Examination of Anthropometric Databases for Aircraft Design

Robert E. Joslin, Ph.D.
Federal Aviation Administration

Presently there is no prescribed anthropometric database provided or specified in the Federal Aviation Regulations, hence aircraft designs often utilize legacy anthropometric databases that may not reflect the target pilot population. This study was an information synthesis of anthropometric databases for aircraft design. The findings indicated that, although most current aviation designs have utilized legacy anthropometric data, there are a sufficient number of valid existing and emerging anthropometric databases that include body dimension measurements and weight/mass measurements compiled from data sets gathered either through large surveys, or statistically derived, that are representative of the target pilot population. Furthermore, new scanning technologies, along with more sophisticated statistical techniques for matching/forecasting target populations from legacy anthropometric databases, have enhanced the ability to effectively and efficiently gather these data on a periodic basis, hence anthropometric data that are not representative of the pilot population should no longer be accepted as a limitation in aircraft design. The one area that demands further study are current data for human-strength/control force measurements. Although there have been some recent small-scale surveys conducted to gather these data, there is a paucity of any current large-scale comprehensive human strength/control force data applicable to aircraft design.
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INTRODUCTION

One of the most significant safety advances in aviation has been the incorporation of human factors in the design and certification of aircraft. However, the current governing regulations for aircraft design and certification continue to address only a few anthropometric issues, one of which is a person's height and how it affects unrestricted movement of aircraft controls. Aircraft cockpits are only required to be designed and certified for flight crewmembers between the heights of 5'2" and 6'3" for transport category airplanes (14 CFR §25.777), and 5'2" to 6'0" for helicopters (14 CFR §27.777, §29.777). The origin of the anthropometric design requirements for pilot stature in airplanes and helicopters can be traced back to the 1950's vintage Civil Air Regulations [CAR §4b.353(c) and CAR §7.353(b)] which stated that airworthiness compliance shall be demonstrated for individuals ranging from 5'2" to 6"0" in height. These design heights for stature remained in effect until 1975 when the regulation was changed, just for transport category airplanes, to increase the maximum crewmember heights to be considered from 6'0" to 6'3" for the design of cockpit controls. The stated reason for this regulatory 3" increase in pilot stature for transport category airplanes was as follows:

Explanation. The flight stations of modern transport category airplanes have been designed for the 5th to 95th percentiles of pilot stature. Because the average human height continues to increase, the proposed change to Sec. 25.777(c) would increase the maximum flight crewmember height to be considered from 6'0" to 6'3" for the design of cockpit controls. (U.S. Federal Register- Airworthiness Review Program, Volume 40, Number 12, p. 24808, June 10, 1975)

Although a person's standing height is an important parameter when it comes to aircraft design and certification, it is not the only parameter that should be considered for the first and foremost reason that the pilot is in a seated position, other than when piloting lighter-than-air hot air balloons. Furthermore, pilots who share identical standing heights have a wide range of individual arm lengths, torso lengths, and leg lengths, as well as strengths. Hence, the body part measurements and human strengths that are relevant are those that directly affect the pilot's ability to see/read aircraft instruments, view the world outside the cockpit, manipulate switches and knobs, move aircraft flight controls without restriction, and safely egress the aircraft (Joslin, 2009).

Anthropometrically speaking, there are a vast number of possible bodily dimension and strength/control force measurements. Some of the most relevant ones for aircraft flight-deck design and certification are functional reach, sitting eye height, buttock-to- knee length, sitting knee height, shoulder-to-elbow arm length, and strength/control force for the hand (and thumb), arm, and leg. Measurements of hand/finger length, breadth, and circumference have also increased in relevance with the advancements in touch-screens, hand controllers, and cursor control devices.

In addition to standing height requirements, U.S.C. Title 14 of the CFR has both quantitative and qualitative force and skill requirements for manipulation of flight controls. For example, throughout the 14 CFR design and certification requirements for aircraft performance and flying qualities, the statement is made that the aircraft should be designed so that it does not require "exceptional piloting skill, alertness, or strength". However, there is no guidance for the magnitude or the associated appendage in the regulations that require a qualitative assessment of "exceptional strength". Furthermore the maximum force requirements that are quantitatively specified in 14 CFR for manipulation of flight controls were originally derived from data for 5th to 95th percentile males applying for military service between 1955 and 1957, thus are not representative of the current pilot population (Beringer, 2008; 2009). Consequently, the regulations for pilot strength/control force generate more discussion than agreement between Federal Aviation Administration (FAA) regulators and aircraft designers.

