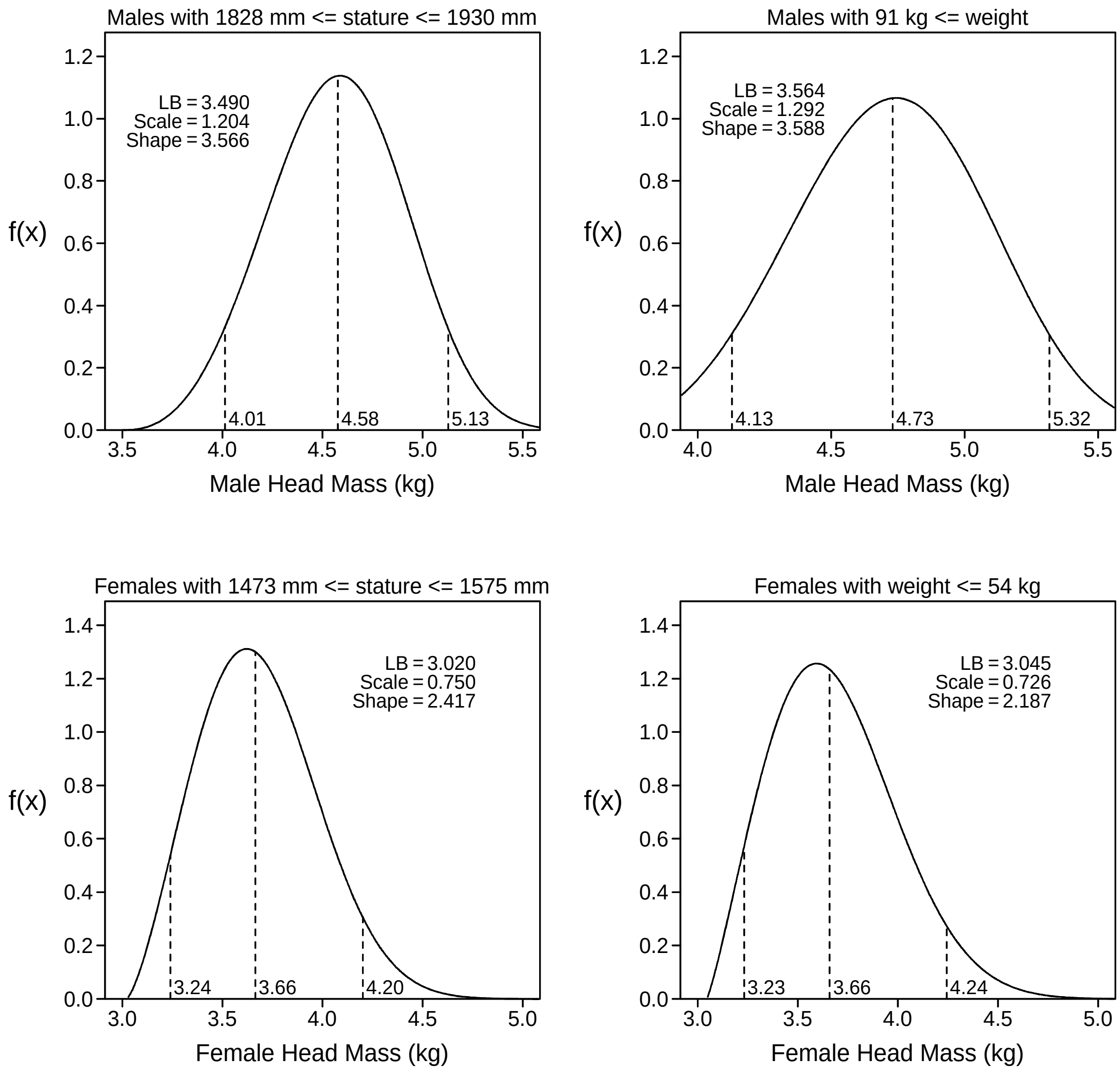


Figure B-9. Estimated density functions for sections 2, 3, 4, & 5.

Section 7

The following table contains those male or female subjects who had a head mass after rounding within 0.03 kg of the 5th percentile (3.23 kg) for the short or light females (sections 4 & 5). Following this table is a bubble plot containing the same subjects where size of the dot is relative magnitude of head breadth.

Table B-3. Subjects with head mass within 0.03 kg of the 5th percentile (3.23 kg) for short or light females.

