Fitting the Man to the Machine: The ADAPT Project

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Introduction

The size and shape of humans have been changing dramatically over the last 100 years. People have grown taller and fatter, with relatively longer legs and higher waist–hip ratios. Aircraft, on the other hand, are often designed to last for several decades. Consequently, there is an increasing mismatch between the size and shape of crewstations and the size and shape of aircrew. This mismatch has been exacerbated by the introduction of female aircrew. This is particularly true in Australia, where the most recent anthropometric survey dates from the 1970s, and crewstations are designed based on overseas specifications. In the past, anthropometric surveys have been conducted with the traditional instruments of tape measures and calipers. The Australian Defence Anthropometric Personnel Testing (ADAPT) project is taking a different approach, using a combination of 3D whole-body scanners, laser scans of crewstations, human modelling and animation software, and mathematical optimisation, to refine anthropometric recruitment standards for the RAAF. The project will additionally improve clothing and equipment fit, human functionality in aircraft, reduce the risk of injury and provide the opportunity to open recruitment to a wider selection of applicants. The work done in the ADAPT project has applications across the ADF, and will spill over into many civilian fields.

Background

Because of their enormous development costs, most of the aircraft used by advanced air forces around the world are designed to last for 30 years or more. For instance, the Iroquois has been in service for 39 years, the Caribou for 43 years and the F111 for 32 years. The 707, while not in RAAF service the whole time, has been flying since 1959. Over that span of years, however, human bodies change. In most countries, adult human body size has been increasing by about 1 cm in height and 1 kg in weight each decade for over 100 years (Meredith, 1976). Shape has also been changing. Almost all of the increase in height has occurred in the upper leg (and almost all the increase occurs before two years of age), which has obvious implications for ejection safety. Waist girth has been increasing at a far greater rate than hip or chest girth. The changing ethnic mix of most populations, and the integration of women into wider workplace and operational domains have also changed the body size and shape mix. The consequent mismatch between man and machine is not limited to the defence area. In the US, sports stadiums have had to install tiers of extra-wide seats to accommodate obese patrons; furniture sizes such as bed lengths and door heights have increased *pari passu* with the secular increase in body size; clothing size–shape templates are being revised. There is even talk of increasing the size of soccer goals and the height of basketball rings.

The most recent anthropometric survey in the ADF dates from 1977, involving 30 measurements on 3000 male personnel (Hendy, 1979) and a survey of aircrew goes back to 1973. Human factors experts now rely heavily on US data, mainly from the US ANSUR survey in 1987. The need for new anthropometric data was the driver for the establishment of the ADAPT (Australian Defence Anthropometric Personnel Testing) project, initiated and financed by the Australian Defence Force, and conducted by a consortium including the University of South Australia, engineering firm Sinclair Knight Merz, software engineers Permian, the University of Ballarat and the Australian Institute of Sport. The aim of the project is to conduct an anthropometric survey of young Australians, and to use the data to revise recruitment guidelines for aircrew. The data may also be used to optimise the cockpit human–machine interface and improve the fit of clothing and equipment.

Crewstations are also scanned as part of this project, and the human and aircraft scans brought together in a human modelling program that permits an evaluation of the fit in static and active situations.

Recruiting anthropometry standards have been in place for many years without change. The limits are a standing height of 163 to 193 cm, and a maximum sitting height of 100 cm, maximum buttock to knee length of 63.5 cm and maximum buttock to heel length of 112 cm. These are no longer based on any fit requirements in current aircraft. Standing height is of only indirect relevance in a seated posture, and the lower limit of 163 cm eliminates over 40 per cent of young females. The need to update these standards to accurately reflect fit in the modern ADF platforms has become acute.

Methods

Traditional methods

Previous anthropometric surveys have used physical measurements made with tape measures and calipers. Traditionally, cockpit accommodation guidelines have been established using live subjects in a cockpit, with dimensions measured physically using tape measures. Usually, about 30 subjects representative of the anthropometric extremes of a population are dressed in flight gear and assessed for fit in a cockpit based on a number of criteria specific to the particular cockpit and aircrew role. Critical crewstation dimensions (such as the distance from the back of the seat pan to the instrument panel) can then be compared to corresponding body dimensions (such as the buttock to knee length), and judgments made as to what body sizes and shapes can be accommodated. Crewstations can then be designed to accommodate all but the most extreme bodies. Typically, an aircraft fit assessment requires access to an aircraft for several weeks, however access to aircraft in the ADF for that length of time is problematic. To capture the distribution of body measurements in the general population, it is necessary to measure a large number of subjects from the population eligible for recruitment.