Another design parameter extensively used by the aviation industry is Design Eye Point (DEP). Design Eye

Point is typically achieved by adjusting the pilot's seat position (i.e. vertically, horizontally, tilt) to set a common "sitting eye height" for all operators in order to fulfill regulatory field-of-view requirements for primary/secondary instruments and external field of view. However, the DEP does not provide any design assurance for the ability of the pilot's arms or legs to effectively reach and operate cockpit controls or interact with other equipage such as a head-up display (HUD).

The aircraft design requirement for a 5th percentile female to a 95th percentile male that have been adopted by the FAA and the aviation industry, was based on historical military standards. The design requirement was most recently reaffirmed in Mil-Std-1472G (2012) as the center 90% of the target user population. Some aircraft designers have interpreted and applied the rule as a mere stature requirement and reported to the FAA that they have designed and conducted simulations, and mock-up tests for the 5th to 95th percentile by utilizing test subjects with standing heights of 5'2" (female) and 6'3" (male). Although the specific individuals who participated in the design development and simulations may be effective and comfortable in the aircraft cockpit, this methodology is misleading and flawed. The design of aircraft for the 5th to 95th percentile is only valid if there is a specific definition of the population basis reflecting the target pilot population, and if the specific relevant body measurements and muscular strengths are defined. An increasing number of aviation designs have utilized a multi-variate approach of body dimension combinations versus univariate percentiles (Hudson, & Zehner, 2008; Choi et al., 2009). Whereas the body measurements in aircraft design have been typically bounded by the 5th and 95th percentiles, strength design limits for control forces often specify a lower boundary typically based upon the 5th percentile of the female user population (1st percentile for critical skills), as recommended in Mil-Hdbk-759C (1995). NASA has adopted design criteria from the 1st to the 99th percentile (male and female) for the Constellation program, with the rationale being that people with anthropometric measurements predominantly in the extremes of the 5th or 95th percentile, often have some measurements/strengths outside the bounded range (NASA, 2007; 2009).

Presently there is no prescribed anthropometric database for body dimensions or strength/control forces specified in the Federal Aviation Regulations (FAR) or any other FAA regulatory guidance, hence it is left to the discretion of each aircraft designer to negotiate with the FAA Aircraft Certification Service (ACS) to determine an acceptable database.

METHODOLOGY

Although anthropometric databases have been formally compiled as early as the 1940's by various civilian and military entities, any sources that pre-dated the 1988 Anthropometric Survey of U.S. Army Personnel, or that had been stagnant/not updated in the last twenty years, were not considered in this informational synthesis study as valid for aviation design. Dismissing databases more than 20 years old was considered a valid delimitation based on population demographic changes coupled with secular growth rates due to human variation in body measurements from generation to generation. While it has not been determined if secular change is due to nutrition, health, or biological selection, the concept has been adopted by NASA (2010; 2007) and others (Hertzberg, 1972). A comparative analysis of anthropometric data collected from U.S. Army personnel in 1988 and 2008 provided compelling data to support a requirement to update anthropometric databases for each generation (~ 20 years) in order to be considered valid in aviation design (Paquette, Gordon, & Bradtmiller, 2009). It is important to note that a U.S. Army study that was conducted to validate the 1988 survey for applicability in 1995 indicated that those data were still valid for design and sizing of the U.S. Army, hence a 10 year threshold to update anthropometric data was considered too conservative for this study (Gordon, 1996).

Anthropometric Database Desired Characteristics

A valid anthropometric database applicable to aircraft design was considered to be one that provided operationally relevant anthropometric measurements beyond just stature, to include but not limited to functional reach, buttock-knee length, sitting-eye-height. The database should also include static and dynamic muscle strength, along with muscle endurance data for prolonged control force applications. Additional variables that should be considered for strength data are body position and handedness. Pilot weight/mass should be included for crashworthiness design. Furthermore, the databases should be derived from a statistically significant data set that is representative of the target pilot population, to include demographic variables such a gender, age, ethnicity/race.