Gender	Subject Number	Stature (mm)	Sitting Height (mm)	Weight (kg)	Head Circumference (mm)	Head Height (mm)	Head Length (mm)	Head Breadth (mm)	Head Mass (kg)
Female	1709	1633	844	64.0	536	208	183	145	3.20
Female	2838	1580	842	51.0	521	206	183	132	3.20
Female	1664	1515	822	48.5	525	219	187	139	3.23
Female	2023	1611	883	51.7	522	224	169	151	3.25
Female	1538	1728	901	55.8	530	211	177	147	3.26
Female	1947	1696	904	65.1	530	237	182	139	3.26
					Mean	218	180	142	

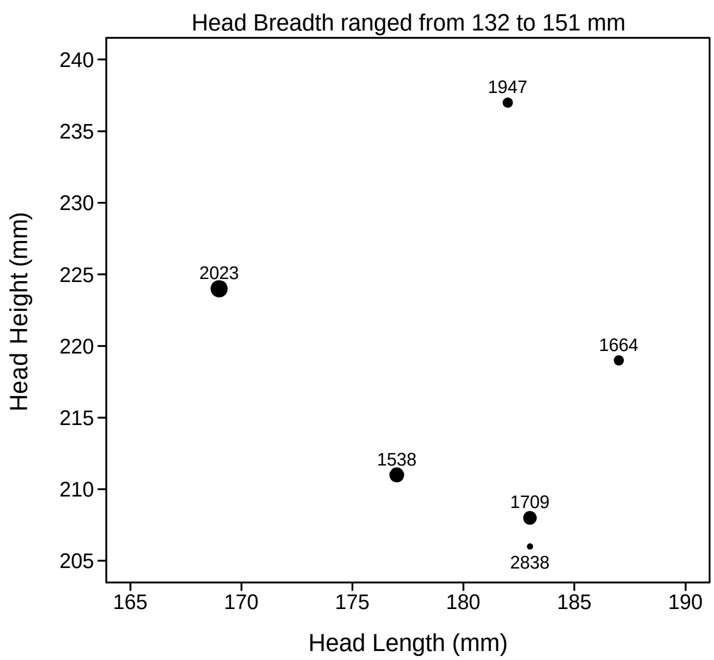


Figure B-10. Head height and length of subjects who had head mass within 0.03 kg of the 5th percentile (3.23 kg) for short or light females. Legend = subject number.

Section 8

The following table contains those male or female subjects who had a head mass after rounding equal to the 50th percentile (3.66 kg) for the short or light females (sections 4 & 5). Following this table is a bubble plot containing the same subjects where Size of the dot is relative magnitude of head breadth..

Table B-4. Subjects with head mass equal to the 50th percentile (3.66 kg) for short or light females.

Gender	Subject Number	Stature (mm)	Sitting Height (mm)	Weight (kg)	Head Circumference (mm)	Head Height (mm)	Head Length (mm)	Head Breadth (mm)	Head Mass (kg)
Female	2262	1666	893	60.1	557	232	192	142	3.66
Female	2755	1542	823	49.0	548	214	185	149	3.66
Female	1369	1716	888	67.8	544	208	186	147	3.66
Female	2114	1657	899	66.4	557	223	190	146	3.66
Female	2558	1676	880	63.7	545	215	191	145	3.66
Female	1675	1570	852	54.9	549	216	188	136	3.66
Female	163	1574	851	59.6	538	211	180	148	3.66
Female	1877	1622	843	59.2	542	213	189	139	3.66
Female	2958	1641	877	63.5	542	216	186	152	3.66
					Mean	216	187	145	