These methods suffer from a number of limitations. Physical measurements are time-consuming and invasive. The American ANSUR survey required up to three to four hours of measurement time for each subject (Clauser, et al., 1988). They also require highly-trained and experienced anthropometrists to be sufficiently accurate. More importantly, only a certain number of dimensions can be captured, and those dimensions might not capture the three-dimensional shape of the body in relevant ways, or in ways which might in future become relevant (for example, with the introduction of a new piece of equipment). The same applies to physical measurements of crewstations. Even the obvious idea of capturing and comparing critical body and crewstation dimensions is mined with assumptions about which dimensions are critical. It may be that some pilots will have buttock to knee lengths which allow them to easily clear the instrument panel in case of ejection, but have hips which are too wide to fit into the seat. Finally, physical measurements procedures do not allow dynamic modelling—simulating the movements aircrew need to make during routine and critical operational tasks.

The ADAPT methodology

The ADAPT project developed a different methodology from previous human factors work in this area. It uses virtual rather than physical measurements of aircrew and crewstations; it matches every body with every crewstation, rather than relying on 'extreme bodies'; and it permits dynamic task modelling. These advances have been made possible by the development of new hardware and software.

3D whole-body scanning

Three-dimensional whole-body laser scanners produce 'digital statues' of human bodies. A low-power, eye-safe laser passes down the body in about 10 seconds, and the reflected light is captured by CCD-coupled video cameras. Computers convert the information into a 'point cloud' of 600,000 points representing the surface of the body (Paquette, 1996). After being cleaned up, the points are joined up into tiny polygonal facets, which can then be smoothed and 'rendered' (the metaphor is from plastering) into a seamless surface. The ADAPT project will scan 1410 young Australians from the general population, with the age (18–30 years) and qualifications typical of the aircrew recruitment population. It will also scan up to 600 serving aircrew.

Landmarks associated with bony or fleshy prominences on the body can be identified either from physical markers or by automatic software identification. Critical body dimensions are defined in terms of these landmarks. This hardware–software solution generates an extremely high-resolution, reusable representation of the body. Special measurement extraction software can be used to determine point-to-point distances, contour distances across the body surface, cross-sectional and surface areas and volumes.

Crewstation scanning

Technologies for 3D scanning of objects are better established. For close work, the Faro Arm is typically used. A triple jointed arm allows a scanning head to be moved like a paintbrush over the object's surface, creating as it does so a 3D image of the object. Individual movable objects, such as the pedals, collective and cyclical can be stored as separate files, as can individual hard points. The ADAPT project will scan 39 crewstations in a range of fast jet, transport and rotary aircraft. Of these, 30 will be used in accommodation modelling. All the scans will be high resolution 3-dimensional digital images of the crewstation which will provide the opportunity to assess the impact of any proposed changes to the crewstation on fit and operability.

Human modelling programs

In the early 1960s computer aided design (CAD) software became available, and aerospace and automotive manufacturers saw the potential for much of the design process to take place in a virtual environment. The development of CAD modelling software meant that designs could be created on a greatly reduced timescale, while at the same time allowing for the exploration of a wider range of design solutions. Recognising the potential to accelerate the design process and at the same time optimise the human machine interface, digital human modelling tools emerged in the late 1960s in the automotive and aviation industries. With the increasing power of computers, the capabilities of modern human modelling tools have increased dramatically compared to their predecessors developed in the 1960s and 1970s. The most modern day tools, such as *Safeworks*, *Ramsis* and *Jack,* are widely used in the automotive, defence and manufacturing industries, by organisations and companies like NASA, the US Army and General Motors. These tools have human models that have complex kinematic linkages, joints that obey physiological range of motion restrictions and a geometric shell that closely resembles the human shape. The model selected for this project was *Jack*, which was originally developed at the University of Pennsylvania in the 1980s. Using an additional *Jack* software module, the scan of a human can be imported into the *Jack* environment. Furthermore, the equipment the aircrew typically wears can be digitised and positioned on the *Jack* human.

Human Modelling Programs (HMPs) create human models (manikins) which can interact with a virtual 3D environment. Manikins obey the kinematic principles which govern real human movement (range of motion, joint dependencies), and so can simulate a wide range of tasks in a naturalistic way. The linkage skeletons of manikins can be rescaled using the extracted measurements of real people, and 'fleshed out' based on height and weight. It is also possible to directly import 3D scans to create a plausible flesh envelope. However, the modelling remains less than perfect; in particular, flesh compression has not been incorporated adequately. Hard equipment items can be scanned separately and 'bolted on' to the manikin. Virtual environments are imported into HMPs from computer-assisted design programs or from scans of real scenes.