The FAA has recognized the importance of extending anthropometric design beyond just stature, and over the years has issued various policy statements such as the following:

<u>Height is not the only variable of interest</u>, because people of the same height may have different lengths of arms, legs, etc. So, consideration must be given to various representative body proportions that fall within the height range identified in the regulation. (FAA Policy Statement PS-ANM100-01-03A"Factors to Consider when Reviewing an Applicant's Proposed Human Factors Methods of Compliance for Flight Deck Certification, 02/07/2003)

FINDINGS

Anthropometric Database Annotated Bibliographies

While there have been numerous bibliographies compiled that reference anthropometric databases applicable to aviation design, none provided data sources representative of a current target population.

SAE AIR-5145 Directory Of Databases Part I - Whole Body Anthropometry Surveys(1996). This report lists anthropometric surveys that have been conducted for designs across a broad range of industries and provides current sources for the survey raw data and summary statistics, however, only one survey provided "strength" data. The directory was placed in a "stabilized" status in 2013 by SAE and is not scheduled to be updated (SAE,1996).

DOD Handbook 743A Military Handbook-Anthropometry of U.S. Military Personnel (1991). This handbook provides a historical listing of all the formal anthropometric databases published by the U.S Armed Forces up until 1991. Detailed body size information for design, sizing, and human engineering purposes was provided for 40 of the reports, however the handbook has not been updated since 1991 (DoD, 1991).

AAMRL-TR-88-013-An Annotated Bibliography of United States Air Force Engineering Anthropometry-1946 to 1988 (1988). The document only provides information on anthropometric studies conducted by the Air Force Aerospace Medical Research Laboratory from 1946-1988.

NASA Reference Publication 1024. Anthropometric Source Book Volume III: Annotated Bibliography of Anthropometry (1978). This document contains a broad range of historical annotated anthropometric references from U.S. and foreign populations, as well as material on zero-gravity anthropometric considerations.

Databases In Use For Aircraft Design

The anthropometric database that has been most broadly used in aviation design over the last two decades for civilian and military aircraft of all types has been the 1988 Anthropometric Survey of U.S. Army Personnel, which is also embedded in DoD Hdbk 743A (DoD, 1991; Gordon et al., 1989). The 1988 survey was conducted to update the 1966 U.S. Army Anthropometric survey (Men) and the 1977 U.S. Army Anthropometric Survey (Women), after the Army recognized that the data they were using for design and sizing was a generation old and not representative of the 1988 U.S. Army population (Gordon, et al, 1989). However, an increasing number of recent aircraft designs have utilized more current anthropometric databases, such as the Civilian American and European Surface Anthropometry Resource (CAESAR) compiled from data gathered in 2000. (Choi et al., 2009)

Strength and Control Force Data

The only large anthropometric reference that provides extensive strength/control force data is Mil-Std-1472G, which provides guidelines for the 5th and 95th percentile male and female, without reference to any specific database. Whereas in aircraft design the body measurements are typically bounded by the 5th and 95th percentile, strength design limits for control forces normally only have a lower boundary, typically based upon the 5th percentile of the female user population or the weakest person in the population, as recommended in Mil-Hdbk-759C (1995). Strength data for the NASA Constellation program were derived from Mil-Std-1472F and the *Occupational and Biomechanics* textbook by Chaffin, Andersson, and Martin (1991) (NASA, 2007). Over the years there have been some small-scale surveys focused specifically on civil aircraft design, such as those conducted by Beringer (2007; 2008; 2009), Meyer, Pokorski, and Ortel (1996), and McDaniel (1981). However, there has not been any recent large-scale surveys of human strength/control force. NASA recognized this shortfall and relied on statistically manipulating the requirements from Mil-Std-1472 to develop strength requirements for the NASA 2015 Constellation program (NASA, 2010; 2007).