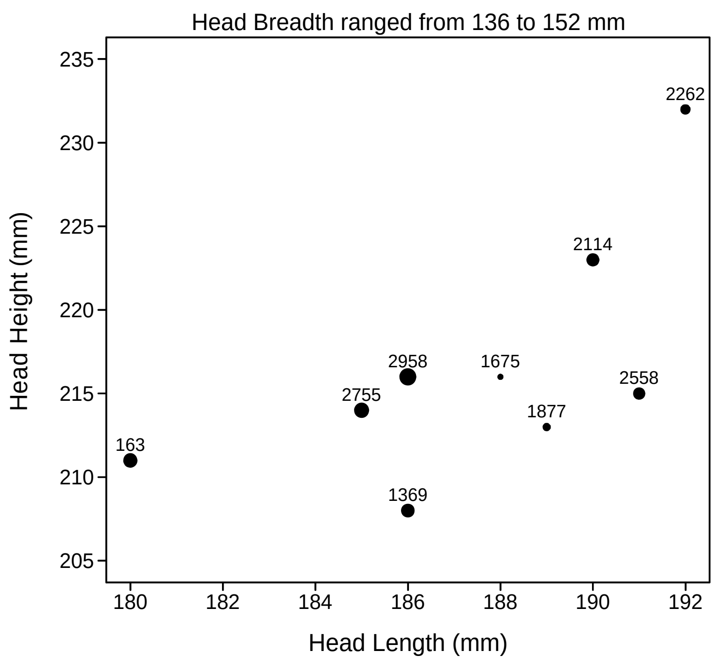


Figure B-11. Head height and length of subjects who had head mass equal to the 50th percentile (3.66 kg) for short or light females. Legend = subject number.

Section 9

The following table contains those male or female subjects who had a head mass after rounding equal to the 95th percentile (4.22 kg) for the short or light females (sections 4 & 5). Following this table is a bubble plot containing the same subjects where Size of the dot is relative magnitude of head breadth..

Table B-5. Subjects with head mass equal to the 95th percentile (4.22 kg) for short or light females.

Gender	Subject Number	Stature (mm)	Sitting Height (mm)	Weight (kg)	Head Circumference (mm)	Head Height (mm)	Head Length (mm)	Head Breadth (mm)	Head Mass (kg)
Male	2147	1845	965	88.4	572	239	193	156	4.22
Male	1505	1840	914	85.9	566	239	199	148	4.22
Male	1346	1762	939	70.8	577	247	198	158	4.22
Female	2660	1611	840	59.2	569	224	189	153	4.22
Female	1952	1688	895	68.3	582	246	194	147	4.22
Female	2692	1575	891	53.3	554	209	178	154	4.22
Female	1896	1775	908	73.7	564	225	198	145	4.22
					Mean	233	193	152	

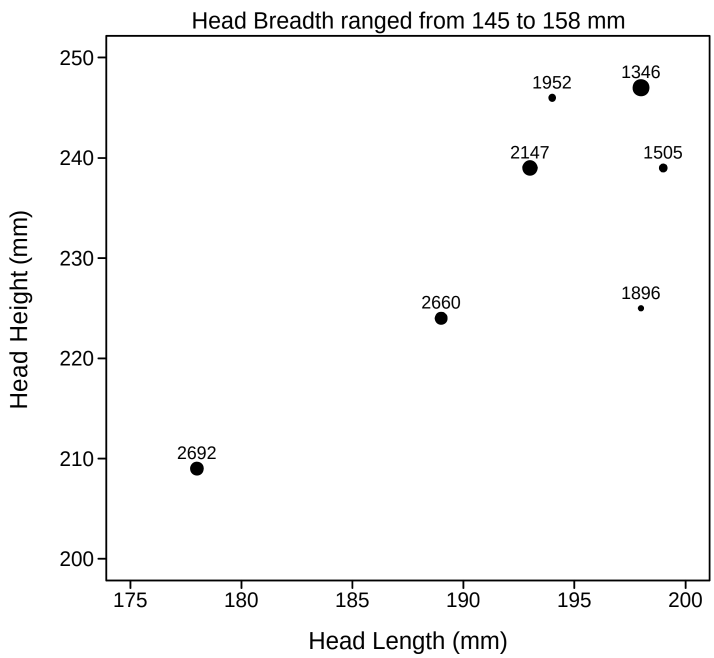


Figure B-12. Head height and length of subjects who had head mass equal to the 95th percentile (4.22 kg) for short or light females. Legend = subject number.

Section 10

The following table contains those male or female subjects who had a head mass after rounding within 0.02 kg of the 95th percentile (5.13 kg) for tall males (section 2). Following this table is a bubble plot containing the same subjects where Size of the dot is relative magnitude of head breadth.

Table B-6. Subjects with head mass within 0.02 kg of the 95th percentile (5.13 kg) for tall males.