The overall project methodology is shown in Figure 1. The left-hand side of the flowchart shows the capture of bodies, and the right-hand side the capture of crewstations. Measurements derived from scans and from HMP representations can be compared with physical measurements at a number of points.

Mathematical modelling

The combination of 3D body scanners, measurement extraction software, object laser scanners and HMPs makes it possible to verify the accommodation and task performance of any individual in any crewstation. However, this process requires a 3D body scan of the individual and processing through the human modelling software. More widespread assessment of potential recruits, such as might occur at the first contact in a ADF 'shop front' environment requires a set of simplified anthropometric guidelines.

To arrive at these guidelines, it is important to isolate a few easily measured anthropometric dimensions which are strongly predictive of whether an individual will fit in a crewstation or

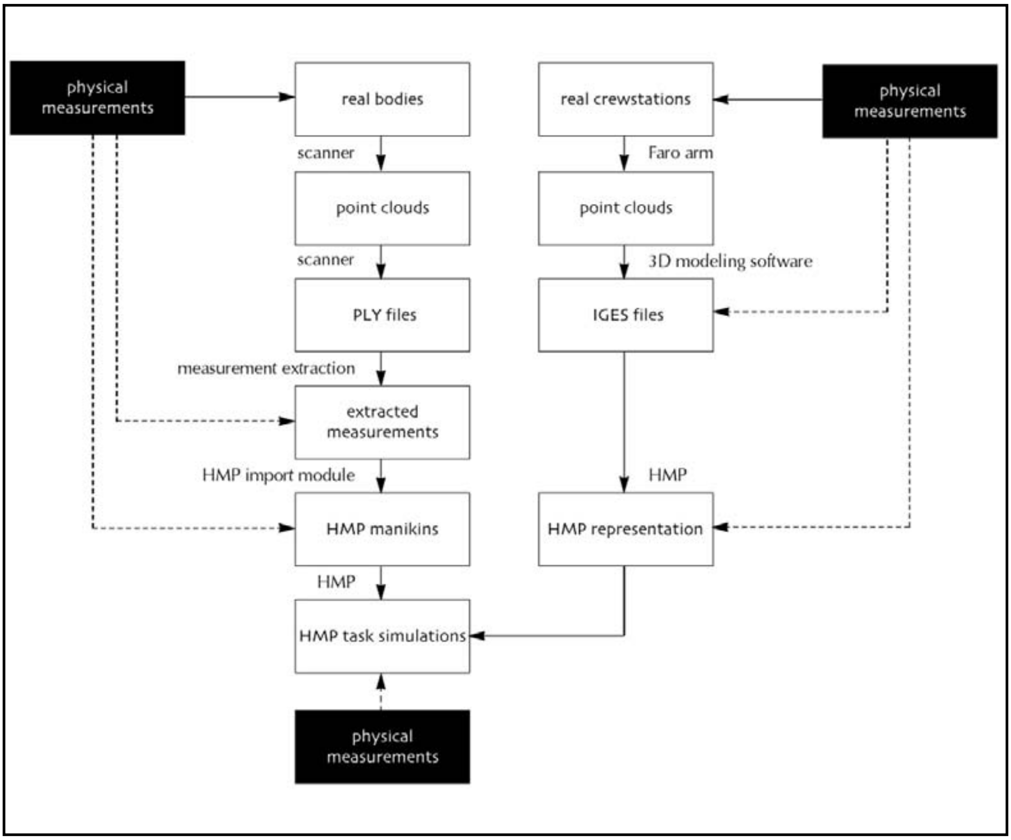

Figure 1: The overall project methodology.

group of crewstations. A number of mathematical techniques can be deployed to determine this set of measurements, including statistical pattern recognition, discriminant function analysis, and optimisation. Using these tools, it is also possible to plan an 'anthropometric career path' for any individual. For example, a recruit may not be able to fit into fast jets, but may be suitable for transports or rotary wing aircraft. The mathematical modelling component of the project will also identify 'bottleneck' aircraft in pilot training, and highlight specific areas of crewstations which cause accommodation problems.

Accuracy and validity

A process as complex as this involves many assumptions. Scanned bodies and crewstations are represented as rigid objects, whereas in reality flesh and seats are compressible. Human joints are much more complex than the linkage models used in even the most advanced HMPs, and people use many different movement patterns to accomplish the same task and exhibit a wide spread in joint ranges of motion. What confidence can we have that the representations of bodies and environments in HMPs match reality?

The ADAPT project has conducted meticulous testing of the accuracy of each step in the pathway shown in Figure 1, including the measurement of task performance in real crewstations.