Databases in Use for Non-Aviation Design

Although anthropometric accommodation is considered in designs across a broad range of industries (i.e. clothing, forensics, health, furniture, insurance, sports medicine), the vast majority of the data is specialized with measures not applicable to cockpit tasks (i.e. carrying, lifting), demographics not representative of the target civilian pilot population or small sample sizes (Ciriello, & Snook,1983; Diffrient,Tilley, & Bardagjy,1974) . The industry that most closely resembled the operating environment, body movement, and control force requirements of aviation design was the motor vehicle/tractor-cab industry. However the anthropometric databases for these industries either relied on small sample sets gathered exclusively from their actual operators, or otherwise utilized composite generic adult models (small, medium, or large) none of which were representative of a target pilot population, hence were not considered valid for aircraft design (Gryp, 2002; Bove, Fisher, Ciccarelli, & Cargill,2006; Hsiao et al., 2005).

Recent Anthropometric Surveys (2000-Present)

Anthropometric Survey Of U.S. Marine Corps Personnel: Methods And Summary Statistics(2010). This survey for body dimensions and weight was conducted as an update to the last full-scale anthropometric survey of U.S. Marine Corps (USMC) men that was conducted in 1966, which was superseded in 1994 by a small-scale survey that was conducted to validate statistical matching of the 1988 U.S. Army ANSUR to a Marine Corps population. Hence, since 1994 the Marine Corps has utilized the 1988 U.S. Army ANSUR survey for design and sizing applications (Gordon, et al., 2013). The survey consisted of 1921 subjects that were demographically and anthropometrically representative of the USMC 2010 population, who provided 94 measurements, 41 derived dimensions, and 3-D head, foot, and whole-body scans. The limitations of this survey, as related to aviation design, was that the data did not include "strength" and the subjects were from a military population, which may not be representative of the civilian pilot target population.

Anthropometric Survey (ANSUR) II Pilot Study: Methods And Summary Statistics (2009). This survey was a pilot study that was conducted as a an interim measure to update the 1988 U.S. Army's ANSUR Database. The survey consisted of 3462 subjects that were demographically and anthropometrically representative of the U.S. Army 2007 population, who provided 25 measurements, and 3-D body scans (Paquette, Gordon, & Bradtmiller, 2009). The limitations of this survey, as related to aviation design, was that the data did not include "strength" and the subjects were from a military population, which may not be representative of the civilian pilot target population. Based on the results of the pilot study, a full-scale study of 12,000 subjects representative of the 2012 U.S. Army population was conducted from 2010-2012. The survey gathered 94 measurements and 3-D body scans, with results scheduled for publication in 2014.

Anthropometric Survey of Federal Aviation Administration Technical Operations Personnel (2006-2008). The Human Factors Design Standard (Ahlstrom, & Longo,2003) and the Human Factors Design Guide (FAA, 1996) were developed by the Federal Aviation Administration (FAA) for the design and sizing of FAA systems, equipment, and facilities, however they were based on percentile data collected 20-50 ago taken on military personnel. This survey was conducted in response to the recognition by the FAA that the aforementioned Guide and Standard no longer constituted an accurate anthropometric reflection of the current FAA Technical Operations (Tech Ops) workforce (FAA, 2008). The survey consisted of 1244 subjects that were demographically and anthropometrically representative of the FAA Technical Workforce, who provided 25 measurements. The limitations of this survey, as related to aircraft design, was that the data did not include "strength", the subjects were not uniformly clothed for the measurements, and the demographic may not have been representative of the civilian pilot target population

National Health and Nutrition Examination Survey (2011-2012). Every two years the Center for Disease Control and Prevention (CDC) surveys a nationally representative sample of about 5,000 persons as an interim supplement to the census data that is collected every 10 years. The NHANES survey includes eight body measurements for adults; weight, standing height, upper leg length, upper arm length, mid-upper arm circumference, waist circumference, and sagittal abdominal diameter. Since the data are typically the most current available, the NHANES survey is often used to validate that the test subjects of a specific survey are representative of the United States population for the desired demographic. The survey consisted of 5000 subjects that were demographically and anthropometrically representative of the U.S. population. The limitations of this survey, as related to aircraft design, was that the data did not include "strength" and there were insufficient number of body dimensions measured.