Gender	Subject Number	Stature (mm)	Sitting Height (mm)	Weight (kg)	Head Circumference (mm)	Head Height (mm)	Head Length (mm)	Head Breadth (mm)	Head Mass (kg)
Male	1687	1855	1015	91.4	609	260	213	161	5.11
Male	107	1732	938	77.1	594	255	205	160	5.12
Male	149	1826	973	91.6	595	270	206	163	5.13
Male	108	1825	950	85.9	599	246	208	158	5.14
Male	1555	1824	965	87.8	606	237	210	158	5.14
Male	49	1854	956	76.6	601	260	214	160	5.15
Male	1080	1879	956	92.3	607	242	206	170	5.15
					Mean	253	209	161	

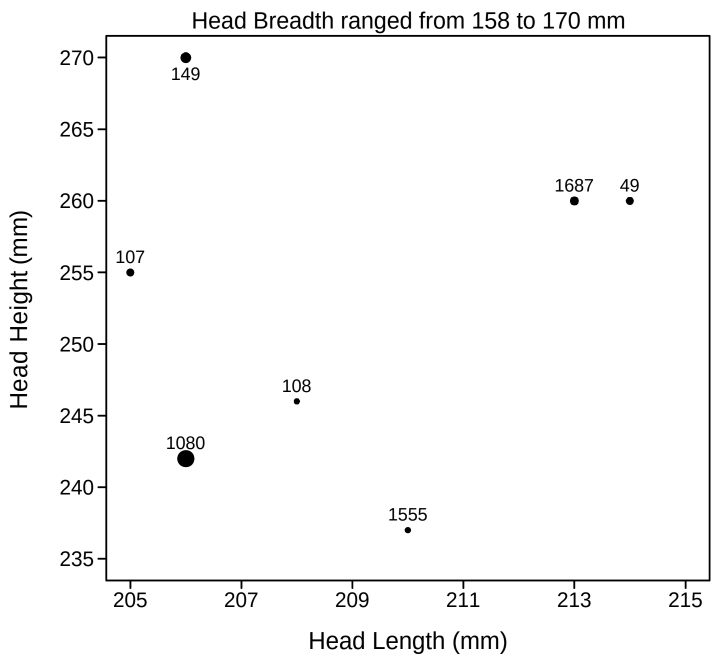


Figure B-13. Head height and length of subjects who had head mass within 0.02 kg of the 95th percentile (5.13 kg) for tall males. Legend = subject number.

Section 11

From estimated Weibull cumulative distributions, as shown on the following pages, density functions of stature and weight, for all males (N = 716) and females (N = 739) separately, were determined and shown in the following figure. The male stature modeling had 4 outliers removed and the male weight modeling had 3 outliers removed.