When compared to physical measurements taken by expert anthropometrists, measurements extracted from 3D scans differ by an average of 5 mm (95 per cent confidence limits –9 to +20 mm). The dimensions of the rescaled manikin in the HMP differ by an average of 7 mm (95 per cent confidence limits –16 to +31 mm), and task simulation is accurate to 5 mm on average (95 per cent confidence limits –35 to +46 mm).

The key deliverables will be new anthropometric standards, and two application programs—one that will permit the rapid assessment of an applicant's capacity to meet the new standards and a second that will allow the ADF to reproduce all the modelling steps as new people, crewstations or equipment are contemplated in the future. Recruits who meet the broad physical requirements and proceed further with their applications will be body-scanned and fed into the modelling of this second application. The recruits' ability to function in all platforms can then be, almost instantly, assessed.

Future directions

Clothing and equipment

One of the major drivers of 3D body scanning technology has been the apparel industry (Istook & Hwang, 2001). It is well-known that both men and women have great difficulty in finding well-fitting clothes, in part because the size–shape templates recommended by groups such as Standards Australia do not accurately describe the actual shapes of 3D bodies. Using data from 3D scanning, our recent analyses suggest that lack-of-fit in standard women's clothing can be reduced by 40 per cent with template redesign. Data gathered in the ADAPT project will allow us to rationalise inventories of clothing and equipment for aircrew, and to redesign size–shape templates so as to produce better fits. Ultimately, 3D scan data can be used to create 'mass customised' perfect-fit garments, where computerised pattern cutters, interfaced with 3D scanners, can automatically create personalised templates. Several military centres in North America and Europe are already using automated and semi-automated uniform production systems based on 3D scanning.

Human–machine interface optimisation

Using HMPs along with valid anthropometric data on current aircrew and potential aircrew, the design of cockpit interfaces can be optimised for aircraft upgrades and acquisitions. HMPs can locate specific areas of lack-of-fit, such as canopy or instrument panel clearance, modelling can identify anthropometric design flaws in existing crewstations. Using CAD models as environment inputs, samples can be run through a variety of alternative crewstation designs, to determine which provide the best fit. In this way, the model provides the design of new crewstations. The focus of the ADAPT project has been on aircraft, but the same methodology can be applied to naval vessels and land vehicles. In addition, three-dimensional scanning technology has been applied to the design of mass transport systems, factory production lines and functional buildings such as airports.

Health applications

The ability of 3D body scanning to generate contour, girth, cross-sectional area and volume measurements has some interesting potential medical applications. Scans have already been used to assess the proportion of body surface area affected by burns. They can be used to test the usefulness of abdominal girth, cross-sectional area and volume measurements in predicting the risk of diabetes and cardiovascular disease. Body and segmental volume estimates can be used to quantify œdema, and to assess the effects of dietary and training interventions.

Conclusion

The human body has changed dramatically in size and shape over the last century, with the most significant changes occurring in the last 30 years. These changes in height and girth particularly have meant that the most current data taken in the 1970s is no longer valid. Poor quality anthropometric data has proven problematic, especially for aircraft designers and the flying clothing and personal safety equipment industry in particular. The Australian ADAPT project has been developed to remedy this situation. Using scanning, measuring and modelling techniques, ADAPT will catalogue 39 aircraft crewstations and over 600 aircrew (from all Services) to provide a larger, more comprehensive database that can be used for recruiting, aircraft cockpit and clothing design and to update aircrew and aircraft standards.

Tim Olds is a Professor with the School of Health Sciences at the University of South Australia. He is currently Project Director for the Australian Defence Anthropometric Personnel Testing (ADAPT) study. He has research interests in mathematical modelling of sports performance, anthropometry, and secular trends in the fitness, fatness, food intake and physical activity of children.

James Ross completed 26 years as a Medical Officer in the Permanent Air Force in January 2007, and is now in the Specialist Reserve. He had postings in clinical, command and policy and with the USAF. He is a specialist in Occupational and Public Health Medicine. One theme in his career was Human Systems Integration, and specifically anthropometry. He was and remains the Project Director for the Aircrew and Crewstation Anthropometry project. He is now based in Singapore.

Peter Blanchonette is a Senior Research Scientist at the Defence Science and Technology Organisation. He joined DSTO in 1995 after completing a PhD in Applied Mathematics at Monash University. During his time at DSTO he has worked across a broad range of areas, including operations research, software engineering, simulation, ergonomics, vision, human machine interface assessment, anthropometry and human modelling.

David Stratton is a Senior Lecturer in the School of Information Technology and Mathematical Sciences at Ballarat University. He is currently Technical Director for the Australian Defence Anthropometric Personnel Testing (ADAPT) study. The human modelling in the ADAPT study fits into a range of modelling investigations—with a strong emphasis on the application of Distributed Simulation techniques to this modelling.

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