Civilian American and European Surface Anthropometry Resource (CAESAR) (2002). CAESAR was the first NATO survey of civilians and the first 3-D whole-body surface anthropometry survey. The civilian populations of three countries were sampled between 1998 and 2001 in an effort to characterize the population of NATO countries as a whole. The United States was chosen because it was considered to have the largest and the most diverse population in NATO. The Netherlands and Italy were chosen because they were considered to have the tallest and smallest populations in NATO respectively (Robinette, & Daanen, 2003; Robinette, et al, 2002; Robinette, Daanen, & Paquet, 1999). The survey consisted of 4431 subjects that were demographically and anthropometrically representative of the NATO population, and consisted of 100 measurements, and 3-D scans of three postures. The limitations of this survey, as related to aircraft design, was that the data did not include "strength" and the subjects were from NATO, which may not be representative of the U.S. civilian pilot target population. A representative sample for the United States by itself was obtained by statistically weighing the data, using the data from the National Health and Nutritional Examination Survey III (NHANES III) and the U.S. Census from 1990, as reported by Harrison and Robinette (2002).

Statistically Derived Databases

Statistical methods can be applied to anthropometric data from a non-representative population, to match a target population (Nadadur, & Parkinson,2008; Nadadur, Chiang, Parkinson, & Stephens, 2009). The U.S military used statistical methods to apply the 1988 Anthropometric Survey of U.S. Army Personnel for the design of the Joint Primary Aircraft Training System (JPATS), and also statistically derived anthropometric data from CAESAR for the Joint Strike Fighter (JSF) (Choi, Zehner, Hudson, & Fleming, 2009). Statistical methods can also be applied to forecast a future target population. NASA has extensive historical and current anthropometric data for their astronauts, however they recognized that the demographics and anthropometry of future astronauts may differ significantly, which highlighted a gap in identifying future design requirements for extended space travel, such as for the Constellation program. The anthropometric body measurement data for the 2015 NASA Constellation program for males and females between 35-50 years old were derived from the 1988 Anthropometric Survey of US Army Personnel, through linear regression statistical methods (NASA, 2010; 2007; Tillman, & McConville, 1991).

DISCUSSION

There are a sufficient number of valid existing and emerging anthropometric databases that include body dimension measurements and weight/mass measurements, compiled from data sets gathered within the last 10-20 years, which are representative of a target U.S. pilot population. New scanning technologies along with more sophisticated statistical methods for matching/forecasting valid data from an existing database, represent a significant improvement over legacy 1-D (i.e. tape measure, calipers) body measuring techniques. Body scanning technology has proven to be less expensive, faster, and a more reliable way to measure, especially for large surveys. Although there have been some recent small-scale surveys conducted to gather human strength/control force data, there is a paucity of any current large-scale comprehensive data applicable to aircraft design. A recent report from the Aviation Safety Reporting System (ASRS) provides some insight on the safety implications of continued reliance on outdated human strength/control force data.

The FO was flying a visual approach to landing runway 17. As she approached final she was fast on speed, but ok on altitude. When she flared, speed was decreasing, but she still *had some power in, and the aircraft floated. I told her to get it down quick. The mains touched then the nose came down. when she reached for the power levers, she got them caught on the gate and couldn't get them into reverse. When she did get them into reverse she couldn't pull it back into full reverse. I took over the controls as the nose-wheel went off the end of the runway (we were just about stopped). Since the nose went off I added power and kept the plane moving and taxied it back onto the runway. No lights or anything else was damaged. causes: lack of strength by FO, and bad setup on approach.* (ASRS ACN: 291906)

Furthermore, a recent report from the FAA Accident and Incident Database provides some insight on the safety implications of continued reliance on outdated body dimension data.

The helicopter lost power while in cruise flight at 1000' AGL and the student pilot landed hard in the center of Chapin, SC high school football field collapsing the landing skids of the helicopter. minor injuries to passenger's wife . After further investigation it was determined the a/c lost rotor speed due to the fact that the female occupant slipped her left arm out of her shoulder strap to be able to reach forward to make a GPS range adjustment. as she slipped her arm out of the left shoulder strap, the strap caught the idler pulley/clutch T-handle (located between the two seats at shoulder height) when she leaned forward this caused the rotor to become disengaged by pulling the T-handle forward. thus disengaging the clutch. (Rpt#20050924021629I, 24 September 2005)

The ability to effectively and efficiently gather anthropometric data on a periodic basis has been demonstrated, hence non-availability of anthropometric data that is representative of the target population should be considered a safety hazard that should no longer be accepted as a limitation in aircraft design.

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