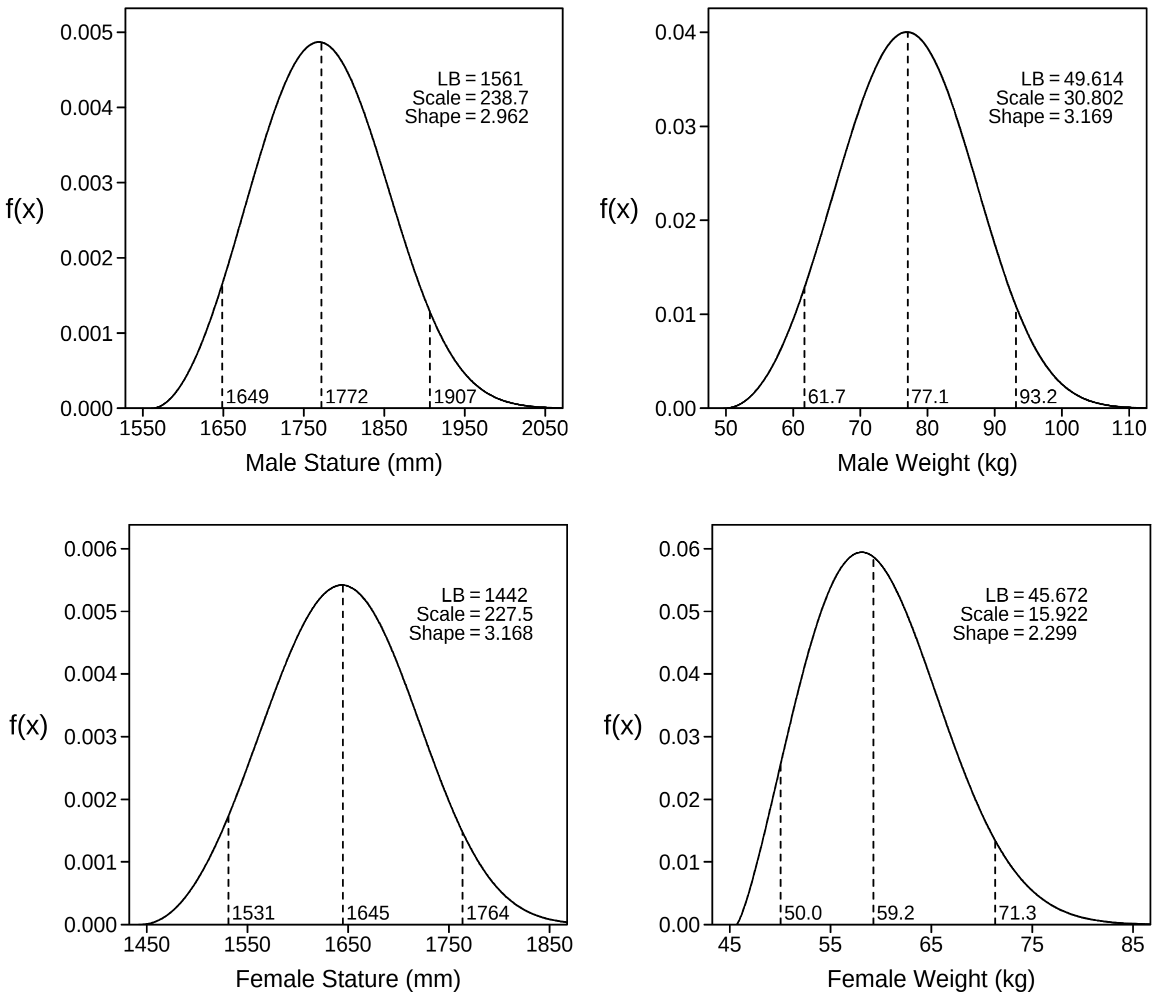


Figure B-14. Estimated Weibull density functions. Referenced values are 5th, 50th, and 95th percentiles.

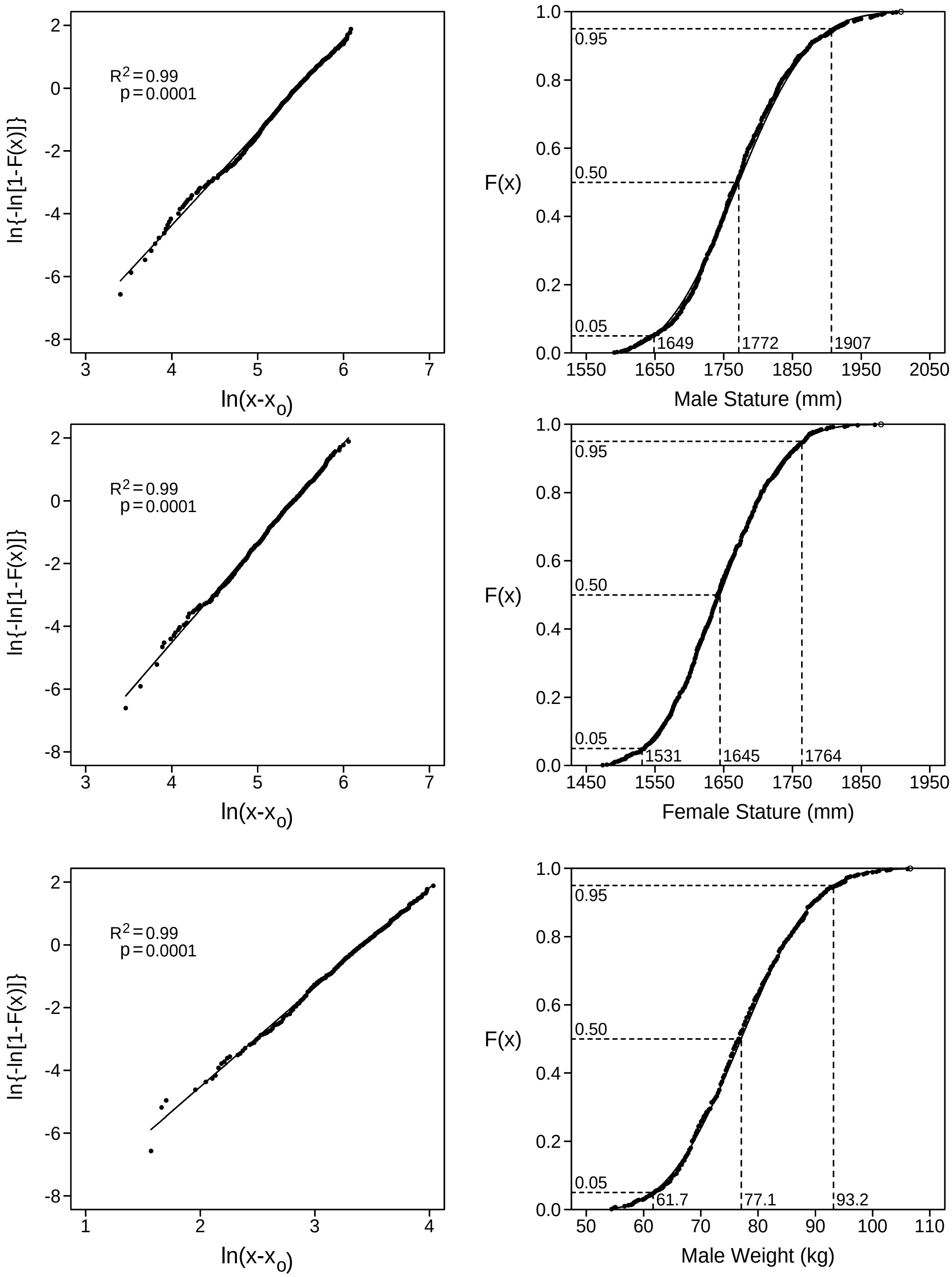


Figure B-15. Weibull fit of male stature and weight, and female stature.
Referenced values are 5th, 50th, and 95th percentiles.

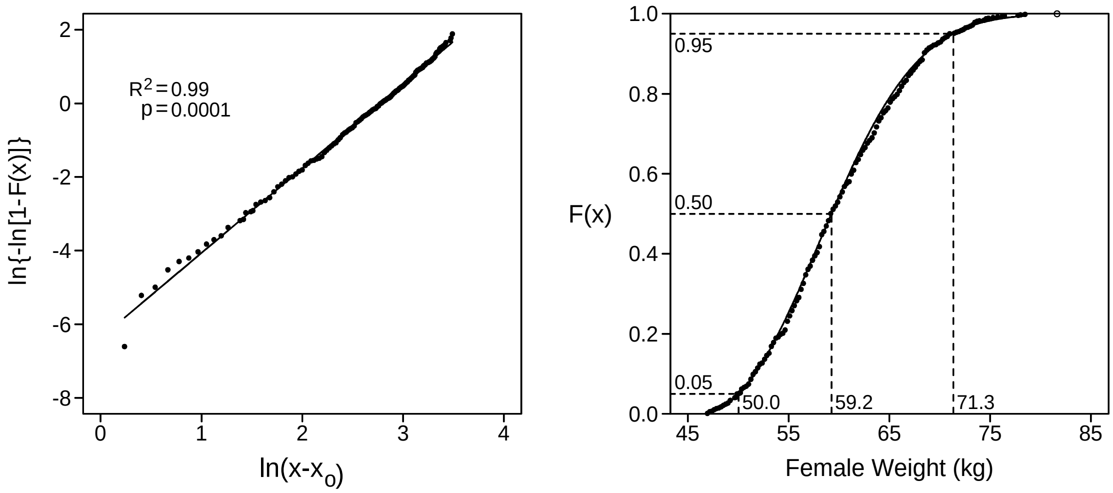


Figure B-16. Weibull fit of female weight. Referenced values are 5th, 50th, and 95th percentiles.

Table B-7. Army percentiles of stature, sitting height, and weight.

	Male			Female		
Percentile	**Stature (mm)**	**Sitting Height (mm)**	**Weight (kg)**	**Stature (mm)**	**Sitting Height (mm)**	**Weight (kg)**
1	1602.7	827.9	55.27	1483.2	774.8	45.23
5	1646.9	854.5	61.58	1527.8	795.3	49.63
10	1670.3	867.9	64.92	1549.7	807.0	51.97
15	1686.2	876.8	67.21	1564.3	815.2	53.60
20	1698.9	883.8	69.06	1575.8	821.8	54.93
25	1709.9	889.9	70.70	1585.8	827.6	56.11
30	1719.8	895.3	72.20	1594.8	832.8	57.20
35	1729.0	900.3	73.60	1603.2	837.7	58.23
40	1737.8	905.1	74.97	1611.4	842.3	59.23
45	1746.4	909.7	76.31	1619.3	846.9	60.23
50	1754.9	914.2	77.67	1627.2	851.4	61.24
55	1763.4	918.8	79.06	1635.3	855.9	62.28
60	1772.1	923.4	80.49	1643.5	860.5	63.36
65	1781.1	928.2	82.00	1652.1	865.2	64.50
70	1790.6	933.2	83.63	1661.3	870.2	65.74
75	1800.9	938.6	85.43	1671.3	875.7	67.12
80	1812.4	946.8	87.18	1682.7	881.7	68.71
85	1825.7	954.1	89.95	1695.9	888.7	70.60
90	1842.3	959.9	93.15	1712.7	897.5	73.10
95	1866.5	971.9	98.05	1737.3	910.2	76.97
97	1881.6	979.1	101.33	1752.8	918.3	79.58
99	1908.7	991.4	107.69	1780.4	933.1	84.69

Table B-8. Pearson Product-Moment and partial R^2 of stature and weight with head mass for males (N = 710) and females (N = 739).

	Pearson Product-Moment				Partial			
	Male		Female		Male		Female	
Measure	**R^2**	**p-value**	**R^2**	**p-value**	**R^2**	**p-value**	**R^2**	**p-value**
Stature	0.13	0.0001	0.11	0.0001	0.01	0.1631	0.02	0.0003
Weight	0.23	0.0001	0.13	0.0001	0.12	0.0001	0.04	0.0001

Stature and weight both had significant positive correlations with head mass as shown in the preceding table and in the following figure. Low R^2 values indicate that much of the variability in head mass was not accounted for by stature and weight. The male insignificant partial correlation between stature and head mass (p = 0.1631) indicates that head mass did not increase significantly with stature for men of the same weight. The male sample (N = 710) was reduced by the 6 subjects having outlier stature and/or weight values.

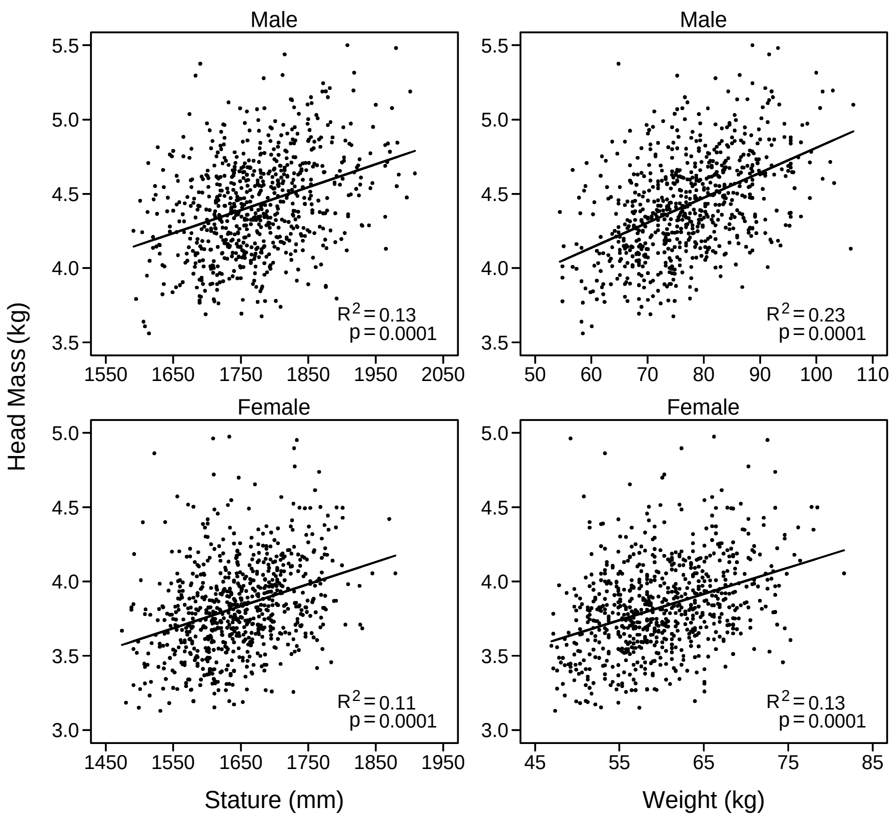


Figure B-17. Pearson Product-Moment correlations for males (N = 710) and females (N = 739).